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Developing a System Dynamics Model of the El Paso Water Resources System

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In 2011, I was admitted to the University of Texas at El Paso (UTEP). However, it was not until four years full of complications such as visa issuance problems, and family loss that I was able to come to the United States. Today, I present the product of not only my own academic effort, but also the product of my professors and family.

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Last but not least, I want to thank my wife for her patience and support throughout the time we were apart and for being such a strong woman in dealing with difficulties on her own. Now that we are about to reach a year of being married, I want to dedicate this work to her fortitude and persistence.

Developing a System Dynamics Model of the El Paso Water Resources System

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ABSTRACT

The city of El Paso is growing rapidly, increasing water demand in a water-scarce region. In this research system dynamics modeling is applied to simulate dynamic behavior of the El Paso water resources system in order to investigate the city's portfolio based upon a supply-demand side and demand side management approach. System Dynamic simulation involves several steps, including system conceptualization, data collection, simulation model development, and model verification and sensitivity analysis. A high-level conceptualization of the El Paso water resources system is presented, including withdrawal sources, water and wastewater treatment facilities, water demands, and flow linkages are will be presented. The conceptual model provides the basis for quantitative stock-and-flow model, which is developed under development using data inputs and data from water local management agencies. The modeling process facilitates understanding of potential vulnerabilities to of the system and likely causes of failure, thereby offering a useful platform for water resources planning and management at the strategic level.

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Chapter 1 INTRODUCTION

Natural resources are essential for socio-economic development and the well-being of people. Exploiting these valuable resources beyond their carrying capacity can have serious harmful environmental and public health impacts on a society's development. Modern engineering approaches have made fresh water resources readily accessible, triggering their overexploitation across much of the planet. In addition, population growth, economic development, and climate change place additional stress on this vital resource (Winz & Brierley, 2009). To fulfill the requirements of sustainable development, the efficiency with which resources are utilized should be improved through better management of natural resources (Mirchi et al., 2014). Due to the alarming rate of water exploitation, it is extremely important to devise adaptive management approaches to use water resources sustainably.

In general, the main concerns associated with fresh water resources management are water supply, water demand, resource allocation, and environmental impacts of overuse. Understanding water demand and supply relationships as a practical indicator of water availability for human use and for maintaining ecosystem services is an important component of comprehensive water management studies. As a result, depletion of water resources can be delayed and potentially avoided through timely adaptation of water resources management systems using supply-side and demand-side water management strategies.

Modeling the dynamic performance of water resources provides a reliable platform for exploring practical management strategies, and understanding the adaptive capacity of the system. Effective approaches to generation and use of such tools enable analysts to develop system-specific applications pertinent to the context of the water resources management problem at hand. Such

exercises present an opportunity to test our understanding, examining its implications and contradictions by formulating and evaluating hypotheses (Winz & Brierley, 2009).

System Dynamic (SD) is a simulation method that facilitates the application of systems thinking to water resources problems (Mirchi et al., 2012). Using simultaneous equations that describe dynamic change, this approach facilitates analysis of the behavior of the modeled system and its response to policy interventions. Such dynamic analysis aids in evaluating system performance under scenarios of system change. As long as the model is able to represent reality reasonably well, the modeling process and its outcomes can be used to improve our understanding of the problem as a necessary step towards sustainable and effective change. By capturing the feedbacks within and among subsystems, SD simulation helps improve understanding of potential unintended consequences of system perturbations (i.e., management options), thereby offering a suitable platform for predictive modeling for sustainable water resources planning and management at the strategic (Mirchi et al., 2012).

Taking feedback mechanisms into account is crucial for understanding the long-term dynamic behavior of the water resources system. System dynamics simulation provides a useful feedback-based modeling platform for water management policy analysis in the El Paso area. The city of El Paso is growing rapidly, increasing the water demand in an area where water resources are already severely stressed. The city's population is projected to exceed 1 million people by mid-century (Hoque, 2014). Climate change is significantly increasing the pressure on water resources in the Desert Southwest by reducing snowpack and timing of flows in the headwaters and increasing demand due to heightened temperatures and greater evapotranspiration (the sum of evaporation from water sources and transpiration from plants) (Garin, 2013). To cope with the chronic water scarcity, El Paso has pioneered innovative urban water management strategies to provide residents

with reliable water supply using rigorous water conservation programs (e.g., low flow fixtures, efficient lawn irrigation, and xeriscaping), wastewater reclamation for outdoor purposes, groundwater desalination, and pricing schemes (i.e., increasing block rates).

This thesis reports on the application of system dynamics modeling to El Paso's water resources system. The main objectives of this research are as follows:

- Develop a systems dynamics model of water resource management in the El Paso area based on a high-level conceptual model of the system's main components and their interactions (i.e., withdrawal sources, lumped water and wastewater treatment facilities, and flow linkages). An alpha version of the model was developed as a descriptive stock-and-flow model using Vensim DSS 6.4 (Ventana Systems, 2010), an object-oriented software package for building large and complex SD models.
- Evaluate the model performance through behavior replication tests and sensitivity analysis to ensure key system functions can be reproduced to provide a basis for performance analysis in terms of system reliability and vulnerability.
- Apply the model to analyze the impacts of a set of water management policies, including
  Scenario 1: Use of reclaimed water for agricultural purposes
  Scenario 2: System-wide use of reclaimed water
  Scenario 3: Groundwater conservation
  Scenario 4: Extreme stress without interbasin transfer
  Scenario 5: Extreme stress with interbasin transfer.

The model was used to simulate the interactions between urban, agricultural, and environmental subsystems in terms of the flow of water in the El Paso water resources system, which is governed by long-term change in demand and water availability.

Chapter 2 METHODOLOGY

2.1 System Dynamics Modeling

The inception of system dynamics simulation as a feedback-based modeling approach dates back to the 1960's (Winz & Brierley, 2009). The approach facilitates the implementation of systems thinking paradigm by simulating system behavior while representing the underlying system structure and interconnections of different parts that constitute the system (Mirchi et al., 2012). The method has since been widely used by analysts from various disciplines as a powerful tool to explore the causal relationships forming feedback loops between different components of complex problems. In the past 50 years, system dynamics has become a well-established methodology that has been applied in many different fields, including management, ecology, economics, education, engineering, public health, and sociology (Sterman, 2000). Application of system dynamics in water resources engineering and management has grown over the past two decades (Mirchi et al., 2012).

System dynamics modeling consists of qualitative or conceptual and quantitative or numerical modelling methods (Dolado, 1992). The approach involves several steps, including system conceptualization, simulation model formulation and development, data collection, confidence building through model evaluation using appropriate tests such as behavior replication and sensitivity analysis, and management policy analysis (Albin, 1997; Sterman, 2000; Mirchi et al., 2012). A general description of these steps is given below, and more details are provided in the Model Development Section in Chapter 3.

- System conceptualization

The first step in any system dynamics modelling project is to determine the system structure consisting of positive and negative relationships between variables, feedback loops, system archetypes, and delays (Sterman, 2000). System conceptualization consists of four main steps of defining the purpose of model, defining the model boundary and key variables, describing the behavior and drawing the reference modes of the key variables, and diagraming the basic mechanism and feedback lops of the system that could be responsible for such reference modes of behavior. Causal loop diagraming is a widely used system dynamics qualitative modeling tool that helps gain a conceptual understanding of the system.

- Model formulation

Model formulation includes two main steps of converting feedback diagrams to stock (level) and flow (rate) equations along with inputting appropriate parameter values. Stock-and-flow models facilitate quantitative simulations, which enable the analyst to investigate and visualize the effects of different intervention strategies. In this step, analysists will be able to incorporate various model assumptions, identify uncertainties in regard to system structure, and detect gaps in data availability, all of which promote model transparency (Winz & Brierley, 2009). In this thesis, a stock-and-flow model of water and wastewater treatment facilities and system-level flow linkages has been developed as a tool for simulating the governing processes and management policies.

- Data collection

Like any other modeling exercise, system dynamics models need various input data to represent the system and perform quantitative simulations. The main data requirements of the system dynamics model of El Paso's water management include system operations data such as source-

specific supply capacity, sectoral demands, and consumptive use coefficients, among others, to run the model at monthly time scale.

- Model evaluation

Model evaluation encompasses testing the dynamic hypothesis (i.e., system structure) of simulated models, testing the model's assumptions and behavior and sensitivity to perturbations. Model evaluation can be accomplished through structure test, behavior tests, and sensitivity analysis under extreme conditions. Structure tests help determine how well the structure of a model represents the structure of the system in reality. Behavior tests help determine how consistently model outputs match real world behavior. This can either be based on available time-series data or the correlation of mental models with established reference modes (Winz & Brierley, 2009). The usefulness of the former clearly depends on the quality of the available historical data, while the latter necessitates a substantive and coherent collective mental model of the system. Furthermore, extreme values simulations within a sensitivity analysis framework will help determine whether system dynamics models are set up correctly and render reasonable system behavior when certain extreme cases are simulated.

- Policy analysis and implementation

System dynamics modeling is ultimately aimed at providing valuable insights into the problem structure of dynamically complex processes that have important short- and long-term effects. This aim is typically achieved by analyzing a set of management policies of interest. Policy analysis and implementation is characterized as simulating the system's response to different policies and translating study insights into an accessible form.

2.2 Water Management in El Paso

2.2.1 El Paso Area

The City of El Paso is the sixth largest city in Texas with an estimated population of 787,208 as of 2015 (EPWU, 2014). With an average daily temperature of almost 70º and over 300 days of sunshine each year and an average annual rainfall of 8 inches (EPWU, 2014), El Paso is an exemplar of water scarcity in the southwestern U.S. Located in the Chihuahuan Desert, the city has three main potable water supply sources, namely surface water from the Rio Grande River and groundwater from two aquifers, the Hueco and Mesilla Bolsons. El Paso shared borders with the state of New Mexico and the country of Mexico in a metropolitan area where more than 2 million residents are mainly distributed between El Paso, Texas, Cuidad Juarez, Mexico, and Las Cruces, New Mexico.

In 2013, El Paso produced about 362 billion gallons (112,000 acre-feet) of potable water. The Hueco Bolson provided 67% of total demand followed by the Mesilla Bolson (24%) and the Rio Grande River (9%). El Paso also uses reclaimed water to meet non-potable water demands. Over 8,000 acre-feet of water are distributed annually to customers for industrial uses and turf irrigation (EPWU, 2014). The total water production from capacity groundwater in El Paso including brackish and Hueco and Mesilla bolsons is about 164 MGD (EPWU, 2014). The amount of surface water that is available each year is variable depending on drought condition but estimated to be around 100 MGD (EPWU, 2014) .

2.2.2 Water Demand

The main water users in the El Paso area can be classified into urban and agricultural. The urban water demand can be sub-categorized into domestic, industrial, commercial and outdoor demands. The definition of each water demand sector is given below (TWDB, 2015):

- Domestic

  Domestic water uses in El Paso are categorized as single-family and multi-family residential. These categories are based on the similarity of their water use pattern. Water that is delivered to single-family residences is used for indoor and outdoor purposes. Multi-family residential use is defined as multiple separate housing units within one residential complex where water is mainly used indoor.

- Industrial

  Water that is used for power generation or designated to convert material from a lower order of value into forms having greater usability and commercial value.

- Institutional

  All facilities like schools, universities, churches, hospitals, nursing homes, prisons, and government facilities dedicated to public service are considered institutional regardless of ownership.

- Commercial

  Commercial use is defined as the use of water by a place of business, such as a hotel, restaurant, or office building.

- Outdoor

  Outdoor water use is categorized as water supply for irrigation of parks, golf courses, and landscapes.

- Agriculture

  Agricultural demand includes both beef industry and irrigated farming which are the main agricultural economic activities in Far West Texas.

2.2.3 Surface water

The Rio Grande River, which originates in southern Colorado and northern New Mexico, is managed at Elephant Butte and Caballo reservoirs to meet urban and agricultural demands in southern New Mexico and El Paso area. The region also experiences occasional flash-floods due to intense rainfalls that fall on parched terrain during monsoon season. El Paso has surface water right transfer agreements with El Paso County Water Improvement District No.1 which manages agricultural water. Currently, the city's water rights through leasing of agricultural water from the Rio Grande Project amount to about 70,000 AF/yr (EPWU, 2014). El Paso's surface water treatment plants have a combined capacity of 112,000 AF/yr (100 mgd), which are used to produce treated surface water during irrigation season when releases are made from the upstream reservoirs (EPWU, 2014).

2.2.4 Groundwater

Groundwater from the regional aquifers serve as El Paso's primary source of water supply during non-irrigation season and they play a critical role by supplementing surface water during irrigation season, especially in drought condition. Groundwater overdraft causes groundwater table drawdown, which is an important indicator of unsustainable water withdrawal. As groundwater table decline continues, water withdrawal from deeper wells will become increasingly expensive due to higher energy needs. Groundwater table decline in the El Paso area has been a major driver of water conservation, wastewater reclamation, and aquifer recharge practices that are aimed at mitigating groundwater depletion. El Paso reached its peak annual groundwater withdrawal of 23

billion gallons (86 million m3 or 70.5×10^3 acre-feet) in 1990 and thereafter continuously reduced its pumpage to 10.6 billion gallons (40 million m3 or 32.5×10^3 acre-feet) in 2009 (Sheng, 2013).

The Hueco Bolson aquifer system in southern New Mexico, Far West Texas, and Northern Chihuahua, Mexico has a surface coverage of approximately 6,475 km^2 an estimated storage of about 3.1 trillion gallons (11.6 billion m^3 or 9.5 million acre-feet) (Sheng, 2013). The aquifer is naturally recharged by seepage from the Rio Grande and irrigation canals and artificially by reclaimed water through deep injection wells and infiltration basins in El Paso. The annual recharge of Hueco Bolson by Rio Grande is almost 11 billion gallons (40.7 million m^3 or 33.7 $\times10^3$ acre-feet). In addition to the natural recharge, the El Paso Water Utilities has also used reclaimed wastewater to recharge Hueco Bolson under Aquifer Storage Recovery (ASR) plan through a series of 10 injection wells and infiltration basins providing a total artificial recharge capacity of 1.2 billion gallons (4.7 million m^3 or 3.7×10^3 acre-feet) annually.

The Mesilla Bolson aquifer has a surface drainage area of 28,500 km^2, which extends south from southern New Mexico to Far West Texas and northern Chihuahua, Mexico(SHENG, 2013). The net recharge to the aquifer is directly related to the Rio Grande streamflow and the volume of river water used for irrigation. The volume of fresh water in storage is estimated at about 182 billion gallons (560,000 acre-feet) in the Santa Fe and Texas part of the valley, and 320 billion gallons (980,000 acre-feet) in the New Mexico part (Leggt, et al., 1963). Brackish water underlies the fresh water zone impose limitations to groundwater withdrawal.

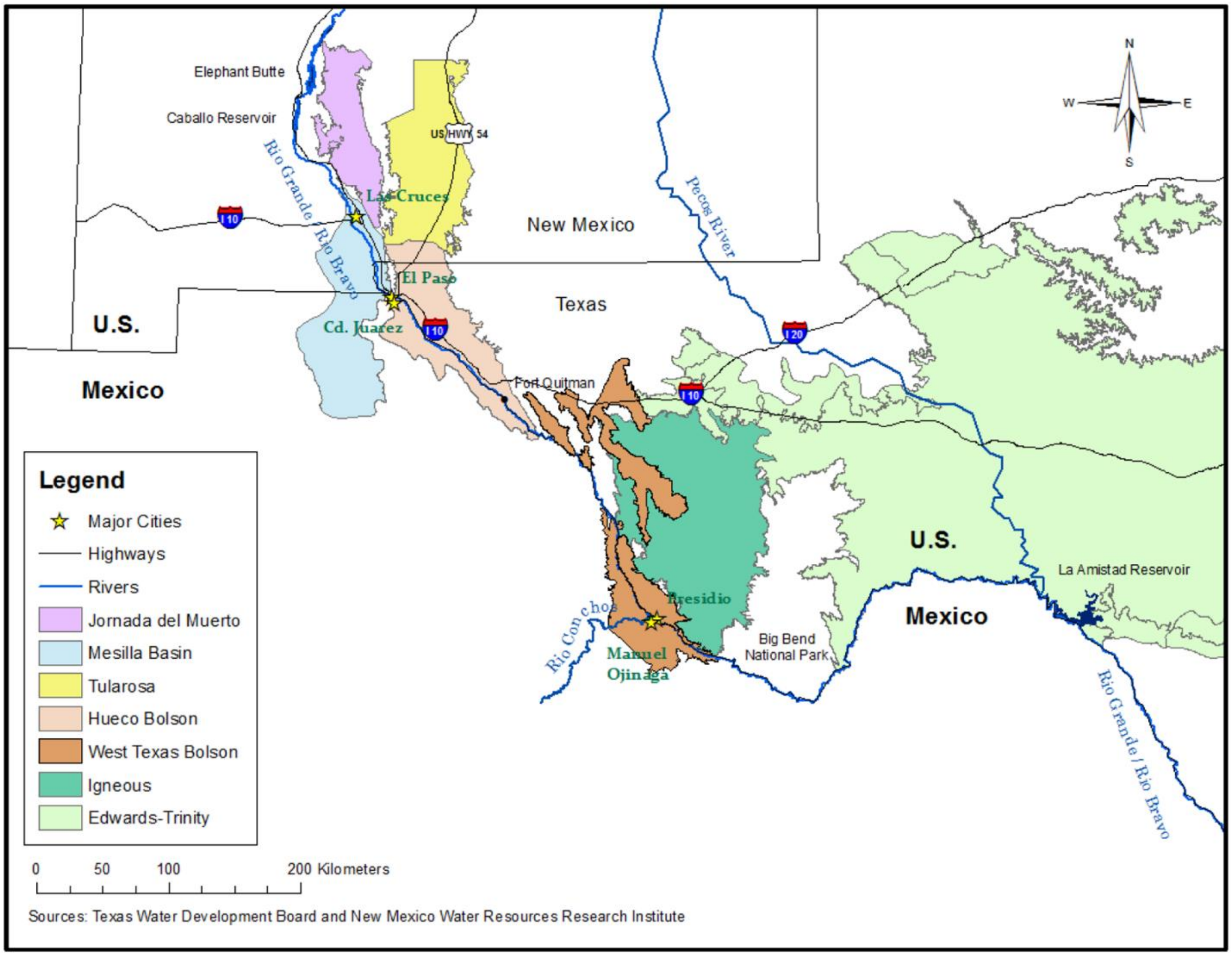


FIGURE 2-1 MAJOR AQUIFERS IN THE NEW MEXICOTEXAS- MEXICO BORDER REGION (Sheng, 2013)

2.2.5 Brackish Water

Since early 1990's El Paso Water Utilities has adopted a portfolio-based water management approach to reduce reliance on groundwater. Inland brackish groundwater desalination is an important technology-based water management strategy in El Paso, allowing the city to buffer the seasonal water shortages and handle the impacts of prolonged droughts. The amount of brackish water in the Hueco Bolson exceeds the amount of potable water by approximately 600% (EPWU, 2014). In 2007, El Paso started producing desalinated water from brackish groundwater as an alternative water source to address concerns about the future availability of fresh groundwater to

sustain the city's socio-economic development. The Kay Bailey Hutchison desalination plant has the capacity to produce over 27 million gallons of fresh water daily (85 AF/day), which has effectively increased El Paso Water's fresh water production capacity by approximately 25%, based on current demand.

2.2.6 Reclaimed Water

Use of reclaimed water is considered a sensible alternative in water-scarce regions to conserve valuable fresh water resources. El Paso Water Utilities has been reclaiming wastewater since 1963. Using non-potable reclaimed water for irrigation helps alleviate drinking water shortage in some service areas where potable water supply is inadequate for meeting the peak summer water demand which is governed by which is driven by landscape irrigation. Also, the use of reclaimed water for irrigation provides flexibility in water management options during a period of drought. Wastewater within the El Paso Water Utilities service area is collected and treated at one of four wastewater reclamation plants using advanced secondary or tertiary treatment to supply over 5.83 million gallons per day non-potable demands at city parks, school playgrounds and sport fields, landscape nurseries, golf courses, street sweeping and street median landscaping, construction projects, fire protection, industrial cooling towers, and industrial processes (EPWU, 2014).

2.2.7 Groundwater Importation

As a long-run supply-oriented management option, El Paso Water Utilities has obtained the rights to withdrawal and transfer groundwater from ranches in Dell City, Texas. Successful implementation of the portfolio-based water management approach has enabled El Paso Water Utilities to postpone interbasin water transfer for 10 years. Thus, this expensive water supply strategy is planned to begin in 2050 with 10,000 AF/yr. In 2060, the amount of importation would increase to 20,000 AF/year.

Chapter 3 SYSTEM DYNAMICS MODEL

3.1 Conceptual Model

The system at its core can be conceptualized using supply and demand components that are interconnected at a high level through flow linkages. A general conceptual model of the system is shown in Figure 3-1. In this figure, supply indicates fresh water sources including groundwater and surface water along with reclaimed water. On the other side, demand includes urban and agricultural demands. Drinking water is produced at water treatment plants, which meet the city's total potable demand. Furthermore, demand and supply are connected through wastewater production and the capacity to produce reclaimed water and direct potable reuse of treated wastewater as a next-generation urban water management strategy. This feedback effect is captured by estimating non-consumptive proportion of water supply use as return flow, which is recycled through wastewater treatment plants. The recycling adds treated wastewater back to the water supply system through artificial groundwater recharge through injection wells and infiltration basins. The recycled water may also be used directly in the form of non-potable reclaimed water or untreated water meet urban and agricultural water demands for purposes other than drinking (e.g., landscape and agricultural irrigation), or it may be further purified through advanced water treatment plants for potable usage.

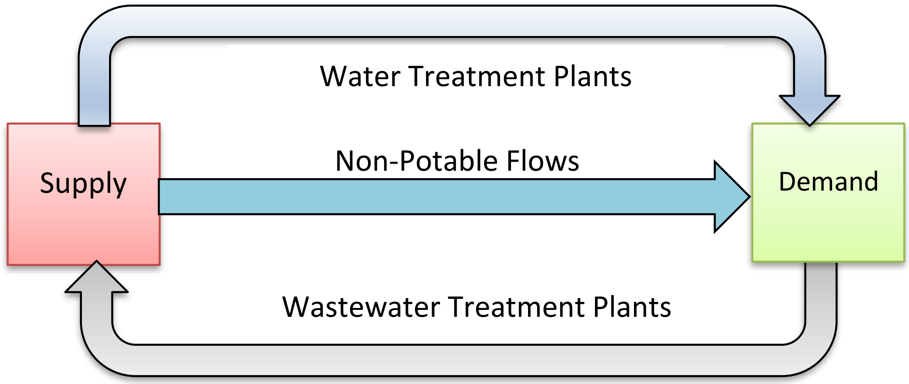


FIGURE 3-1 GENERAL DEMAND-SUPPLY CYCLE

Based on the fundamental systems premise that a system's structure generates its behavior, the next step is to map the supply-demand relationships by developing a sufficiently detailed conceptual model of the El Paso water system. The detailed high-level system structure helps establish system boundary and serves as the basis for representing the water supply portfolio, and disparate demand sectors. The supply side of the system consists of the physical flows of water; the demand side of the system focuses on the distribution of the supplied water. A representative high-level conceptual model of El Paso's water resources system is shown in Figure 3-2. The city's supply sources including river water, groundwater withdrawal from Hueco Bolson and Mesilla Bolson, desalination brackish groundwater from Hueco Bolson, and interlinkages between El Paso Water Improvement District No. 1 and the city are all illustrated. Raw river water and groundwater is routed through three urban water treatment plants, with a fourth plant planned to add advanced purification capability for direct potable reuse of treated wastewater. The water is delivered to various demand sector in the city (e.g., domestic, commercial, industrial, and outdoor). Wastewater is routed back and treated at four wastewater treatment facilities that produce reclaimed water for direct non-potable use, or indirect potable reuse through aquifer recharge, as well as for agricultural uses. This detailed conceptual model of the system was used to develop the system dynamics simulation model in Vensim DSS 6.4.

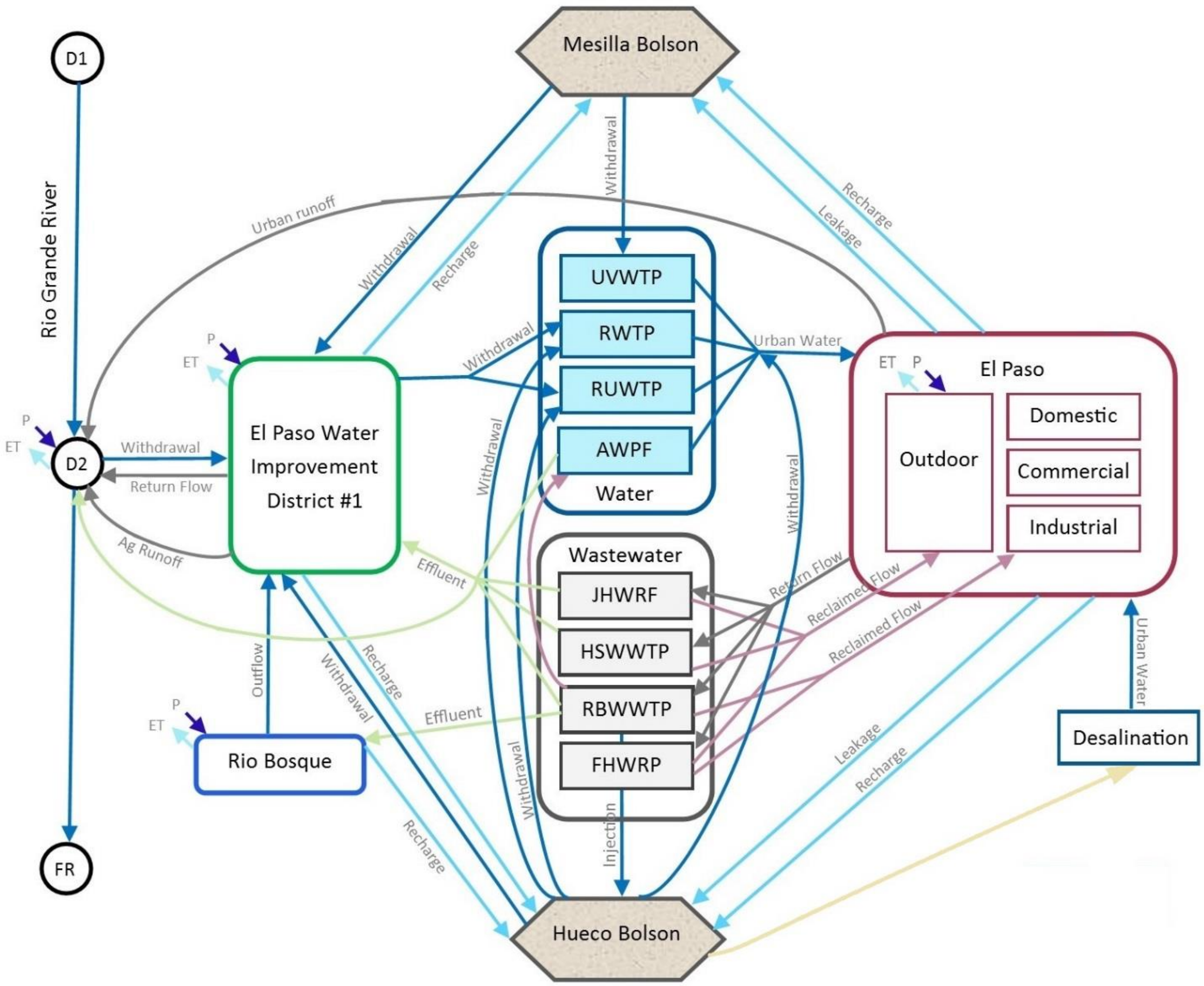


FIGURE 3-2 CONCEPTUAL MODEL OFTHE EL PASO WATER SYSTEM-

ADVANCED WATER PURIFICATION FACILITIES (AWPF) IS CURRENTLY IS UNDER DESIGN

3.2 Causal Loop Diagram

Causal loop diagrams (CLDs) are fundamental qualitative modeling tools in system dynamics modeling. They are developed as a combination of words and polarized arrows to identify the relationships between individual system components and to depict reinforcing or balancing feedback loops that affect system behavior. Positive sign on the arrow from variable A to B means that an increase in A will trigger an increase in B. In other words, A and B change in the same direction. An example CLD of feedback effects associated with domestic water supply within the El Paso water resources system is illustrated in Figure 3-3. Population is a major driver of demand within the system. Demand increases in response to population increase. Demand, in turn, determines the magnitude of fresh water withdrawal for domestic water use, which is comprised of potable and non-potable uses whose effluents are collected at wastewater treatment plants. Returning treated wastewater for inclusion as part of the city's total water supply will reduce the need for withdrawing additional water creating a negative or balancing feedback loop in which freshwater withdrawal is curbed. Similar causal loop diagrams were developed for industrial, commercial, and outdoor demands.

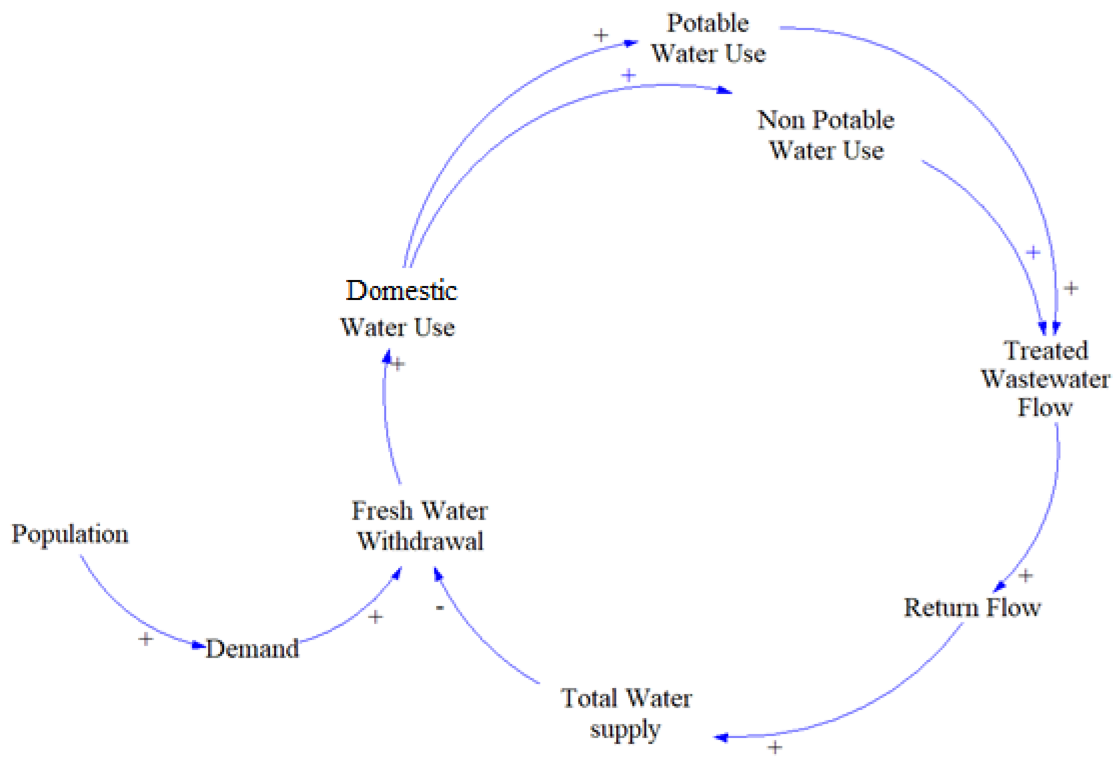


FIGURE 3-3. EL PASO WATER SYSTEM CAUSAL LOOP DIAGRAM SHOWING THE EFFECT OF DOMESTIC WATER USE ON SUPPLY

3.3 Stock and Flow Diagram

In the next step of model development, the system's CLDs (also known as dynamic hypothesis) are translated into a set of stocks, flow links, and information links. Figure 3-4 shows a stock-and-flow (SFD) representation of the water resources system in El Paso. The SFD distinguishes between stock variables, or places water accumulations in the system, and flow variables that regulate the rate at which water moves from one stock to another. In this representation, water is withdrawn from fresh water sources (i.e., surface water and groundwater) and distributed among customers based on water demand. Part of the withdrawn water is treated at municipal wastewater treatment plants. Water reclaimed in the wastewater treatment plants becomes part of water supply,

through treated return flow or it is introduced into groundwater through aquifer storage and recovery (ARS).

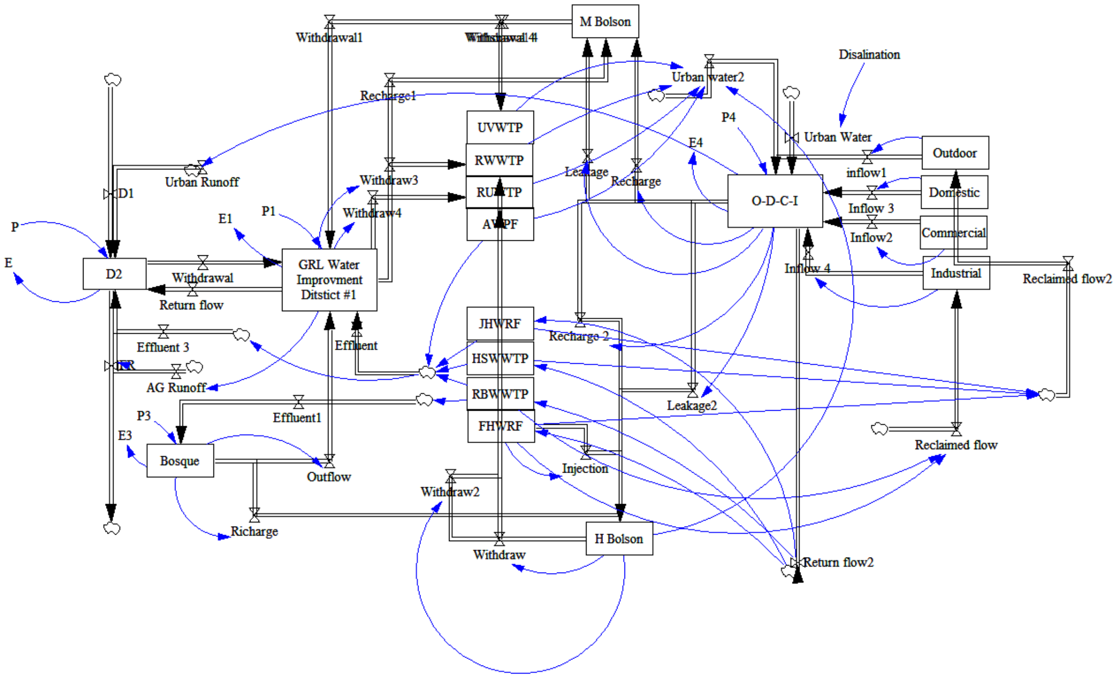


Figure 3-4. El Paso water system model structure. Boxes represent stocks, or accumulations in the system. Double arrows represent material flow which is regulated by rate variables. Single arrows are information flow or feedback between variables.

The system dynamics simulation model was developed based on a simplified version of the SFD shown in Figure 3-4. Critical interlinkages between water supply and demand interaction which were essential to simulating system behavior were included within the system boundary. Individual water and wastewater treatment plants were lumped to represent total urban water supply and total wastewater. Likewise, the two groundwater sources were merged and simulated as single stock. Sectoral demands were considered as simple variables. Furthermore, agricultural demand was added to simulate interaction between urban and agricultural subsystems. Desalination and interbasin water transfer were also included in the model to provide capability for simulating the effectiveness of supply-side management options. These modifications to detailed SFD of the system facilitated the implementation of the high-level system dynamics simulation. The resulting

modified SFD is shown in Figure 3-5, which displays two separate sections representing the supply sources and the demand sectors. The SFD also includes a number of auxiliary variables that are used for introduction of various model equations.

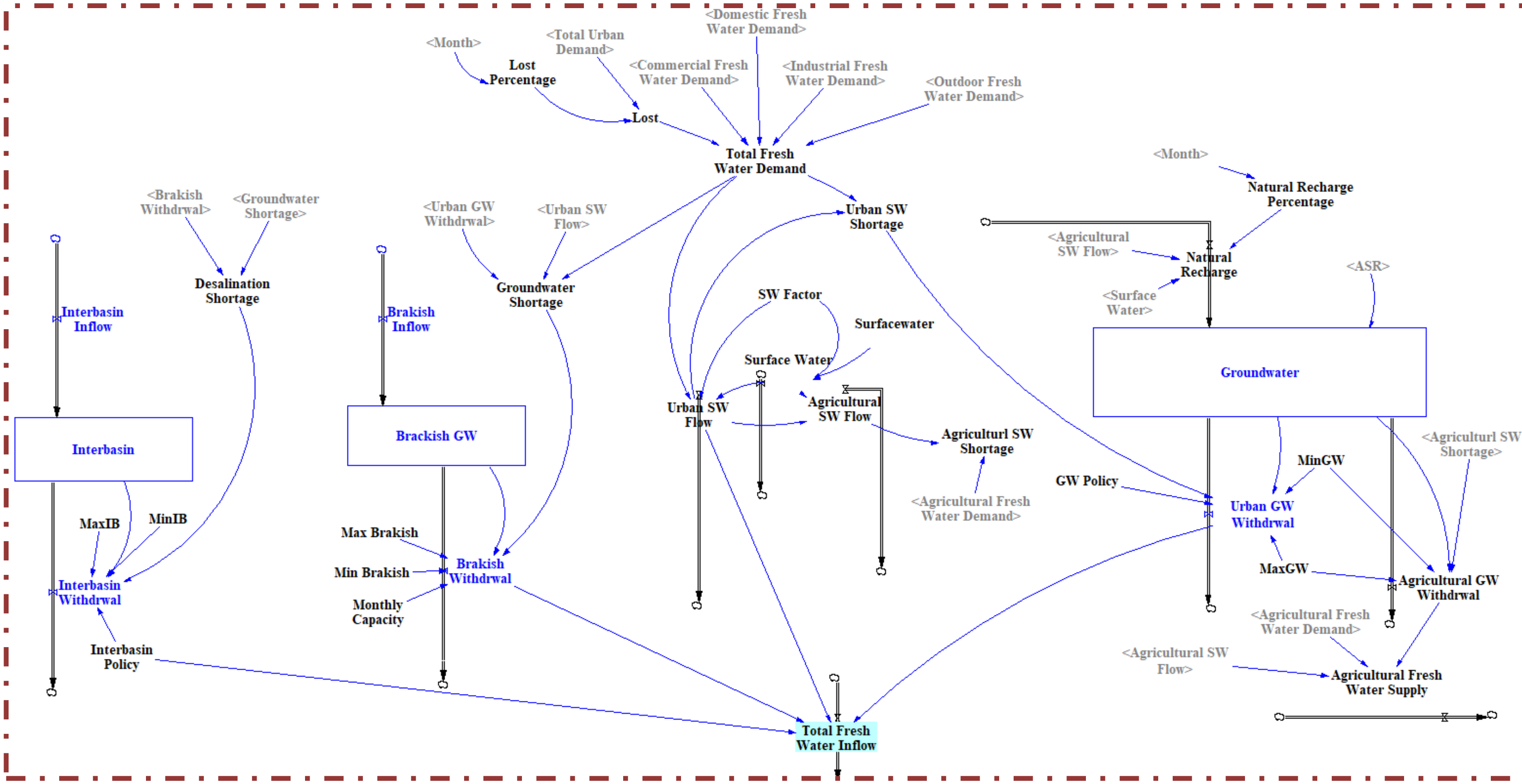


FIGURE 3-5-A EL PASO WATER SYSTEM MODEL STRUCTURE RATIONALIZED, AND SCALED VERSION OF STOCK-FLOW DIAGRAM PURPOSED FOR DEFINED PROBLEM (SUPPLY SECTION)

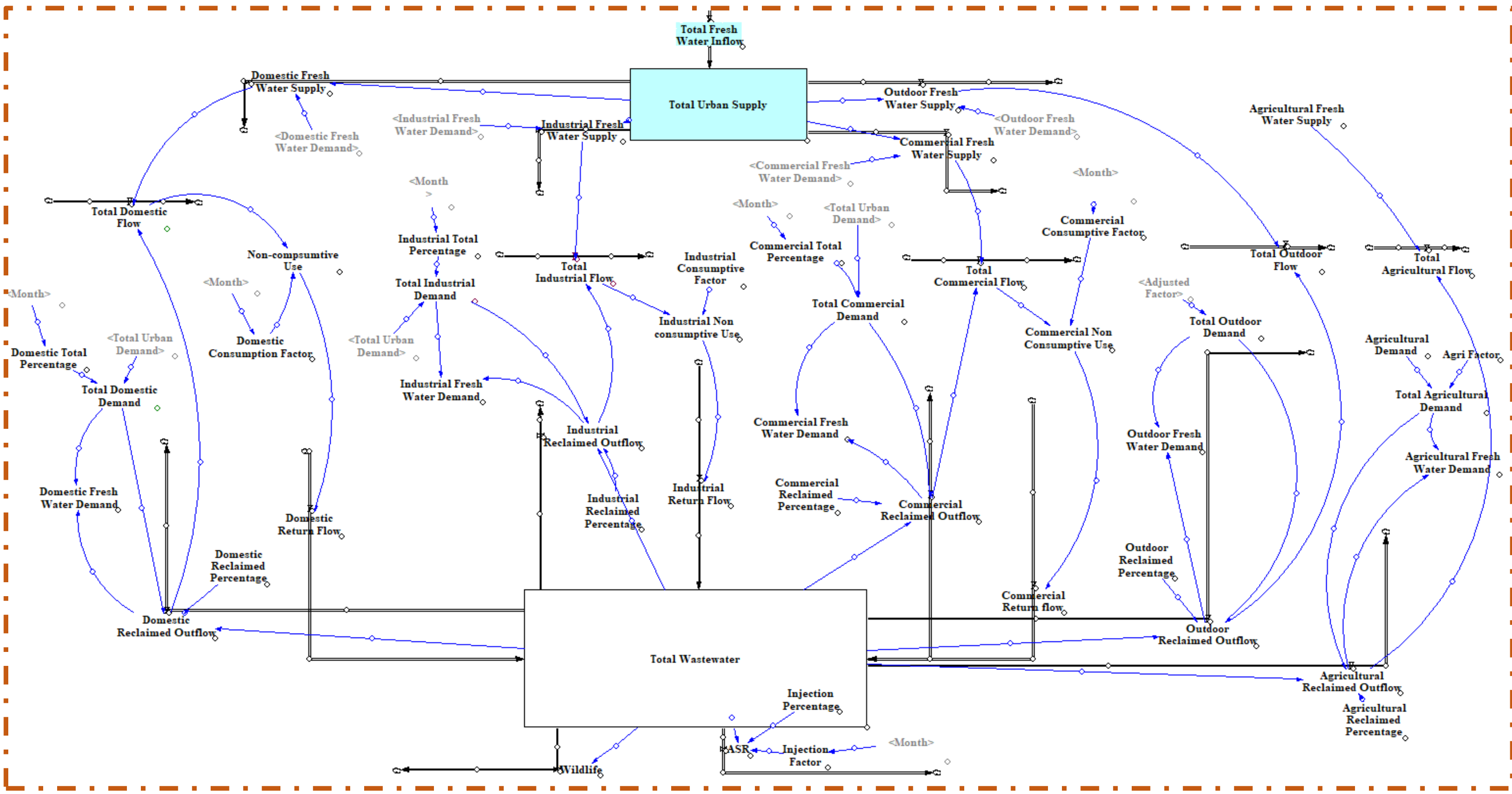


FIGURE 3-6-B EL PASO WATER SYSTEM MODEL STRUCTURE RATIONALIZED, AND SCALED VERSION OF STOCK-FLOW DIAGRAM PURPOSED FOR DEFINED PROBLEM (DEMAND SECTION)

The current version of the system dynamics model has a number of assumptions to account for feedbacks between various supply sources and sectoral demands. The model assumes the surface water is the first source of water to meet the urban and agricultural demands. The second defined water source is groundwater including Hueco and Mesilla bolsons that will provide water when surface water is unavailable during non-irrigation season or during the summer peaks. In the occasions that water demand exceeds the total water supply from surface water and ground water, the system will start using desalinated brackish groundwater. This is a logical assumption because desalination consumes more energy to produce water and it is therefore a more expensive source of water supply as compared to groundwater and surface water. Furthermore, to circumvent challenges associated with unavailability of data to model different sectors of the system, the current modeling effort focuses on a 5-year period (i.e., 2009-2013) using a monthly time step. The working model provides a platform which can be used for analyzing water different water management policies.

Table 3-1 presents monthly urban water demands for the simulation period. Urban water demand was partitioned into urban sub-demand categories by applying monthly disaggregation factors (i.e., percentages of total urban demand), which were obtained from El Paso Water Utilities (Table 3-2) for the period of study, 2009 to 2013 (EPWU, 2014). In addition to representing different sectoral urban demands, the model accounts for water lost in the system due to evaporation or leakages (Table 3-2). The same approach was used for determining consumptive and non-consumptive proportion of the supplied water. Monthly consumptive use factor based on a synthetic study of consumptive uses in the Great Lakes Region of the United States (Shaffer & Runkle , 2007). While there are climatic differences between the Great Lakes Region and the southwestern U.S., applying the consumptive use factors was a practical step in developing the alpha version of the model by

avoiding information gaps about consumptive characteristics of water use. Table 3-3 Consumptive use coefficients used for simulation

Consumption Percentage Factor (%)												
Demand	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Domestic	5	5	5	5	5	13	19	16	11	3	3	3
Industrial	8	9	9	9	8	8	9	9	9	8	9	9
Commercial	4	4	5	7	7	7	8	18	17	16	3	4
Outdoor	100	100	100	100	100	100	100	100	100	100	100	100
Agricultural	100	100	100	100	100	100	100	100	100	100	100	100

provides the consumptive use coefficients used in the current version of the model. The model determines return flows from different sectors based on non-consumptive proportion of sectoral supply (i.e., 1-consumptive use coefficient).

TABLE 3-1 EL PASO URBAN WATER DEMAND FOR THE PERIOD OF 2009 TO 2013

El Paso Urban Water Demand (Billion Gallons)													
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total Annual**
2009	2.23	2.18	2.74	3.11	3.79	3.91	4.08	4.08	3.29	2.99	2.47	2.18	37.1
2010	2.20	2.02	2.60	3.02	3.78	4.31	3.93	4.13	3.53	3.11	2.45	2.29	37.4
2011	2.26	2.14	2.93	3.35	3.83	4.40	4.27	4.19	3.63	3.20	2.45	2.17	38.8
2012	2.23	2.18	2.80	3.41	3.80	4.34	3.92	4.20	3.47	3.11	2.49	2.25	38.2
2013	2.16	2.04	2.71	3.16	3.76	4.22	3.81	3.83	3.17	2.99	2.37	2.19	36.4

TABLE 3-2 MONTHLY FRACTION OF URBAN WATER DEMAND IN DIFFERENT SECTORS

Urban Water Allocation (Monthly Percentage)												
Demands	**% Jan**	**% Feb**	**% Mar**	**% Apr**	**% May**	**% Jun**	**% Jul**	**% Aug**	**% Sep**	**% Oct**	**% Nov**	**% Dec**
Domestic	54.0	55.1	54.8	54.6	56.5	59.5	60.1	58.1	55.5	55.0	53.1	53.7
Industrial	6.2	6.6	7.2	8.1	8.1	8.2	7.8	8.4	8.8	8.6	7.9	6.2
Commercial/institutional	28.9	27.5	26.5	24.9	23.3	22.4	21.8	23.3	25.4	27.2	29.4	29.7
Lost	10.9	10.7	11.6	12.4	12.1	9.9	10.2	10.1	10.3	9.2	9.6	10.5

TABLE 3-3 CONSUMPTIVE USE COEFFICIENTS USED FOR SIMULATION

Consumption Percentage Factor (%)												
Demand	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Domestic	5	5	5	5	5	13	19	16	11	3	3	3
Industrial	8	9	9	9	8	8	9	9	9	8	9	9
Commercial	4	4	5	7	7	7	8	18	17	16	3	4
Outdoor	100	100	100	100	100	100	100	100	100	100	100	100
Agricultural	100	100	100	100	100	100	100	100	100	100	100	100

Total urban and agricultural demands were specified as data inputs. Table 3-4 reports monthly total surface water availability in the El Paso area as recorded at USGS Gauge at El Paso 08364000. Table 3-5 summarizes monthly surface water diversions to meet urban demand. The agricultural water demand was estimated by calculating the monthly evapotranspiration for major crops in the area, which indicates how much water is required for irrigation purposes. Data about major crops (i.e., alfalfa, cotton, pecan, corn, and vegetables) were compiled from annual crop reports for the simulation period (EPWID1, personal communication). In effect, all surface water that is not diverted for urban use purposes is available to the agricultural sector. The surface water shortages in urban and agricultural sectors trigger water withdrawal from groundwater. Furthermore, urban water deficit will activate desalination operations. The Kay Bailey Hutchison desalination plant can produce up to 27.5 million gallons in a day (almost 820 million gallons per month). The model includes inter-basin water transfer as a supply-oriented water management option whose effect is evaluated under extreme conditions simulated in sensitivity analyses.

TABLE 3-4- MONTHLY TOTAL SURFACE WATER AVAILABILITY IN THE EL PASO AREA (USGS GAUGE 08364000).

Total Surface Water Flow In El Paso (Billion Gallons)													
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual Flow**
2009	1.12	1.69	14.36	15.57	14.71	17.49	19.07	19.60	12.44	4.45	0.80	0.84	122.1
2010	0.72	0.72	11.72	14.43	12.82	19.38	21.16	20.14	10.75	3.38	0.59	0.46	116.3
2011	0.41	0.44	8.10	13.53	8.05	12.26	12.98	11.37	5.97	0.22	0.18	0.21	73.7
2012	0.22	0.19	0.17	8.05	2.08	7.62	9.31	10.51	3.98	0.16	0.14	0.15	42.6
2013	0.16	0.16	0.17	0.12	0.05	8.75	7.09	0.23	1.05	0.24	0.22	0.21	18.5

TABLE 3-5 THE VOLUME OF URBAN WATER FLOW IN EL PASO

Total Surface Water Flow In El Paso (Billion Gallons)													
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual Flow**
2009	0.0	0.1	14.7	24.6	28.8	29.4	30.1	31.7	26.7	13.0	0.0	0.0	199.1
2010	0.0	0.0	8.1	23.6	28.4	30.4	29.5	30.7	28.4	10.6	0.0	0.0	189.7
2011	0.0	0.0	4.5	26.3	30.1	29.7	30.5	30.9	13.0	0.0	0.0	0.0	165.1
2012	0.0	0.0	0.0	5.3	2.4	23.8	28.7	29.7	16.0	0.0	0.0	0.0	106.0
2013	0.0	0.0	0.0	0.0	0.0	16.2	18.2	0.0	0.0	0.0	0.0	0.0	34.4

The model accounts for dynamic dependency of natural recharge to the surface water flow and irrigation. It is assumed that up to 7.02 billion m^3 of fresh groundwater can be withdrawal from the aquifers (Leggt et al., 1963), which was defined as minimum groundwater capacity in the simulation. Later, we can see how the model's defined mechanism limits the water withdrawn by urban and agricultural demands to the below of this capacity. The amount of groundwater recharge from the Rio Grande River and irrigation are estimated at 41 million m^3 and 14 m^3, respectively (Sheng, 2013). Seepage from canals, laterals, and from irrigation water applied to the land was considered 17% (non-consumptive use) of total surface water used for agricultural purposes (Leggt et al., 1963). The resulting recharge estimate is close to an annual recharge estimate of 7 million m3 reported in the literature (Sheng, 2013). The derived groundwater annual recharge by Rio Grande River was considered as monthly factors applied to river flow. Because Mesilla Bolson

aquifer underlies a small area in El Paso, the natural recharge of this aquifer is neglected in the current version of the model. Table 3-6 Groundwater simulation parameters reports estimates of aquifer capacities, and annual recoverable fresh water and recharge.

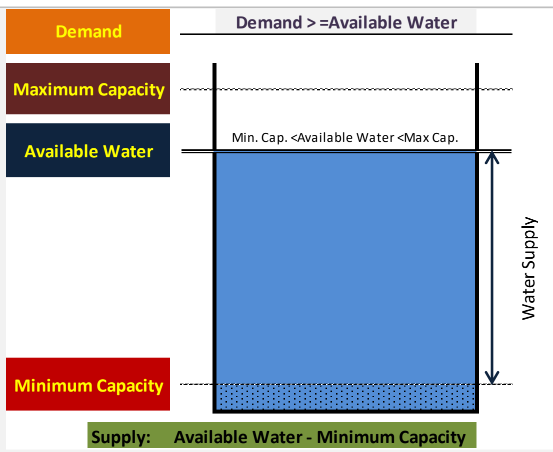
TABLE 3-6 GROUNDWATER SIMULATION PARAMETERS

Aquifer (Basin)	Current Capacity (m^3)	Recoverable (m^3)	Annual Natural Recharge (m^3)
Hueco Bolson (TX)	$11.60x10^9$	$7.0x10^9$	$55x10^6$ + 17%× Agricultural Surface Water
Mesilla Bolson (TX)	$6.91x10^8$	$2.00x10^7$	0
Total (Used for simulation)	**$12.3x10^9$**	**$7.02x10^9$**	**Calculated by model**

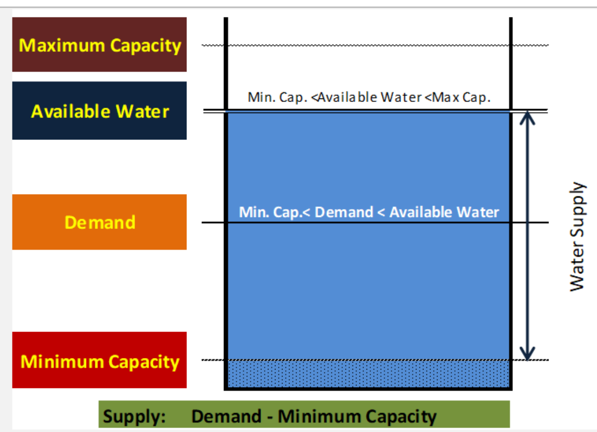
It is assumed that the groundwater stock has a maximum or minimum capacity which means the aquifers have a limited combined capacity to store and provide water. The assumption denotes that storing too much water in the aquifers will cause flooding due to high groundwater table while withdrawing water beyond minimum groundwater capacity means that groundwater is exhausted beyond limits allowed by groundwater conservation policy. In effect, the latter case indicates unsustainable use of groundwater sources, which leads to resource depletion. Groundwater is withdrawn in response to surface water shortage, which is calculated at each time step. Limits to groundwater availability are coded into how much withdrawal can occur by comparing the simulated groundwater stock (i.e., available groundwater) with the defined minimum capacity. The following figures illustrate different scenarios of water availability in terms of demand and groundwater availability, which, together, simulate three possible groundwater withdrawal cases (Figure 3-7 through Figure 3-9); (A) when groundwater stock value is between specified minimum and maximum capacities, (B) when groundwater stock value exceeds maximum groundwater

storage capacity, which denotes an unlikely case of groundwater flooding, and (C) when groundwater is withdrawn beyond minimum capacity set to represent groundwater conservation.

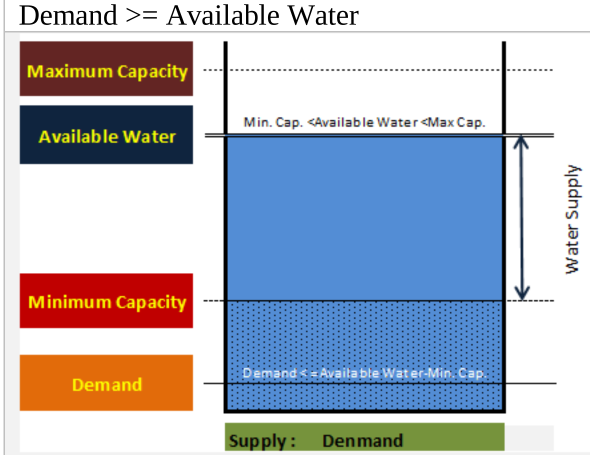
A- Min Capacity<Available Water <Max capacity



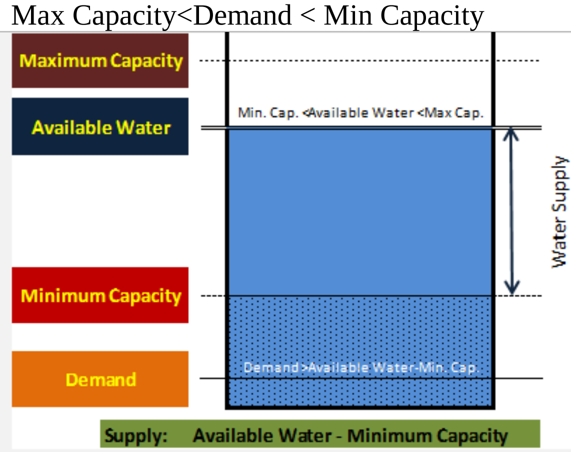
Demand >= Available Water



Max Capacity<Demand < Min Capacity



Demand<= Available Water – Min Capacity

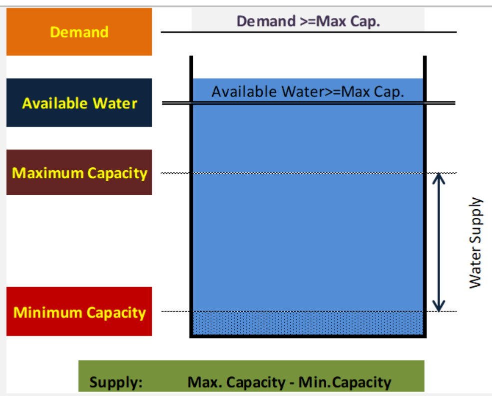


Demand>Available Water – Min Capacity

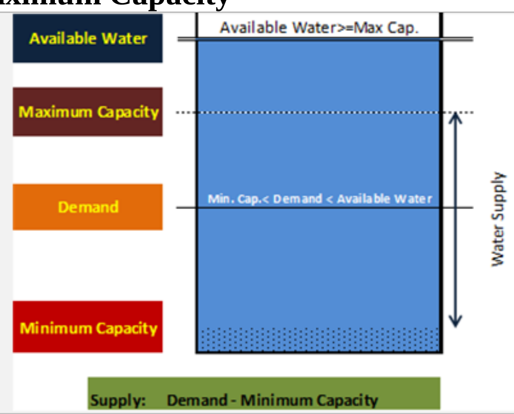
Groundwater Withdrawal: IF THEN ELSE(Groundwater>MinGW:AND:Groundwater<=MaxGW , (IF THEN ELSE(Urban SW Shortage>=Groundwater , (Groundwater-MinGW), IF THEN ELSE(Urban SW Shortage<=Groundwater-MinGW , Urban SW Shortage , (Groundwater-MinGW))))

FIGURE 3-7 GROUNDWATER WITHDRAWAL WHEN MIN CAPACITY<AVAILABLE WATER <MAX CAPACITY

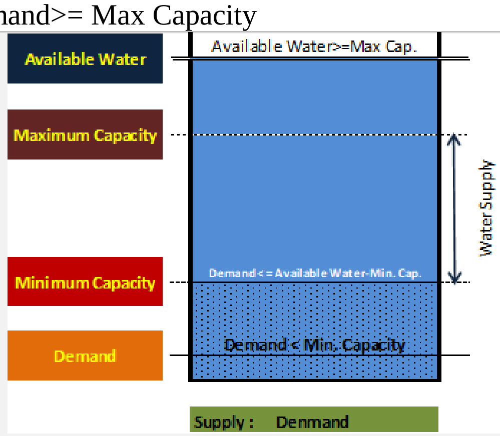
B-Available Water > Maximum Capacity



Demand>= Max Capacity



Max Capacity<Demand < Min Capacity

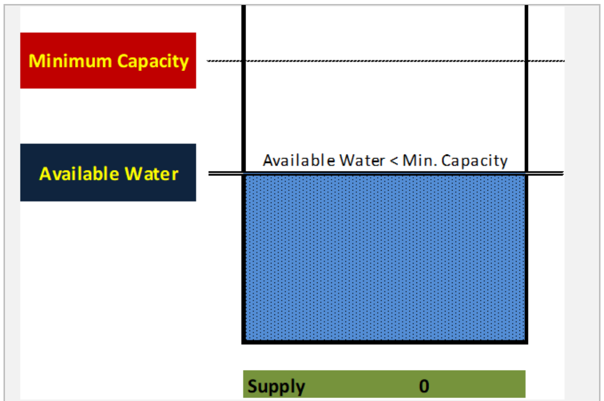


Demand<= Available Water – Min Capacity

Grounwater Withdrawal: IF THEN ELSE(Groundwater>MaxGW , IF THEN ELSE(Urban SW Shortage>=MaxGW , MaxGW-MinGW , IF THEN ELSE(Urban SW Shortage>MinGW :AND:Urban SW Shortage<=MaxGW, (Urban SW Shortage-MinGW) , Urban SW Shortage)))

FIGURE 3-8 GROUNDWATER WITHDRAWAL WHEN THE AVAILABLE WATER > MAXIMUM CAPACITY

C-Available Water< Minimum Capacity



All possible scenarios of Demand

Groundwater withdrawal:0

FIGURE 3-9- GROUNDWATER WITHDRAWAL WHEN THE AVAILABLE WATER< MINIMUM CAPACITY

Similar interlinked if-statements were used to simulate water supply from the desalination plant and inter-basin water transfer (as a next-generation supply-oriented policy), accounting for feedbacks between water shortage within the system and water supply from different sources. Figure 3-9 displays the contribution of different fresh water sources to meet water demand in El Paso from 2009 to 2013, showing increasing water supply from desalination plant during the recent prolonged drought. In 2013 desalinated water constituted about 7% of the total supply, saving almost 2 million gallons of groundwater. Furthermore, feedbacks related to recycling of reclaimed water within the system affects total freshwater water availability and withdrawal of additional water through El Paso’s portfolio of water sources. The recycling of reclaimed water within the system is adjustable to allow evaluation of the impact of water recycling policy. For example, if it is specified that outdoor demand is fully met by reclaimed water no additional fresh water withdrawal will be used to meet this demand category. Additionally, artificial groundwater recharge (i.e., aquifer storage and recovery (ASR)) using reclaimed water was simulated using the EPWU data. In the hot months of the year a considerable quantity of reclaimed water is used for irrigation and other non-potable urban purposes. The fraction of monthly reclaimed water used for

ASR increases during cooler off-peak months, denoting a seasonal artificial recharge pattern (Table 3-7). Figure 3-11 illustrates how reclaimed water can be redistributed to allow meeting different sectoral demands within the system under policy scenarios representing water recycling and reuse. The table is prepared by using EPWU 2009-2013 data.

TABLE 3-7 MONTHLY PERCENTAGE OF RECLAIMED WATER APPLIED TO ASR

Monthly Percentage of Reclamied Water Used For Aquifer Storage Recovery(ASR)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.5%	5.9%	4.9%	2.3%	0.9%	0.9%	2.6%	2.0%	3.0%	3.2%	5.3%	4.6%

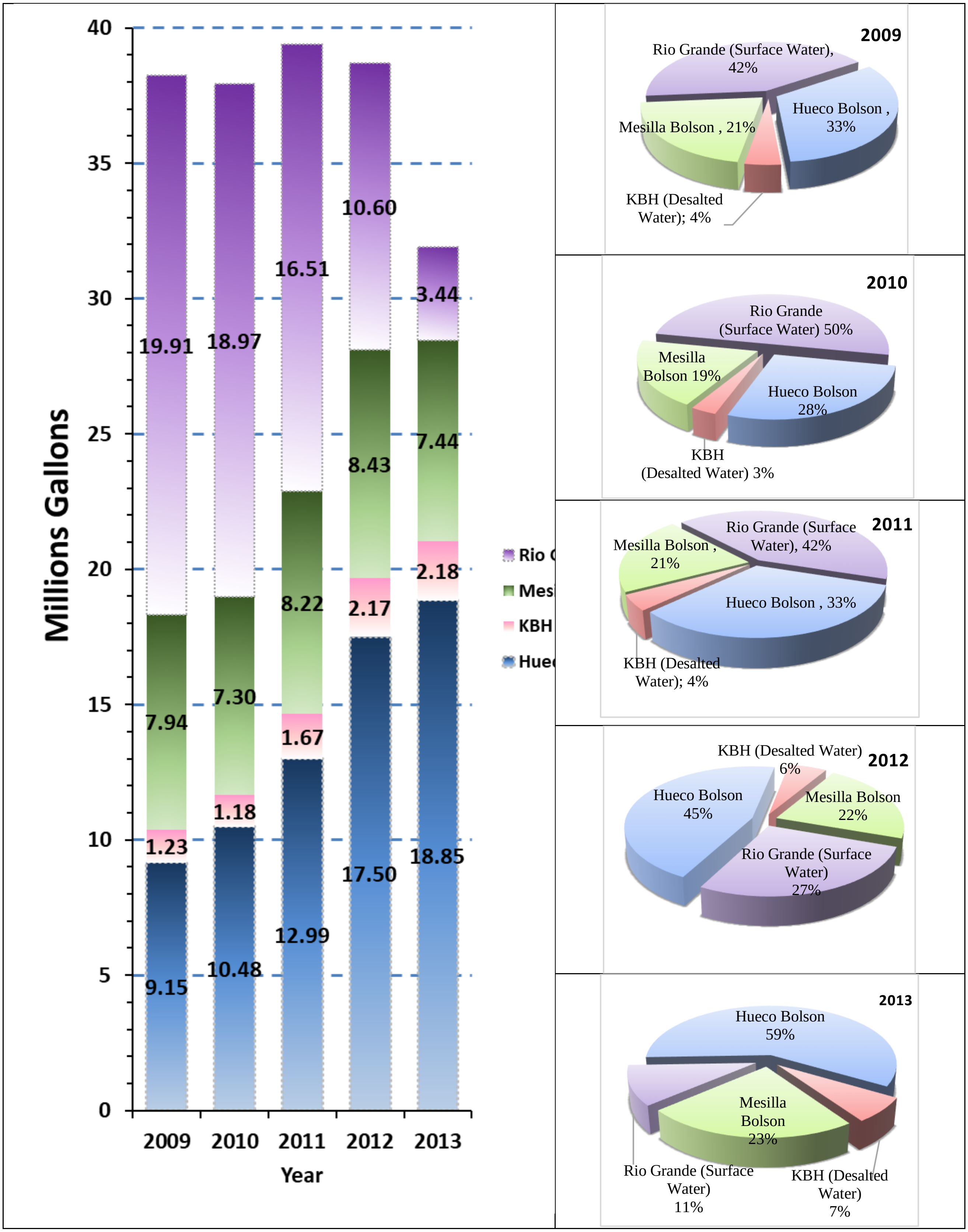


FIGURE 3-10 FRESHWATER SUPPLY PERCENTAGES IN THE STUDY PERIOD (2009-2013)

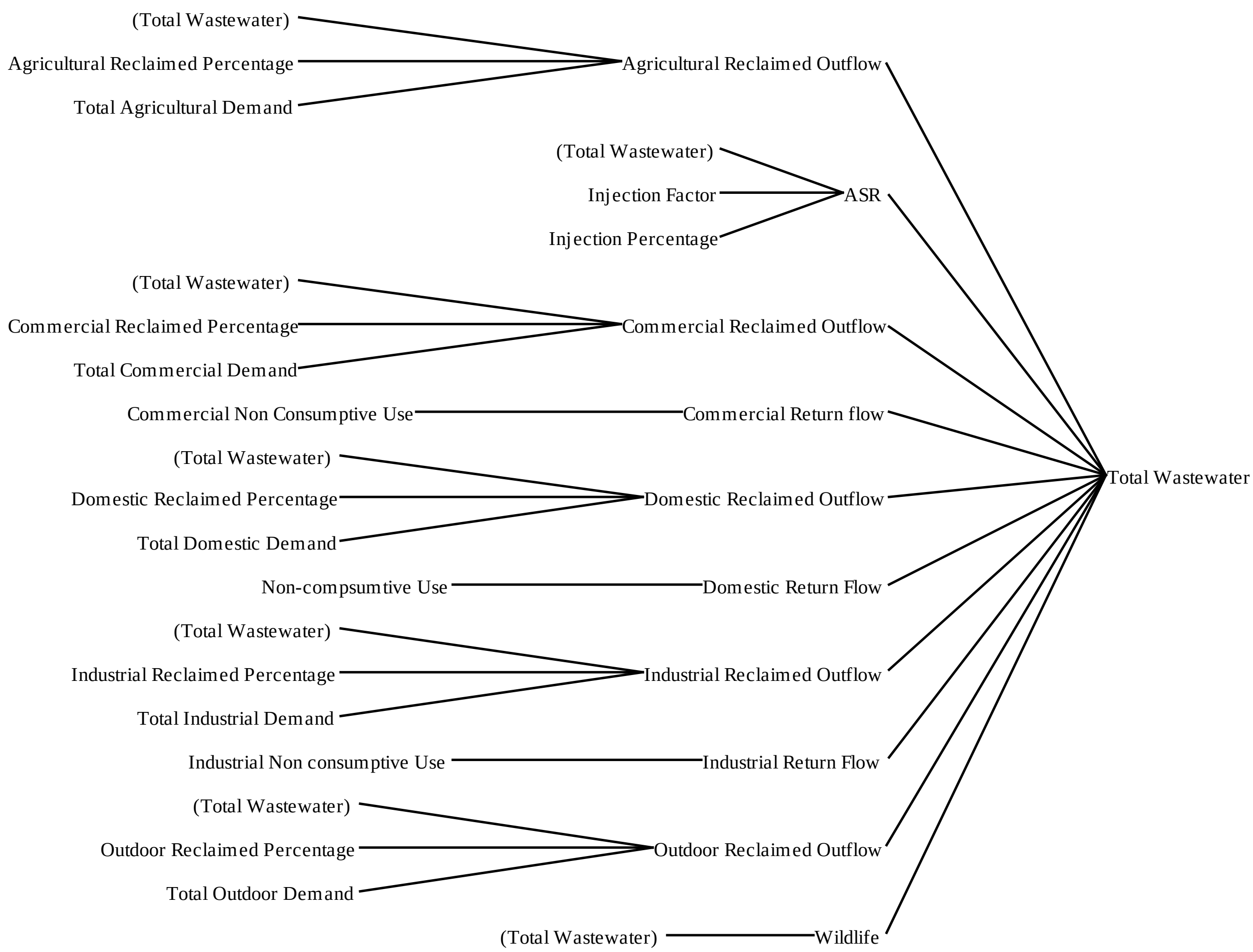


FIGURE 3-11 TOTAL WASTEWATER FLOWCHART ILLUSTRATES RECLAIMED WATER ALLOCATION

Chapter 4 RESULTS AND DISCUSSION

4.1 Model Evaluation

The system dynamics model of El Paso's water resources system was developed based on a conceptual model of the system that represent major components of the water supply and demand. The conceptual model was discussed at a meeting with water managers and technical staff at EL Paso Water Utilities in order to receive feedback on the conceptual model of the system. A number of data inputs and simplifying assumptions are included in the model. An important method to evaluate model set up and performance was to check water balance at different parts of the system to ensure water is routed correctly without flow gains and losses that are unaccounted for.

Figure 4-1illustrates a comparison of actual (average over the five year) and simulated produced wastewater as an indicator of model's reasonable performance in terms of withdrawing water from different sources to meet various demands and routing water back for reclamation and recycling policy analysis. Simulated wastewater flows are close to actual records of produced wastewater, especially during cooler months in the simulation period. The average difference of 25% between actual and simulated results is in part due to the fact that the current version of the model uses consumptive use coefficients from the Great Lakes Region for different demand sectors. In general, actual consumptive use coefficients in El Paso are likely larger than in the Great Lakes Region, particularly during hot dry summer months.

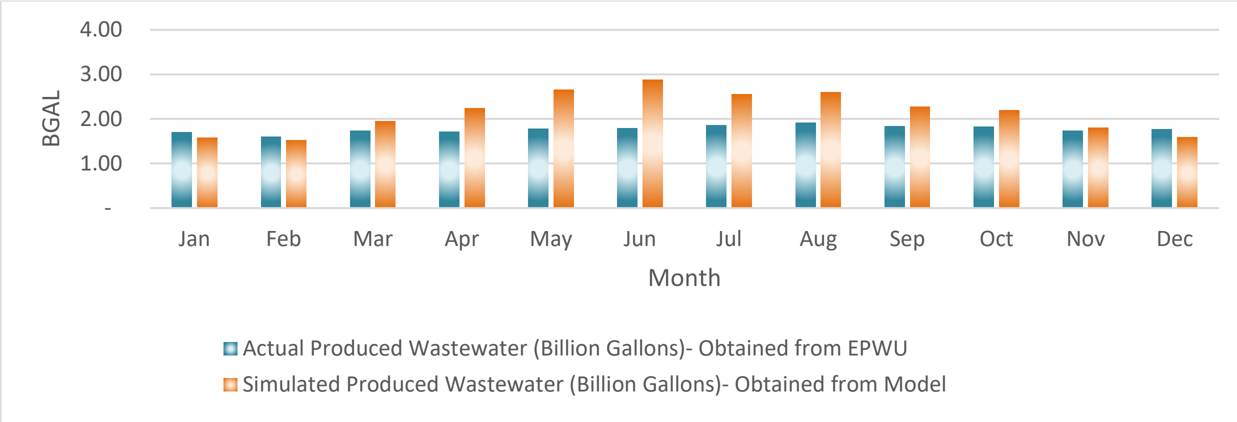


FIGURE 4-1 COMPARISON OF OBSERVED AND SIMULATED AVERAGE MONTHLY PRODUCED WASTEWATER IN THE SIMULATION PERIOD (2009-2013)

The model was developed as a platform for analyzing the impacts of a set of water management policies on El Paso water resources system taking into account the interactions between urban, agricultural, and environmental subsystems. Different policy scenarios were simulated to evaluate system performance in terms of reliability (i.e., providing service without failure) and vulnerability (i.e., the degree to which a system is unable to cope (i.e., severity of failure) with the adverse effects of external and internal changes). These scenarios are listed in Table 4-1.

TABLE 4-1 SIMULATED SCENARIOS

Scenario	Description
BaseCase: Use of freshwater for demand sectors	Actual monthly demand during the simulation period (2009-2013); no recycling of reclaimed water for urban and agricultural use; no desalination and inter-basin transfer
Scenario 1: Use of reclaimed water for agricultural purposes	Delivery of reclaimed water to agricultural sectors
Scenario 2: System-wide use of reclaimed water	Delivery of reclaimed water to all demand sectors
Scenario 3: Groundwater conservation	Groundwater withdrawal reduced by 30%; deficit compensated by desalinated brackish groundwater
Scenario 4: Extreme stress without interbasin transfer	Demand increased by 100%, surface water reduced by 50%; groundwater assumed to compensate for 50% of surface water deficit; desalination active; no interbasin transfer
Scenario 5: Extreme stress with interbasin transfer	Scenario 4 with interbasin transfer

To establish a benchmark for policy analyses, a baseline model run was performed using actual monthly demand during the simulation period (2009-2013). Results of this model run improve understanding of the changes in water budget as water is withdrawal to meet baseline demand. It is assumed that recycling of reclaimed water does not take place under baseline condition. As such, percentages of reclaimed water to meet domestic, industrial, outdoor, agricultural, and aquifer storage and recovery were set to 0. The results of baseline model run indicate that the system is able to meet the existing demand without activating water supply from desalination plant and inter-basin water transfer. The performance indicators show highest reliability level (100%) and no vulnerability because the system does not fail. However, since no water supply is fed into the system from the desalination plant and no reclaimed water is recycled within the system, meeting the total demand is only possible by placing excessive pressure on groundwater, which helps compensate for surface water deficit. Figure 4-2 and Figure 4-3 illustrate a significant drop in groundwater storage from 3.3 trillion gallons to about 2.84 trillion gallons at the end of the baseline simulation run. These results indicate a rapid decline in groundwater table with potential adverse impacts on groundwater quality. At the end of this run, about 130 billion gallons of wastewater is produced that can be managed to meet demands and implement aquifer recovery and storage plans in order to reduce fresh water withdrawal, which improves regional water resources sustainability. Figure 4-4 through Figure 4-7 illustrate example flow components of El Paso's water resources system under baseline scenario, including urban surface water, urban groundwater, agricultural surface water, and agricultural groundwater. Urban and agricultural water supply from surface water and groundwater sources display an asynchronous seasonality, indicating that meeting urban water demand through acquisitioning of agricultural surface water rights helps relieve the pressure on groundwater for meeting urban demands. However, in the absence of reclamation policies and

downstream agricultural use of treated wastewater, the effectiveness of this urban groundwater conservation policy is limited. It is worth noting that the simulated period includes an extended drought between 2011 and 2013 during which time contribution of surface water declined and groundwater withdrawals increased significantly to meet urban and agricultural demands.

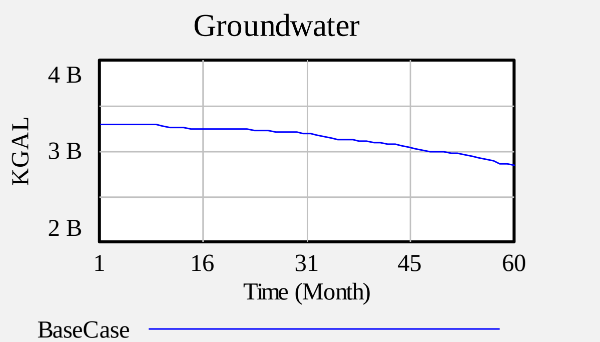


FIGURE 4-2 GROUNDWATER STORAGE IN BASECASE SCENARIO

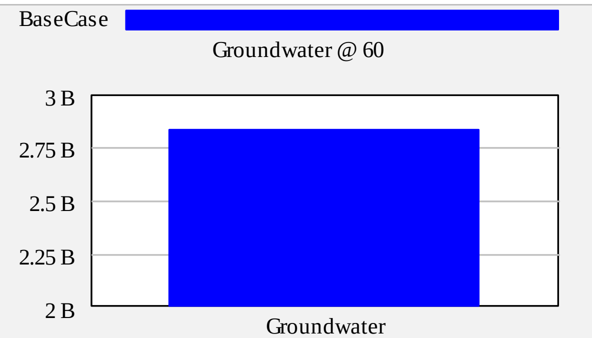


FIGURE 4-3 GROUNDWATER STORAGE AT THE END OF PERIOD BASECASE SCENARIO

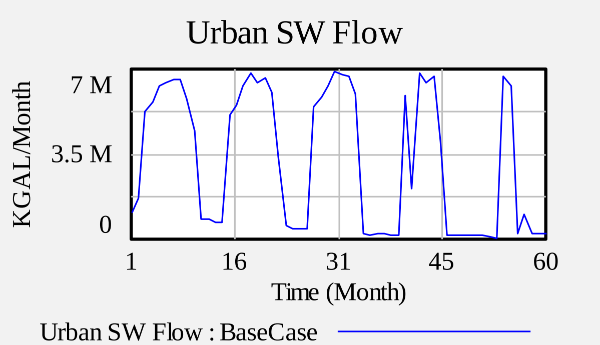


FIGURE 4-4 SURFACE WATER FLOW FOR URBAN DEMANDS IN BASECASE SCENARIO

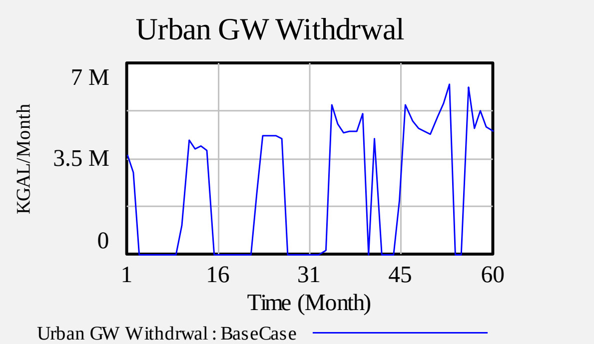


FIGURE 4-5 GROUNDWATER FLOW FOR URBAN DEMANDS BASECASE SCENARIO

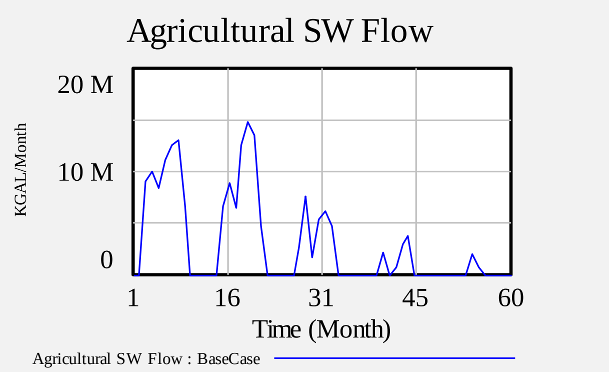


FIGURE 4-6 SURFACE WATER FLOW FOR AGRICULTURAL DEMANDS BASECASE SCENARIO

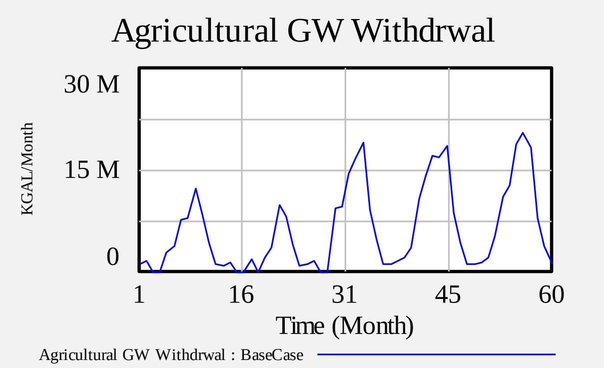


FIGURE 4-7 GROUNDWATER FLOW FOR AGRICULTURAL DEMANDS BASECASE SCENARIO

In Scenario 1 the effectiveness of using reclaimed water was investigated as a policy for groundwater conservation. This was done by increasing the percentages of reclaimed water that could be used to meet agricultural demands, thus eliminating the need to withdraw groundwater for the same purpose. To simulate this scenario, the reclaimed participation factors for agricultural demand were gradually raised from 0 up to 100% at 20% increments, while keeping the percentages of reclaimed water use for urban demand sectors and aquifer storage recovery were 0 (Table 4-2). Results illustrate the effectiveness of the policy for conserving groundwater resources by saving about 300 million gallons of groundwater over the study period (Figure 4-8 through Figure 4-13).

TABLE 4-2 RECLAIMED WATER ALLOCATION PERCENTAGE FACTOR FOR SCENARIO 1

Demand Sectors	**Reclaimed Percentage**				
	Scenario 1A	**Scenario 1B**	**Scenario 1C**	**Scenario 1D**	**Scenario 1E**
Domestic	0	0	0	0	0
Industrial	0	0	0	0	0
Commercial	0	0	0	0	0
Outdoor	0	0	0	0	0
Agricultural	**20%**	**40%**	**60%**	**80%**	**100%**
ASR	0	0	0	0	0

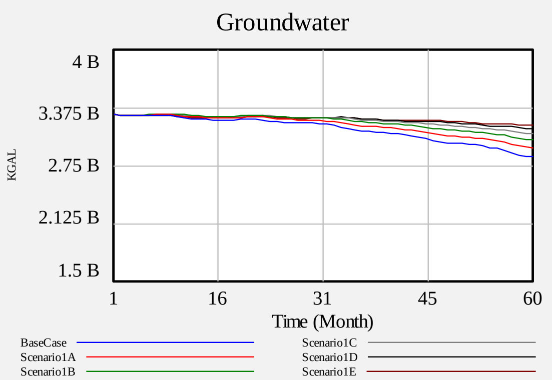


FIGURE 4-8 GROUNDWATER STORAGE GRAPH FOR SCENARIO 1

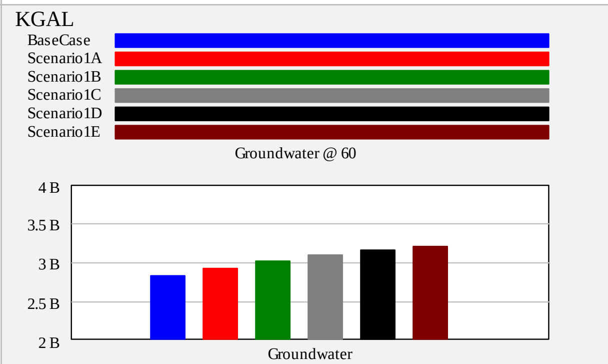


FIGURE 4-9 GROUNDWATER STORAGE AT THE END OF STUDY PERIOD FOR SCENARIO 1

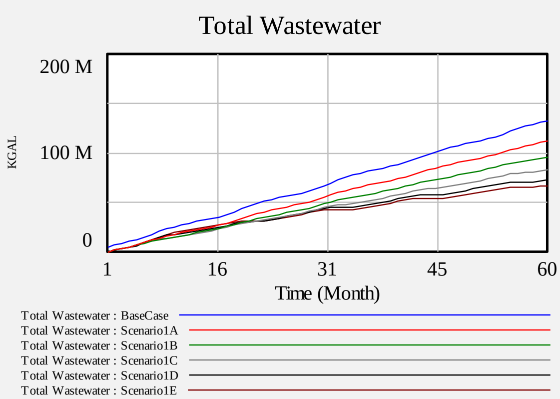


FIGURE 4-10 TOTAL PRODUCED WASTEWATER GRAPH FOR SCENARIO 1

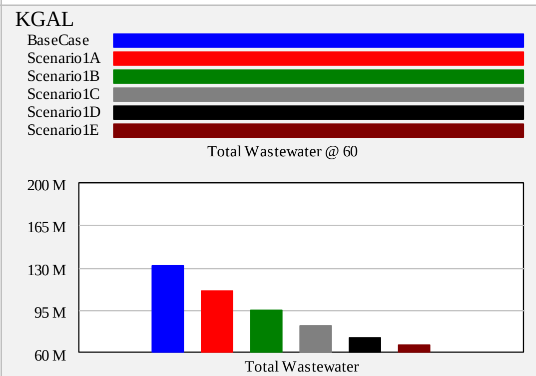


FIGURE 4-11 TOTAL PRODUCED WASTEWATER BAR CHART FOR SCENARIO 1

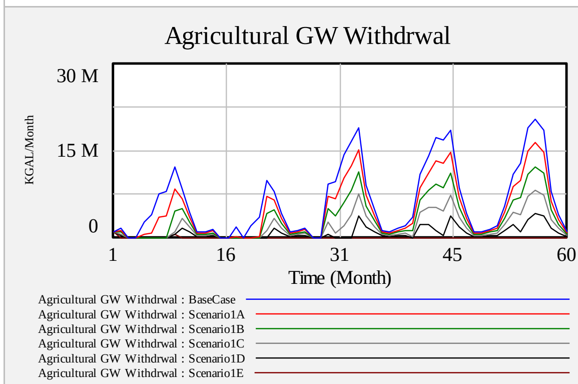


FIGURE 4-12 GROUNDWATER SUPPLY FOR AGRICULTURAL DEMAND SCENARIO 1

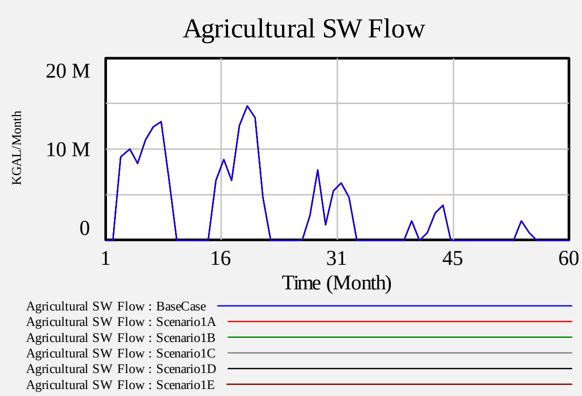


FIGURE 4-13 SURFACE WATER SUPPLY FOR AGRICULTURAL DEMAND SCENARIO 1

In Scenario 2, the contribution of reclaimed water in urban water demand sectors were investigated, including the use of direct potable reuse of treated wastewater to meet domestic demand. Purified water will become a new source of drinking water to augment the water supply as a next generation technology-based water management option (EPWU, 2014).

Table 4-3 summarizes the percentages of reclaimed water used for domestic, industrial, commercial, outdoor, and agricultural sectors, while also considering aquifer storage and recovery according to Table 3-7. Results indicate increased effectiveness of using reclaimed water to meet different sectoral demands with commensurate groundwater savings. Interestingly, by using reclaimed water within a closed loop, the system's reliance of surface water also decreases, and thus more surface water can directly be used in the agricultural sector. While these results require further investigation in terms of cost tradeoffs of direct potable reuse as an urban water management strategy, as well as system-wide analysis, this preliminary evaluation of reclamation indicates improvements to the sustainability of the regional water resources.

TABLE 4-3 RECLAIMED WATER ALLOCATION PERCENTAGE FACTOR FOR SCENARIO 2

Reclaimed Percentage	Percentage
Domestic	30%
Industrial	80%
Commercial	30%
Outdoor	100%
Agricultural	100%
Aquifer Recovery Storage	Table 3-7

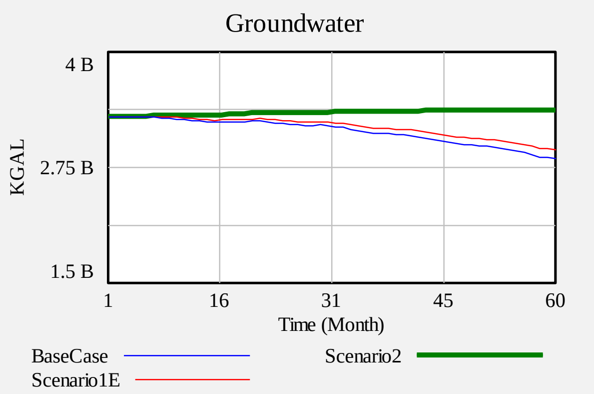


FIGURE 4-14 GROUNDWATER STORAGE GRAPH IN SCENARIO2

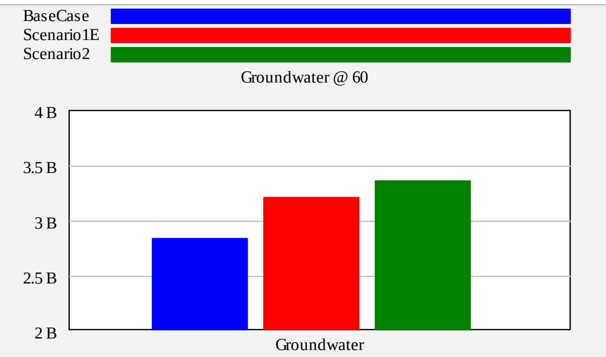


FIGURE 4-15 GROUNDWATER STORAGE AT THE END OF STUDY PERIOD SCENARIO2

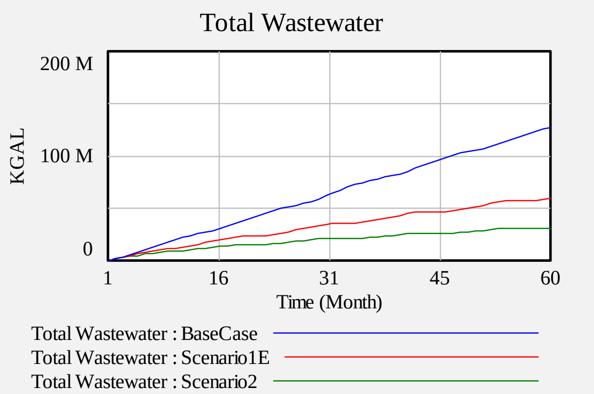


FIGURE 4-16 PRODUCED WASTEWATER GRAPH IN SCENARIO 2

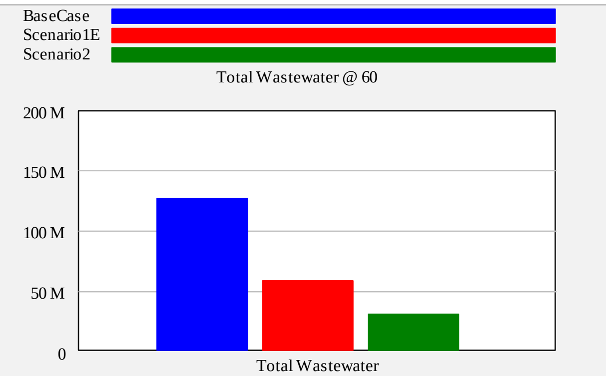


FIGURE 4-17 TOTAL PRODUCED WASTEWATER BAR CHART IN SCENARIO 2

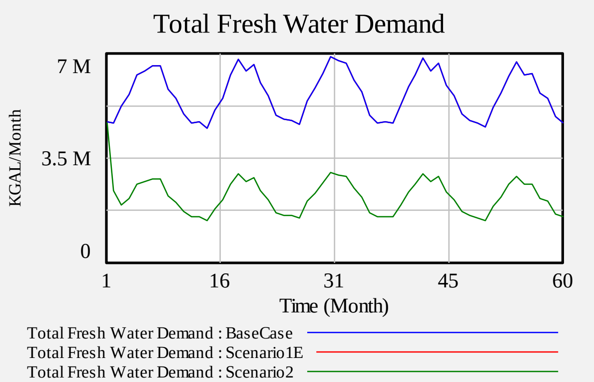


FIGURE 4-18 FRESH WATER DEMAND SLUMPS IN SCENARIO 2

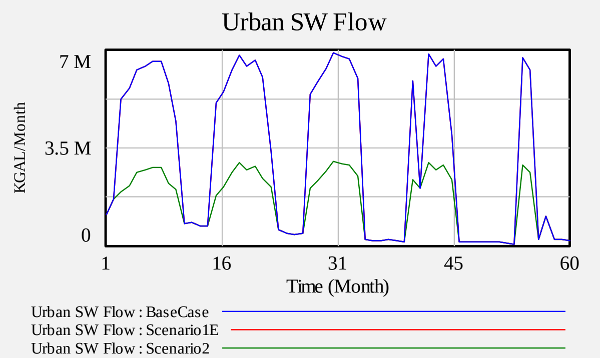


FIGURE 4-19 URBAN SURFACE WATER DEMAND SLUMPS IN SCENARIO2

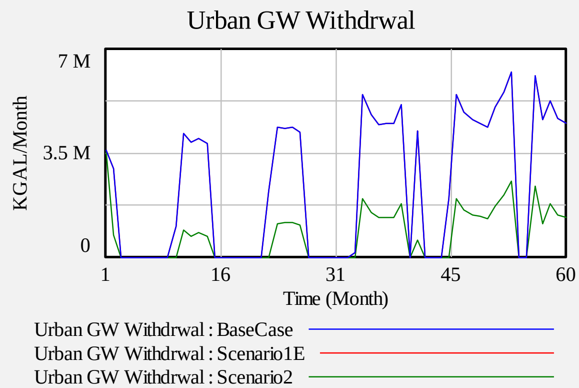


FIGURE 4-20 GROUNDWATER WITHDRAWAL SLUMPS IN URBAN DEMAND SCENARIO 2

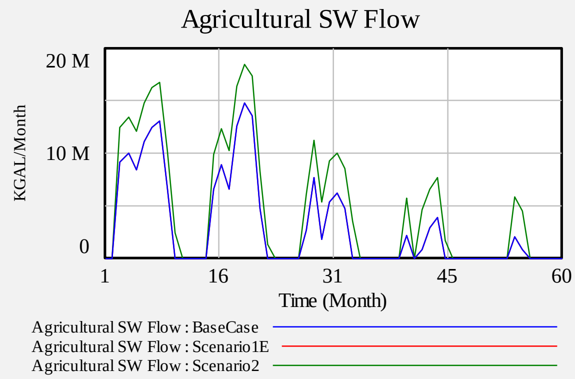


FIGURE 4-21 SURFACE WATER CAPACITY RAISE FOR AGRICULTURAL DEMAND SCENARIO 2

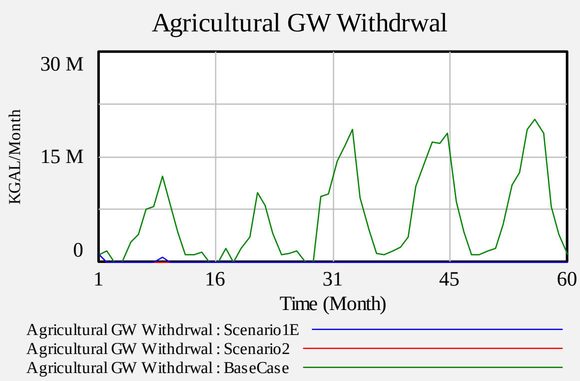


FIGURE 4-22 GROUNDWATER AGRICULTURAL WITHDRAWAL SLUMPING SCENARIO 2

The third scenario considers the effect of implementing strict fresh groundwater conservation policy through increased use of desalinated brackish groundwater. In this scenario, fresh groundwater withdrawal was decreased by 30% compared to baseline scenario, representing an extreme case of groundwater conservation. A specific variable (Urban Surface Water Shortage) was introduced to automatically activate urban water groundwater withdrawal. The results of this scenario simulation show that fresh groundwater stock has a slight upward shift, which confirms

the successful implementation of the groundwater conservation policy in saving about 15 billion gallons of groundwater throughout the simulation period. Interestingly, the system can be operated reliably using desalination water supply, which is automatically activated to prevent urban water shortages due smaller groundwater withdrawal.

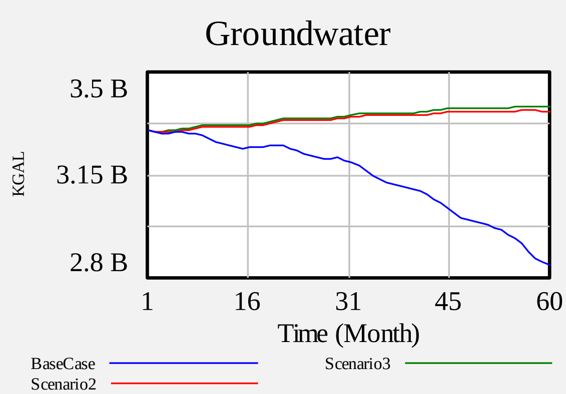


FIGURE 4-23 GROUNDWATER STORAGE IN SCENARIO 3

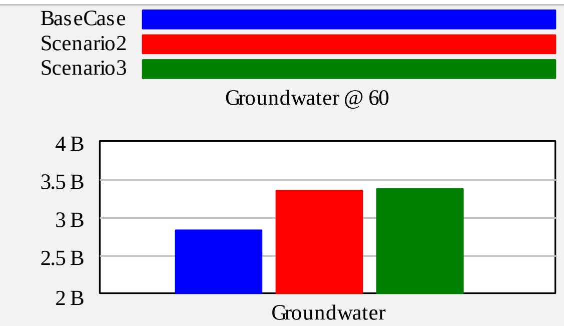


FIGURE 4-24 GROUNDWATER STORAGE AT THE END OF STUDY PERIOD SCENARIO 3

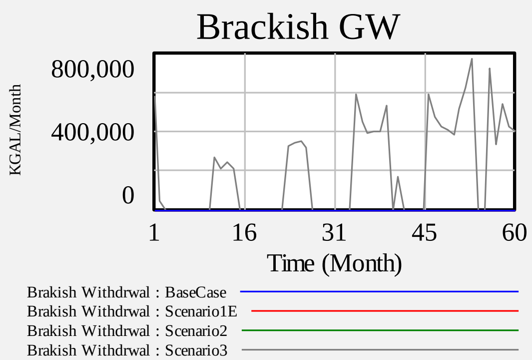


FIGURE 4-25 BRACKISH GROUNDWATER WITHDRAWAL IN SCENARIO 3

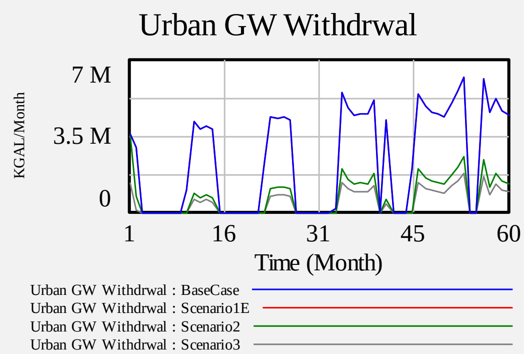


FIGURE 4-26 GROUNDWATER WATER WITHDRAWAL UNDER URBAN DEMAND IN SCENARIO 3

An extreme water shortage condition is simulated under Scenario 4, assuming that demand is increased by 100%, surface water diversions to meet urban demand have decreased by 50% and groundwater is only able to compensate for 50% of the resulting deficit. Under this scenario, water production at the desalination plant is expected to increase to alleviate urban water shortage. The reclaimed water use policy is assumed to be in effect with sectoral percentages defined in Scenario2. Scenario 4 turns out to be too extreme for the system unless water is added externally, for example, through inter-basin water transfer. The system starts experiencing deficits soon after the beginning of the simulation, resulting in failure to meet demands despite the fact that the desalination plant produces water at full capacity throughout the simulation period. Consequently, the system's reliability declined to slightly more than 50%.

These results are illustrated n Figure 4-27 through Figure 4-30.

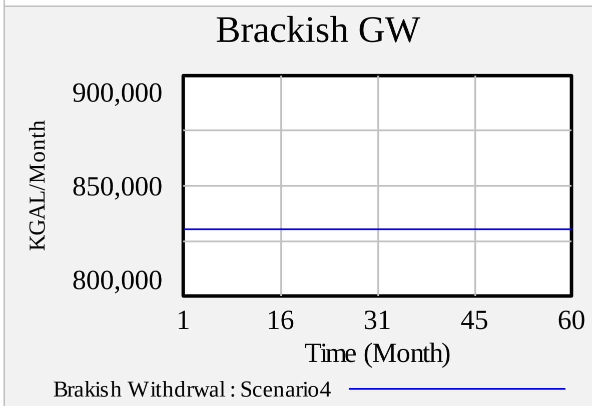


FIGURE 4-27 BRACKISH GROUNDWATER WITHDRAWAL IN SCENARIO 4

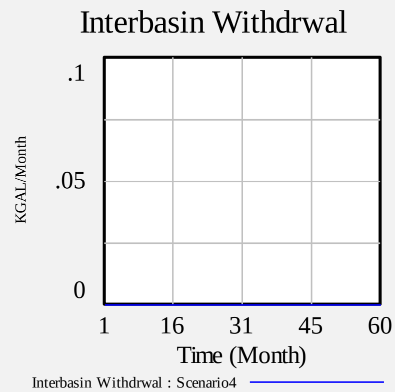


FIGURE 4-28 INTERBASIN FLOWS N SCENARIO 4

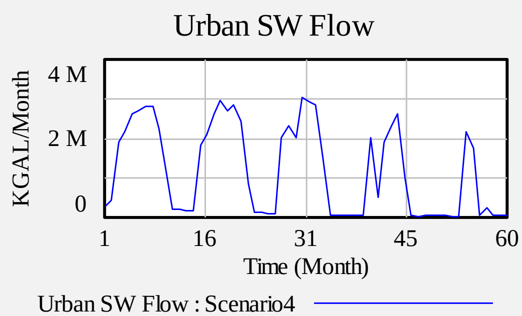


FIGURE 4-29 SURFACE WATER FLOW UNDER URBAN DEMAND FOR SCENARIO 4

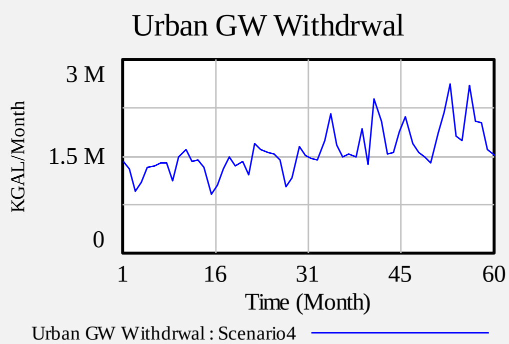


FIGURE 4-30 GROUNDWATER WITHDRAWAL UNDER URBAN DEMAND FOR SCENARIO 4

The fifth and final scenario helps evaluate the effect of adding external water to the system to handle very extreme conditions that were simulated under Scenario 4. Thus, interbasin water transfer from Dell City was added to the model under Scenario 5 without changing other assumptions specified for Scenario 4. Expectedly, the planned inter-basin water transfer helps maintain high reliability of meeting different demands within the system. The results are illustrated in Figure 4-31 through Figure 4-34 .

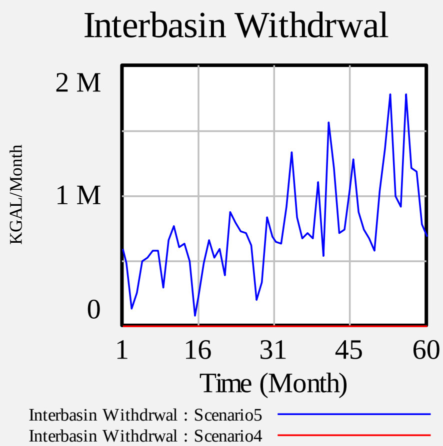


FIGURE 4-31 INTERBASIN WATER INTERACTION IN SCENARIO 5

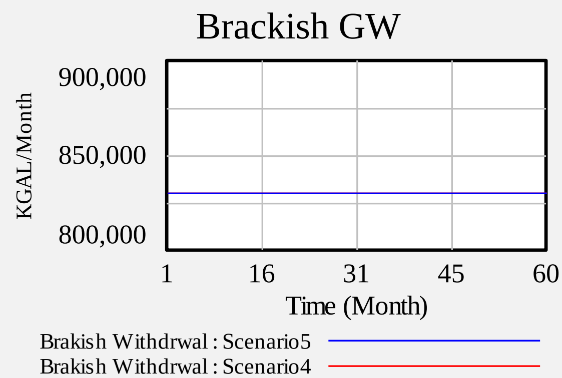


FIGURE 4-32 BRACKISH GROUNDWATER INTERACTION IN SCENARIO 5

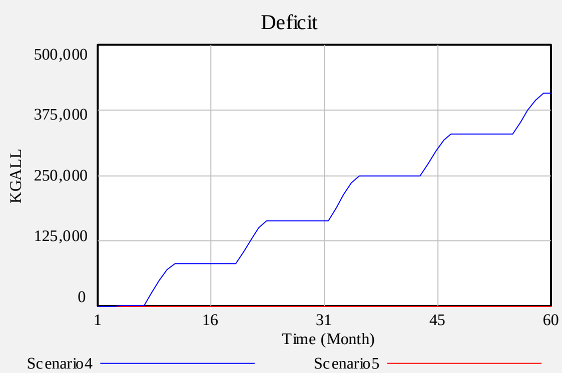


FIGURE 4-33 SYSTEM WATER DEFICIT IN SCENARIO 5

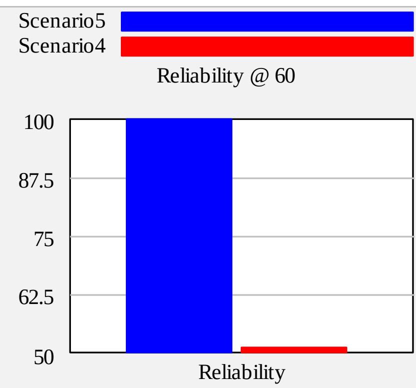


FIGURE 4-34 SYSTEM RELIABILITY IN SCENARIO 5

Chapter 5 CONCLUSIONS AND FUTURE WORK

A system dynamics model of the El Paso water resources system was developed as a platform to evaluate the effectiveness of the city's portfolio of water management policies. The system dynamics model is based on a representative high-level conceptual model of the system, which includes water withdrawal from various sources to meet different sectoral demands. Water withdrawals from the Rio Grande River, Mesilla Bolson, and Hueco Bolson were considered along with water supply from the Kay Bailey Hutchison desalination plant, and interbasin water transfer. Additionally, recycling of reclaimed water for meeting domestic, industrial, commercial, outdoor, and agricultural demands was simulated. Although, many simplifying assumptions were made from a practical modeling standpoint and to circumvent challenges posed by unavailability of data, the model performs reasonably well when evaluated based on structural tests, behavior reproduction, and sensitivity analysis. It includes dynamic feedbacks between different water supply sources such that water demands are met using surface water first while groundwater is used to compensate for water shortages. Likewise, in extreme cases, the role of desalinated water becomes more important in maintaining high system reliability. While the city has a robust water management portfolio, long-run supply-oriented management options such as interbasin water transfer from Dell City, complemented with strict demand management measures, will postpone the threat of significant system failure. Results indicate great potential to conserve groundwater resources by using reclaimed water to meet various demands.

Future work can address the current data and technical limitations to use this modeling platform on wider basis for water management policy analysis in El Paso. The quantitative simulations, require sufficient data on various components of the system. Better understanding of groundwater storage and sectoral demands will significantly improve the current system dynamics modeling

application. Furthermore, estimating regionally relevant consumptive use coefficients will allow more accurate estimates of return flows and the potential for using recycling of reclaimed water as a promising water management strategy. The current version of the model uses estimates of consumptive use coefficients from the Great lakes Region, creating inaccuracies due to different climatic characteristics and water use patterns.

The model will also benefit from incorporating appropriate water demand models that provide the capability to examine the effects of population and climate change. Other improvements include simultaneous simulation of the water systems in El Paso and the neighboring city of Ciudad Juarez, Mexico to provide a better understanding of the sustainability of shared water resources. Furthermore, adding data about the cost and energy requirements of supplying water from different sources will provide opportunities for conducting tradeoff analysis to illustrate broader implications of maintaining a highly reliable water resources system in an arid region in the face of continuous socioeconomic growth and climate change. Further technical work is needed in terms of establishing input-output protocols and developing the required cyberinfrastructure to make the model available online for public use.

The feedback-based system dynamics modeling framework is useful for evaluating long-term effectiveness of various water management policies. However, in light of limitations of the current version of the model, results should be interpreted from a high-level system standpoint. In other words, the model illuminates the trends of water supply and resource availability as opposed to accurate quantitative estimates.

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Chapter 7 APPENDIX

Adjusted Factor=

1

Units: **undefined** [0,?]

:GROUP .1201-2-for scenario 1

Used by:

Total Outdoor Demand

Total Urban Demand

Vulnerability

Agri Factor=

1

Units: **undefined**

:GROUP .1201-2-for scenario 1

Used by:

Total Agricultural Demand

Agricultural Demand:INTERPOLATE:

Units: **undefined**

:GROUP .1201-2-for scenario 1

Used by:

Total Agricultural Demand

Analysis of units error:

Last two entries in IF THEN ELSE must have same units

Total Agricultural Demand

Has Units: KGAL/Month

(1

- Agricultural Reclaimed Percentage)

* Total Agricultural Demand

Has Units: KGAL*Percentage/Month

Agricultural Fresh Water Demand=

IF THEN ELSE(Agricultural Reclaimed Outflow=0, Total Agricultural Demand, (1-Agricultural Reclaimed Percentage)*Total Agricultural Demand)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Agricultural Reclaimed Outflow

Agricultural Reclaimed Percentage

Total Agricultural Demand

Used by:

Agricultural Fresh Water Supply

Agriculturl GW Shortage

Agricultural Fresh Water Supply=

IF THEN ELSE(Agricultural SW Flow>Agricultural Fresh Water Demand ,Agricultural Fresh Water Demand

, Agricultural GW Withdrwal+Agricultural SW Flow

)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Agricultural Fresh Water Demand

Agricultural GW Withdrwal

Agricultural SW Flow

Used by:

Total Agricultural Flow

Agricultural GW Withdrwal=

IF THEN ELSE(Groundwater>MinGW:AND:Groundwater<=MaxGW , (IF THEN ELSE(Agriculturl GW Shortage

>=Groundwater , Groundwater

-MinGW, IF THEN ELSE(Agriculturl GW Shortage<=Groundwater-MinGW , Agriculturl GW Shortage

, Groundwater-MinGW))),

IF THEN ELSE

(Groundwater>MaxGW , IF THEN ELSE(Agriculturl GW Shortage>=MaxGW , MaxGW

-MinGW , IF THEN ELSE(Agriculturl GW Shortage

>MinGW :AND:

Agriculturl GW Shortage<=MaxGW, Agriculturl GW Shortage-MinGW , Agriculturl GW Shortage

)) , 0))

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Groundwater - Ground Water

Agriculturl GW Shortage

MaxGW - Max Ground Water Capacity

MinGW - Min Ground Water Capacity

Used by:

Groundwater - Ground Water

Agricultural Fresh Water Supply

Analysis of units error:

Units mismatch

Total Wastewater

Has Units: KGAL

Agricultural Reclaimed Percentage

* Total Agricultural Demand

Has Units: KGAL*Percentage/Month

Agricultural Reclaimed Outflow=

IF THEN ELSE(Total Wastewater>=Agricultural Reclaimed Percentage*Total Agricultural Demand

, Agricultural Reclaimed Percentage

*Total Agricultural Demand,0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Wastewater

Agricultural Reclaimed Percentage

Total Agricultural Demand

Used by:

Total Wastewater

Agricultural Fresh Water Demand

Total Agricultural Flow

Agricultural Reclaimed Percentage=

1

Units: Percentage [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Agricultural Fresh Water Demand

Agricultural Reclaimed Outflow

Agricultural SW Flow=

Surface Water-Urban SW Flow

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Surface Water

Urban SW Flow

Used by:

Agricultural Fresh Water Supply

Agriculturl GW Shortage

Natural Recharge

Agriculturl GW Shortage=

IF THEN ELSE(Agricultural Fresh Water Demand>Agricultural SW Flow,Agricultural Fresh Water Demand

-Agricultural SW Flow,

0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Agricultural Fresh Water Demand

Agricultural SW Flow

Used by:

Agricultural GW Withdrwal

ASR=

Total Wastewater*Injection Factor*Injection Percentage

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Wastewater

Injection Factor

Injection Percentage

Used by:

Groundwater - Ground Water

Total Wastewater

Brackish GW= INTEG (

Brakish Inflow-Brakish Withdrwal,

3.3e+009)

Units: KGAL

:GROUP .1201-2-for scenario 1

Desalination

Brakish Inflow - Desalinated Water Inflow

Brakish Withdrwal - Disalinated Water Withdrawal

Used by:

Brakish Withdrwal - Disalinated Water Withdrawal

Brakish Inflow=

0

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Desalinated Water Inflow

Used by:

Brackish GW - Desalination

Analysis of units error:

Units mismatch

Groundwater Shortage

Has Units: KGAL/Month

Min Brakish

Has Units: KGAL

Brakish Withdrwal=

min(Monthly Capacity, (IF THEN ELSE(Brackish GW>Min Brakish:AND:Brackish GW

<=Max Brakish , IF THEN ELSE(Groundwater Shortage>=Brackish GW ,

Brackish GW-Min Brakish, IF THEN ELSE(Groundwater Shortage<=Brackish GW-

Min Brakish , Groundwater Shortage , Brackish GW

-Min Brakish)) , IF THEN ELSE(Brackish GW>Max Brakish , IF THEN ELSE(

Groundwater Shortage>=Max Brakish , Max Brakish

-Min Brakish , IF THEN ELSE(Groundwater Shortage>Min Brakish :AND:Groundwater Shortage

<=Max Brakish, Groundwater Shortage

-Min Brakish , Groundwater Shortage)) , 0))))

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Disalinated Water Withdrawal

Brackish GW - Desalination

Groundwater Shortage - Ground Water Shortage

Max Brakish

Min Brakish

Monthly Capacity

Used by:

Brackish GW - Desalination

Desalination Shortage - Desalinated Water Shortage

Total Fresh Water Inflow

Commercial Consumptive Factor= WITH LOOKUP (

Month,

([(0,0)-(12,10)],(1,0.04),(2,0.04),(3,0.05),(4,0.07),(5,0.07),(6,0.07),(7,0.08),(8,0.18),(9,0.17),(10,0.16),(11,0.03),(12,0.04)))

Units: Percentage

:GROUP .1201-2-for scenario 1

Month

Used by:

Commercial Non Consumptive Use

Analysis of units error:

Last two entries in IF THEN ELSE must have same units

Total Commercial Demand

Has Units: KGAL/Month

(1

- Commercial Reclaimed Percentage)

* Total Commercial Demand

Has Units: KGAL*Percentage/Month

Commercial Fresh Water Demand=

IF THEN ELSE(Commercial Reclaimed Outflow=0, Total Commercial Demand,(1-Commercial Reclaimed Percentage

)*Total Commercial Demand)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Commercial Reclaimed Outflow

Commercial Reclaimed Percentage

Total Commercial Demand

Used by:

Commercial Fresh Water Supply

Total Fresh Water Demand

Commercial Fresh Water Supply=

IF THEN ELSE(Total Urban Supply>=Commercial Fresh Water Demand, Commercial Fresh Water Demand

, 0)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Urban Supply

Commercial Fresh Water Demand

Used by:

Total Urban Supply

Total Commercial Flow

Commercial Non Consumptive Use=

(1-Commercial Consumptive Factor)*Total Commercial Flow

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Commercial Consumptive Factor

Total Commercial Flow

Used by:

Commercial Return flow

Analysis of units error:

Units mismatch

Total Wastewater

Has Units: KGAL

Total Commercial Demand

* Commercial Reclaimed Percentage

Has Units: KGAL*Percentage/Month

Commercial Reclaimed Outflow=

IF THEN ELSE(Total Wastewater>=Total Commercial Demand*Commercial Reclaimed Percentage

,Total Commercial Demand*Commercial Reclaimed Percentage,0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Wastewater

Commercial Reclaimed Percentage

Total Commercial Demand

Used by:

Total Wastewater

Commercial Fresh Water Demand

Total Commercial Flow

Commercial Reclaimed Percentage=

0

Units: Percentage [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Commercial Fresh Water Demand

Commercial Reclaimed Outflow

Commercial Return flow=

Commercial Non Consumptive Use

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Commercial Non Consumptive Use

Used by:

Total Wastewater

Commercial Total Percentage= WITH LOOKUP (

Month,

([(1,0)-(12,30)],(1,0.289),(2,0.275),(3,0.265),(4,0.249),(5,0.233),(6,0.224
),(7,0.218),(8,0.233),(9,0.254),(10,0.272),(11,0.294),(12,0.297)))

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Month

Used by:

Total Commercial Demand

Deficit=

IF THEN ELSE (Total Urban Demand-Total Domestic Flow-Total Industrial Flow

-Total Commercial Flow-Lost<0.1*Total Urban Demand

,0,Total Urban Demand-Total Domestic Flow-Total Industrial Flow-Total Commercial Flow

-Lost)

Units: Gallons

:GROUP .1201-2-for scenario 1

Lost

Total Commercial Flow

Total Domestic Flow - Total Domestic Flow

Total Industrial Flow - Total Industrial Flow

Total Urban Demand

Used by:

Deficit Counter

Reliability Counter

Vulnerability Counter

Analysis of units error:

Right hand and left hand units do not match

Deficit Counter

Has Units: Gallons

INTEG(integer (Deficit) ,

0)

Has Units: Gallons*Month

Deficit Counter= INTEG (

integer(Deficit),

0)

Units: Gallons

:GROUP .1201-2-for scenario 1

Deficit

Used by:

Vulnerability

Demand Counter= INTEG (

Total Urban Demand,

0)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Urban Demand

Used by:

Vulnerability

Desalination Shortage=

IF THEN ELSE(Groundwater Shortage> Brakish Withdrwal, Groundwater Shortage -Brakish Withdrwal,0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Desalinated Water Shortage

Brakish Withdrwal - Disalinated Water Withdrawal

Groundwater Shortage - Ground Water Shortage

Used by:

Interbasin Withdrwal - Interbasin Withdrawal

Domestic Consumption Factor= WITH LOOKUP (

Month,

([(0,0)-(12,10)],(1,0.05),(2,0.05),(3,0.05),(4,0.05),(5,0.05),(6,0.13),(7
,0.19),(8,0.16),(9,0.11),(10,0.03),(11,0.03),(12,0.03)))

Units: Percentage [0,1]

:GROUP .1201-2-for scenario 1

Month

Used by:

Non-compsumtive Use

Analysis of units error:

Last two entries in IF THEN ELSE must have same units

Total Domestic Demand

Has Units: KGAL/Month

(1

- Domestic Reclaimed Percentage)

* Total Domestic Demand

Has Units: KGAL*Percentage/Month

Domestic Fresh Water Demand=

IF THEN ELSE(Domestic Reclaimed Outflow=0, Total Domestic Demand, (1-Domestic Reclaimed Percentage

)*Total Domestic Demand)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Domestic Reclaimed Outflow

Domestic Reclaimed Percentage

Total Domestic Demand

Used by:

Domestic Fresh Water Supply

Total Fresh Water Demand

Domestic Fresh Water Supply=

IF THEN ELSE(Total Urban Supply>=Domestic Fresh Water Demand, Domestic Fresh Water Demand

, 0)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Urban Supply

Domestic Fresh Water Demand

Used by:

Total Urban Supply

Total Domestic Flow - Total Domestic Flow

Analysis of units error:

Units mismatch

Total Wastewater

Has Units: KGAL

Domestic Reclaimed Percentage

* Total Domestic Demand

Has Units: KGAL*Percentage/Month

Domestic Reclaimed Outflow=

IF THEN ELSE(Total Wastewater>=Domestic Reclaimed Percentage*Total Domestic Demand

,Domestic Reclaimed Percentage*Total Domestic Demand,0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Wastewater

Domestic Reclaimed Percentage

Total Domestic Demand

Used by:

Total Wastewater

Domestic Fresh Water Demand

Total Domestic Flow - Total Domestic Flow

Domestic Reclaimed Percentage=

0

Units: Percentage [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Domestic Fresh Water Demand

Domestic Reclaimed Outflow

Domestic Return Flow=

"Non-compsumtive Use"

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Non-compsumtive Use

Used by:

Total Wastewater

Domestic Total Percentage= WITH LOOKUP (

Month,

([(0,0)-(12,70)],(1,0.54),(2,0.551),(3,0.548),(4,0.546),(5,0.565),(6,0.595),(7,0.601),(8,0.58),(9,0.555),(10,0.55),(11,0.531),(12,0.537)))

Units: Percentage

:GROUP .1201-2-for scenario 1

Month

Used by:

Total Domestic Demand

Factor=

70

Units: **undefined**

:GROUP .1201-2-for scenario 1

FINAL TIME = 60

Units: Month

:GROUP .Control

The final time for the simulation.

Fp=

(Fpi*Rainfall+1)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Fpi

Rainfall

Fpi= WITH LOOKUP (

Month,

([(1,-0.07)-(13,0.07)],(1,-0.032),(2,-0.061),(3,-0.043),(4,-0.043),(5,0.012
),(6,0.002),(7,-0.015),(8,-0.048),(9,-0.013),(10,-0.021),(11,0.061),(12,-0.004
)))

Units: **undefined**

:GROUP .1201-2-for scenario 1

Month

Used by:

Fp

Groundwater= INTEG (

ASR+Natural Recharge-Agricultural GW Withdrwal-Urban GW Withdrwal,

3.3e+009)

Units: KGAL

:GROUP .1201-2-for scenario 1

Ground Water

Agricultural GW Withdrwal

ASR

Natural Recharge

Urban GW Withdrwal - Ground Water Withdrawal

Used by:

Agricultural GW Withdrwal

Urban GW Withdrwal - Ground Water Withdrawal

Groundwater Inflow=

0

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Groundwater Inflow

Groundwater Shortage=

IF THEN ELSE(Total Fresh Water Demand>Urban SW Flow+Urban GW Withdrwal,Total Fresh Water Demand

-Urban SW Flow-Urban GW Withdrwal

,0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Ground Water Shortage

Total Fresh Water Demand

Urban GW Withdrwal - Ground Water Withdrawal

Urban SW Flow

Used by:

Brakish Withdrwal - Disalinated Water Withdrawal

Desalination Shortage - Desalinated Water Shortage

GW Policy=

1

Units: **undefined** [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Urban GW Withdrwal - Ground Water Withdrawal

Industrial Consumptive Factor=

0.1

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Used by:

Industrial Non consumptive Use

Analysis of units error:

Last two entries in IF THEN ELSE must have same units

Total Industrial Demand

Has Units: KGAL/Month

(1

- Industrial Reclaimed Percentage)

* Total Industrial Demand

Has Units: KGAL*Percentage/Month

Industrial Fresh Water Demand=

IF THEN ELSE(Industrial Reclaimed Outflow=0, Total Industrial Demand,(1-Industrial Reclaimed Percentage

)*Total Industrial Demand)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Industrial Reclaimed Outflow

Industrial Reclaimed Percentage

Total Industrial Demand

Used by:

Industrial Fresh Water Supply

Total Fresh Water Demand

Industrial Fresh Water Supply=

IF THEN ELSE(Total Urban Supply>=Industrial Fresh Water Demand, Industrial Fresh Water Demand

, 0)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Urban Supply

Industrial Fresh Water Demand

Used by:

Total Urban Supply

Total Industrial Flow - Total Industrial Flow

Analysis of units error:

Right hand and left hand units do not match

Industrial Non consumptive Use

Has Units: KGAL/Month

Total Industrial Flow

* (1

- Industrial Consumptive Factor)

Has Units: KGAL*KGAL/(Month*Month)

Industrial Non consumptive Use=

Total Industrial Flow*(1-Industrial Consumptive Factor)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Industrial Consumptive Factor

Total Industrial Flow - Total Industrial Flow

Used by:

Industrial Return Flow

Analysis of units error:

Units mismatch

Total Wastewater

Has Units: KGAL

Industrial Reclaimed Percentage

* Total Industrial Demand

Has Units: KGAL*Percentage/Month

Industrial Reclaimed Outflow=

IF THEN ELSE(Total Wastewater>Industrial Reclaimed Percentage*Total Industrial Demand

,Industrial Reclaimed Percentage*Total Industrial Demand,0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Wastewater

Industrial Reclaimed Percentage

Total Industrial Demand

Used by:

Total Wastewater

Industrial Fresh Water Demand

Total Industrial Flow - Total Industrial Flow

Industrial Reclaimed Percentage=

0

Units: Percentage [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Industrial Fresh Water Demand

Industrial Reclaimed Outflow

Industrial Return Flow=

Industrial Non consumptive Use

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Industrial Non consumptive Use

Used by:

Total Wastewater

Industrial Total Percentage= WITH LOOKUP (

Month,

([(0,0)-(12,30)],(1,0.062),(2,0.066),(3,0.072),(4,0.081),(5,0.081),(6,0.082
),(7,0.078),(8,0.084),(9,0.088),(10,0.086),(11,0.079),(12,0.062)))

Units: Percentage

:GROUP .1201-2-for scenario 1

Month

Used by:

Total Industrial Demand

INITIAL TIME = 1

Units: Month

:GROUP .Control

The initial time for the simulation.

Used by:

Time - Internally defined simulation time.

Injection Factor= WITH LOOKUP (

Month,

([(0,0)-(12,10)],(1,0.045),(2,0.06),(3,0.05),(4,0.025),(5,0.1),(6,0.1),(7,0.025),(8,0.02),(9,0.03),(10,0.035),(11,0.055),(12,0.05)))

Units: **undefined** [0,1]

:GROUP .1201-2-for scenario 1

Month

Used by:

ASR

Injection Percentage=

1

Units: **undefined** [0,1]

:GROUP .1201-2-for scenario 1

Used by:

ASR

Interbasin= INTEG (

Interbasin Inflow-Interbasin Withdrwal,

4.5e+009)

Units: KGAL

:GROUP .1201-2-for scenario 1

Inter Basin

Interbasin Inflow - InterBasin Inflow

Interbasin Withdrwal - Interbasin Withdrawal

Used by:

Interbasin Withdrwal - Interbasin Withdrawal

Interbasin Inflow=

0

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

InterBasin Inflow

Used by:

Interbasin - Inter Basin

Interbasin Policy=

1

Units: **undefined** [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Interbasin Withdrwal - Interbasin Withdrawal

Interbasin Withdrwal=

IF THEN ELSE(Interbasin>MinIB:AND:Interbasin<=MaxIB , IF THEN ELSE(Desalination Shortage

>=Interbasin , Interbasin Policy*Interbasin-MinIB

, IF THEN ELSE(Desalination Shortage<=Interbasin-MinIB , Interbasin Policy

Desalination Shortage ,Interbasin Policy(Interbasin-MinIB))), IF THEN ELSE

(Interbasin

>MaxIB , IF THEN ELSE(Desalination Shortage>=MaxIB , MaxIB-MinIB , IF THEN ELSE

(Desalination Shortage>MinIB :AND:Desalination Shortage

<=MaxIB, Interbasin Policy*(Desalination Shortage-MinIB) , Interbasin Policy

*Desalination Shortage)) , 0))

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Interbasin Withdrawal

Interbasin - Inter Basin

Desalination Shortage - Desalinated Water Shortage

Interbasin Policy

MaxIB

MinIB

Used by:

Interbasin - Inter Basin

Total Fresh Water Inflow

Lost=

Lost Percentage*Total Urban Demand

Units: **undefined**

:GROUP .1201-2-for scenario 1

Lost Percentage

Total Urban Demand

Used by:

Total Urban Supply

Deficit

System Lost

System Waste

Total Fresh Water Demand

Lost Percentage= WITH LOOKUP (

Month,

([(0,0)-(12,10)],(1,0.109),(2,0.108),(3,0.115),(4,0.124),(5,0.121),(6,0.1),(7,0.1),(8,0.1),(9,0.1),(10,0.09),(11,0.096),(12,0.105)))

Units: **undefined**

:GROUP .1201-2-for scenario 1

Month

Used by:

Lost

Max Brakish=

8.8e+010

Units: KGAL

:GROUP .1201-2-for scenario 1

Used by:

Brakish Withdrwal - Disalinated Water Withdrawal

MaxGW=

8.8e+010

Units: **undefined**

:GROUP .1201-2-for scenario 1

Max Ground Water Capacity

Used by:

Agricultural GW Withdrwal

Urban GW Withdrwal - Ground Water Withdrawal

MaxIB=

5e+012

Units: KGAL

:GROUP .1201-2-for scenario 1

Used by:

Interbasin Withdrwal - Interbasin Withdrawal

Min Brakish=

1.55e+009

Units: KGAL

:GROUP .1201-2-for scenario 1

Used by:

Brakish Withdrwal - Disalinated Water Withdrawal

MinGW=

1.5e+009

Units: **undefined**

:GROUP .1201-2-for scenario 1

Min Ground Water Capacity

Used by:

Agricultural GW Withdrwal

Urban GW Withdrwal - Ground Water Withdrawal

MinIB=

100000

Units: KGAL

:GROUP .1201-2-for scenario 1

Used by:

Interbasin Withdrwal - Interbasin Withdrawal

Month=

Time-integer(Time/12)*12

Units: **undefined**

:GROUP .1201-2-for scenario 1

Time - Internally defined simulation time.

Used by:

Commercial Consumptive Factor

Commercial Total Percentage

Domestic Consumption Factor

Domestic Total Percentage

Fpi

Industrial Total Percentage

Injection Factor

Lost Percentage

Natural Recharge Percentage

NOD

Monthly Capacity=

810000

Units: **undefined**

:GROUP .1201-2-for scenario 1

Used by:

Brakish Withdrwal - Disalinated Water Withdrawal

Natural Recharge=

Surface Water*Natural Recharge Percentage+0.017*Agricultural SW Flow

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Agricultural SW Flow

Natural Recharge Percentage

Surface Water

Used by:

Groundwater - Ground Water

Natural Recharge Percentage= WITH LOOKUP (

Month,

([(0,0)-(12,10)],(1,0.01),(2,0.01),(3,0.1),(4,0.12),(5,0.11),(6,0.17),(7,
0.18),(8,0.17),(9,0.09),(10,0.03),(11,0.01),(12,0)))

Units: **undefined**

:GROUP .1201-2-for scenario 1

Month

Used by:

Natural Recharge

NOD= WITH LOOKUP (

Month,

([(0,0)-(13,40)],(1,31),(2,29),(3,30),(4,31),(5,30),(6,31),(7,30),(8,31),
(9,30),(10,31),(11,30),(12,31)))

Units: **undefined**

:GROUP .1201-2-for scenario 1

Month

Analysis of units error:

Right hand and left hand units do not match

"Non-compsumtive Use"

Has Units: KGAL/Month

(1

- Domestic Consumption Factor)

* Total Domestic Flow

Has Units: KGAL*Percentage/Month

"Non-compsumtive Use"=

(1-Domestic Consumption Factor)*Total Domestic Flow

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Domestic Consumption Factor

Total Domestic Flow - Total Domestic Flow

Used by:

Domestic Return Flow

Outdoor Fresh Water Demand=

IF THEN ELSE(Outdoor Reclaimed Outflow=0, Total Outdoor Demand,(1-Outdoor Reclaimed Percentage

)*Total Outdoor Demand)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Outdoor Reclaimed Outflow

Outdoor Reclaimed Percentage

Total Outdoor Demand

Used by:

Outdoor Fresh Water Supply

Total Fresh Water Demand

Outdoor Fresh Water Supply=

IF THEN ELSE(Total Urban Supply>=Outdoor Fresh Water Demand, Outdoor Fresh Water Demand

,0)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Urban Supply

Outdoor Fresh Water Demand

Used by:

Total Urban Supply

Total Outdoor Flow - Total Outdoor Flow

Outdoor Reclaimed Outflow=

IF THEN ELSE(Total Wastewater>=Outdoor Reclaimed Percentage*Total Outdoor Demand

,Outdoor Reclaimed Percentage*Total Outdoor Demand,0)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Wastewater

Outdoor Reclaimed Percentage

Total Outdoor Demand

Used by:

Total Wastewater

Outdoor Fresh Water Demand

Total Outdoor Flow - Total Outdoor Flow

Outdoor Reclaimed Percentage=

1

Units: **undefined** [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Outdoor Fresh Water Demand

Outdoor Reclaimed Outflow

Rainfall=

0.1

Units: **undefined**

:GROUP .1201-2-for scenario 1

Used by:

Fp

Reliability=

100*(Reliability Counter)/60

Units: Percentage

:GROUP .1201-2-for scenario 1

Reliability Counter

Reliability Counter= INTEG (

IF THEN ELSE(Deficit=0,1,0),

IF THEN ELSE(Deficit=0,1,0))

Units: **undefined**

:GROUP .1201-2-for scenario 1

Deficit

Used by:

Reliability

SAVEPER =

TIME STEP

Units: Month [0,?]

:GROUP .Control

The frequency with which output is stored.

TIME STEP - The time step for the simulation.

Surface Water=

Surfacewater*SW Factor

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Surfacewater

SW Factor

Used by:

Agricultural SW Flow

Natural Recharge

Urban SW Flow

Surface Water Factor=

1

Units: **undefined**

:GROUP .1201-2-for scenario 1

Surfacewater:INTERPOLATE:

Units: **undefined**

:GROUP .1201-2-for scenario 1

Used by:

Surface Water

SW Factor=

1

Units: **undefined** [0,1]

:GROUP .1201-2-for scenario 1

Used by:

Surface Water

Urban SW Flow

System Lost=

IF THEN ELSE(Total Urban Supply>=Lost, Lost , Lost)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Urban Supply

Lost

System Waste=

IF THEN ELSE(Total Urban Supply>=Lost, Lost , 0)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Urban Supply

Lost

TIME STEP = 1

Units: Month [0,?]

:GROUP .Control

The time step for the simulation.

Used by:

SAVEPER - The frequency with which output is stored.

Total Agricultural Demand=

Agri Factor*Agricultural Demand

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Agri Factor

Agricultural Demand

Used by:

Agricultural Fresh Water Demand

Agricultural Reclaimed Outflow

Total Agricultural Flow=

Agricultural Reclaimed Outflow+Agricultural Fresh Water Supply

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Agricultural Fresh Water Supply

Agricultural Reclaimed Outflow

Analysis of units error:

Right hand and left hand units do not match

Total Commercial Demand

Has Units: KGAL/Month

Commercial Total Percentage

* Total Urban Demand

Has Units: KGAL*KGAL/(Month*Month)

Total Commercial Demand=

Commercial Total Percentage*Total Urban Demand

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Commercial Total Percentage

Total Urban Demand

Used by:

Commercial Fresh Water Demand

Commercial Reclaimed Outflow

Total Commercial Flow=

Commercial Fresh Water Supply+Commercial Reclaimed Outflow

Units: **undefined**

:GROUP .1201-2-for scenario 1

Commercial Fresh Water Supply

Commercial Reclaimed Outflow

Used by:

Commercial Non Consumptive Use

Deficit

Analysis of units error:

Right hand and left hand units do not match

Total Domestic Demand

Has Units: KGAL/Month

Total Urban Demand

* Domestic Total Percentage

Has Units: KGAL*Percentage/Month

Total Domestic Demand=

Total Urban Demand*Domestic Total Percentage

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Domestic Total Percentage

Total Urban Demand

Used by:

Domestic Fresh Water Demand

Domestic Reclaimed Outflow

Total Domestic Flow=

Domestic Fresh Water Supply+Domestic Reclaimed Outflow

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Domestic Flow

Domestic Fresh Water Supply

Domestic Reclaimed Outflow

Used by:

Deficit

Non-compsumtive Use

Total Fresh Water Demand=

Lost+Outdoor Fresh Water Demand+Commercial Fresh Water Demand+Domestic Fresh Water Demand

+Industrial Fresh Water Demand

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Commercial Fresh Water Demand

Domestic Fresh Water Demand

Industrial Fresh Water Demand

Lost

Outdoor Fresh Water Demand

Used by:

Groundwater Shortage - Ground Water Shortage

Urban SW Flow

Urban SW Shortage - Surface Water Shortage

Total Fresh Water Inflow=

Brakish Withdrwal+Interbasin Withdrwal+Urban SW Flow+Urban GW Withdrwal

Units: **undefined**

:GROUP .1201-2-for scenario 1

Brakish Withdrwal - Disalinated Water Withdrawal

Interbasin Withdrwal - Interbasin Withdrawal

Urban GW Withdrwal - Ground Water Withdrawal

Urban SW Flow

Used by:

Total Urban Supply

Analysis of units error:

Right hand and left hand units do not match

Total Industrial Demand

Has Units: KGAL/Month

Total Urban Demand

* Industrial Total Percentage

Has Units: KGAL*Percentage/Month

Total Industrial Demand=

Total Urban Demand*Industrial Total Percentage

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Industrial Total Percentage

Total Urban Demand

Used by:

Industrial Fresh Water Demand

Industrial Reclaimed Outflow

Total Industrial Flow=

Industrial Fresh Water Supply+Industrial Reclaimed Outflow

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Industrial Flow

Industrial Fresh Water Supply

Industrial Reclaimed Outflow

Used by:

Deficit

Industrial Non consumptive Use

Total Outdoor Demand=

2.5e+006*Adjusted Factor

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Adjusted Factor

Used by:

Outdoor Fresh Water Demand

Outdoor Reclaimed Outflow

Total Outdoor Flow=

Outdoor Fresh Water Supply+Outdoor Reclaimed Outflow

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Total Outdoor Flow

Outdoor Fresh Water Supply

Outdoor Reclaimed Outflow

Total Urban Demand=

Urban Demand*Adjusted Factor

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Adjusted Factor

Urban Demand

Used by:

Demand Counter

Deficit

Lost

Total Commercial Demand

Total Domestic Demand

Total Industrial Demand

Total Urban Supply= INTEG (

MAX(0,Total Fresh Water Inflow-Domestic Fresh Water Supply-Commercial Fresh Water Supply

-Outdoor Fresh Water Supply-Industrial Fresh Water Supply-Lost),

5e+006)

Units: Gallons

:GROUP .1201-2-for scenario 1

Commercial Fresh Water Supply

Domestic Fresh Water Supply

Industrial Fresh Water Supply

Lost

Outdoor Fresh Water Supply

Total Fresh Water Inflow

Used by:

Commercial Fresh Water Supply

Domestic Fresh Water Supply

Industrial Fresh Water Supply

Outdoor Fresh Water Supply

System Lost

System Waste

Total Wastewater= INTEG (

MAX(0,0.85*(Domestic Return Flow+Industrial Return Flow+Commercial Return flow

)+0.15*(-Agricultural Reclaimed Outflow-ASR-Domestic Reclaimed Outflow-Outdoor Reclaimed Outflow

-Wildlife-Commercial Reclaimed Outflow-Industrial Reclaimed Outflow)),

0)

Units: KGAL

:GROUP .1201-2-for scenario 1

Agricultural Reclaimed Outflow

ASR

Commercial Reclaimed Outflow

Commercial Return flow

Domestic Reclaimed Outflow

Domestic Return Flow

Industrial Reclaimed Outflow

Industrial Return Flow

Outdoor Reclaimed Outflow

Wildlife

Used by:

Agricultural Reclaimed Outflow

ASR

Commercial Reclaimed Outflow

Domestic Reclaimed Outflow

Industrial Reclaimed Outflow

Outdoor Reclaimed Outflow

Wildlife

Wildlife Water Supply

Urban Demand:INTERPOLATE:

Units: **undefined**

:GROUP .1201-2-for scenario 1

Used by:

Total Urban Demand

Urban GW Withdrwal=

IF THEN ELSE(Groundwater>MinGW:AND:Groundwater<=MaxGW , (IF THEN ELSE(Urban SW Shortage

>=Groundwater , GW Policy*(Groundwater-MinGW)

, IF THEN ELSE(Urban SW Shortage<=Groundwater-MinGW , GW Policy*Urban SW Shortage

, GW Policy*(Groundwater-MinGW)))), IF THEN ELSE(Groundwater

>MaxGW , IF THEN ELSE(Urban SW Shortage>=MaxGW , MaxGW-MinGW , IF THEN ELSE

(Urban SW Shortage>MinGW :AND:Urban SW Shortage

<=MaxGW, GW Policy*(Urban SW Shortage-MinGW) , GW Policy*Urban SW Shortage

)) , 0))

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Ground Water Withdrawal

Groundwater - Ground Water

GW Policy

MaxGW - Max Ground Water Capacity

MinGW - Min Ground Water Capacity

Urban SW Shortage - Surface Water Shortage

Used by:

Groundwater - Ground Water

Groundwater Shortage - Ground Water Shortage

Total Fresh Water Inflow

Urban SW Flow=

SW Factor*IF THEN ELSE(Total Fresh Water Demand>=Surface Water, Surface Water ,Total Fresh Water Demand)

Units: KGAL/Month

:GROUP .1201-2-for scenario 1

Surface Water

SW Factor

Total Fresh Water Demand

Used by:

Agricultural SW Flow

Groundwater Shortage - Ground Water Shortage

Total Fresh Water Inflow

Urban SW Shortage - Surface Water Shortage

Analysis of units error:

Right hand and left hand units do not match

Urban SW Shortage

Has Units: Gallons/Month

IF THEN ELSE (Total Fresh Water Demand

> Urban SW Flow ,

Total Fresh Water Demand

- Urban SW Flow ,

0)

Has Units: KGAL/Month

Urban SW Shortage=

IF THEN ELSE(Total Fresh Water Demand>Urban SW Flow,Total Fresh Water Demand -Urban SW Flow,0)

Units: Gallons/Month

:GROUP .1201-2-for scenario 1

Surface Water Shortage

Total Fresh Water Demand

Urban SW Flow

Used by:

Urban GW Withdrwal - Ground Water Withdrawal

UrbanSWFlow:INTERPOLATE:

Units: **undefined**

:GROUP .1201-2-for scenario 1

Vulnerability=

IF THEN ELSE(Vulnerability Counter=0,0,Deficit Counter/(Vulnerability Counter *Adjusted Factor*Demand Counter)*100)

Units: Percentage

:GROUP .1201-2-for scenario 1

Deficit Counter

Demand Counter

Vulnerability Counter

Adjusted Factor

Vulnerability Counter= INTEG (

IF THEN ELSE(Deficit>0, 1, 0),

0)

Units: **undefined**

:GROUP .1201-2-for scenario 1

Deficit

Used by:

Vulnerability

Wildlife=

0.001*Total Wastewater

Units: **undefined**

:GROUP .1201-2-for scenario 1

Total Wastewater

Used by:

Total Wastewater

Wildlife Water Supply=

0.1*Total Wastewater

Units: **undefined**

:GROUP .1201-2-for scenario 1

VITA

Majid Alahmoradi Akbarabadi, was born at March 25th, 1979 at Khorramshahr, Iran. He has a B.S. in Civil Engineering from Azad University of Tehran, Iran (2003), and a M.Sc. in Structural Engineering from Zanjan University, Zanjan, Iran (2006) along with M.Sc. in Civil Engineering at the University of Texas at El Paso (2017). I also got a Construction Management certificate at the University of Texas at El Paso (2017).

He has almost two years of Teaching assistant in different courses of civil, construction and structural engineering including Steel Structural Design, Mechanics of Material, Earth Construction and Electrical and Mechanical Construction.

Besides, he has gained over than 12 years of experience in civil and structural engineering and construction management sectors mainly in large billion-dollar projects including oil and gas, powerplant and highway construction.

His area of research in his previous academic endeavors were mainly focused on system analysis techniques and structural performance based design.