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A System Dynamics Approach to Integrated Water and Energy Resources Management

by

Yilin Zhuang

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Civil Engineering
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

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ABSTRACT

Water and energy are two of the most important resources for societal prosperity and economic development. It is clear that water and energy are intrinsically linked together and depend on one another in modern society. To date, however, efforts on water-energy nexus concentrate on quantifying the energy use in water cycle or the water use in energy production. From management perspective, water and energy are still managed separately. Little work has been done to investigate the impacts of the management options associated with one resource on the other and examine the integrated water and energy management options. Accordingly, the overall goal of this study is to examine the integrated management options for long-term regional water and energy resources management with consideration of their interactions through a system dynamics approach.

System dynamics is based on systems thinking, which focuses on the system structure and offers a deeper insight into problems. It can link ecological, human, and social elements of water and energy systems in one modeling platform to investiaget their interactions A four-step system dynamics modeling process was used in this study, which includes problem articulation, model formulation, model testing, and scenario design and simulation. Tampa Bay region was chosen as the study area, which is located on the west central coast of Florida and estuary along the Gulf of Mexico. This study considered a 100-year time scale with monthly interval, the first 30 years of which are used for model validation and the rest of which are for simulation.

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In order to investigate the interrelationship between water and energy systems, two sub-models (i.e., water sub-model and energy sub-model) were developed first. The water sub-model is composed of sectoral water demand (agriculture, industry, municipality, and energy sector), water supply (surface water, groundwater, reclaimed water, and water imports), and water quality and energy consumption associated with water supply. The result shows that surface water level increases by 1.32~1.39% when considering water quality and 1.10~1.30% considering both water quality and energy consumption. There is a slight decrease in groundwater storage (0.02~0.08%) compared with the reference behavior. The result also reveals that water conservation education is the most effective option to reduce the freshwater withdrawals (~17.3%), followed by rebates on indoor water-efficient appliances (~15.4%). Water loss control has a high potential to reduce freshwater withdrawals but it is not effective currently due to limited budget. The implementation of minimum surface water level reduces the surface water withdrawal by 26 MGD (million gallons per day) and requires alternative water supply sources to meet the water demands.

The energy sub-model consists of sectoral energy demand (agriculture, industry, municipality, and water sector), energy supply (coal, natural gas, oil, and electricity), and greenhouse gas (GHG) emissions and water pollution associated with energy supply. The result finds that cost of fuels is the primary concern of determining the energy mix for power generation. The current electricity mix in the study area consists of 35.4% fuels from coal, 44.6% from natural gas, and 20% from oil. When considering the environmental impacts associated with energy supply, this percentage of coal reduces to 10.6%, and GHG emissions and water pollution can be reduced by 22% and 43% accordingly. The result also shows that energy price is most effect of reducing the demand (~16.3%), followed by energy conservation education

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(~10.6%). Rebates on household appliances are the least effective option (~3.6%) due to consumers' low willingness to pay. Combining the supply decision incorporating environmental impacts and the demand option of energy price increase, the reductions of GHG emissions and water pollution can reach 37% and 55%, respectively.

The integrated model is developed by linking the water and energy models through the interactions between water and energy systems identified by the system archetypes. The result shows that water demand is reinforced by energy demand, and vice versa. This growth, however, is limited by water and energy availability. The result also reveals that some decisions to solve the problems of one resource result in the problems of the other resource. The increase of water price is one of these, which decreases the water demand by 24.3% but leads to increase of the energy demand by 1.53% due to the use of reclaimed water. Rebates on indoor water-efficient appliances are effective to reduce both water and energy demands largely due to the household energy use in water heating. In addition, this study demonstrates that integrated management options can improve the uses of water and energy, but decisions without considering each other may lead to more issues. For example, reclaimed water, a supply management option considering the energy, can increase the water balance index by 27.3% and the energy balance index by 0.14%; it can also reduce the water pollution by 11.76% and the GHG emissions by 13.16%. Seawater desalination, a supply management option without integrated consideration, intends to decrease the water shortage but eventually increases the water balance index by 29.7%. It also causes the increases in water pollution and GHG emissions by 89.79% and 14.53%, respectively. Similarly, solar energy presents the advantage in increasing the balance indices and reducing the environmental impacts.

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This study is an initial attempt to link water and energy systems to explore integrated management options. It is limited by the data availability, assumptions for model simplification, and lack of consideration of climate change. The recommendations for future study include (a) employing a more accurate projection or representation of precipitation, (b) testing the energy model with local data, (c) considering water and energy allocation between different users under shortages, (d) examining the environmental impacts associated with bay water withdrawal for power generation, (e) investigating the water and energy use under climate change, and (f) involving stakeholders early in model development and continuous participation in policy analysis.

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CHAPTER 1.

INTRODUCTION

1.1. Water-Energy Interaction and Management

In today's world, many resources are needed to sustain human development. Water and energy are perhaps the two most basic but important resources for societal prosperity and economic development. The world GDP increased by 3% per year accompanying with an annual 1.5% increase in oil demand in past three decades (Hirsch et al., 2005). Without energy, our ability to maintain the quality of life is also severely affected (Pacific Institute, 2009). Water is essential for all lives on this planet and almost all human activities (UNIDO, 2003). However, nearly 80% of the world's population are threatened by water security (Clarke, 2013; UNEP, 2005). Water provision is a major challenge that humanity is facing in the twenty-first century due to limited water resources and the deterioration of water quality (Schwarzenbach, 2010; Vörösmarty et al., 2000; Gössling et al., 2012). In order to meet increasing water demand, a large amount of energy is required for pumping, treating and delivering water. It is estimated that about 4 percent of U.S. power generation is used for water and wastewater services (DOE, 2006b; Stillwell et al., 2011). If there were unlimited energy, there would not be a problem supplying water for use. For example, vast resources of saline water could be desalinized and provided for all the imaginable demands for water. However, this is not the case; energy is limited in reality (Fuller, 2001). The worldwide coal reserves are estimated to be available up to

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2112; oil and gas will be depleted by 2042 (Heinberg and Fridley, 2010; Shafiee and Topal, 2009).

In addition, the fossil-based energy consumption results in adverse environmental impacts. Coal, natural gas, and oil are the dominant energy sources in the U.S. The use of fossil fuels has impacts on air, water, and land at different geographical scale. It is also directly responsible for large proportions of the greenhouse gas (GHG) emissions (Hillman and Ramaswami, 2010; Omer, 2008; Veil et al., 2004). On the other hand, most of the energy production is heavily dependent on water (DOE, 2006b). The U.S. Geological Survey (USGS) estimated that thermoelectric generation withdrew approximately 201 billion gallons of freshwater per day in 2005, which accounts for 41% of the total freshwater withdrawals in the U.S. (Kenny et al., 2009).

It is clear that water and energy are intrinsically linked together and depend on one another in modern society (Cohen, 2004; DHI, 2008; DOE, 2006b; Gleick, 1994; Pate et al., 2007). It has become increasingly evident that the water or energy professionals alone can no longer solve water or energy problems. As a result, International Water Association (2008) recommends that water and energy management should consider the competing interests of both resources, as well as the mutually reinforcing synergies between two resources. U.S. Department of Energy (DOE) also initiated the road map and identified the needs in the energy and water management, which includes: (a) considering the interactions between water and energy at a watershed or regional level, (b) developing databases or models to investigate the water-energy nexus, (c) examining the impacts of climate change on water supplies and energy production, and (d) improving the efficiency and conservation of water and energy uses (Hightower et al., 2007).

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To date efforts on water-energy nexus concentrate on quantifying the energy use in water cycle or the water use in energy production as shown in Figure 1-1. For example, there are studies to quantify the water use in energy production or the energy use in the water and wastewater treatment (DOE, 2006b; O'Hagan and Maulbetsch, 2009; Stillwell et al., 2010; Stillwell et al., 2011; Stokes and Horvath, 2006). However, little work has been done to examine the impact of water or energy management options on both systems (as the red dashed lines shown in Figure 1-1). Currently water and energy are still managed separately. The effectiveness of water management options to improve resource use efficiency and reduce environmental impacts is only examined on the water side. Energy professionals are not actively involved in water resource management (Bowles and Henderson, 2012; Johnston and Kummu, 2012; Olmstead, 2013; Weinzierl and Schilling, 2013). Similarly, the effectiveness of energy management options is only investigated from the energy side (Bale et al., 2012; Bunse et al., 2011; Suganthi and Samuel, 2012). Due to the segmental management, some issues have surfaced. Strategies in energy planning have resulted in some unintended consequences in the water system. For example, biofuels can relieve the stress of fossil fuels demand, but it puts stress on municipal water use. Citizens in Illinois of Champaign and Urbana have already opposed an ethanol plant because the water withdrawal of the plant reduces the potential residential water use (Webber, 2008). On the other hand, the options to address the water supply crisis such as water transfer and seawater desalination requires considerable amount of energy and caused problems in the energy system. Such issues raise some important scientific questions: Will solutions to the problems of one resource exacerbate shortages or unsustainable patterns of use in the other? Will integrated management improve the overall efficiency of resource use and reduce the environmental impacts?

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1.2. Research Goal, Hypotheses, and Tasks

The overall goal of this study is to develop a decision support tool for long-term regional water and energy resources management through a system dynamics simulation modeling using Tampa Bay Region as the study site. The impacts of water management options on both water and energy systems are investigated. Similarly, the impacts of energy management options are also examined for both systems (as the red dashed lines shown in Figure 1-1). This study is helpful to understand the implications of water and energy interactions, and recognize the benefits of integrated water and energy management in terms of reducing resource uses and the environmental impacts while meeting the demands for both water and energy.

There are two hypotheses related to the research questions raised before.

Hypothesis 1: Management strategies for one resource may have the negative impacts on the other through complex linkages and feedback loops.

Hypothesis 2: Integrated water and energy management has the potential to reduce demands for both resources and the associated environmental impacts.

A water sub-model, an energy sub-model, and an integrated water and energy model are developed in this study as shown in Figure 1-2. The water and energy model developments follow a 3-step modeling process described in Chapter 2. The detailed modeling steps for water sub-model and energy sub-model and policy analysis are specified in Chapter 3 and Chapter 4, respectively. The development of the integrated model and the analysis of management options on both water and energy systems are provided in Chapter 5. Chapter 6 summarizes the conclusions of this study and recommendations for future studies.

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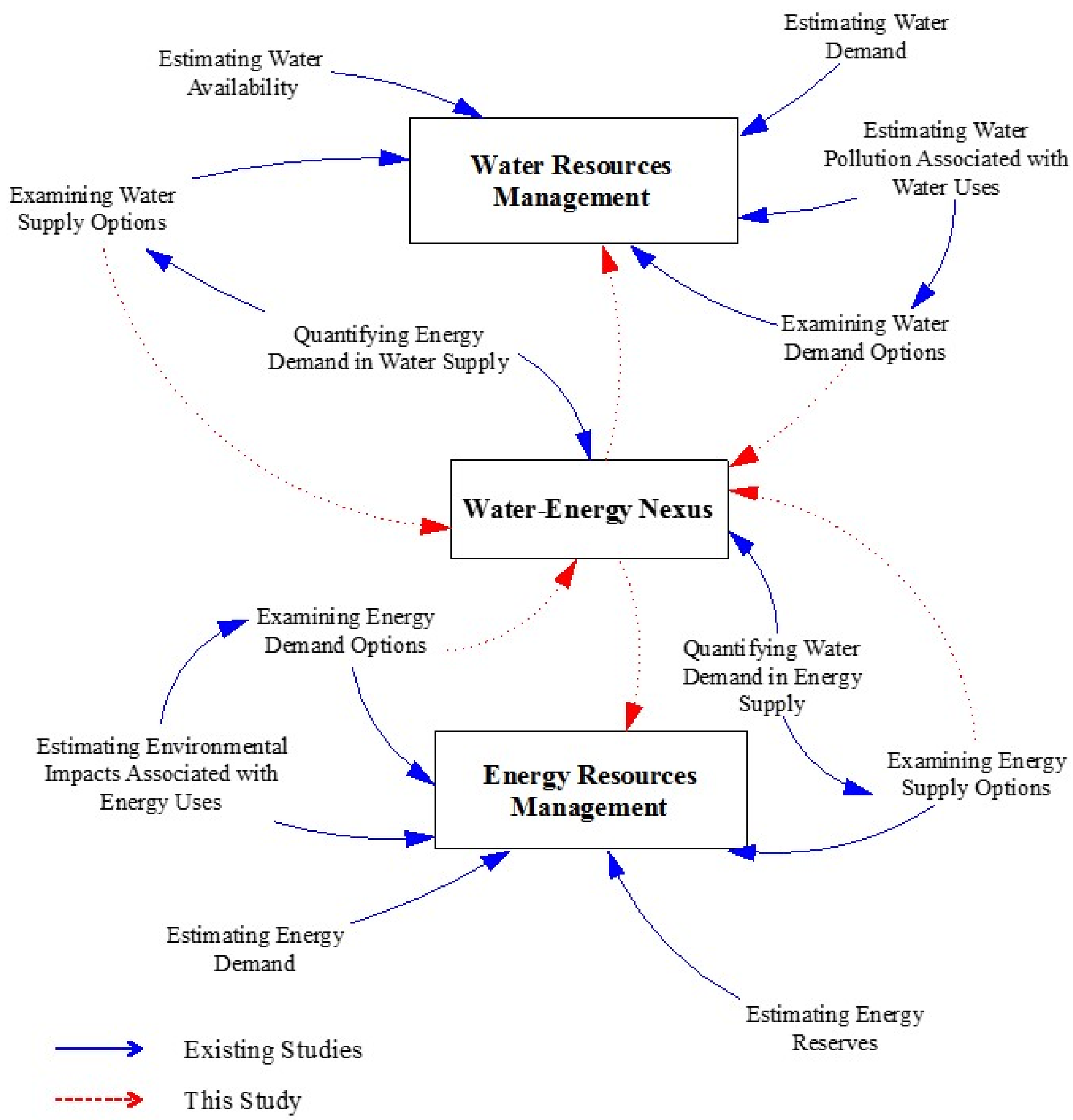

Figure 1-1 Studies in Water and Energy Resources Management. The blue solid arrow represents the aspect that has been studied in water and energy management; red dashed arrow represents the aspect that is missing and is studied by this dissertation.

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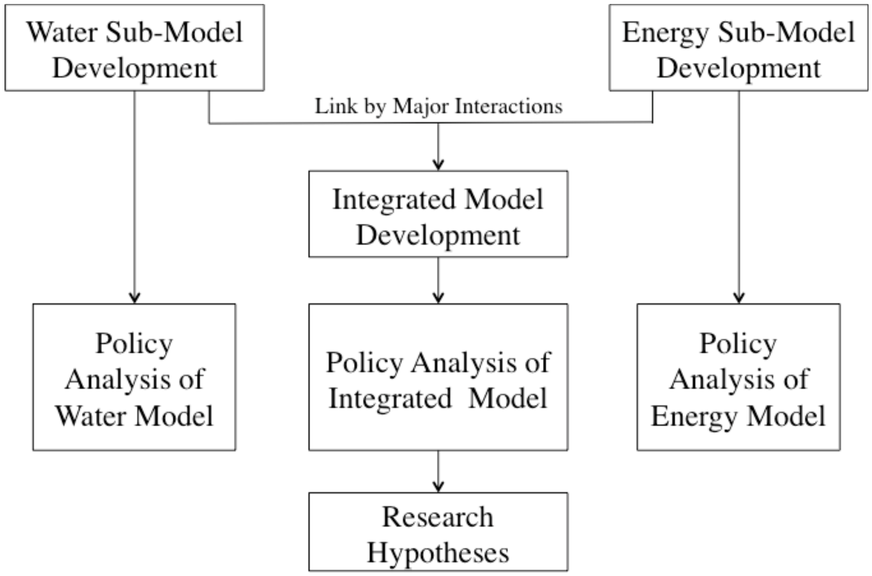

Figure 1-2 Framework of Research Tasks

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CHAPTER 2.

RESEARCH APPROACH AND STUDY AREA

System dynamics approach is applied to investigate the interactions between water and energy systems in this study. This chapter introduces the system dynamics approach and the modeling steps, as well as the spatial and temporal boundary associated with the study area.

2.1. Systems Thinking and System Dynamics

Systems thinking considers the whole system, especially the interactions rather than the isolated things (Senge, 1997). Nowadays, systems thinking is being applied to the field of engineering due to the recognition of system complexity (Bahill and Gissing, 1998; Forrester, 1994; Frank, 2000). The real problems and the solutions to a problem is not intuitive due to the interactions and time delays occurred in a system (Assaraf and Orion, 2005; Gharajedaghi, 2011; Lewis, 1998; Zoller, 1990). Systems thinking offers a deeper insight into problems. It focuses on the system structure and the system behavior produced by the structure (Senge, 1997).

System dynamics (SD) is a modeling and simulation approach using systems thinking (Assaraf and Orion, 2005; Forrester, 1994). It is capable of (a) capturing the interconnections among different components within the system, (b) identifying the stock-flow relationships, (c) recognizing delays and their impacts, (d) simulating the structure of the system, and (e) explaining the behavior that the system produces (Draper, 1993; Forrester, 1994; Frank, 2000; Sterman, 2000; Sweeney and Sterman, 2000).

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System dynamics modeling was initially applied to industrial and business system management and later expanded to diverse problems (Ford, 1999b; Kelly, 1998). SD applications to environmental and resources management are constantly increasing since the early applications such as Urban Dynamics (Forrester, 1969), World Dynamics (Forrester, 1971), and Limits to Growth (Meadows et al., 1972). System dynamics is well suited for modeling water and energy systems, as they involve large spatial units and many ecological, human, and social elements that depend on and affect water and energy resources. With SD modeling, these elements can be linked together to investigate their interactions (Ford, 1999; House-Peters and Chang, 2011; Saysel et al., 2002; Stave, 2003)

2.2. Modeling Process

SD modeling is an iterative process. A four-step system dynamics modeling process introduced by Sterman (2000) and Ford (1999b) is used in this study. Table 2-1 summarizes the modeling process, and the details of each modeling step are provided in the following sections.

2.2.1. Step 1: Problem Articulation

Problem articulation is the most important step in SD modeling, and the rest three steps are related to problem articulation. A clear identification of the model purpose based on the problem can increase the usefulness and effectiveness of a SD model. The problem articulation includes (a) defining the problem, (b) identifying the key variables related to the problem, such as stocks, exogenous and endogenous variables, and (c) identifying the temporal and spatial scales to be considered.

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2.2.2. Step 2: Model Formulation

2.2.2.1. Causal Loop Diagram

Model formulation aims to represent the structure of the problem, which is based on the problem articulation. Causal loop diagrams (CLDs) and stock flow diagrams (SFDs) are the two basic tools used in model formulation. A CLD is capable of visually representing the feedback structure and causal relationships of a system. It consists of variables connected by arrows and signs, which indicate the causal relationships among the variables. As summarized in Table 2-2, a positive sign represents that the changes of cause and effect occur in the same direction. For example, the effect increases with the increase of the cause. A negative sign represents that the changes of cause and effect move in the opposite direction. For example, the effect decreases with the increase of the cause.

These variables are linked together to form a feedback loop. Figure 2-1 takes population as an example to explain the concept of a causal loop diagram. On the left side of the figure is a reinforcing loop for population. The increase of births leads to the increase of population, and the increase of population along with the birth rate cause the increase of births, which further adds to the population. This forms a clockwise reinforcing feedback loop, which is denoted as R or positive sign (+). The right side shows the balancing loop for population. If the population increases, the deaths increase which decreases the population. This forms a counter balancing feedback loop, which is denoted as B or negative sign (-).

Delays are also important in SD modeling, as they produce late responses, which create difficulties to understand the system behavior and link it with the feedback structure without simulations. There are different types of delays, including information delays and material delays. For example, an information delay occurs in the change of energy demand as a response to

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the increase of energy price. The time needed to expand water supply capacity is a material delay. Delays are caused by the system inertia, which creates oscillations of the system behavior, such as overshoot or undershoot. Therefore, delays should also be identified in addition to the causal relationships in a CLD.

2.2.2.2. Stock and Flow Diagram

A causal loop diagram emphasizes the feedback structure of a system, while a stock and flow diagram emphasizes the underlying mathematical relationships. Stock and flow along with feedback are the core concepts of system dynamics. Stock is the accumulation over time, which represents the state of the system. It is only changed by the flows, which is represented by a pipe with a valve pointing into or out of the stock. Figure 2-2 shows a generic structure of a SFD. Each stock represents an ordinary differential equation, as presented in Eqs. 2-1 and 2-2.

$$Stock_t = \int_{t_0}^{t} [Inflow_t - Outflow_t]dt + Stock_{t_0} \tag{2-1}$$

or $$dStock_t / dt = Inflow_t - Outflow_t \tag{2-2}$$

An initial condition should be defined for the stock, and all the other variables should be quantified by equations or values. Vensim® software is used to construct the CLDs and SFDs in this study.

2.2.3. Step 3: Model Testing

Model testing is a critical step in SD modeling. The validity of the results is dependent on the validity of the model. A three-step model validation suggested by Barlas (1996) is used in this study as shown in Figure 2-3.

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2.2.3.1. Structure Test

The system behavior is produced by the underlying structure. The first step of model testing is the structure test. It is conducted by comparing the model structure with the available knowledge about the real system presented in literature including governmental reports, journal publications, and grey literature. The structure refers to the causal relationships, mathematical equations, and units. There is no simulation involved in structure test.

2.2.3.2. Structure-Oriented Behavior Test

The structure-oriented behavior test is to evaluate the structure indirectly (through simulation). It is helpful to find out the potential structure flaws. The structure-oriented behavior test carried out in this study includes extreme condition test and sensitivity analysis. Extreme condition is to test if the model is robust under extreme or highly unlike condition. It is performed by comparing the simulated behavior under the scenario with extreme or unrealistic values of the input parameters with the expected behavior of the real system. If the simulation does not produce the expected behavior, the structure-oriented behavior test fails and structure should be revised and tested again.

Sensitivity analysis is to determine to which input the system is sensitive. It is performed by the Monte Carlo method with a random uniform distribution for -20%~20% change of the selected inputs. Similar to extreme condition, the simulated behavior is compared with the expected output. If the real system exhibits similar sensitivity to the corresponding input, the sensitivity test passes. If the sensitivity test fails, the structure needs to be revisited and tested again (as shown in Figure 2-3). Besides, the value of the input parameter with a high sensitivity should be quantified more accurately.

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2.2.3.3. Behavior Test

Once the validity of system structure is confirmed, behavior test can be performed to evaluate the accuracy of the behavior produced by the system. The behavior test is not to evaluate the point-by-point estimation (e.g., average, standard deviation), but the behavior pattern. Therefore, mean-square-error (MSE) and inequality statistics are used to test the system behavior as shown in Eqs. 2-3 ~ 2-6 (Sterman, 1984).

$$MSE = \frac{1}{n}\sum (X_s - X_o)^2 \quad (2\text{-}3)$$

$$U^M = \frac{\overline{X_s}^2 - \overline{X_o}^2}{MSE} \quad (2\text{-}4)$$

$$U^s = \frac{S_s^2 - S_o^2}{MSE} \quad (2\text{-}5)$$

$$U^C = \frac{2(1-r)S_s S_o}{MSE} \quad (2\text{-}6)$$

where, s and o represent simulation and observation; MSE means the mean-square-error, which quantifies the difference between estimated and true values; n is the number of the data points; X is the value of variable at time t, and $\overline{X}$ is the average value of the variable over time; S is the standard deviation of the data; r is the degree to which the simulation and observation covary; U^M is the bias, which measures the bias between simulated and actual data; U^s is the unequal variation, which measures the degree of unequal variation between two datasets; U^c is the unequal covariation, which measures the degree of divergence between simulated and actual data in point-by-point estimation.

The behavior test is passed if MSE is lower than 10%. If MSE is higher than 10%, but 50% of the error is caused by unequal covariation ($U^C > 50\%$ and $U^M + U^S < 50\%$), the

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behavior test is also passed (Sterman, 1984). Otherwise, the behavior test fails, and structure needs to be revised and tested again.

2.2.4. Step 4: Scenario Design and Evaluation

Once the validity of the model is confirmed, the model can be used to evaluate the scenarios that are designed to address the problem. The SD simulation is to answer what-if questions. The purpose is to investigate how the system responds to the change of input, not to predict the system value at certain time step.

2.3. System Boundary

2.3.1. Spatial Boundary

Tampa Bay region is chosen as the study area, which is located on the west central coast of Florida and estuary along the Gulf of Mexico. The definitions of Tampa Bay region vary by organizations. This study defines Tampa Bay region as Hillsborough, Pinellas, and Pasco counties, which aligns with the definition of Southwest Florida Water Management District (SWFWMD) (as shown in Figure 2-4). The populations for these three counties in 2012 are 1.278, 0.921, and 0.470 million (U.S. Census, 2013). The average annual rainfall for Tampa Bay region is 51.5 inches (SWFWMD, 2012), which seems plentiful in Florida. However, rainfall is not always readily available due to seasonal change. The rainfall rate is high from May to September, but low from October to April. Besides, more than half of the land is urbanized, which may impact surface water quality through urban runoff. The industrial water demand decreased from 83 to 10 MGD, as the manufacturing industry is gradually replaced by financial service and information technology, which is a major industry in Tampa Bay (BEBR, 2013; Ferguson, 2014; Marie, 2011). However, the municipal water demand has increased from 148

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MGD (million gallons per day) to 318 MGD from 1970 to 2009. The water supply highly relies on freshwater with the reclaimed water less than 15 MGD. As a result, the surface- and ground-water withdrawals keep increasing. Recently, a minimum water level is proposed for Hillsborough River to protect the aquatic habitat (Leeper et al., 2010; SWFWMD, 2009 and 2010). This regulation limits the surface water withdrawal, which put a conflict between human water use and natural resource protection. Besides, most groundwater is pumped from the deepest formation, the Upper Floridan aquifer; however, the Floridan aquifer, as a source for potable water, is diminishing as the water quality deteriorates in the south (e.g., dissolved solids, chlorides and sulfates exceed maximum recommended drinking water standards). The traditional water supply sources will not be sufficient to meet the increasing demand. Alternative water supply sources, such as reclaimed water and desalinated water, need to be explored, which not only requires capital investment but also energy input for water treatment.

Regarding to the energy side, although there is no specific energy use data for Tampa Bay region, the energy consumption is generally high across the counties in Florida. The annual residential electricity use per capita is 6,842 kWh, 43% higher than national average, among the highest in the U.S. The high energy consumption is partly contributed by the intensive electricity used for air-conditioning and heating in summer and winter (EIA, 2009). Similar as many states in the U.S., the electricity generation in Florida is highly dependent on nonrenewable energy, especially coal. Thus, around 48.7% of carbon emissions in 2011 were contributed by electricity generation in Florida (EIA, 2011). Like other U.S. states, Florida is in a transition stage of shifting from traditional energy sources to clean energy. The Florida State government established the Florida Energy Systems Consortium (FESC) to support the development and implementation of energy strategic plan through collaboration between energy experts. The

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production of renewable energy currently, however, is still more cost intensive than conventional energy production. As a result, only 2.2 percent of Florida's total net electricity generation is produced by renewable energy (EIA, 2012). Meanwhile, the energy demand for alternative water supply, especially desalination, adds to the energy production and greenhouse gas (GHG) emissions due to the reliance on fossil fuel. For example, the energy intensity for Tampa Bay seawater desalination plant, which has a capacity of 75 MGD, is 8 to 20 times higher than surface water treatment (FDEP, 2010). Tampa Bay Water also initiated an energy program roadmap to estimate the GHG emissions associated with energy use in water treatment (Tampa Bay Water, 2011). Despite the recognition of the nexus between water and energy, there is not an integrated water and energy management in place in Tampa Bay region. Therefore, Tampa Bay region is an ideal study site for evaluating the potential integrated water and energy management strategies to support future decisions.

2.3.2. Temporal Boundary

This study considers a 100-year time period from 1980 to 2080 for simulation. The time span varies from 10 years (Zarghami and Akbariyeh, 2012) to 100 years (Naill, 1976; Rehan et al., 2011; Simonovic and Rajasekaram, 2004) in previous water or energy SD models. The long simulation period is used to understand the impacts of management options on both water and energy systems in long-term. The reported data from 1980 to 2010 is used to compare with the simulated results for model validation. The simulations from 2011 to 2080 are to investigate the future changes in water and energy resources corresponding to various management strategies. Due to the seasonal change (e.g., temperature, rainfall) in Tampa Bay region, the modeling is based on monthly step, and the results are aggregated to yearly level for further analysis.

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2.4. Data Sources

Data were mainly obtained from the Southwest Florida Water Management District (SWFWMD), the U.S. Geological Survey (USGS), U.S. Energy Information Administration (EIA), and related literature. Table 2-3 lists the main variables and the data sources.

2.5. Chapter Summary

System dynamics provides an insight into problems, as it focuses on the system structure. The SD modeling consists of four steps. Problem articulation defines the model purpose and key variables, which is the first and most important step of all. Model formulation is the second step, which includes mapping the causal loop diagram and stock flow diagram, followed by variable quantification. The third step is a 3-step model testing, from structure, to structure-oriented behavior, to behavior tests. The last step is scenario design and simulation, which investigates the effect of the policies to address the problem. Tampa Bay region is chosen as the study area. The model uses a monthly step for the simulation period from 1980 to 2080.

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Table 2-1 System Dynamics Modeling Process (Ford, 1999b; Sterman, 2000)

Step	Contents
Problem Articulation	What is the problem? Why is it a problem? What are the key variables related to the problem? What are temporal and spatial boundaries of the problem?
Model Formulation	Causal loop diagram Stock and flow diagram Variable quantification
Model Testing	Structure test Structure oriented behavior test (e.g. extreme condition, sensitivity) Behavior test
Scenario Design and Simulation	What are the policies or strategies to solve the problem? What are the effects of the policies?

Table 2-2 Definitions and Examples of Sign Polarity (Sterman, 2000)

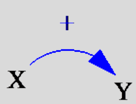
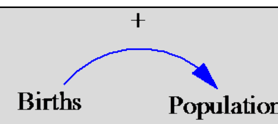
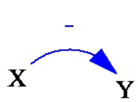
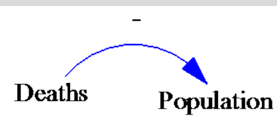
Sign	Meaning	Mathematics	Example
	If X increases (or decreases), Y increases (or decreases)	$\frac{\partial y}{\partial x} > 0$	
	If X increases (or decreases), Y decreases (or increases)	$\frac{\partial y}{\partial x} < 0$	

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Table 2-3 Main Data Sources

Main Variables	Data Sources
Water Withdrawal	Annual Water Use Reports from Southwest Florida Water Management District (SWFWMD): http://www.swfwmd.state.fl.us/documents/#general
Precipitation	Rainfall Summary Data by Region (SWFWMD): http://www.swfwmd.state.fl.us/data/hydrologic/rainfall_data_summaries/
Evaporation	Florida Automated Weather Network (FAWN): http://fawn.ifas.ufl.edu/data/reports/
Surface Water Hydrology	USGS Surface-Water Data for the Nation http://waterdata.usgs.gov/nwis/sw
Groundwater Hydrology	USGS Groundwater Data for the Nation: http://waterdata.usgs.gov/nwis/gw
Water Quality	Tampa Bay Water Atlas: http://www.tampabay.wateratlas.usf.edu/ Hillsborough County & City of Tampa Water Atlas: http://www.hillsborough.wateratlas.usf.edu/ Pinellas Water Atlas: http://www.pinellas.wateratlas.usf.edu/ USGS Water-Quality Data for the Nation: http://waterdata.usgs.gov/nwis/qw
Energy Production and Consumption, Greenhouse Gas Emissions	U.S. Energy Information Administration (EIA): http://www.eia.gov/state/?sid=FL

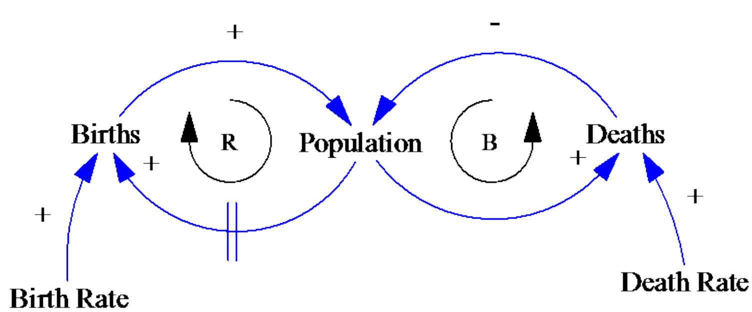

Figure 2-1 Causal Loop Diagram of Population. The positive and negative signs represent reinforcing and balancing causal relationships. R and B represent the reinforcing and balancing feedback loops. A link with a two-line bar in the middle represents a time delay.

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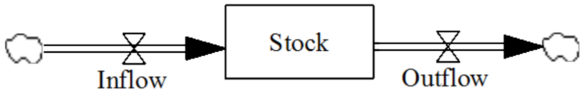

Figure 2-2 Generic Structure of Stock Flow Diagram. The variable represented by the rectangle is a stock, and the variable represented by the pipe with the valve is a flow. The cloud represents a sink or a source, which is out of the system boundary.

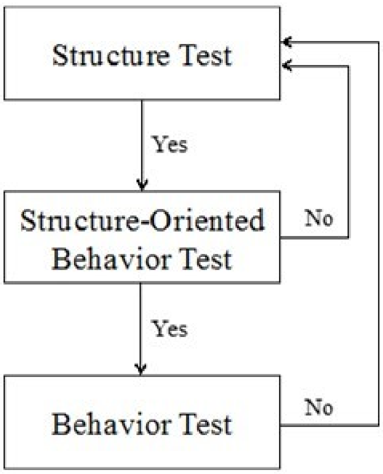

Figure 2-3 Model Testing Process (Barlas, 1996)

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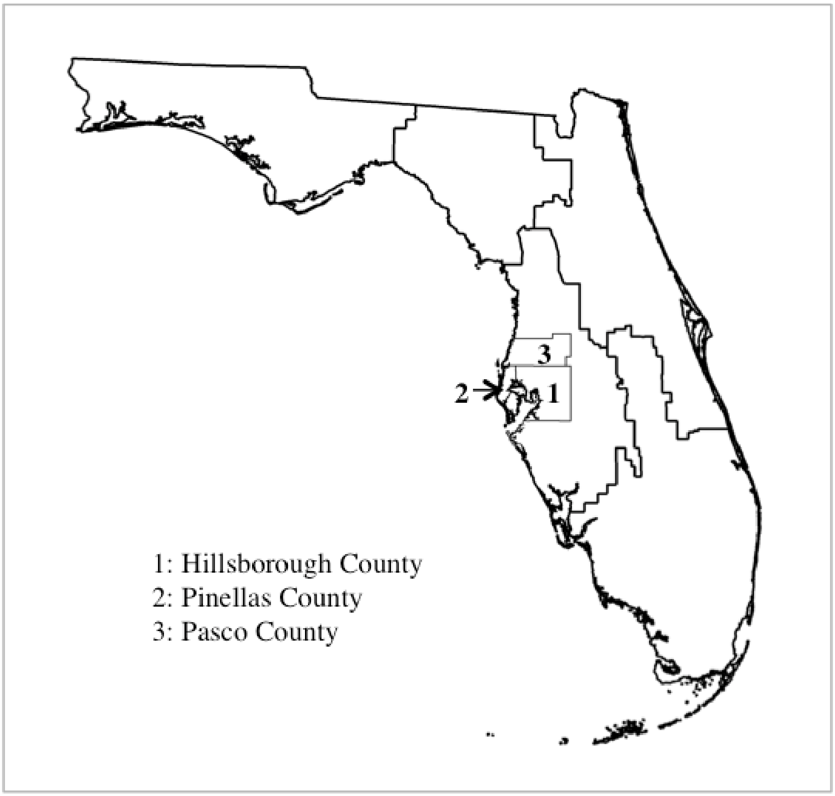

Figure 2-4 Geographic Location of Study Area

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CHAPTER 3.

WATER RESOURCE MANAGEMENT MODEL[1]

3.1. Literature Review

Increasing population, expanding irrigated land and economic development lead to an increasing demand for water resources (Rosegrant et al., 2009; Wada et al., 2010). Meanwhile, non-point water pollution from agricultural runoff and climate change are posing the challenges on water quality (Bouwer, 2000; Delpla et al., 2009; Rosegrant et al., 2009). The limited water resources result in conflicts between different water users. These call for the integrated water resource management, which "promotes coordinated development and management of water, land and related resources, in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital systems" (GWP, 2000).

System dynamics (SD) has a long tradition of analyzing the behaviors of a physical system with social considerations (Forrester, 1971a, 1993; Juarrero, 2000; Sterman, 2000), particularly water systems (Simonovic et al., 1997). So far, only two studies reviewed the application of SD in water resources management. One is Winz (2009), which traced the historical development of SD in water resources management by the model purposes: watershed

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[1] This chapter was published in Zhuang, Y., Zhang, Q. 2013 Integrated water resources management incorporating water quality, energy consumption, and ecological requirement. Proceedings of the 31st International Conference of the System Dynamics Society, Cambridge, Massachusetts, U.S., July 21-25, 2013. Permission is included in Appendix E.

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planning, urban water planning, flooding control, irrigation management, and pure system dynamics modeling process. The other is Mirchi (2012), which summarized the SD models from the perspective of physical watershed processes, strategic policies testing and selection, and stakeholder participation. Both studies provided an overview on the application of SD in water resources management and agreed on the importance of SD approach in water resource management. They, however, only reviewed and pointed out the gaps related to the first step of SD modeling: model purposes. Issues in the rest three steps: key factors, model structure, model validation, and policy analysis (Sterman, 2000), have not been reviewed.

In order to provide a more comprehensive view of SD modeling in water resources management, the following section reviews the SD models in water resources management according to the modeling steps. Sixty-five peer-reviewed SD models (including journals and conference proceedings) in water resources management were reviewed. Despite an extensive search, this study is limited by the accessible research publications and some manuscripts may have been missed. Table A-1 summarizes the applications of SD in water resources management regarding to model purpose, water supply sources, water demand users, water quality consideration, and model validation.

3.1.1. Model Purpose

The purposes of existing SD models can be summarized as four groups: examination of management strategies for regional water resources, evaluation of management strategies for utility companies, simulation of hydrological processes, and explanation of stakeholder participation. As shown in Figure 3-1, a majority of the models are developed for regional water resources management. These models analyzed different strategies to meet increasing water demands with limited water resources, such as increasing water supply through alternative water

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sources, reducing water demand through conservation, or both. For example, Chen et al. (2006) investigated the effect of building a new reservoir to solve water shortage in the Hsinchu region. Ahmad and Prashar (2010) tested the water conservation policies including low flow appliances, xeriscaping, and pricing to reduce water demand in the Lake Okeechobee region. Zarghami and Akbariyeh (2012) examined both water supply and demand options to bridge the gap between water supply and demand in the city of Tabriz, which include reusing and transferring water to increase water supply, and installing water efficient appliances and increasing water price to decrease the water demand. The spatial boundary of regional water resources management models can be one or several watersheds, such as the Yellow River Basin model (Xu et al., 2002), or administrative boundaries (a city or a nation), such as the Tianjin model (Zhang et al., 2008) and the Canada model (Simonovic and Rajasekaram, 2004). The temporal scale is usually long-term, such as 20 to 50 years, due the time delay of the policies to take effect.

SD models are also developed for water utility management. They evaluated the effect of different decisions made in water treatment plants on their financial aspect. For example, Adeniran and Bamiro (2010) analyzed the operation and maintenance cost associated with different locations of pumping stations for a water treatment plant. These models are short-term, such as 1 to 3 years. However, the strength of SD models is to investigate long-term system behavior pattern not day-to-day operation issues. To date, only 4 models have been developed in this category.

In recent years, the complexity of water system has been acknowledged. Water professionals realize the importance to collaborate with other agencies across the sectors affecting water resources. Accordingly, another group of SD models is developed as an

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interactive and education tool for stakeholder participation. It helps non-technical individuals to understand the impacts of management decisions and to identify the problematic trends in water resources management from a holistic view. For example, the Las Vegas Basin model (Stave, 2002) convinced 83 community members that water conservation is more effective than increasing water supply to solve water shortage in a 2.5-hour workshop. The visual description of causal relationships and graphic simulation results make a SD model an ideal bridge across disciplines.

Another main group of models focuses on the hydrological process. They analyzed the impact of external factors on the water cycle. For example, Li and Simonvoic (2002) determined the impact of temperature on canopy interception and soil water storage through the consideration of snowmelt in the hydrological process. However, this group of models usually considers the physical parameters (e.g., temperature) as external factors instead of the management related factors (e.g., water pricing). They are useful to understand the water cycle and to facilitate the development of water supply aspect in SD models but are limited in terms of evaluating management strategies.

With the increasing concerns on climate change, two models were developed to address the issue of flood (Ahmad and Simonovic, 2004) and sea level rise (Ruth and Pieper, 1994). The impacts of climate change vary by spaces, so these two models incorporate spatial dimension into SD to capture the spatial variability. For example, Ahmad and Simonovic (2004) divided the study area (Red River Basin) into 43 cells and captured the movement of water (i.e., flows) by the topographic data of neighboring cells (e.g., elevation, ground slope, presence of dikes). The spatial interaction requires the incorporation of spatial

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analysis tools, such as a geographic information system (GIS), and software development. It limits the number of models developed to address the issues associated with climate change.

Other emerging water issues, especially sustaining a healthy aquatic environment and managing the water-energy nexus (Bazilian et al., 2011; Biswas, 2004; Hussey and Pittock, 2012), are not considered in existing water SD models. For example, the increase in energy demand contributes to the increase in water demand and in turn reduces the water availability in many regions (Cohen, 2004). The discharge from power plants to water bodies has an impact on the health of an ecosystem (Guo et al., 2000; Poornima et al., 2005). The lack of consideration of such emerging water issues in model purpose will affect the following steps in model development: key factors, model structure, and scenario evaluation. Eventually, this will cause unintended consequences of the management strategies recommended by the model.

3.1.2. Key Factors

Key factors are associated with the model purpose. The utility company management models focus on the financial cost of operation and maintenance, so the key factors center on cost, such as cost for new pump stations and energy consumption. The stakeholder participation models are used for expert consulting or public education. Their audiences are non-technical individuals, so the models are usually highly aggregated or simplified. The manuscripts documenting such studies are detailed in how to involve stakeholders not how to develop the model. Information, such as key variables, model structure, is not provided in those manuscripts. The hydrological processes simulation models are interested in the water cycle, so the key factors include surface water storage, soil water storage, and groundwater storage. The following sections (including key factors, model structure, model validation, and policy analysis) focus on

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regional water resources management models, which account for seventy percent of the models reviewed in this study.

Figure 3-2 shows the key factors considered in the existing regional water SD models. The primary interest in majority of these models is still to meet the water demand, so the main factors are related to water demand. Population, economic development, and land use are the three key factors, as they are drivers of municipal, industrial, and agricultural water demand.

Investment is also a key factor, as both water supply and demand management options require investment. For example, the expansion of pipeline construction for reclaimed water is constrained by the capital investment. The improvement in water efficiency and water loss control is also depended on the budget on water efficient appliances rebates and pipeline renovation. However, investment on water quality improvement is not included in these models.

Wastewater is another key factor included in twenty-two of the existing models. Seven of them considered the quantity of wastewater as to analyze the return flow after water use and the potential of water reuse (Bassi et al., 2010; Chung et al., 2008; Gao and Liu, 1997; Qaiser et al., 2011; Stave, 2002; Tidwell et al., 2004; Zarghami and Akbariyeh, 2012). Water quality is considered along with quantity in 15 studies. For example, Anderson et al (1975) considered the water quality in industrial wastewater discharge along with the economic scale of industrial production. Guo et al. (2001) considered water quality in agricultural runoff and industrial discharge. Simonovic and Rajasekaram (2004) included the water quality in industrial and residential water discharge. The water quality indicators used in these studies, however, are not explicitly listed. For example, Guo et al. (2001) listed the three water quality indicators (i.e., N, P, and COD), but Simonovic and Rajasekaram (2004) only pointed out the number of water quality indicators (i.e., 30 indicators).

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Four models include energy as a key factor. Among them, two models considered energy consumption associated with water supply options as a decision factor. For example, Shrestha et al. (2011) compared the cost and carbon footprint associated with energy consumption in water transfer and desalination. Adeniran and Bamiro (2010) included the energy cost in a water treatment plant as a main factor to maintain the operational sustainability. The rest two studies considered the energy consumption for the whole region (including residential, commercial and industrial needs) to determine water demand in power generation (Saysel et al., 2002; Simonovic and Rajasekaram, 2004).

Climate change is considered a main factor in 8 models. It is used to examine the change of surface water availability due to its impact on precipitation. However, climate change results in various issues, such as seawater intrusion, which is not included. As key factors are determined by the model purpose, most key factors are associated with water quantity. Variables associated with emerging water issues, such deteriorated water quality, climate change, energy as a constraint in water supply options, are not fully considered in existing models.

3.1.3. Model Structure

All the models developed for regional water resources management consider both water supply and demand. Most models just consider the traditional supply sources, such as surface water and groundwater. Other water supplies sources are usually considered when there is a crisis of water supply. For example, Leave and Unsworth (2007) considered rainwater for cooling where there is limited surface water but abundant precipitation. Zarghami and Akbariyeh (2012) included water reuse and water import due to arid weather and extremely limited freshwater resources in Iran. In addition, the non-traditional water sources, such as reclaimed water and seawater desalination, require capital investment and technology support. The high

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infrastructure cost is a main barrier to consider non-traditional supply sources when the freshwater shortage is not critical. However, current water shortage or crisis emphasizes the amount of water resources. The available water resources will decrease with the consideration of water quality. Water deterioration has already posed a challenge on water availability.

The main water demand users include municipal, industrial and agricultural water uses. Human water need is still first priority in water resources management; very recently studies consider the ecological water demand (Ahmad and Prashar, 2010; Davies and Simonovic, 2011; Langedale et al., 2007; Langsdale et al., 2009; Wang et al., 2011). The water demand users in most studies are consistent with the U.S. Geographical Survey (USGS) classification. A watershed or a regional scale SD model includes water demand in municipality, agriculture, and industry, while a city scale SD model emphasizes the municipal water demand as agricultural and industrial water demands are insignificant in the study area. Similarly, water demand for energy sector is not considered in most models due to the lack of power plants or fuel extraction sites within the system boundary. For the nine models with power plants in the study area, only two (Simonovic, 2002; Simonovic and Rajasekaram, 2004) included the water use in primary energy production along with power generation, such as fuel extraction and mining. The rest of seven models have not considered water demand for fuel mining or just lumped it into industrial water demand. However, fuel mining, especially coal mining, has a significant impact on water quality. For example, surface coal mining has contributed to the impairment of more than 22 percent of streams and rivers in southern West Virginia (Tomblin et al., 2012).

The majority of model structures are still demand driven, because water resource management and planning is always defined as managing the supply to meeting the demand (Brown et al., 2009; Loucks, 2000). The increasing demand drives the exploration of additional

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water supply sources, such as pumping from deeper aquifer, water reuse, or water transfer. Seven out of 45 regional water resource management models considered water conservation strategies driven by limited water supply. In the real world, there is a feedback loop between demand and supply. The limited water supply could drive the management options to reduce the demand, and the increase in water demand could also lead to diverse water supply options. However, the interaction between water supply and demand is not well developed in the existing models. Only 16 models considered such interactions through an index quantifying the balance between demand and supply as summarized in Table 3-1.

Although these studies attempted to address the interaction between water supply and demand, not all the indices include the feedback between supply and demand. Take the water shortage index ($WSI = D / S$) for example. The water shortage index is defined as the ratio of water supply and demand (consumption) in Zarghami and Akbariyeh (2012) (Figure 3-3a). In order to decrease the water shortage index, both demand and supply management options were considered. The demand management options include increasing the water price and implementing conservation tools, and the supply management options include transferring water from other water basins or investing for leak reduction. Supply and demand management options are considered at the same time, and the option that reduces the largest degree of water shortage index with the lowest investment is most effective. Yang et al. (2008) (Figure 3-3b) also considered the water shortage index; this index is only linked to the water supply options. No demand options are considered to reduce the shortage index.

3.1.4. Model Validation

System dynamics models are always criticized by its subjective model structure and variable quantification (Balci, 1994; Winz et al., 2009), so it is essential to conduct a formal

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model validation (Barlas, 1996; Forrester and Senge, 1978). Figure 3-4 exhibits the statistics of model validation for reviewed publications. Among 65 studies, only four completed a formal model validation (Bagheri et al., 2010; Fernandez and Selma, 2004; Qaiser et al., 2011; Zarghami and Akbariyeh, 2012). The tests conducted were mentioned in these four studies, but no explanation was provided on how the tests were carried out. Besides, the testing results were evaluated qualitatively, such as satisfactory, rather than quantitatively.

A formal model validation is time consuming, so most studies only conducted sensitivity analysis. The results of sensitivity analysis were expressed as sensitivity degree:

$$S = \frac{\Delta O / O}{\Delta I / I}$$

where, S is the sensitivity degree, Δ represents the change, O is the system output, and I is the system input.

However, sensitivity analysis is only able to determine which inputs have large impacts on the system outputs. It is a type of structure-oriented behavior test and cannot replace the behavior test. Twenty-four studies did behavior test, but 18 of them only did the value test. They compared the average and standard deviation between simulated results and real data. This is because of a misunderstanding of system dynamics. The art of system dynamics is not for prediction, but for understanding the system behavior (Simonovic and Fahmy, 1999; Sterman, 2001). Seven studies did both value and pattern test for behavior validation. Overall, most SD models are not formally validated and sensitivity analysis and value test are always adopted as a substitute for formal model validation.

3.1.5. Policy Analysis

Policy analysis is dependent on the model purpose and key variables. Table 3-2 summarizes the main policies evaluated in the previous studies. As most models focus on water

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quantity management, these policies aim to decrease water uses or increase the water supply. Economic development is a common scenario designed for agriculture and industry, because agricultural and industrial water uses are influenced by the economic input and output. Water conservation is designed for both agricultural and municipal sectors, because they are the two largest water users. Agricultural water conservation includes the efficient irrigation systems or change of irrigated crops. Municipal water conservation includes water efficient appliances, such as low-flow toilets. No water conservation scenarios, however, have been considered in industrial and power generation sectors. Water rate is a common water conservation policy to reduce municipal water use, but its impacts on agricultural, industrial, and power generation water use are not analyzed. Similarly, water supply options, such as water reuse, water transfer, or expansion of water treatment capacity, only focus on municipal water use mainly due to the high priority of public supply. For the models considering wastewater, policies on pollution control are also considered. Pollution can be decreased by improving the wastewater treatment level, controlling the use of fertilizers, and tightening the discharge standard. These policies are considered in all sectors, including power generation.

3.1.6. Research Gaps and Future Research Needs

Problem articulation is the most important step in SD modeling (Eskinasi and Fokkema, 2006; Sterman, 2000; Winz et al., 2009). The lack of a consideration of emerging water issues in problem articulation results in the knowledge gaps in model formulation and policy analysis. Table 3-3 summarizes the major research gaps and corresponding future research needs of water SD models.

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One significant research gap of current water SD models is the lack of consideration of water quality in the model purpose, mainly because present water resources management still emphasizes the quantity (e.g., to meet the amount of water demand). However, meeting the demand is not only in terms of water quantity, but also the acceptable water quality. Due to the lack of water quality consideration, water quality and its related variables, such as energy required to treat water to the acceptable quality, are not considered key variables. The lack of water quality consideration also affects the model structure. It leads to improper evaluation of non-traditional water supplies, such as reclaimed water and desalinated water, as viable options. It also leads to the lack of attention to water pollution, especially the deterioration of water quality due to the fossil fuel extraction and the non-point agricultural water pollution. Besides, the purpose focusing on meeting the demands results in another major research gap: lack of considering the dynamic interactions between supply and demand. Most models are demand driven or supply driven, such as finding new water supply sources, or decreasing water demand. The feedback loop between supply and demand should be considered as a driver for diverse management options. Moreover, a formal model validation is not conducted for most models.

3.2. Model Development

As Section 3.1 indicated, current water resource management models lack the consideration of water quality and energy consumption; however, will the incorporation of water quality and energy consumption in the model structure improve the status of water resource (e.g., increase the water levels)? If the water resource management model considers the water quality and energy consumption, which management option is more effective to

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improve the water resource? In order to address the above two research questions, the water model developed in this Chapter incorporates water quality in the model purpose and key variables, as well as energy consumption associated with water supply as a key variable. The key modeling factors include water supply, water demand, and water quality as shown in Table 3-4.

3.2.1. Water Demand

3.2.1.1. Water Demand in Municipality

Water demand in municipality refers to the residential water use through public supply systems and self-domestic supply. It is divided into indoor and outdoor water demand. The stocks considered in this section include the number of indoor water efficient appliances, the number of outdoor water efficient appliances, and the number of people with municipal water conservation awareness. These stock variables impact on the indoor water use efficiency and outdoor water use (municipal irrigation) efficiency, which further influence the water demand in municipality. Figure 3-5 shows the causal relationships within the water demand in municipality.

Indoor water demand is determined by indoor water per capita and population. Indoor water demand per capita can be reduced by the demand options, including budget on municipal water conservation education, indoor water appliance rebate program, and water rate. Increase of the budget on water conservation education can increase the water conservation awareness, such as shortening the time of showering, decreasing the times using dishwasher, and so on. These will decrease per capita water requirement (Nieswiadomy, 1992).

The increase of water conservation awareness and rebate program can increase the installation of water efficient appliances, such as low-flow toilets (Campbell et al., 2004) as shown in Figure 3-5. The number of efficient appliances will impact on the indoor water

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efficiency. It decreases with the aging of the appliances and the difference between existing and potential number of indoor water efficient appliances drives the financial needs for the rebate program. However, the actual installation of indoor water efficient appliances is determined by the expenses, which are limited by budget (the detailed variable quantifications and equations are shown in Appendix C).

Similarly, the increase of water rate can also decrease the per capita water demand. The price elasticity is used to determine the percentage of reduction. The price elasticity varies depending on the change of water rate; large change of rate will result in a high elasticity (Campbell et al., 2004; Espey et al., 1997a; Nieswiadomy, 1992; Young, 1973). However, there is a threshold for the indoor water demand per capita, such as minimum amount for drinking, cooking, and hygiene. When the per capita demand reaches the threshold, the reduction will be negligible even under extremely high increase of water rate.

Outdoor water demand mainly refers to the lawn irrigation, which is determined by weather (e.g., precipitation, evapotranspiration), lawn area, municipal irrigation efficiency, water rate, irrigation restriction, and conservation awareness (Eq. 3-1).

$$WD_{m,o} = \frac{(ET_g - EP) \times A_l}{E_{m,o}} \times (1 - f_w) \times (1 - f_r) \times (1 - f_c) \tag{3-1}$$

where, $WD_{m,o}$ is the outdoor water demand in municipality; ET_g is the grass evapotranspiration; EP is effective precipitation; A_l is the lawn area; $E_{m,o}$ is lawn irrigation efficiency; f_w, f_r, and f_c represent the percentage of reduction in outdoor water demand due to water rate, restriction, and water conservation awareness, respectively.

The irrigation efficiency can be reduced by rebate program for outdoor water efficient appliances and water conservation awareness, which is similar to indoor water use efficiency as shown in Figure 3-7. Increase of water rate can result in a direct reduction of outdoor water

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demand. The reduction is determined by price elasticity, but the price elasticity (average at 0.2) is larger compared with indoor water demand (average at 0.02) (Young, 1973). Irrigation restriction and water conservation awareness will directly reduce outdoor water demand. However, different from indoor water demand, there is no threshold for outdoor water demand. For example, it can reach to zero with extremely high water rate.

3.2.1.2. Water Demand in Agriculture

Water demand in agriculture is influenced by irrigated land, irrigation efficiency, precipitation, and crop evapotranspiration as shown in Figure 3-8. It is determined by the following equation (Saysel et al., 2002; Smajstrla and Zazueta, 1995):

$$WD_a = \frac{(ET_c - EP) \times A_i}{E_a} \tag{3-2}$$

where, WD_a is the water demand in agriculture; ET_c is crop evapotranspiration; EP is effective precipitation; A_i is the area of irrigated land; E_a is the agricultural irrigation efficiency.

Irrigated land, the number of irrigated land with best management practices (BMPs), and the number of people with agricultural water conservation awareness are considered stock variables. Irrigated land decreases due to the conversion to residential land. When the irrigated land reaches to the minimum (i.e., variable “Diff b/w Irrigated Land” is zero), no irrigated land will be converted to residential land, and irrigated land development will be initiated. Residential land development is determined by the required residential land and current state; the required residential land is driven by population as shown in Figure 3-9.

Agricultural irrigation efficiency can be increased by agricultural water management options, including budget on agricultural water conservation education and budget on BMP program. BMPs include nutrient management, water management, pest management, and sediment management (2013). This study lumps four managements together. Increase of

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agricultural water conservation awareness can increase the participation in BMPs. More land with BMPs, such as installation of drip or line source irrigation systems (Smajstrla et al., 1991), can increase the irrigation efficiency. Besides, BMPs are related to not only the use of water but also the water discharge, which will further influence the surface water quality through non-point pollution.

The net water requirement of agricultural irrigation is associated with the weather condition, including precipitation and evapotranspiration. The crop pattern (e.g., types of crops, growth period) will affect the crop evapotranspiration. The crop evapotranspiration is determined by the reference evapotranspiration and crop coefficient (Irmak and Haman, 2003).

$$ET_c = K_c \times ET_0 \tag{3-3}$$

where, ET_c is the crop evapotranspiration; ET_0 is the reference evapotranspiration, which is collected and reported by Florida Automated Weather Network (FAWN). However, only data from 1990 to 2011 is available. The rest of ET_0 is estimated based on the monthly normal distribution (as shown in Appendix E); K_c is the crop coefficient, which is mainly determined by crop type. Table 3-5 lists the main crop types, crop coefficients (Allen et al., 1998), and land uses by crop types (Scott and White, 2011) within the study area. Due to the lack of historical land use data, this study does not differentiate the water demand for each type of crop. An average crop coefficient normalized by the percentage of land use is used to calculate the average crop evapotranspiration (Eq. 3-2).

$$K_c = \sum (f_i \times K_{c,i}) \tag{3-4}$$

where, K_c represents the average crop coefficient; $K_{c,i}$ represents the crop coefficient for each type of crop; f_i represents the fraction of land use by crop type.

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3.2.1.3. Water Demand in Industry

Water demand in industry refers to the water demand in food processing and product manufacturing as shown in Figure 3-10. Water demand in industry is usually driven by economic production (Renzetti, 1992; Tong and Dong, 2008; Zhang et al., 2010). The economic data, such as gross domestic production, is only reported at state level not broken down to county level. It sets the barrier to establish the mathematical relationship between economic development and water demand in industry. However, the water demand in industry is relatively low compared with municipal water use, which is 9.22 MGD, 0.06 MGD 1.14 MGD for Hillsborough, Pinellas, and Pasco counties, respectively (Scott and White, 2011). Therefore, water intensity (water demand for food processing and product manufacturing per employee) is used, which is influenced by temperature.

$$WI_{i,t} = \overline{WI_i} \times T_t / \overline{T} \tag{3-5}$$

where, i is type of industry, 1 refers to food processing and 2 refers to product manufacturing; $WI_{i,t}$ is the water intensity at time t, and $\overline{WI_i}$ is the average water intensity, which is 10,237 gallon/employee for food processing, and 346,378 gallon/employee for product manufacture (Jackson and White, 2012; Scott and White, 2011); T_t and $\overline{T}$ are temperature at time t and average temperature, respectively.

3.2.1.4. Water Demand in Energy

As Figure 3-11 presents, water demand in energy includes water demand in fuel production and water demand in power generation. Population drives the power generation, which determines the fuel production to generate electricity. The water demand in power generation and fuel production is determined by the water intensity. The water intensity varies by fuel type, power generation, and cooling technology as summarized in Table 3-6. Due to the lack

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of fossil fuel mining within the boundary, the water demand in energy mainly refers to the water demand in power generation. Once-through cooling technology is used in Tampa Bay region due to its coastal location. The majority of water for cooling is directly withdrawn from the bay, where water is abundant. Less than 1% of water is from surface- and ground-water. As water is not a limiting factor, the once-though cooling system is used. As indicated in Table 3-7, the once-through cooling system has the lowest capital cost but the highest water withdrawal and potential environmental impacts due to the thermal discharge.

3.2.2. Water Supply

3.2.2.1. Freshwater

Freshwater includes surface- and ground-water, which interact through soil water storage. Figure 3-12 exhibits the causal loop diagram of surface- and ground-water, which is according to the hydrological processes (Elshorbagy et al., 2007; Jothityangkoon et al., 2001; Khan et al., 2009; Li and Simonovic, 2002). Surface water increases with surface water inflow, precipitation, return flows after water uses, and runoff; it decreases with evaporation, infiltration (to soil), and surface water withdrawals. However, the surface water withdrawal is determined by surface water level, which is discussed in Section 3.2.4. Similarly, groundwater storage increases with groundwater inflow, infiltration (from soil), seawater intrusion, and groundwater recharge; it decreases with groundwater outflow and groundwater withdrawal. Water movements from soil to surface water, and from groundwater to soil are assumed to be negligible because of the insignificant suction rate.

Surface water storage, groundwater storage, as well as soil water storage are considered stocks (Figure 3-13) and expressed as Eq. 3-6.

$$dV_i/dt = \sum I_i - \sum O_i \qquad (3\text{-}6)$$

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where, V is the volume of the water; I and O represent the inflow and outflow. i represents the type of water body, 1 to 3 represent surface, soil, and ground water, respectively.

3.2.2.2. Reclaimed Water

Reclaimed water is used for residential irrigation, non-food agricultural irrigation, and power generation cooling. Due to the relatively low use in cooling, this study focuses on the reclaimed water to offset the potable water use in municipal irrigation and groundwater use in agricultural irrigation (Figure 3-14). Reclaimed water demand and capacity are the two competing factors to determine the reclaimed water supply. Reclaimed water demand increases with the public acceptance, which is influenced by peer endorsement (who are using reclaimed water). The advantage of reclaimed water price compared with potable water price, and water conservation awareness can also increase the public acceptance. However, the supply is limited by reclaimed water capacity. Reclaimed water capacity is determined by (a) sources (i.e., the amount of wastewater), and (b) infrastructure, such as pipelines, which is a main limiting factor of the capacity. When the demand is lower than the capacity, the reclaimed water supply equals to the demand. When the demand is higher than the capacity, it drives the expansion, but the construction of pipelines is also constrained by the budget. The increase of budget can increase the capacity, which in turn increases the supply. The amount of reclaimed water used will eventually influence the reclaimed water price.

3.2.2.3. Bay Water and Water Transfer

Bay water is a primary water source for power generation cooling. Because of the large storage of bay water, no limit is set for the bay water withdrawal. Water transfer is one alternative water supply option when the water demand is larger than the water availability.

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3.2.3. Water Quality

Water quality is considered in every inflow and outflow in surface- and ground-water withdrawals. Figure 3-15 shows the stock-flow diagram of surface- and ground-water quality. The sources of pollutants in surface water include runoff, surface water discharge, and surface water inflow (stream flow); the sinks of pollutants include surface water self-purification, surface water withdrawals, surface water outflow (stream flow), and infiltration (to soil). Similarly, pollutants in groundwater also change with the pollutants in groundwater inflow and outflow, groundwater withdrawals, intruded seawater, infiltrated water, and groundwater self-purification. Several assumptions have been made to simplify the model: a) treated wastewater discharge meet the Class I or proposed standards in terms of quality; b) the quality of reclaimed water meets the requirement for groundwater recharge; c) pollutants transferred to the surface water through wet deposition are not significant; and d) the pollutants transferred through evaporation are also negligible.

The water quality is represented using a water quality index as following:

$$I_Q = \frac{\sum (I_Q^{high})_i}{N_{high}} + \frac{\sum (I_Q^{low})_j}{N_{low}} \tag{3-7}$$

$$(I_Q^{high})_i = \begin{cases} \dfrac{(c_{high})_i}{(c_{high}^{standard})_i} \times 100, & (c_{high})_i < (c_{high}^{standard})_i \\ 100, & otherwise \end{cases} \tag{3-8}$$

$$(I_Q^{low})_i = \begin{cases} \dfrac{(c_{low}^{standard})_i}{(c_{low})_i} \times 100, & (c_{low})_i > (c_{low}^{standard})_i \\ 100, & otherwise \end{cases} \tag{3-9}$$

where, I_Q is the water quality index (WQI), which is dimensionless with the scale between 0 and 100; I_Q^{high} is the water quality index for the high concentration preferred indicator, and I_Q^{low} is

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water quality index for the low concentration preferred indicator; N is the number of indicators. c is the concentration; i represents the high concentration preferred indicator, and j represents the low concentration preferred indicator. Table 3-8 lists the key surface water quality parameters and Class I or proposed standards. Water quality varies by monitoring sites. This study averaged water quality parameters from 1980~2005 at five monitor stations, including Lithia Spring, Buckhorn Spring, Bell Creek, Sulphur Spring, and Lettuce Spring.

Average concentration of calcium, magnesium, total nitrogen, total phosphorus, and total dissolved solids in five monitor stations are higher than the standard. The concentration of total dissolved solids is mostly influenced by calcium, bicarbonate, magnesium, sodium, sulfate, and chloride and selected as a representative indicator. The concentration of total nitrogen and phosphorus is a critical parameter to evaluate eutrophication level of surface water. Since the study area is a phosphate mining region and phosphorous is generally not a limiting nutrient for eutrophication, the total nitrogen is selected as another water quality indicator. The concentration of total dissolved oxygen in surface water directly influences the aquatic systems and is an indicator for the health of aquatic ecosystems. Therefore, three water quality indicators, total dissolved solids, total nitrogen, and dissolved oxygen, are considered in calculating water quality index in this study. Except for dissolved oxygen, the rest two are low concentration preferred indicators.

3.2.4. Consideration of Water Quality and Energy Consumption Associated with Water Supply

Water quality and energy consumption are considered in water supply, especially for municipal water supply. They are incorporated in the percentages of surface- and ground-water withdrawals as following:

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$$f_k = w_1 I_{A,k} + w_2 I_{E,k} \tag{3-10}$$

$$I_{A,k} = \frac{w_3(l/l^{Regulated})_k + w_4(I_Q/I_Q^{Regulated})_k}{\sum(w_3(l/l^{Regulated})_k + w_4(I_Q/I_Q^{Regulated})_k)} \tag{3-11}$$

$$I_{E,k} = 1 - \frac{E_t \times \frac{(I_Q^{Required} - I_Q)_k}{(I_Q^{Required} - \overline{I_Q})_k} + (E_{p1} \times \frac{d}{\overline{d}} + E_{p2})_k}{\sum\left(E_t \times \frac{(I_Q^{Required} - I_Q)_k}{(I_Q^{Required} - \overline{I_Q})_k} + (E_{p1} \times \frac{d}{\overline{d}} + E_{p2})_k\right)} \tag{3-12}$$

where, f is the fraction of freshwater withdrawals; k is the type of water sources, 1 represents surface water, and 2 represents groundwater; I_A is the index for water availability; I_E is the index for energy consumption associated with water supply; l and $l^{Regulated}$ are current and regulated minimum water levels, respectively; I_Q, $I_Q^{Regulated}$ and $I_Q^{Required}$ are current water quality index, regulated minimum water quality index, and water quality index for municipal water, respectively; $\overline{I_Q}$ is the average water quality index, which is 65 for surface water and 75 for groundwater; d is current distance for raw water collection and extraction; $\overline{d}$ is the average distance for raw water collection and extraction, which are 30 feet for surface water and 150 feet for groundwater; E_t, E_{p1}, and E_{p2} are the energy intensity for water treatment, raw water extraction, and water distribution, respectively, which are expressed in the unit of kWh/Gallon (Table 3-9); w_1 to w_4 are the weighting factors for water availability, energy consumption, water quantity, and water quality, respectively.

3.2.5. Interaction between Water Supply and Demand

The interaction between water supply and demand is captured using a water demand and supply balance index (Langedale et al., 2007).

$$BI_w = S_w - D_W \tag{3-13}$$

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where, BI_w is the water balance index, S_w is the water availability, and D_W is the estimated water demand.

The water balance index increases with the water availability and decreases with the water demand. When the index is lower than zero or certain value, it triggers the water supply or water demand management options. The demand management options will decrease the water demand, which in turn increases the index. The supply management options will increase the water supply through alternative water supply sources, such as reclaimed water and water transfer, which can offset the freshwater withdrawal and increase the water availability (Figure 3-16).

3.3. Model Validation

A 3-step model validation was also conducted for the integrated model, which includes (1) direct structure tests, (2) structure-oriented behavior tests, and (3) behavior pattern tests as described in Section 2.2.3.

3.3.1. Structure Test

The direct structure test was conducted by comparing the causal and mathematical relationships between variables with the available knowledge about real system. The causal relationships described in the causal loop diagrams are supported by previous studies as detailed in Sections 3.2.1 and 3.2.2. The mathematical relationships based on the literature are explained in details in Appendix C.

3.3.2. Structure-Oriented Test

The structure-oriented behavior test in this study includes the extreme condition test and sensitivity analysis. The extreme condition test examined in this study includes zero precipitation

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and zero population within the system boundary. As expected, the surface water level will gradually drop to zero with no precipitation, and the total water demand will be zero with no people living in the study area as shown in Figure 3-17.

The structure-oriented behavior test also examined the sensitivity of system behaviors to precipitation, water price, and budget for different management options. The values of the inputs vary from -20% to 20% of their original values with a random uniform distribution. The sensitivity analysis was performed with the aid of Vensim® Software. As Figure 3-18 shows that precipitation has the most significant effect on the system behaviors. Surface water level and surface water quality are most sensitive to precipitation, because precipitation is a direct inflow to surface water storage and also a key factor affecting the water quality of runoff. The sensitivity of groundwater level (measured by the groundwater table to surface) to precipitation gradually increases, because the response of groundwater storage to precipitation is delayed by infiltration and soil water storage; however, the groundwater quality is not sensitive to precipitation. Water demand in municipality and agriculture is also sensitive to precipitation, because the weather condition is a key factor in determining the net water requirement.

3.3.3. Behavior Test

The behavior test examined the behaviors of surface water level, municipal water withdrawal, and agricultural water withdrawal. Mean-square-error (MSE) and inequality statistics are used to test the system behavior (Sterman, 1984). Table 3-10 shows that errors of average between simulated and observed data are within 10% (the highest error is 5.31% for municipal water withdrawal). The root-mean-square errors (RMSPE) between simulated and observed data are also within 10% (the highest error is 5.43% for agricultural water withdrawal).

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The majority of the errors are due to divergence in point-by-point prediction (U^C) and the overall trends are well captured as shown in Figure 3-19.

3.4. Results and Discussions

3.4.1. Reference Behavior

The reference behavior was simulated under current water use pattern and weather condition with the population projection from the Florida Housing Data Clearing House (Figure 3-20). The surface water level oscillates around 18 feet, and groundwater level does not change much with a distance of groundwater table to surface around 21 feet. Surface water quality oscillates and increases by 1%. It is because of decrease of agricultural water use, which in turn reduces the pollutants in agricultural runoff. The groundwater quality index decreases by 1% due to the gradual seawater intrusion. Regarding to the water withdrawal, municipal withdrawal will increase by 41% in 2030, mainly due to the population growth. The water withdrawal for agriculture will decrease by 34% in 2030 because of the decrease in irrigated land. However, the change in water withdrawal does not have a significant impact on water levels, because withdrawal is much lower than the storage.

3.4.2. Impacts of Water Quality and Energy Consumption

This study proposed a method to incorporate water quality and energy consumption in choosing the water supply sources. Table 3-11 shows the changes of water levels and quality under different weighting schemes of water quantity, quality and energy consumption for municipal water withdrawal. Currently, 60 percent of water is withdrawn from surface water (Jackson and White, 2012). It is close to the percentage only considering water quantity

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(~61%), which means that water quantity is the primary concern in choosing the supply source in the current water management. The percentage of surface water withdrawal decreases to 50, 48, and 45, when the water quality is taken into consideration with a weighting factor (w_4) of 0.25, 0.5, and 0.75, respectively. The decrease of surface water withdrawal will consequently increase the surface water level by 1.32%, 1.36%, and 1.39% with the expense of the decrease in groundwater level (less than 1%). This means that surface water is preferred if only water quantity is considered because the ratio of surface level to regulated surface level ($l / l^{Regulated}$) is larger than the ratio for ground water. Groundwater, however, is preferred in terms of water quality because the ratio of water quality to regulated water quality ($I_Q / I_Q^{Regulated}$) for groundwater is higher than that for surface water.

If energy consumption is also incorporated, the percentage of surface water withdrawal will be 56, 52, 48 under the equal consideration of water quantity and quality (w_3=w_4=0.5) and the weighting factor of energy consumption (w_2) as 0.25, 0.5, and 0.75, respectively. The percentage is lower compared with the scenario considering only water quantity, but higher compared with the scenario considering both water quantity and quality. Although groundwater quality index is higher than surface water and requires less energy for water treatment, the energy needed for groundwater pumping is 5 times higher than surface water pumping. Overall, the energy consumption for groundwater supply is higher than surface water and the preference of groundwater is decreased with additional consideration of energy consumption. The reduction of surface water withdrawal with considering both water quality and energy consumption will increase surface water level by 1.1%, 1.2%, and 1.3% without significant decrease in groundwater level.

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3.4.3. Effectiveness of Water Supply and Demand Management Options

Section 3.4.2 shows that the incorporation of water quality and energy consumption can improve the surface water level with a slight decrease on groundwater level without considering the management options to reduce the total water withdrawals. This section examines which options are more effective to reduce the water withdrawal or increase the water balance index. Table 3-12 lists the water demand and supply management options, which can be categorized as budget associated and regulation associated options.

3.4.3.1. Water Demand Management Options

Table 3-13 summarizes the impact of water demand options under scenarios considering water quantity only and scenarios considering both water quality and energy consumption. For the scenarios considering water quantity only, which is close to the current water supply strategies, the surface water level will increase from 1.02%~1.41% under demand options mentioned above, and the decrease of groundwater level is less than 0.1%. If the demand management options are combined with the water quality and energy consumption incorporation in choosing the water supply sources, the surface water level will increase from 2.34%~2.67%. The percentage is doubled compared with considering water quantity only. Although the change of surface water level seems not significant, the freshwater withdrawal is reduced up to 17.3%.

Water conservation education is the most effective option (under the same budget) to reduce freshwater withdrawals. It is because the increase in water conservation awareness not only decreases the minimum water demand per capita, but also promotes the use of water efficient appliances. The percentage of people with water conservation awareness increases from 0.3 to 0.6, which is close to the ideal ratio of 2/3 according to Langsdale's study (2007). It also indicates that current percentage of people with water conservation awareness is relatively low

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and changes in the life style of water use through water conservation education will reduce the water withdrawals. Figure 3-21 shows the dynamic change of surface water level change under additional one million dollar budget. The degree of increase is less than 0.5% in the first three years due to the time delay. It usually takes five or more years to observe the outcome of water conservation education (de White and Jacobson, 1994; Middlestadt et al., 2001; Olmstead and Stavins, 2009). The percentage gradually increases to 1.32% in 2020 and 1.41% in 2030.

Rebates for indoor water appliances are the second effective option to improve the surface water level (~1.37%) and reduce the total freshwater withdrawals (~15.4%). The rebates can improve the indoor water use efficiency by installing low-flow rate toilets and clothes washers. However, indoor water use efficiency increases slowly with the increase in rebates, partly because the existing indoor water appliances already have a high efficiency, near 0.83. Besides, rebates are not high enough to motivate residents to reinstall their water appliances. In order to reach the maximum efficiency (0.98), another 10 million dollars should be invested on the rebates of the indoor water appliances, and an annual budget of half million dollars are needed to maintain the efficiency. However, the maximum efficiency is based on assumption that people are economically driven and are willing to replace their water appliances as long as the rebates are high enough.

Rebates for outdoor water appliances can reduce the outdoor water use by 30%, largely because the water saving irrigation systems or the rain sensors are cheaper and easier to install than indoor water appliances. However, this option is less effective than rebates for indoor appliances. Since outdoor water demand accounts for 1/3 of current municipal water uses and decreases to 12.5% of total municipal withdrawal in 2030, this option can decrease the total water withdrawals by only 2.3%. This reduction results in a 1.07% increase in surface water

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level. For the similar reason, water restriction reduces the withdrawal by 1.4%, and increases the surface water level by 1.02%.

A 50% increase in water rate is the third effective option in terms of reducing freshwater withdrawals and improving surface water level. It decreases the withdrawal by 3.0%, which accordingly increases the surface water level by 1.06%. Water rate strategy is effective to reduce the municipal water demand. It reduces the indoor water demand by 2.1% and outdoor water demand by 4.8%. The higher reduction in outdoor water demand is mainly because the elasticity for outdoor water demand (0.2) is higher than indoor water demand (0.02) (Hensher et al., 2005; Jasper M. Dalhuisen et al., 2003; Martin and Kulakowski, 1991; Young, 1973). Also, the increase in water price will promote the use of reclaimed water when there is a significant economic benefits using reclaimed water. However, current water rate is not higher enough to show the advantage of reclaimed water. If the water price increase by 10 times, which is closer to reflect the true value of water (Colby et al., 1993; Hung and Chie, 2013), the reclaimed water demand will increase near to 200 MGD. With enough funding (approximately 1.5 billion dollars) to expand reclaimed water capacity, the change of water rate can offset near 2/3 of the freshwater withdrawal. It will increase the surface water level by 37.7% as shown in Figure 3-22.

The above water demand management options (except for agricultural BMPs), however, do not change the behavior pattern of surface water level. The behavior pattern of surface water level still follows the trend of precipitation. It is largely because surface water level is most sensitive to precipitation, which is a direct inflow to surface water storage, while the management options indirectly influence on the system behavior.

Agricultural BMPs is the only management option of the six does not impact on the surface water level. That is because near 95% of water withdrawal for agricultural irrigation is from

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groundwater. The reduction of water withdrawal is too small compared with the surface- and ground-water storage. However, it can improve the water quality of both groundwater and surface water. Figure 3-23 shows the change of surface- and ground-water quality index under additional one million dollar budget on agricultural BMPs. The reduction of agricultural water withdrawal can increase the surface water quality index by 2.45% and groundwater quality index by 1.04% in 2030. That is because pollutants in agricultural runoff are one source of pollutants in surface water. It is expressed as the product of concentration of pollutants in agricultural runoff and the volume of agricultural runoff. BMPs can reduce the inefficient irrigation, which reduces the volume of agricultural runoff. It can also reduce the unnecessary use of fertilizers, which reduces the concentration of nitrogen in runoff. Therefore, the pollutants loading to surface water bodies are decreased, and water quality index is increased. Similar to surface water level, the change of surface water quality index is small initially and gradually increases. The time for groundwater quality index to reflect the influence of agricultural BMPs is longer than surface water quality index. It is mainly because of the time delay of the interaction between surface water, soil water, and groundwater.

3.4.3.2. Water Supply Management Options

Water supply management options includes (a) additional one million dollar budget on reclaimed water, (b) additional one million dollar budget on water loss control, (c) minimum water level, and (d) water transfer. Table 3-14 summarizes the impact of these water supply options in terms of surface water level, groundwater level, and freshwater withdrawal.

Reclaimed water with additional one million dollar budget is not effective to improve the surface water level. As Figure 3-24 shows, reclaimed water supply will increase to 7.9 MGD in 2030. It will reduce the freshwater withdrawal by 1.1% and in turn increases the surface water level by 0.78%. As Section 3.4.3.1 discussed, increase in the water price rate can increase the

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price advantage of reclaimed water, which can increase the demand (R2). The increase in reclaimed water use will reduce its unit price, which leads to the price advantage over potable water. It in turn increases the reclaimed water demand. However, current reclaimed water supply is mainly constrained by its capacity (B2). Only half of the people who are willing to use reclaimed water have the connections. The high infrastructure cost and limited budget on water resources management constrain the expansion of reclaimed water infrastructure. Current expense on reclaimed water is too low. Even with an additional one million dollar investment on pipeline construction, the capacity still cannot meet the demand. As a result, the reclaimed water supply shows an overall increase with the demand, but it presents a step-wise increase due to the time delay of reclaimed water capacity expansion, such as time to recognize the need, time for planning and pipeline construction. In order to increase the reclaimed water use, more investments should be put on the expansion of reclaimed water infrastructure. Besides, there is also a need to increase the investment on water conservation education to increase the public acceptance of reclaimed water. Only 20% of people within the study area are willing to use reclaimed water.

Water loss control under current budget is not effective. It only reduces the freshwater withdrawal by 0.7%, and it leads to 0.32% increase in surface water level. That is because the extra investment to retrofit the pipelines is not high enough for an effective control of water loss. The total amount of withdrawals that can be reduced through water loss control under current budget is insignificant. However, the average amount of water loss is around 17.5 MGD, almost 5.6% of the total water withdrawals. Water loss control has a high potential to reduce water withdrawals and save electricity for water treatment (~1.1×10^7 kWh annually).

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There are so far no regulations on minimum surface- and ground-water levels within the study area. However, Hillsborough County has proposed the minimum surface water level for Hillsborough River. It is 15% increase of current water level, which is around 20 feet. This study used this value for minimum surface water level. Regarding to groundwater level, in order to prevent the seawater intrusion, this study adopted seawater level as the minimum groundwater level. Figure 3-25 indicates the need for alternative water sources under minimum water levels. The implementation of minimum surface water level requires a reduction of surface water withdrawal by 26 MGD. Two management options can reduce the surface water withdrawal. One option is to offset it from reclaimed water supply, but it requires at least 36 million dollars for reclaimed water capacity expansion. The other way is to suspend the water export. Hillsborough County currently exports 23.8 MGD to Pinellas County (Jackson and White, 2012; Scott and White, 2011). The water export will oscillate around 18.5 MGD from 2010 to 2030. The suspension of water export can reduce the need for alternative water supply to an average of 7.7 MGD. It will also reduce the financial need for reclaimed water infrastructure construction to 10 million dollars. However, the suspension of water export requires Pinellas County to find other alternative sources or adopt water demand options.

In order to maintain the maximum distance from groundwater table to the surface at the distance of 20 feet, alternative water sources are needed. Current distance between groundwater table and the surface land is 20.8 feet, 4% higher than the maximum distance, and it will gradually increase to 21.3 feet in 2030 without any groundwater level regulation. Approximately 450 MGD of water is needed for groundwater recharge in 2030 to maintain the maximum distance. It requires half billion dollar if reclaimed water is used for the aquifer recharge.

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3.5. Chapter Summary

This chapter critically reviewed 65 water resources management models developed by SD approach from the perspective of problem articulation, model formulation, model testing, and policy analysis. Two significant gaps of current water SD models are the lack of consideration of water quality and energy consumption associated with water and wastewater treatment as well as the lack of dynamic interactions between water demand and supply. In addition, current water SD models have not conducted a formal model validation.

This chapter develops a SD model for water resources management with the incorporation of water quality and energy consumption associated water supply, as well as conducts a formal model validation. With considering water quality, the simulated surface water level increases by 1.32~1.39%; with considering both water quality and energy consumption, the surface water level increases by 1.10~1.30%. There is a slight decrease in groundwater storage (0.02~0.08%) compared with the reference behavior.

In addition, ten water demand and supply options are investigated by comparing their effects on reducing freshwater withdrawals. Among the ten options, water conservation education is the most effective option to reduce the freshwater withdrawals (~17.3%), followed by rebates on indoor water-efficient appliances (15.4%). They can improve the surface water level by 1.43~2.67%, and 1.37~2.63%, respectively. Rebates on outdoor water-efficient appliances, increase in water rate, and water restriction are effective to reduce the outdoor water demand, but not the total withdrawals. Reclaimed water has no significant impacts on reducing freshwater withdrawal under current budget due to the high infrastructure cost and low public acceptance. Water loss control has the minimum effect on the reduction of freshwater withdrawals under current budget, but it has a high potential to

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conserve both water and energy. The implementation of minimum surface water level is effective to reduce the surface water withdrawal and maintain the water level, but it requires 26 MGD alternative water supply sources. To maintain the groundwater table to the surface at the distance of 20 feet, near 450 MGD of water is needed for groundwater recharge in 2030. These management options are more effective to increase water levels when water quality and energy consumption are considered in the supply decisions.

The impacts associated with the increase in groundwater withdrawal, such as land subsistence, have not been included in the study. In addition, this model is sensitive to precipitation. A more accurate projection or representation of precipitation should be employed.

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Table 3-1 Index of Water Demand and Supply Interaction

Index Name	Index Expression	References
Water Shortage/Deficit/Crisis Index	$WSI = D/S$, where, WSI is the water shortage index, S is the available water supply, and D is the estimated water demand	Bagheri et al., 2010; Bassi et al., 2010; Davies and Simonovic, 2011; Fernandez and Selma, 2004; Ho et al., 2005; Yang et al., 2008; Zarghami and Akbariyeh, 2012
	$WSI = S/D$, where, WSI is the water deficit index, S is the available water supply, and D is the estimated water demand	Gao and Liu, 1997; Tong and Dong, 2008; Zhang and Liu, 1991; Zhang et al., 2008
Demand and Supply Balance Index	$BI = S - D$, where BI is the demand and supply balance index, S is the available water supply, and D is the estimated water demand	Langsdale et al., 2007
Sustainability Index	$SI = (S - D)/S$, where SI is the sustainability index, S is the available water supply, and D is the estimated water demand	Madani and Mariño, 2009

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Table 3-2 Summary of Main Policies of Water System Dynamics Models

<table>
<tr><th colspan="2">Focus / Scenarios</th><th>Agriculture</th><th>Industry</th><th>Municipality</th><th>Power Generation</th></tr>
<tr><td colspan="2">Economic Development</td><td colspan="2">Gao and Liu, 1997; Guo et al., 2001; Simonovic, 2002; Sun et al., 2002; Simonovic and Rajasekaram, 2004; Sušnik et al., 2012; Yu and Zeng, 1996; Zhang et al., 2008; Zhang et al., 2010;</td><td>Qi and Chang, 2011</td><td></td></tr>
<tr><td colspan="2">Conservation</td><td>Bassi et al., 2010; Elmahdi et al., 2007; Fernandez and Selma, 2004; Tong and Dong, 2008; Xu et al., 2002</td><td></td><td>Ahmad and Prashar, 2010; Bagheri et al., 2010; Qaiser et al., 2011; Simonovic and Sušnik et al., 2012; Rajasekaram, 2004; Stave, 2003; Tidwell et al., 2004; Wang et al., 2011</td><td></td></tr>
<tr><td colspan="2">Water Rate</td><td></td><td></td><td>Ahmad and Prashar, 2010; Rehan et al., 2011; Zarghami and Akbariyeh, 2012</td><td></td></tr>
<tr><td rowspan="2">Pollution Control</td><td>Treat-ment</td><td colspan="3">Davies and Simonovic, 2011; Ford, 1996; Simonovic and Rajasekaram, 2004; Venkatesan et al., 2011</td><td>Saysel et al., 2002</td></tr>
<tr><td>Manag ement</td><td colspan="2">Anderson et al., 1975; Tong and Dong, 2008; Zhang et al., 2008</td><td></td><td></td></tr>
<tr><td rowspan="2">Water Supply Options</td><td>Water Reuse</td><td></td><td></td><td>Davies and Simonovic, 2011; Tong and Dong, 2008; Xu et al., 2002; Yang et al., 2008; Zarghami and Akbariyeh, 2012</td><td></td></tr>
<tr><td>New Sources</td><td></td><td></td><td>Chen et al., 2006; Grigg, 1997</td><td></td></tr>
</table>

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Table 3-3 Main Research Gaps and Future Research Needs of Water System Dynamics Models

Modeling Steps	Research Gaps	Future Research Needs	This Study
Problem Articulation	Lack of the consideration of water quality management	Incorporate water quality in model purpose and key variables	×
Model Formulation	Lack of the consideration of the interaction between water supply and demand	Capture the feedback loops between water supply and water demand	×
	Lack of the consideration of non-traditional water supply options	Include the non-traditional water supply sources (e.g., water reuse) Consider water quality and energy consumption as constraints for water supply	×
	Lack of the consideration of water demand in energy production	Include water demand for energy production, especially fossil fuel mining	×
	Lack of the consideration of ecological water requirement	Include the minimum water level/flow	×
Model Testing	Lack of the formal model validation	Conduct a formal model validation (structural test, structural-oriented behavior test, and behavior test)	×
Policy Analysis	Associated with Problem Articulation and Model Formulation (e.g., insufficient attention on water pollution and water reuse)	Design scenarios related to: a) water conservation in industry and power generation, b) impact of water price on agricultural, industrial, power generation water use, c) water pollution control, and d) water reuse	×

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Table 3-4 Key Model Factors and Variables of Water Sub-model

Factors	Key Variables	Stocks
Water Supply	Surface Water Supply, Groundwater Supply, Reclaimed Water, Water Transfer, Energy Intensity	Surface Water Storage, Groundwater Storage, Reclaimed Water Capacity
Water Demand	Water Demand In Municipality, Water Demand In Agriculture, Water Demand In Industry, Water Demand In Energy	Efficient Household Indoor Water Appliances, Efficient Household Outdoor Water Appliances, People with Water Conservation Awareness, Irrigated Land, Irrigated Land with BMPs
Water Quality	Surface Water Quality, Groundwater Quality	Pollutants in Surface Water, Pollutants in Groundwater

Table 3-5 Crop Type and Land Use

Crop Type	Crop Coefficient	Percentage of Land Use
Citrus	0.775	19.3%
Strawberry	0.850	21.0
Melon	1.000	8.6%
Tomato and Vegetables	1.152	3.7
Sod and Pasture	0.850	37.0
Others	1.000	10.4

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Table 3-6 Water Intensity for Fuel Production and Power Generation (Mielke et al., 2010)

	Fuel Type		Water Intensity (Gallon/MBtu)
Fuel Production	Oil		1.4~6.2
	Natural Gas		0.6~1.8
	Coal		1~6
	Cooling System		Water Intensity (Gallon/MWh)
Power Generation	Steam Turbine (Coal, Gas, and Biomass)	Once-through	20030~50030
		Closed-loop	330~630
		Dry	30
	Combined-cycle Gas Turbine	Once-through	7530~20030
		Closed-loop	260
		Dry	30
	Integrated Gasification Combined Cycle	Closed-loop	387~390

Table 3-7 Advantages and Disadvantages of Different Cooling Technologies (O'Hagan and Maulbetsch, 2009)

Cooling Technology	Advantages	Disadvantages
Once-through (OT)	• Low water consumption • High cooling efficiency • Mature technology • Low capital cost	• Higher water withdrawal than CL • Thermal discharge
Closed-loop (CL)	• Lower water withdrawal than OT • Mature technology	• Higher water consumption than OT • High capital cost than OT • Lower cooling efficiency than OT
Dry	• No or low water consumption	• Higher capital cost than CL • Highest power consumption • Lower cooling efficiency than CL • Large land requirement

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Table 3-8 Key Water Quality Parameters and Standards

Parameter	Average Value (1980~2005) (mg/L)	Class I or Proposed Standard (mg/L)
Calcium	72.55	<75
Magnesium	19.53	<0.1
Sodium	82.52	<160
Potassium	7.65	<12
Bicarbonate	122.89	<150
Chloride	150.19	250
Sulfate	103.11	<250
Total Nitrogen	7.71	<1.0
Total Phosphorus	0.13	<0.1
Total Dissolved Solids	3795.88	<500
Dissolved Oxygen	4.1	>4.0

Table 3-9 Energy Intensity for Municipal Water Supply (Burton, 1996; Carlson and Walburger, 2007)

	Surface Water	Groundwater
Raw Water Pumping, kWh/Gallon	1.21×10^{-4}	6.05×10^{-4}
Water Treatment, kWh/Gallon	9.53×10^{-5}	9.15×10^{-6}
Delivery Pumping, kWh/Gallon	1.21×10^{-3}	1.21×10^{-3}

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Table 3-10 Error Analysis of Behavior Test of Water Sub-model

Variable	Average			RMSPE[1]	Inequality Statistics[2]		
	Observed	Simulated	Error		U^M	U^S	U^C
Municipal Water Withdrawal (MDG)	135.01	127.84	-5.31%	1.23%	0.20	0.01	0.42
Agricultural Water Withdrawal (MGD)	78.98	75.18	-4.75%	5.43%	0.03	0.18	0.45
Surface Water Level (Feet)	18.00	17.96	-0.22%	0.28%	0.00	0.30	0.44

[1] RMSPE is the root mean-squared percent error

[2] Inequality statistics shows the fraction of mean-square-error. U^M measures the bias between simulated and actual data; U^S measures the degree of unequal variation between two datasets; U^C measures the degree of divergence between simulated and actual data in point-by-point estimation.

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Table 3-11 Changes of Water Levels under Different Weighting Schemes

Weighting Scheme			Percentage Change from BAU		
			Surface Water Withdrawal	Surface Water Level	Ground-water Level
BAU			60	N/A	N/A
Only Water Quantity Consideration	1	w_1=1, w_2=0, w_3=1,w_4=0*	61	-0.02	0.00
With Water Quality Consideration	2	w_1=1, w_2=0, w_3=0.75,w_4=0.25	50	1.32	-0.05
	3	w_1=1, w_2=0, w_3=0.5,w_4=0.5	48	1.36	-0.06
	4	w_1=1, w_2=0, w_3=0.25,w4=0.75	45	1.39	-0.08
With Water Quality and Energy Consumption Consideration	5	w_1=0.75, w_2=0.25, w_3=0.5,w_4=0.5	56	1.10	-0.02
	6	w_1=0.5, w_2=0.5, w_3=0.5,w_4=0.5	52	1.20	-0.04
	7	w_1=0.25, w_2=0.75, w_3=0.5,w_4=0.5	48	1.30	-0.08

* w_1 to w_4 are the weighting factors for water availability, energy consumption, water quantity, and water quality, respectively.

Table 3-12 Water Supply and Demand Management Options

	Water Supply Options	Water Demand Options
Additional $1M Budget	• Water loss control • Reclaimed water	• Rebates on indoor water appliances • Rebates on outdoor water appliances • Agricultural BMP • Water Conservation Education
Regulation	• Minimum water level • Water Transfer	• Water price • Lawn irrigation restriction

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Table 3-13 Impact of Water Demand Management Options

Demand Management Option	Percentage Change from BAU					
	Considering Water Quantity			Considering Water Quality and Energy Consumption		
	SWL	GWL	FWW	SWL	GWL	FWW*
Rebates on Indoor Water Appliances	1.37	-0.06	15.4	2.63	-0.14	15.4
Rebates on Outdoor Water Appliances	1.07	-0.01	2.3	2.36	-0.08	2.3
Agricultural BMPs	0.04	0.08	0.3	0.34	0. 08	0.3
Water Conservation Education	1.41	-0.07	17.3	2.67	-0.14	17.3
Water Price (50% Increase)	1.06	0.00	3.0	2.36	-0.08	3.0
Water Restriction (Once A Week)	1.02	0.00	1.4	2.32	-0.08	1.4

* SWL, GWL, and FWW represent surface water level, groundwater level, and freshwater withdrawal, respectively.

Table 3-14 Impact of Water Supply Management Options

Supply Management Option	Percentage Change from BAU (%)		
	Surface Water Level	Groundwater Level	Freshwater Withdrawal
Reclaimed Water	0.78	0.00	-1.1
Water Loss Control	0.32	0.00	-0.7
Minimum Surface Water Level	15.00	0.00	-7.7
Minimum Groundwater Level	0.00	5.92	0~-100

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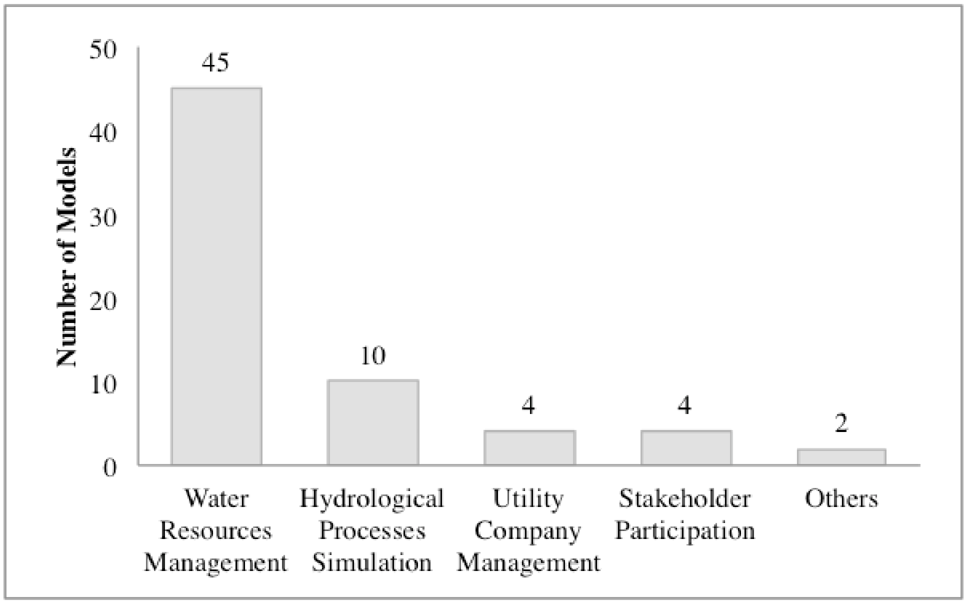

Figure 3-1 Reviews on Model Purposes of Water System Dynamics Models

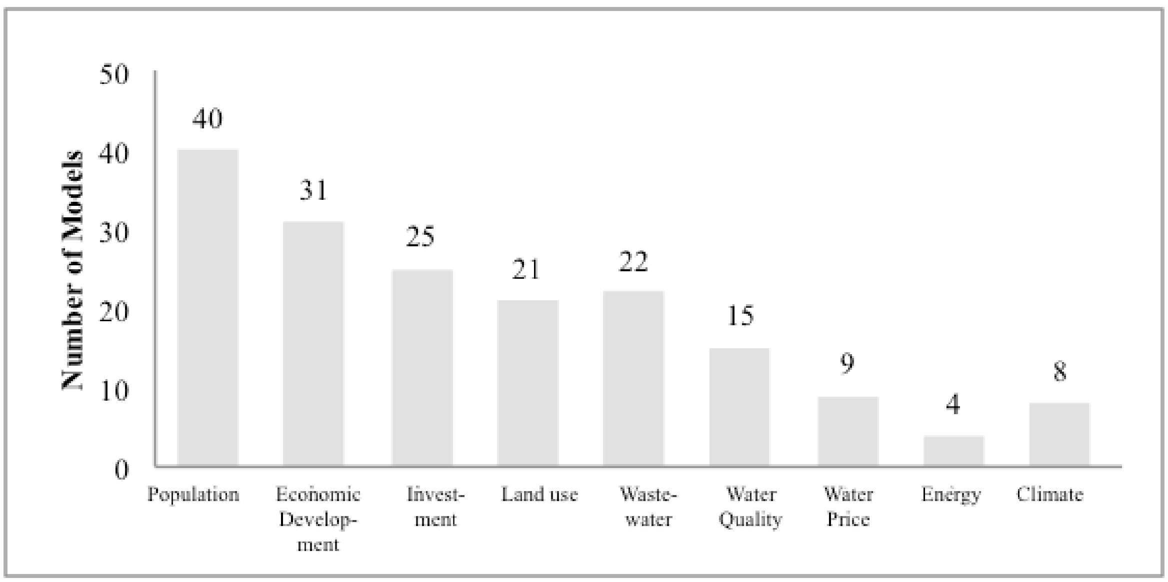

Figure 3-2 Review on Key Factors of Water System Dynamics Models

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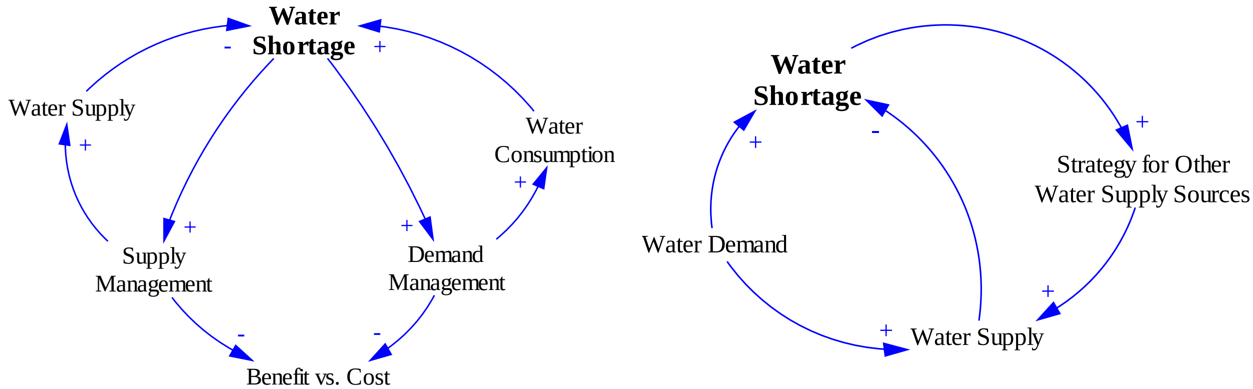

(a) (b)

Figure 3-3 Causal Loop Diagram of Water Shortage Index. (a) is adapted from Zarghami and Akbariyeh, 2012, and (b) is adapted from Yang et al., 2008. A positive sign represents a reinforcing causal relationship, and a negative sign represents a balancing causal relationship.

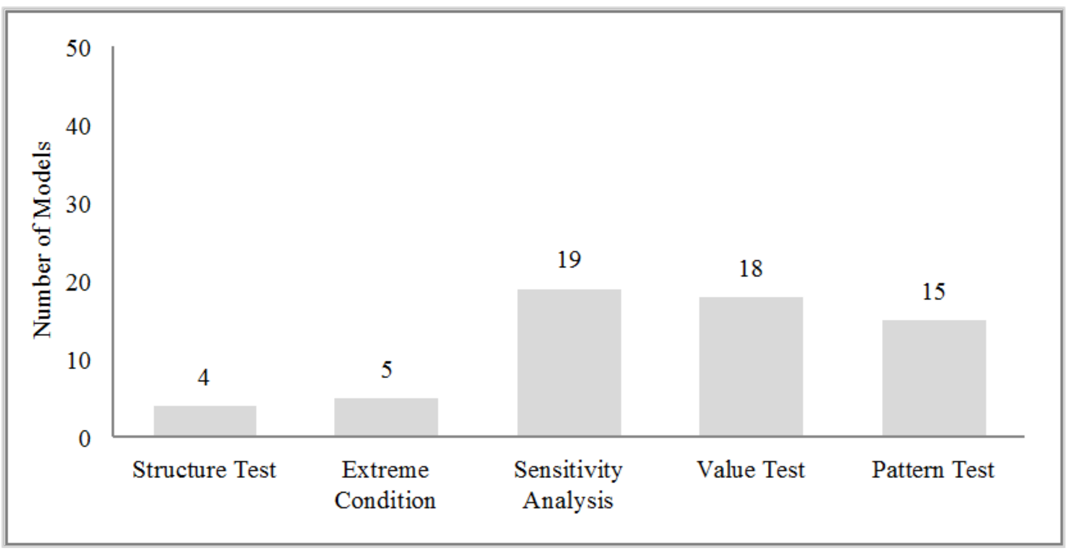

Figure 3-4 Review on Model Validation of Water System Dynamics Models

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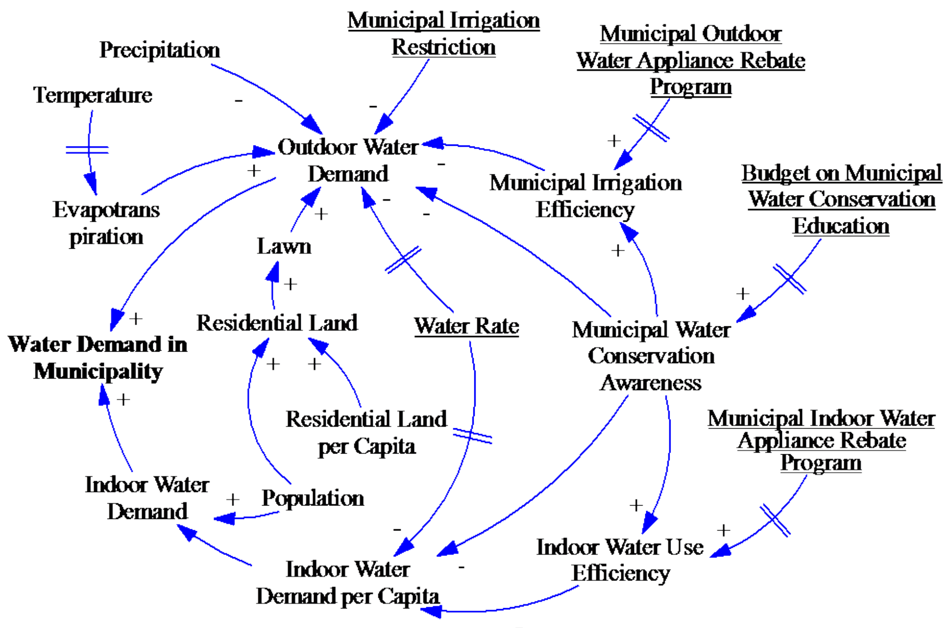

Figure 3-5 Causal Loop Diagram of Water Demand in Municipality. A positive sign represents a reinforcing causal relationship, and a negative sign represents a balancing causal relationship. A link with a two-line bar in the middle represents a time delay. The underlined variables represent the demand options.

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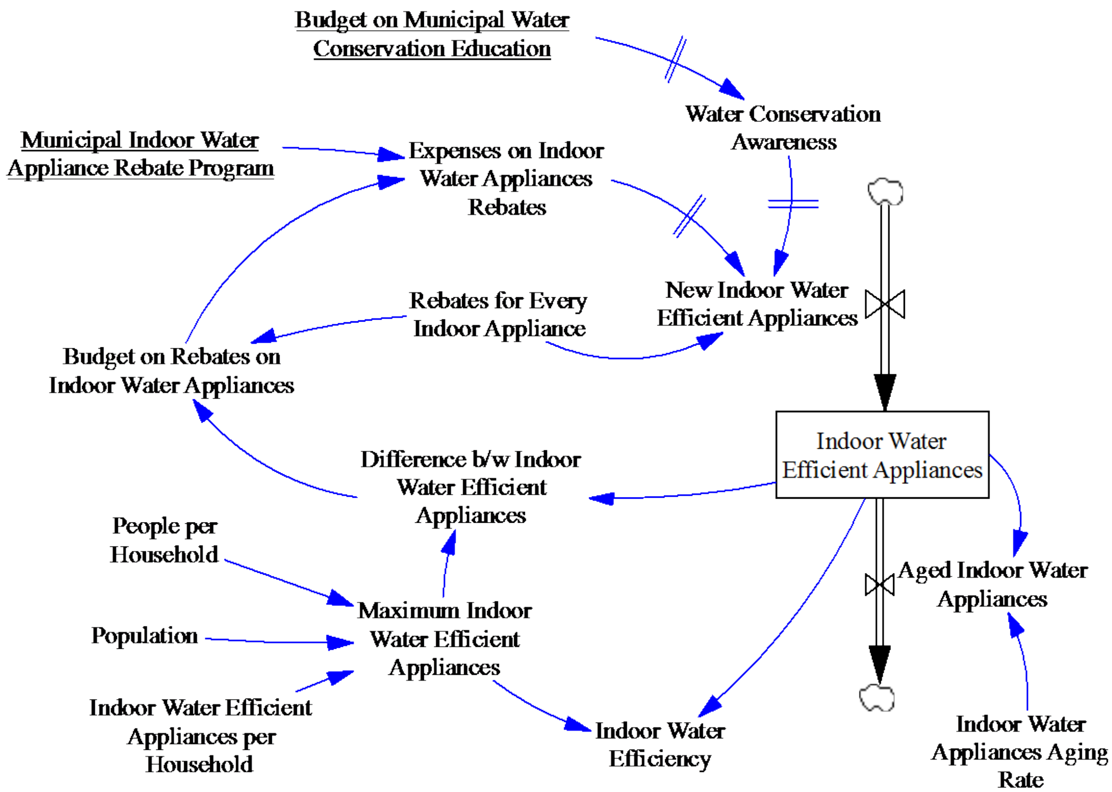

Figure 3-6 Stock Flow Diagram of Indoor Water Efficient Appliances. A variable with a rectangle is a stock. A variable with a pipe pointing into the stock is an inflow, and a variable with a pipe pointing out of the stock is an outflow. Clouds represent sources and sinks for the flows. A link with a two-line bar in the middle represents a time delay. The underlined variables represent the demand options.

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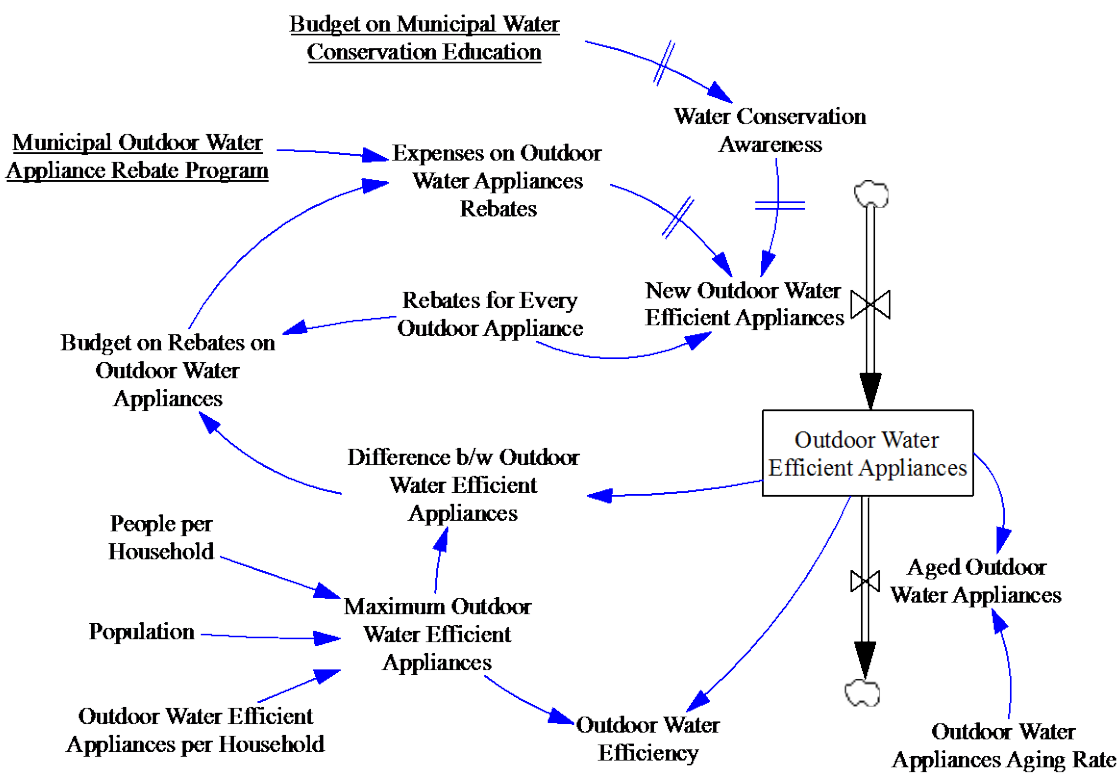

Figure 3-7 Stock Flow Diagram of Outdoor Water Efficient Appliances. A variable with a rectangle is a stock. A variable with a pipe pointing into the stock is an inflow, and a variable with a pipe pointing out of the stock is an outflow. Clouds represent sources and sinks for the flows. A link with a two-line bar in the middle represents a time delay. The underlined variables represent the demand options.

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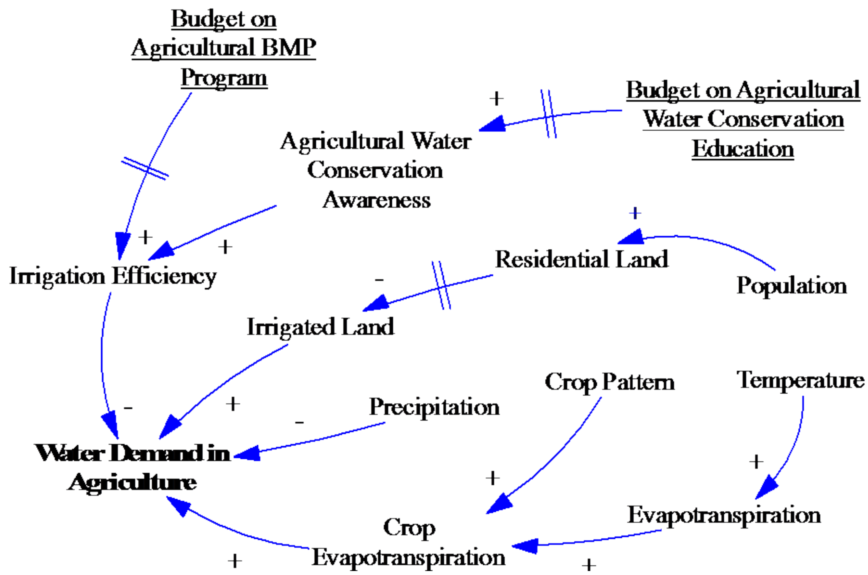

Figure 3-8 Causal Loop Diagram of Water Demand in Agriculture. A positive sign represents a reinforcing causal relationship, and a negative sign represents a balancing causal relationship. The two-line bar in the middle of the link represents time delay. The underlined variables represent the demand options.

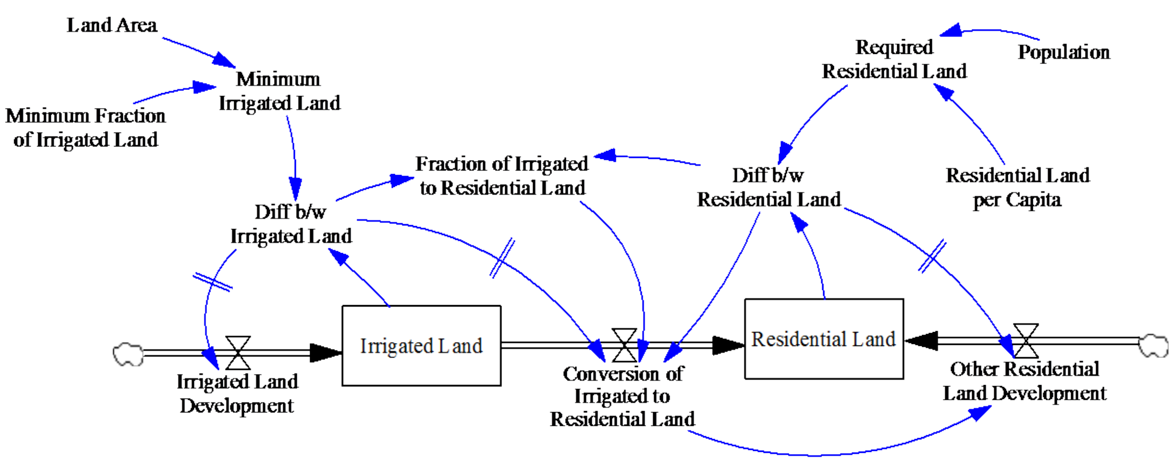

Figure 3-9 Stock Flow Diagram of Irrigated Land. Variable with a rectangle is stock. Variable with a pipe pointing into the stock is inflow, and variable with a pipe pointing out of the stock is outflow. Clouds represent the sources and sinks for the flows. The two-line bar in the middle of the link represents time delay.

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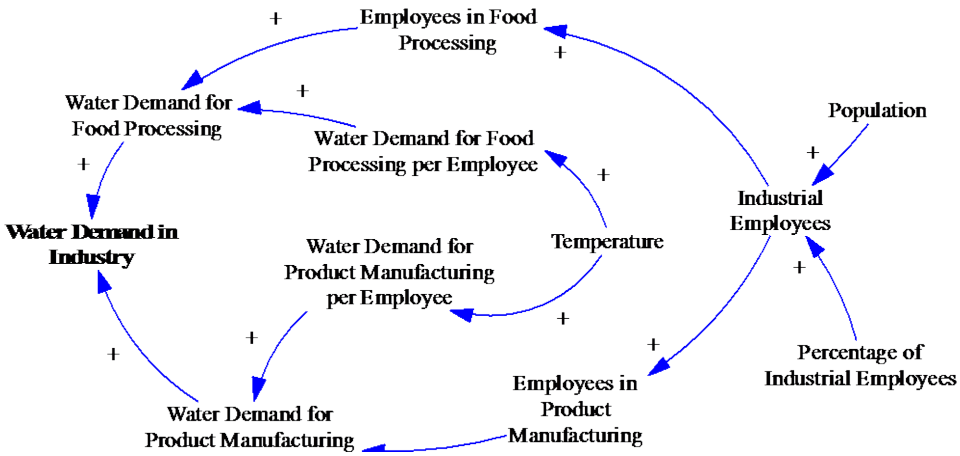

Figure 3-10 Causal Loop Diagram of Water Demand in Industry. A positive sign represents a reinforcing causal relationship.

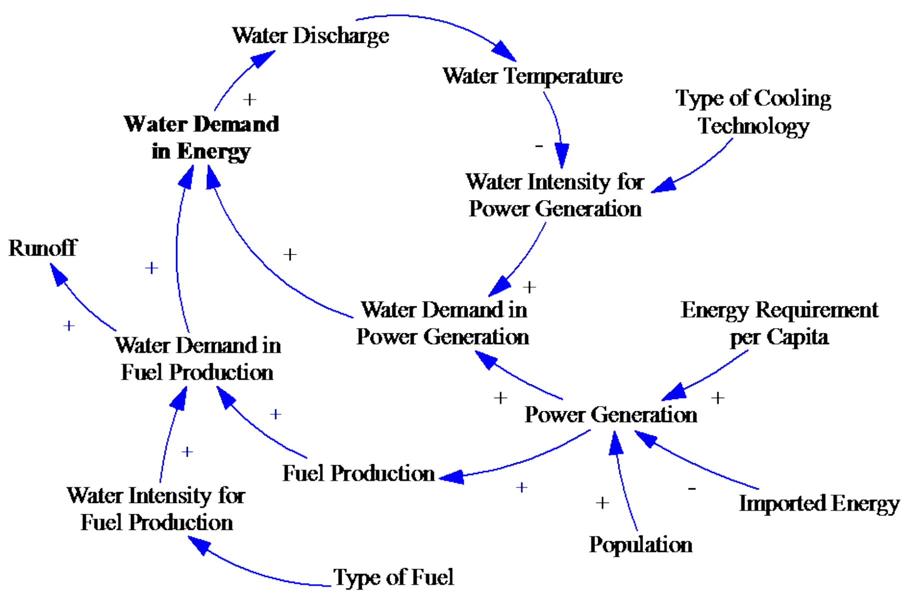

Figure 3-11 Causal Loop Diagram of Water Demand in Energy Sector. A positive sign represents the reinforcing causal relationship, and a negative sign represents balancing causal relationship.

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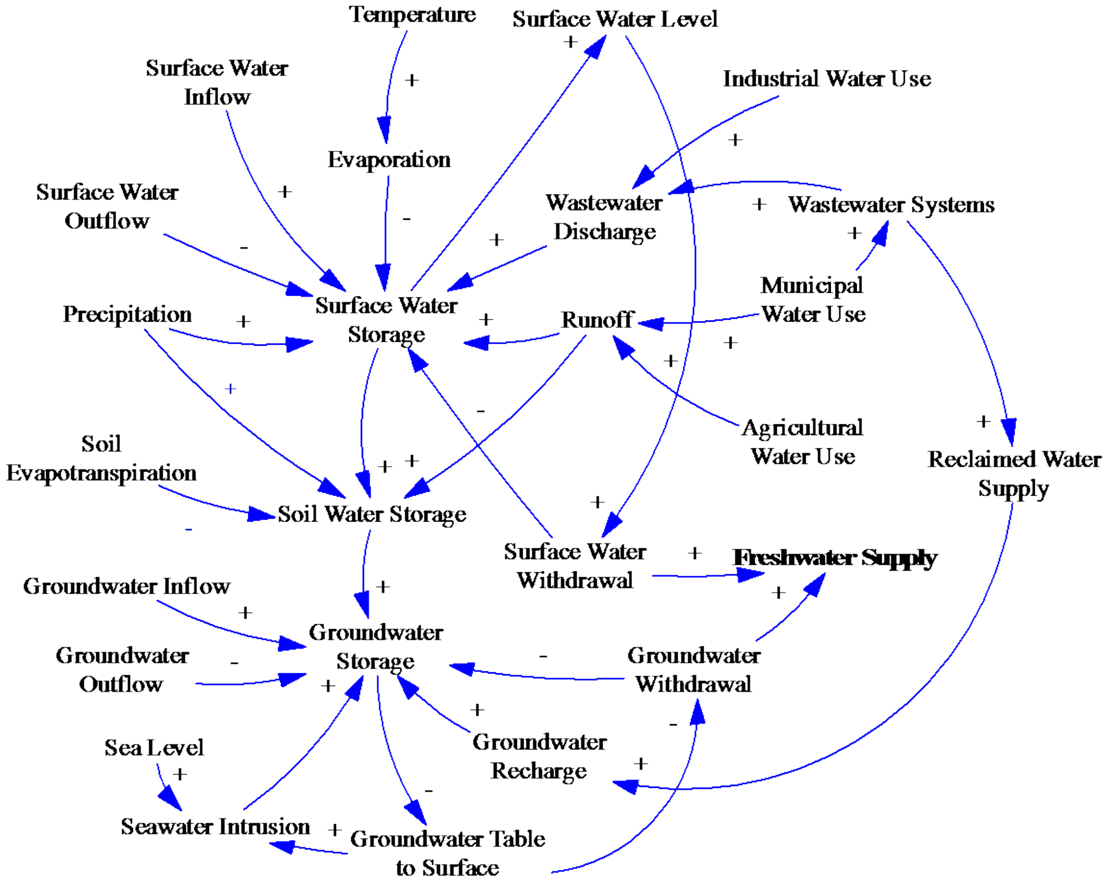

Figure 3-12 Causal Loop Diagram of Freshwater Supply. A positive sign represents the reinforcing causal relationship, and a negative sign represents balancing causal relationship.

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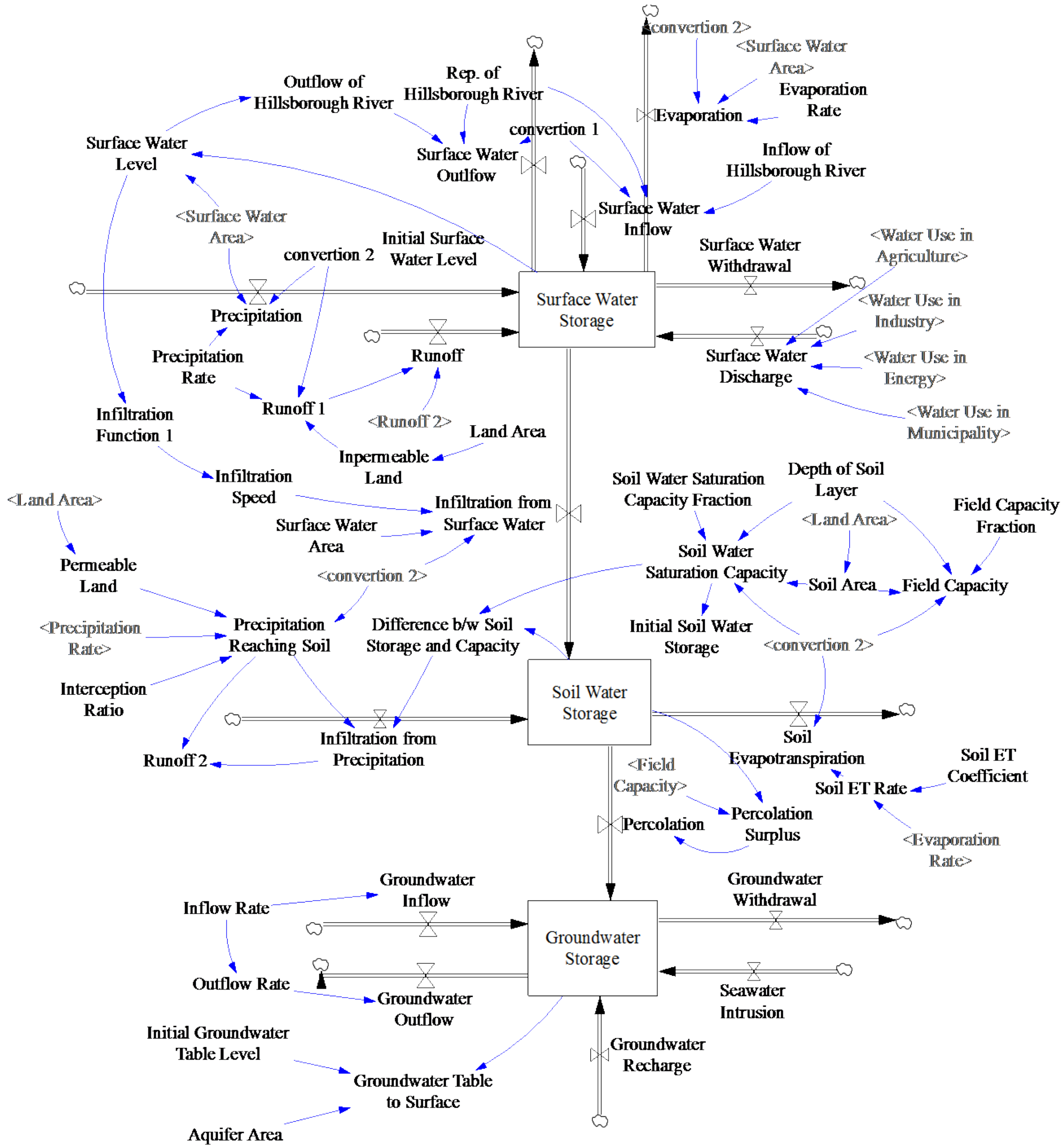

Figure 3-13 Stock Flow Diagram of Surface- and Ground-Water Storages. A variable with a rectangle is the stock. A variable with a pipe pointing into the stock is an inflow, and a variable with a pipe pointing out of the stock is an outflow. Clouds represent the sources and sinks for the flows. The shadow variables represent the existing variables in the diagram.

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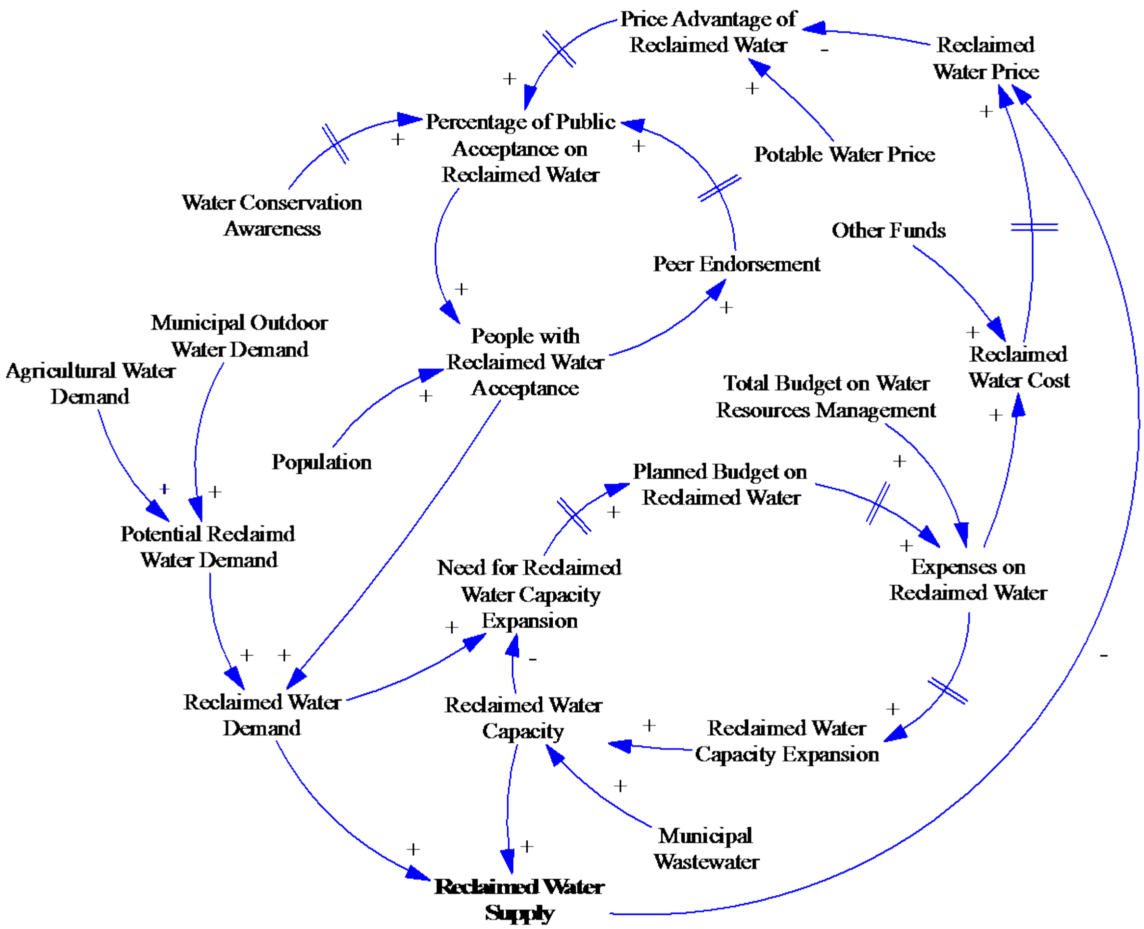

Figure 3-14 Causal Loop Diagram of Reclaimed Water Supply. A positive sign represents a reinforcing a causal relationship, and a negative sign represents a balancing causal relationship. A link with a two-line bar in the middle represents a time delay.

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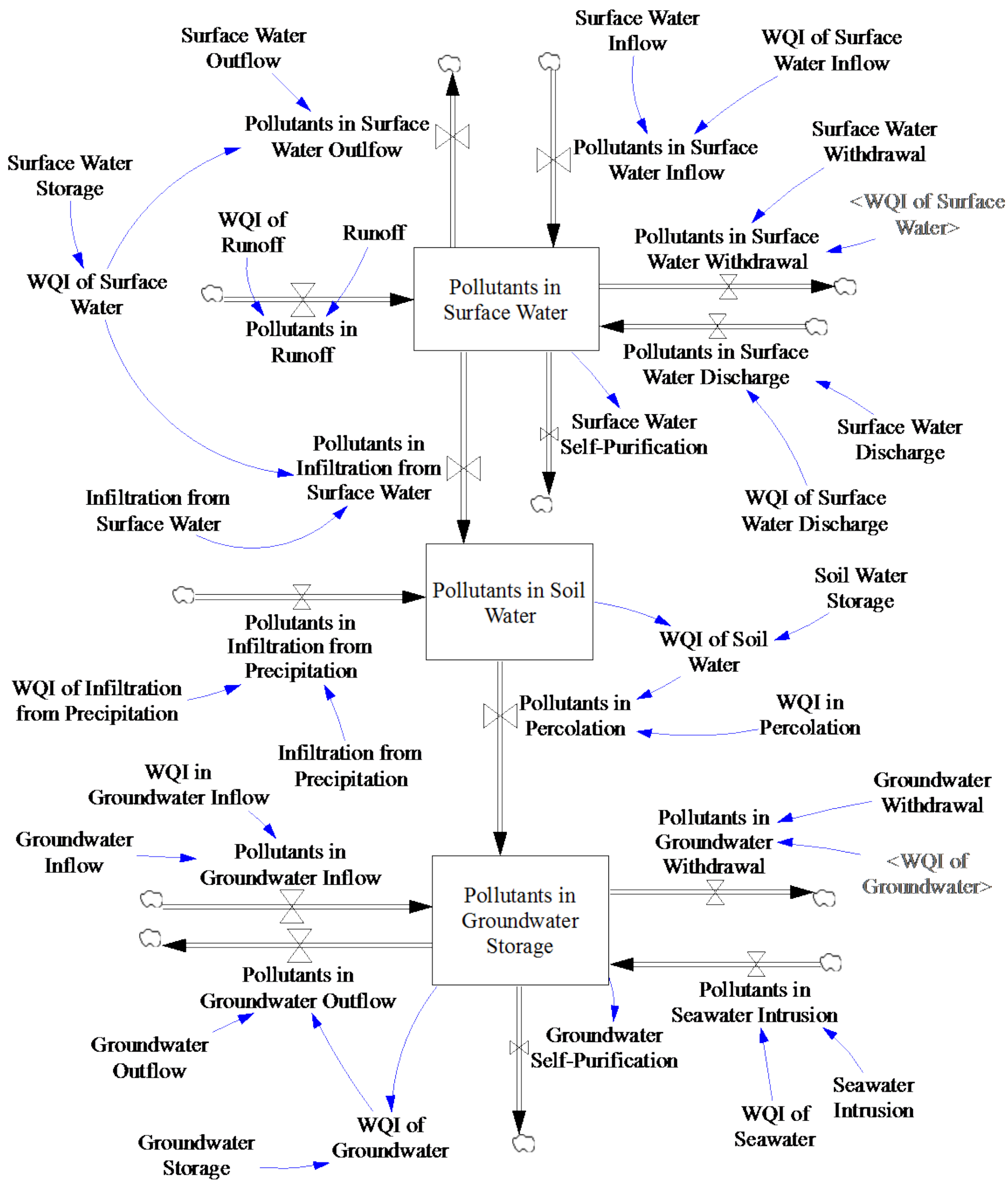

Figure 3-15 Stock Flow Diagram of Surface- and Ground-Water Quality. A variable with a rectangle is a stock. A variable with a pipe pointing into the stock is an inflow, and a variable with a pipe pointing out of the stock is an outflow. Clouds represent the sources and sinks for the flows. The shadow variables represent the existing variables in the diagram.

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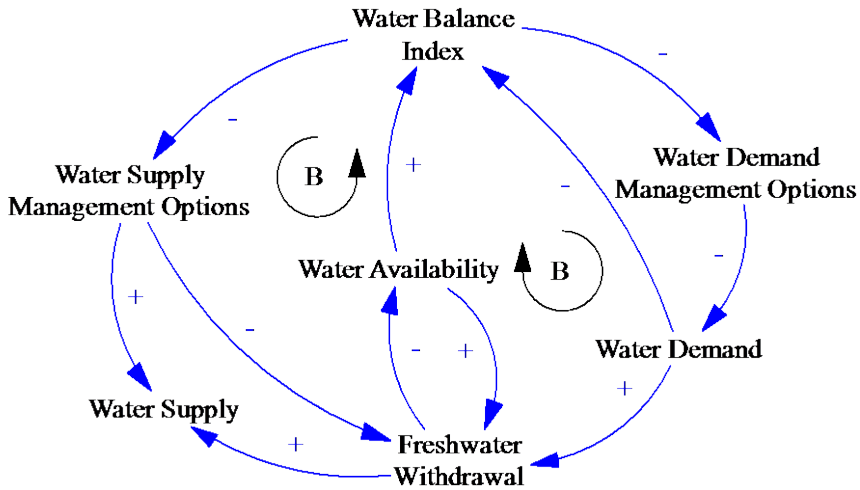
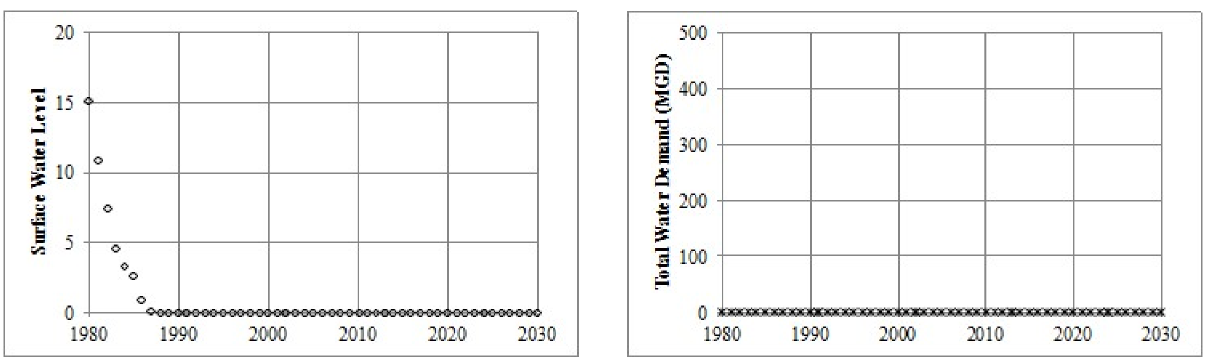


Figure 3-16 Interactions between Water Supply and Demand. A positive sign represents a reinforcing causal relationship, and a negative sign represents a balancing causal relationship.



(a) Surface Water Level with No Precipitation (b) Total Water Demand with No Population

Figure 3-17 Extreme Condition Test of Water Sub-model

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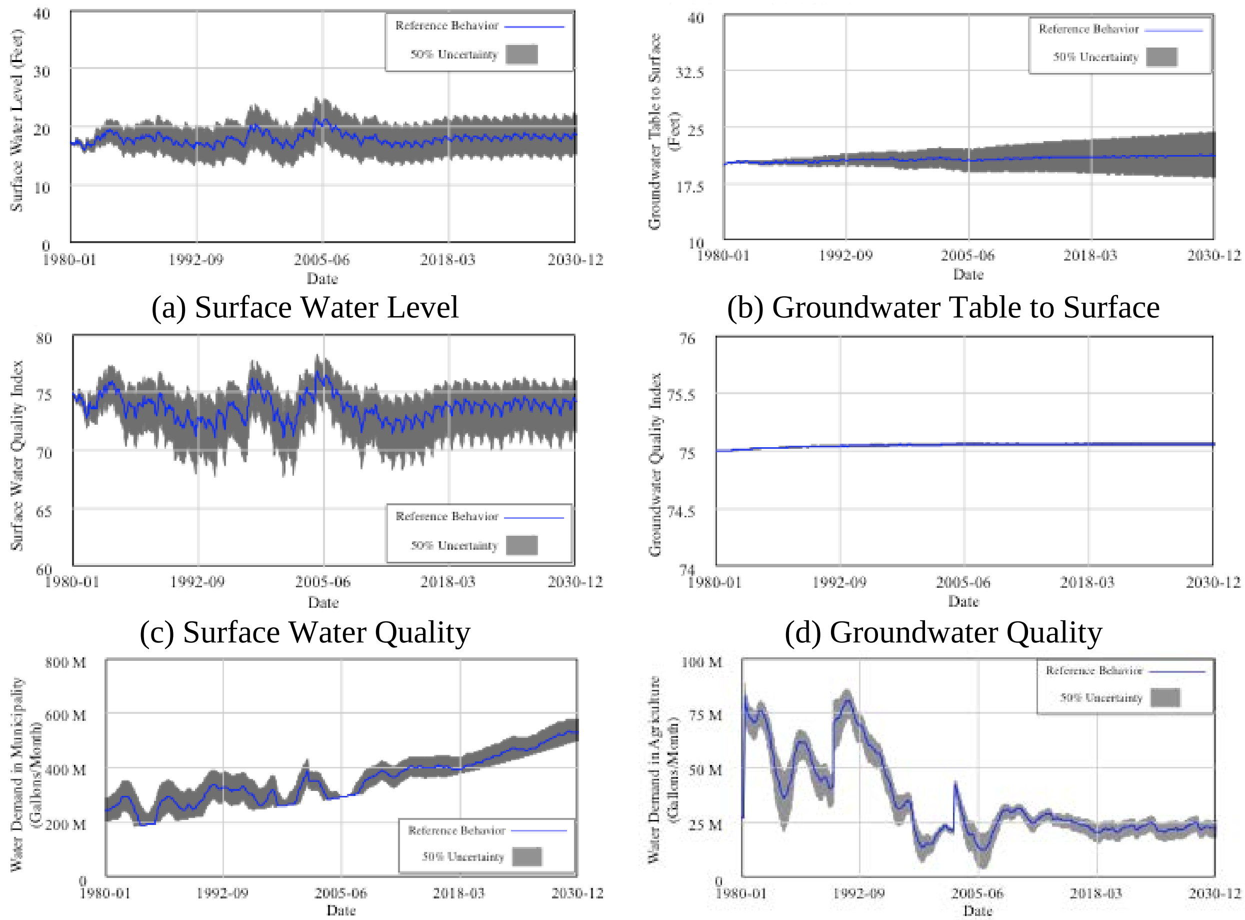

(a) Surface Water Level (b) Groundwater Table to Surface

(c) Surface Water Quality (d) Groundwater Quality

(e) Water Demand in Municipality (f) Water Demand in Agriculture

Figure 3-18 Sensitivity Analysis of Precipitation in Water Sub-model

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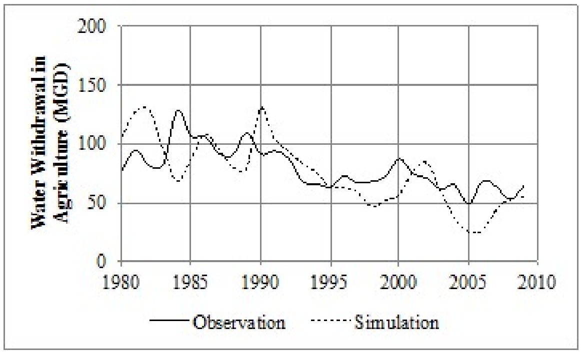
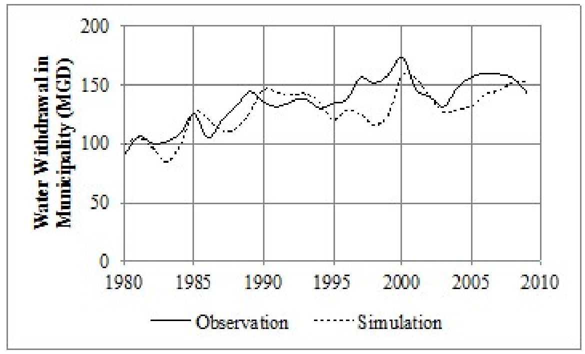
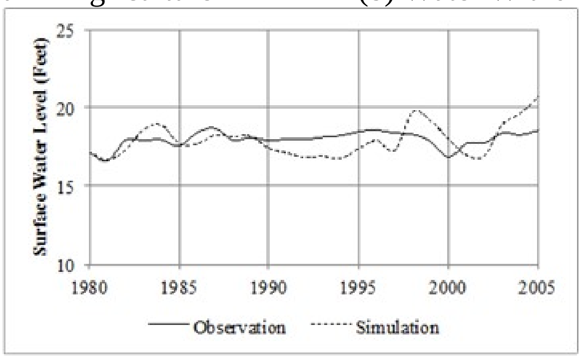


(a) Water Withdrawal in Agriculture



(b) Water Withdrawal in Municipality



(c) Surface Water Level

Figure 3-19 Behavior Test of Water Sub-model

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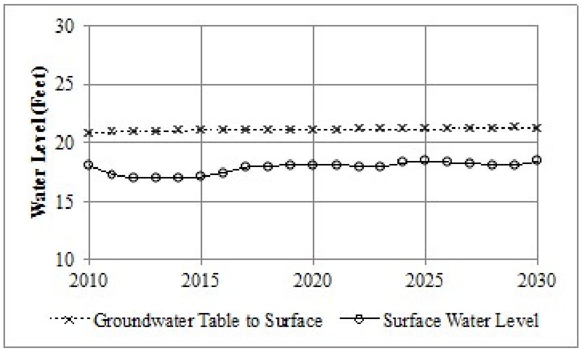
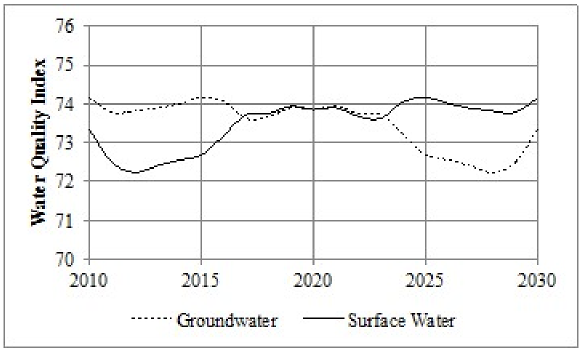
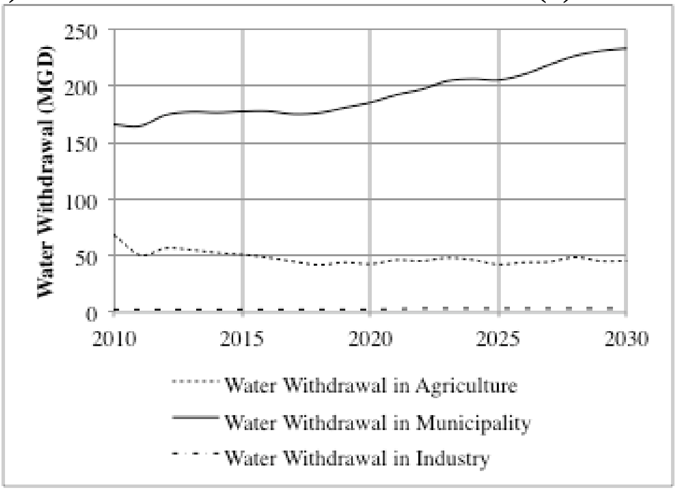


(a) Water Level



(b) Water Quality Index



(c) Water Withdrawal

Figure 3-20 Reference Behaviors of Water Level, Water Quality Index, and Water Withdrawal

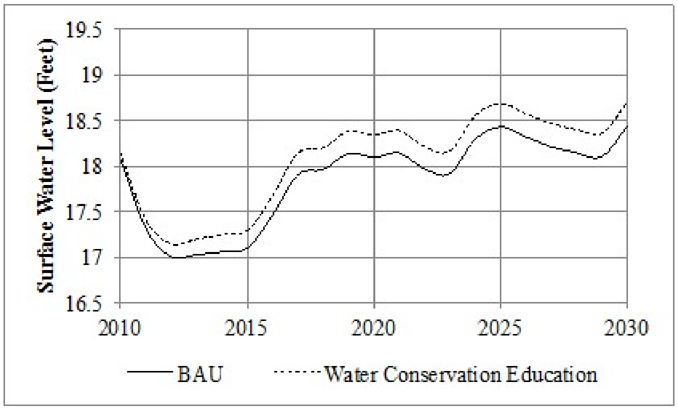


Figure 3-21 Change of Surface Water Level under Additional One Million Dollar Budget on Water Conservation Education

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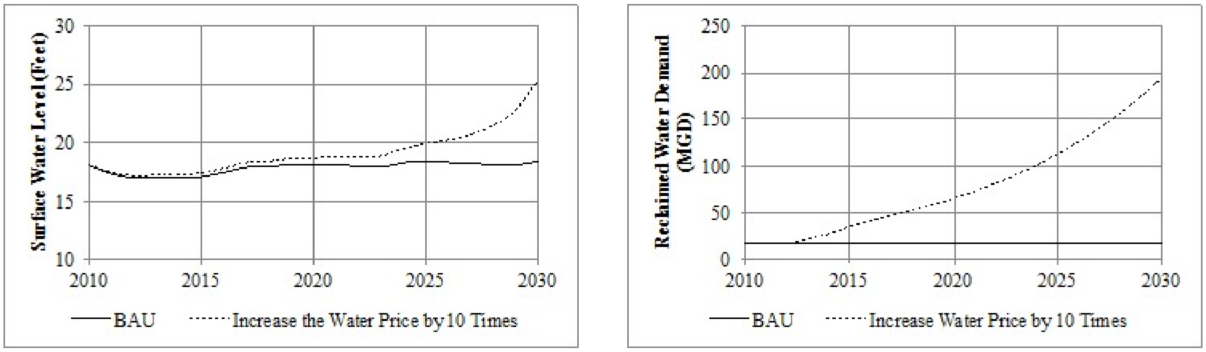
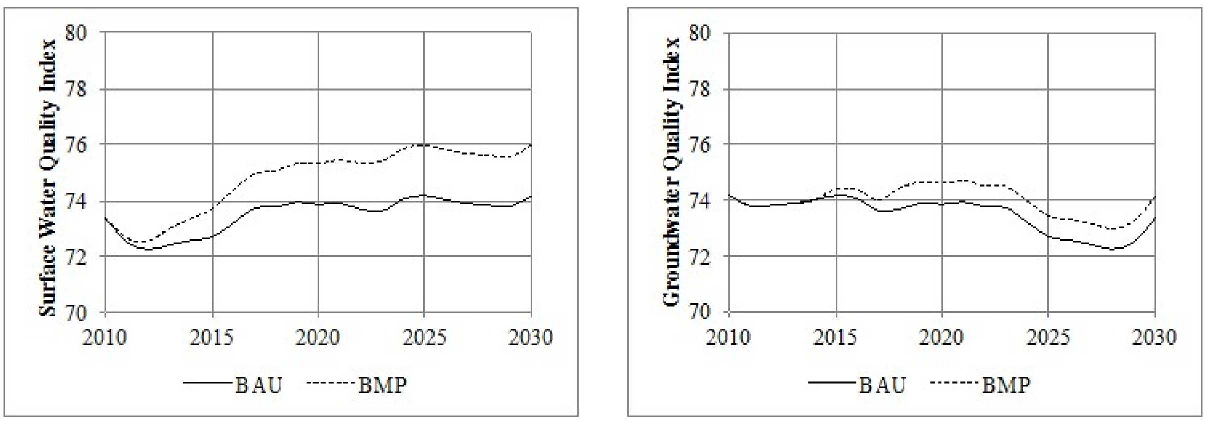


(a) Surface Water Level (b) Reclaimed Water

Figure 3-22 Change of Surface Water Level under Increasing Water Price by 10 Times



(a) Surface Water Quality (b) Groundwater Quality

Figure 3-23 Change of Surface- and Ground-Water Quality under Additional One Million Budget on Agricultural Best Management Practices

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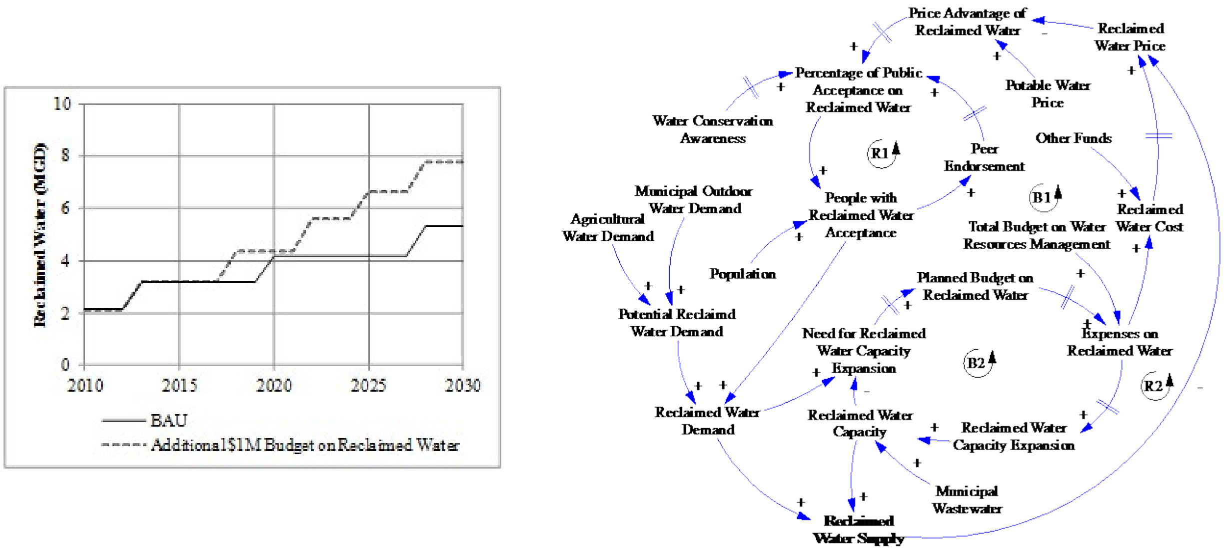
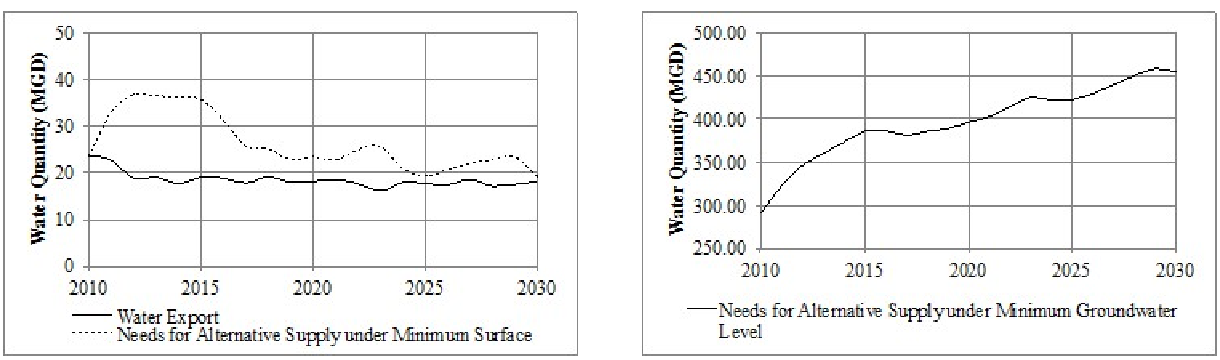


(a) Reclaimed Water Use (b) Causal-Loop Diagram of Reclaimed Water

Figure 3-24 Reclaimed Water Use under Additional One Million Dollar Budget. A positive sign represents a reinforcing causality and a negative sign represents a balancing causality. A link with a two-line bar in the middle represents a time delay. R1 is the reinforcing loop of public acceptance, R2 is the reinforcing loop of reclaimed water supply, B1 is the balancing loop of water demand, and B2 is the balancing loop of reclaimed water capacity.



(a) Minimum Surface Water Level Scenario (b) Minimum Groundwater Level Scenario

Figure 3-25 Water Needs under Minimum Water Levels

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CHAPTER 4.

ENERGY RESOURCE MANAGEMENT MODEL

4.1. Literature Review

The energy sector is receiving an increasing attention worldwide due to its influence on economic development and climate (Jacobson, 2009; Jacobson and Delucchi, 2011; Nordhaus, 2010; Umbach, 2010). In order to find sustainable solutions, a holistic view on energy management is needed to assess the potential impacts of various energy management options as well as to communicate the results of such assessments to a variety of stakeholders. System dynamics (SD) is one of modeling tools to facilitate the development of such a holistic view and capable of facilitate the communication among various stakeholder (Mirchi et al., 2012; Stave, 2002). Application of system dynamics in energy resources management began with the world modeling projects conducted in the early 1970s by the system dynamics group at MIT (Ford, 1997). To date, two studies have reviewed the SD models in energy resource management (Ford, 1997; Kiani et al., 2010). Kiani (2010) provided an overview of SD models in fossil fuel, and Ford (1997) gave a brief history of SD models in electricity planning. Similar to the review studies in water resources management, these two studies only describe the purposes or the categories of existing models, which is only the first step of SD modeling: problem articulation.

Therefore, the aim of this review is (a) to provide an overview of SD models in energy resources management according to the SD modeling steps and (b) to point out the knowledge

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gaps and future research needs. Fifty-six peer-reviewed SD models (including journals and conference proceedings) in energy resources management were reviewed. Despite an extensive search, this study is limited by the accessible research publications. Some other manuscripts may have been missed. Some SD models, such as transmission interconnection (Ojeda et al., 2009), focusing on the transmission grid instead of energy planning or management, are not included in this study. Table A-2 summarizes the applications of SD in energy resource management regarding to the study area, model purpose, types of energy sources, and model validation.

4.1.1. Model Purpose

As shown in Figure 4-1, the main model purposes of SD models in energy resource management can be categorized as policy analysis (~41 models) and investment analysis (~16 models). Only one model is developed for education purposes, which aims to educate the undergraduate and graduate students the risks associated with energy trading (Franco et al., 2000).

The policy analysis models investigate the influence of regulations or policies on energy system. The models in this category can be further divided into 3 groups: energy system, environmental impact, and model algorithm. The energy system models investigate the influence of policies such as incentives or economic development on the energy consumption and production. For example, the COAL-FOSSIL family models evaluated the future energy production and consumption pattern under current economic development (Naill, 1976; Naill et al., 1992). Dyner (2000) evaluated the impact of regulatory incentives on Columbian electricity market. Larsen and Bunn (1999) examined the influence of monopolistic market on electricity consumption price. In addition, these models also performed the uncertainty analysis to address the uncertainty or resilience along with the policies. Nine models are developed to address the

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environmental impacts associated with energy policies. For example, Qudrat-Ullah (2005) examined the air pollution associated with power generation policies, such as improving the efficiency of power generation, reducing the dependence of fuel imports, applying the market price rate to electricity. Ford et al. (2007) evaluated the carbon emission associated with environment-oriented policies, such as implementing wind power. Fiddaman (1997) investigated the relationship between energy consumption, climate change, and economic development. Five models have been developed in the category of policy analysis focusing on the model algorithm, such as adding optimization algorithm into SD modeling (Olsina et al., 2006a; Pereira and Saraiva, 2009), or incorporating decision making tree (Tan et al., 2010a), to determine the optimal energy policy.

The investment analysis models are developed to examine the impacts of investment on the electricity market, such as the interaction between investment and capacity payment estimated from system power reserve margin (Qudrat-Ullah and Davidsen, 2001; Sánchez et al., 2007b), or the relationship between investment and power production (Dimitrovski et al., 2004; Ford, 2001).

Overall, these models are within the traditional paradigm of energy system, to investigate the interaction between economy and non-renewable energy. The policy analysis models link the economic development with the energy production and associated environmental impacts. The investment analysis models link the financial investment or the financial condition to energy system. The strong consideration of economy in energy system modeling is because the energy service is considered a stimulus of economic development (Medlock III and Soligo, 2001; Toman and Jemelkova, 2010). However, some emerging issues of the energy system have not received enough attention; for example, the influence of climate change. The importance of

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considering climate change in energy planning is acknowledged (Kanudia and Loulou, 1999; Pachauri, 2008; Pearman and Jäger, 1989; Wolsink, 2013); however, only one model (Fiddaman, 1997) considered climate change into SD modeling. Fiddaman linked the greenhouse gas (GHG) emissions to energy production. However, the feedback from GHG emissions or climate change to energy source decisions, such as replacing non-renewable energy with renewable energy to mitigate climate change, was not considered. A similar importance of a holistic understanding of the water and energy nexus is gradually being recognized (Bazilian et al., 2011; DHI, 2008; Scott, 2011; Stillwell et al., 2011), but no SD models have considered such interactions.

4.1.2. Key Factors

The key factors included in the models are determined by the model purposes. Since the majority of the previous energy SD models focused on the linkage between energy and economy, the key factors also centered on economic or financial condition. The key factors for the investment analysis models include investment (e.g. new technologies, capacity expansion) and energy price. For the policy analysis models, the key factors include economic development (e.g. economic input and output, domestic gross products), energy price, and government subsidies. The policy analysis models considering environmental impacts also include environmental factors. Ford (2006) attempted to incorporate the impact of GHG emissions using carbon cost or carbon tax, but the other environmental impacts from energy production, especially water withdrawal and water pollution, are not considered in the model.

4.1.3. Model Structure

Figure 4-2 shows the categories of energy types considered in energy models. Most studies (~44 models) focus on electricity. Eight studies considered the primary energy sources (e.g., coal, oil, gas), four of which considered the interaction between the primary energy and

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secondary energy (electricity) (Bunn et al., 1997; Fiddaman, 1997; Naill, 1972, 1976; Ochoa, 2007). Bunn et al (1997) considered natural gas as the energy source to generate electricity and the primary energy sources in the rest three studies include coal, natural gas, oil, and nuclear. Without the consideration of fuel availability leads to a simplification of power generation as a function of technologies or capital costs. Regarding to the energy demand, the energy uses are lumped together to determine the energy production needed. Accordingly, the management options of these models are driven by the demands. For example, decisions to expand the energy production capacity are considered the in most of the investment analysis models (Arango, 2007; Dimitrovski et al., 2004; Smith et al., 1994). The limits of non-renewable sources and potential actions in demand side are not considered.

4.1.4. Model Validation

None of the models did a formal model validation according to Barlas (1996). Most models (30 out of 55) did not specify if the model validation was conducted. Nineteen out of the 55 models are generic or hypothetical cases; no observed data is available to validate the model. Twenty-seven studies did model validation, but the results of behavior test were not presented quantitatively.

4.1.5. Scenario Analysis

As discussed in Chapter 3, problem articulation is the most important step of SD modeling. The model purpose leads to the key factors selection, and the scenarios analysis are determined by the model purposes and key factors. The main scenarios considered in previous energy SD models. The scenarios for investment analysis models focus on different types of investment, such as the investment on technology (He et al., 2008a; Smith et al., 1994) or infrastructure (Arango, 2007; Assili et al., 2008; Bunn and Larsen, 1992, 1994; Ford, 2001;

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Ford and Youngblood, 1983; Sánchez et al., 2007b). For the policy analysis models, the main scenarios include the regulatory options such as energy incentives and government subsides, the management options such as increasing energy price, or the planning goals such as economic growth. One specific group under policy analysis is the environmental impact analysis models. These models also include the scenarios of renewable energy sources. For example, Ford et al. (2007) simulated the carbon emissions of power generation when wind power is a supplementary feed-in.

4.1.6. Research Gap and Future Research Needs

One significant research gap is the under-investigation of the emerging issues in energy planning, for example, climate change, renewable energy, and water-energy nexus. Lacking the consideration of these issues results in the current status of energy SD models: a) the key factors and scenarios focus on economy, b) the energy supply is dominated by non-renewable sources and presented as a function of technology or capital input, and c) the users in energy demand are lumped together to reflect the overall impact of energy consumption on the economy. As a result, the energy model developed in this study tries to fill the research gaps and meet the research needs as listed in Table 4-1.

4.2. Model Development

4.2.1. Model Purpose and Key Factors

As Section 4.1 indicated, current energy resource management models lack the consideration of GHG emissions and water pollution; however, will the incorporation of GHG emissions and water pollution change the behavior of energy use? If the energy resource management model considers the GHG emissions and water pollution, which

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management option is more effective to reduce the energy use? In order to address the above two research questions, the energy model developed in this Chapter incorporates GHG emissions and water pollution associated with energy supply. The key modeling factors include energy supply, energy demand, and environmental impacts as shown in Table 4-2.

4.2.2. Energy Demand

Energy demand consists of sectoral demand in municipality, agriculture, industry, and water sector. The energy demand in this study refers to the electricity demand. It is in the unit of British thermal unit (Btu). The fuel demand to generate electricity is included in this study, but the other uses of fuels (e.g. heating) are not considered.

4.2.2.1. Energy Demand in Municipality

The energy demand in municipality refers to the electricity use in the residential and commercial users. It is composed of three parts as shown in Figure 4-3 (EIA, 2009, 2010). One aspect of the energy demand in municipality is associated with household water use, such as household water heating for showering and bathing. The second part is the energy demand in cooling and heating systems, which is influenced by temperature. The third part is energy demand for electric appliances, such as refrigerators, ovens, televisions, and so on. The increase in the energy price and rebates of energy-saving appliances leads to the decrease of capita energy demand for cooling and heating and electric appliances.

4.2.2.2. Energy Demand in Agriculture

As near 90% of electricity demand in agriculture is used for pumping irrigation water (Cleveland, 1995; Pelletier et al., 2011), the energy demand in agriculture is determined by the energy uses for agricultural irrigation as the Eq. 4-1 shown. Due to lacking the on-site data of energy intensity for agricultural water pumping from the water sources, the energy intensity

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for municipal raw water pumping in Table 3-9 is used. The energy intensity for water treatment is not included.

$$ED_a = {ED_{ai}}/{f_{ai}} \tag{4-1}$$

where, ED_a is the energy demand in agriculture, and ED_{ai} is the energy demand in agricultural irrigation. f_{ai} is the fraction of energy demand in agricultural irrigation, which is 0.9 in this study.

4.2.2.3. Energy Demand in Industry

Energy demand in industry is formulated as a function of production and energy intensity as the following (Ang, 1995; Jacobsen, 2000; Zhen, 1992):

$$ED_i = P_i \times UE_i \times UP_i \tag{4-2}$$

where, ED_i is the energy demand in industry; P_i is the industrial employees; UE_i is the energy demand per industrial production, which is in the unit Btu/Dollar; UP_i is the industrial production per employee, which is in the unit Dollar/Person.

Industrial employee is a function of population, unemployment, labor as force (i.e., the ratio of people available to work to the total population), and fraction of industrial employees (i.e., the ratio of industrial employees to the total employees). Energy demand per production decreases with the improvement of energy use efficiency. Production per employee is determined by total production and production ability per employee. If the required per employee production exceeds the ability, capitals are need to improve the production ability, such installation of machines. It can also be achieved by increasing the working force in industry. Figure 4-5 presents the causal loop diagram of energy demand in industry.

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4.2.2.4. Energy Demand in Water Sector

Energy demand in water sector consists of energy demand in water supply and energy demand in wastewater treatment. The energy intensity for water extraction, treatment and delivery is summarized in Table 3-9. The energy intensity for wastewater treatment is 2.331×10^{-3} kWh/Gallon (Wilkinson, 2000). The total water demand and the agricultural water demand in Section 4.2.2.3 are determined by capita water demand and population.

4.2.3. Energy Supply

Energy supply includes the primary energy (coal, oil, and natural gas) and electricity generated from primary energy. If local supply cannot meet the demand, energy imports are considered. Figure 4-7 shows the stock-flow diagram of energy supply.

There are two stocks for each type of primary energy: energy reserves and power generation capacity. The equations are presented as the following:

$$\frac{dR_i}{dt} = D_i - P_i \tag{4-3}$$

$$\frac{dE_i}{dt} = C_i - A_i \tag{4-4}$$

where, i is the type of energy, 1 to 3 represents coal, oil, and natural gas, respectively. R is the energy reserves, D is the discovery rate, and P is the production rate. E is the electricity production capacity, C is the power generation capacity expansion rate, and A is the power plant aging rate.

4.2.4. Incorporation of Greenhouse Gas Emissions and Water

Greenhouse gas emissions and water are considered in the model structure. The major fuel sources for power generation include coal, natural gas, and oil. Oil accounts for 20% of the fuels, and this percentage slightly oscillates around 20% from 1990 to 2005 (EIA, 2010; EPA,

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2013). Thus, this study assumes that the percentage for oil maintain at 20% and only considers the changes of the percentages for coal and natural gas as feed-in sources for power generation. The percentages of coal and natural gas for power generation are determined as the following:

$$f_j = w_1 I_{E,j} + w_2 I_{G,j} + w_3 I_{W,j} \tag{4-5}$$

$$I_{E,j} = E_j / \sum E_j \tag{4-6}$$

$$I_{G,j} = 1 - G_j / \sum G_j \tag{4-7}$$

$$I_{W,j} = 1 - (w_4 \times \frac{WI_j}{\sum WI_j} + w_5 \times \frac{WP_j}{\sum WP_j}) \tag{4-8}$$

where, j is the type of energy, 1 represents coal, and 2 represents natural gas. f is the percentage of energy used for power generation ($f_1 + f_2 = 0.8$). I_E, I_G, and I_W are the index for energy reserves, greenhouse gas emissions, and water, respectively. E represents the energy reserves, G represents the carbon intensity, WI represents the water intensity for energy production, and WP represents the water pollution for energy production. w_1 to w_5 are the weighting factors for energy reserves, greenhouse gas emissions, impacts on water, water intensity, and water pollution. The carbon intensity, water intensity, and water pollution for coal and natural gas are summarized in Table 4-3.

4.2.5. Interaction between Energy Supply and Demand

A similar concept of water balance index in water model is also used for energy balance index, which is

$$BI_E = S_E - D_E \tag{4-9}$$

where, BI_E is the energy balance index. A higher BI_E value is preferred. S_E is the energy supply and D_E is the energy demand.

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The energy balance index increases with the energy supply and decreases with the energy demand. When the index is lower than certain value, it triggers the energy supply or demand management options. The demand management options will decrease the energy demand, which in turn increases the index. The supply management options will increase the energy supply through renewable energy or energy imports (Figure 4-8). Increase of the discovery rate can also increase the energy reserves. No new energy reserves have been found in the study area since 1960s (EIA, 2013), strategies to increase the discovery rate are not considered in this study.

4.3. Model Validation

This study conducted a 3-step model validation as explained in Chapter 2 (i.e., structure test, structure-oriented test, and behavior test). Since the energy supply and demand data are reported at state level, the model validation tests the structure at state level first. If model structure is robust at the state level, the model is scaled down to county level by normalizing population and production proportionally.

4.3.1. Structure Test

The direct structure test was conducted by comparing the causal and mathematical relationships between variables with the available knowledge about real system. The causal relationships described in the causal loop diagrams are supported by previous studies as detailed in Sections 4.2.1 and 4.2.2. The mathematical relationships based on the literature are explained in details in Appendix C.

4.3.2. Structure-Oriented Test

The structure-oriented behavior test in this study includes the extreme condition test and sensitivity analysis. The extreme condition test examined the scenario of zero population within

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the system boundary. As expected, the total energy supply and demand will be zero (Figure 4-9). The structure-oriented behavior test also examined the sensitivity of system behaviors to temperature, energy price, and budgets for different management options. Figure 4-10 shows that energy supply is most sensitive to budget and energy demand is most sensitive to temperature.

4.3.3. Behavior Test

The behavior test examined the behaviors of consumptions by energy types (i.e. coal, natural gas, and oil production) and consumptions by end users (i.e. municipal and industrial energy demand). Table 4-4 shows that errors of average between simulated and observed data are within 10%, except natural gas consumption (~-11.70%), but its root-mean-square error (RMSPE) is 4.65%, which is considered low. The majority of the errors are due to divergence in point-by-point prediction (U^C) and the overall trends are well captured as shown in Figure 4-11. The energy demand in water sector and energy demand in agriculture are lumped into the energy demand in industry and not reported separately. Thus, no historical data is available to compare the simulation with reported data. However, studies find that the energy demands in water sector and agriculture account for around 4% and 1%, respectively (Cohen, 2004; Stillwell et al., 2011; Wang et al., 2012). The simulation shows that the percentage of energy demand in water sector ranges from 2.5% to 5.2%, and the percentage of energy demand in agriculture ranges from 0.6% to 1.1%, which align with the reported percentages.

4.4. Results and Discussions

4.4.1. Reference Behavior

Figure 4-12 shows the reference behaviors of energy supply and demand. The petroleum (oil) used for power generation increases from 14.6 to 20.5 trillion Btu due to the increase of

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electricity demand, but the percentage of oil to all types of fuels maintains at the value of 20%. The coal production increases from 47.8 to 67.9 trillion Btu (~42.1%), and natural gas production increases from 69.1 to 95.7 trillion Btu (~38.5%) (Figure 4-12b). These fuels, however, are imported since the minor energy reserves within the study area.

Energy demand in municipality is the largest user (~ 80% of the total energy demand in 2030). It increases from 408.9 to 769.7 trillion Btu due to the population growth. 15% of the total demand is contributed by the energy demand in industry, which increases from 81.0 to 132.2 trillion Btu. Population is also a driver for energy demand in industry, as the industrial production is determined by population and production per capita (Eq. 4-2 and Figure 4-5). The energy demands in water sector and agriculture also increase, but the percentages of the total energy demand do not change much, which are 4.7% and 0.9% in 2030, respectively. The energy demands in water and agricultural sectors are associated with water demand.

4.4.2. Impacts of Greenhouse Gas Emissions and Water Pollution

Section 4.2.4 proposed the method of considering greenhouse gas emissions and water pollution in determining the energy mix for power generation. However, there are no coal and natural gas reserves in the study area (EIA, 2013). Studies find that energy price is closely related to the reserves (Gan and Litvinov, 2003; Wang et al., 2003), so I_E is replaced by energy price in this study. Before using these equations to investigate the impacts of incorporating greenhouse gas emissions and water pollution associated with energy supply, the validity of these equations should be tested. Figure 4-13 shows the behaviors of simulated and reported percentages of coal consumption according to Eqs. 4-5~4-8. The weighing scheme used in simulation is w_1=1 and w_2= w_3= w_4= w_5=0. The average coal consumption for observation and simulation is 41% and 37%, respectively, and the mean-square-error (MSE) is 0.37%. This result,

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on one hand, validates the applicability of Eqs. 4-5~4-8; on the other hand, it indicates that cost is the primary concern in choosing the fuel types in current energy planning.

Table 4-5 presents the percentage of coal used in power generation under different weighting schemes. The percentage of coal consumption decreases from 36.0% in 2010 to 29.8% in 2030 in the scenario considering energy cost only. If greenhouse gas emission is also considered with a weighting factor of 0.2, the percentage of coal decreases to 13.4% but the percentage of natural gas increases to 66.6%, since coal is more carbon intensive than natural gas. If water is considered along with GHGs, the percentage reduces to 10.6% due to the higher water intensity and potential water pollution associated with coal mining. The result implies that coal-fired power generation, with a higher environmental impact, is gradually being replaced by natural gas power generation with the consideration of environmental impacts. EIA (2013) also indicates that the concerns about GHG emissions continue to decrease the coal share in the U.S.

4.4.3. Effectiveness of Energy Supply and Demand Management Options

4.4.3.1. Energy Demand Management Options

Section 4.4.2 shows that the energy supply decision considering GHGs and water (water intensity and water pollution) reduces the percentage of coal as a fuel in power generation. This section examines the effectiveness of different demand management options in reducing energy demand, greenhouse gas emissions, and water pollution as shown in Table 4-6. The options include energy price, energy conservation education, and rebate on household appliances. As energy demands in agricultural sector is less than 1%, the energy management options considered in this study focus on municipality and industry, which account for 95% of the total demand.

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Energy price is the most effective option to reduce the energy demand. A 50% increase of energy price reduces the total demand by 16.3%. Energy demand is relative inelastic to price in a short-term, with a value ranging from 0.08 to 0.20, but the price elasticity is around 0.5~0.8 in a long run (Bernstein et al., 2006; Houthakker et al., 1974; Lijesen, 2007). The increase of energy price gradually influences the demands in municipality as well as industry, such as improving the energy use efficiency. Energy conservation education is the second effective option to reduce the energy demand, as it is a long-term investment and its effect is delayed (Dias et al., 2004; Ouyang and Hokao, 2009). Rebate on household appliances reduces the total energy demand by 3.6%, which is the least effective option of the three largely due to the low rebates or incentives compared with the reinstallation costs. Take the Energy Star® qualified refrigerator for example, the average rebate for such product is from $50 to $700 while the cost ranges from $926 to $2,408 (Clark et al.). The consumers, however, are only willing to pay an extra $249.82 to $349.30 for an Energy Star® labeled refrigerator (Ward et al., 2011). Besides cost, other factors, such as education level, income, all influence the effectiveness of rebate program (Datta and Gulati, 2011; Grösche and Vance, 2009). In terms of environmental impacts, under current energy mix for power generation (i.e., $w_1=1$, $w_2= w_3= w_4= w_5=0$), the implementation of these management options can reduce the GHG emissions from 6% to 20% and water pollution from 7% to 21%. With the consideration of environmental impacts in determining the energy mix ($w_1=0.6$, $w_2=w_3=0.2$, $w_4= w_5=0.5$), the maximum reductions of GHG emissions and water pollution can reach to 37% and 55%, respectively, due to the replacement of coal with natural gas.

4.4.3.2. Energy Supply Management Options

Renewable energy only accounts a small portion for the power generation in Florida (~2.2%). The majority of renewable energy comes from biomass (EIA, 2014). Florida has

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plentiful solar energy resources, which have a potential to produce more than 1.8×10^6 Btu. This is about 100 times of the total electricity consumption in Florida in 2011 (EIA, 2013; Solar Energy Industries Association, 2014). However, less than 0.5% of electricity comes from solar energy. Recently, the installations of solar thermal and photovoltaic (PV) are increasing. This study also examines the influence of investing solar systems on reducing the environmental impacts. There are no direct GHG emissions in stage of generating electricity from solar energy. The emissions are associated with manufacturing and transporting PV systems. The life-cycle GHG intensity ranges from 0.009 to 0.024 gCO_2/Btu (Fthenakis and Kim, 2007; Reijnders and Huijbregts, 2007; Weisser, 2007). The water use requirement for solar energy is minor, which is usually used for panel cleaning. The water footprint for solar energy is also low, 0.075 gallon/MBtu (Gerbens-Leenes et al., 2008). The GHG emission and water intensity during the stages of solar panel manufacture and transportation are considered in the following analysis.

The energy supply management options include one million dollar investment on solar energy facilities and incentives for household solar panels as provided in Table 4-7. An additional $1M dollar investment on solar energy facilities decreases the dependence on non-renewable energy by 0.0019%, and the associated decreases in environmental impacts are also low. If the additional $1M dollar budget is used for solar power incentives, the reductions of fossil use and environmental impacts are even lower (less than 0.0003%). It is mainly because the initial cost of installation with a reduction of incentive is still higher than consumers' willingness to pay (Barbara, 1999; Li et al., 2009; Zarnikau, 2003). In order to reach 1% of electricity generating from solar energy, at least half billion dollar is required to invest the solar energy facilities.

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4.5. Chapter Summary

This chapter critically reviewed 55 energy resources management models developed by SD approach from the perspective of problem articulation, model formulation, model testing, and policy analysis. One significant research gap is the under-investigation of the emerging issues in energy planning. It leads to status of current energy SD models: a) the key factors and scenarios focus on economy, b) the energy supply is dominated by non-renewable sources and presented as a function of technology or capital input, and c) the users in energy demand are lumped together to reflect the overall impact of energy consumption on the economy. In addition, current energy SD models have not conducted a formal model validation.

This chapter developed a SD model for energy resource management with the incorporation of greenhouse gas emissions and water pollution associated with energy supply, and conducted a formal model validation. The result indicates that cost of fuels is the primary concern of determining the energy mix for power generation. The current electricity mix in the study area consists of 35.4% fuels from coal, 44.6% from natural gas, and 20% from oil. When considering the environmental impacts associated with energy supply, this percentage of coal reduces to 10.6%, and GHG emissions and water pollution can be reduced by 22% and 43% accordingly. The result also shows that energy price is the most effective to reduce the demand (~16.3%), followed by energy conservation education (~10.6%). Rebates on household appliances are the least effective option (~3.6%) due to consumers' low willingness to pay. Combining the supply decision incorporating environmental impacts and the demand option of energy price increase, the reductions of GHG emissions and water pollution can reach 37% and 55%, respectively. Solar energy has a high potential to reduce GHG emissions and water

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pollution, but current budget is too low. In order to increase the use of solar energy to 1%, at least half billion dollars needs to be invested in solar energy facilities.

Limited by the data availability, the energy model is tested by state data. The validity of the model should be further tested by county-level data if it is available. In addition, the water pollution from fuel production is not fully investigated due to lack of reserves and power plants within the study area. This model should be further studied for a site with energy production facilities.

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Table 4-1 Main Research Gaps and Future Research Needs of Energy System Dynamics Models

Modeling Steps	Research Gaps	Future Research Needs	This Study
Problem Articulation	• Lack of the consideration of the emerging issues in energy planning	• Incorporate greenhouse gas emissions • Incorporate water-energy nexus	×
Model Formulation	• Lack of the consideration of the interaction between energy supply and demand	• Capture the feedback loops between energy supply and energy demand	×
	• Lack of the consideration of primary energy sources for power generation and associated impacts	• Include primary energy sources in the power generation • Consider water requirement and water pollution associated with energy production	×
	• Lack of the consideration of sectoral energy demand	• Formulate the energy demand by sectors (i.e. energy demand in agriculture, industry, municipality, and water)	×
Model Testing	• Lack of the formal model validation	• Conduct a formal model validation (structural test, structural-oriented behavior test, and behavior test)	×
Policy Analysis	• Lack of management options considering the emerging issues	• Design scenarios related to the interaction between energy and water as a constraint	×

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Table 4-2 Key Model Factors and Variables of Energy Sub-model

Factors	Key Variables	Stocks
Energy Supply	Primary Energy (i.e. Coal, Natural Gas, and Oil), Secondary Energy (i.e. Electricity), Energy Imports	Coal Storage, Natural Gas Storage, Oil Storage, Power Generation Capacity
Energy Demand	Energy Demand In Municipality, Energy Demand In Agriculture, Energy Demand In Industry, Energy Demand In Water	Efficient Household Energy Appliances, People with Energy Conservation Awareness
Environmental Impacts	Water Intensity, Water Pollution, Greenhouse Gas Emission	Water Pollution, Greenhouse Gas Emission

Table 4-3 Carbon Intensity, Water Intensity and Water Pollution for Coal and Natural Gas (Mielke et al., 2010; Mitigation, 2011)

	Coal	Natural Gas
Carbon Intensity (gCO_2/Btu)	0.293	0.137
Water Intensity (Gallon/MBtu)	3.5	1.2
Water Pollution (WQI*)	41.09	65.47

* WQI is the water quality index, which considers the concentration of total dissolved solids, total nitrogen, and dissolved oxygen as introduction in Section 3.5.2.

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Table 4-4 Error Analysis of Behavior Test of Energy Sub-model

Variable	Average			RMSPE[1]	Inequality Statistics[2]		
	Observed	Simulated	Error		U^M	U^S	U^C
Coal Consumption	6.62E+14	6.47E+14	-2.21%	0.56%	0.09	0.05	0.52
Natural Gas Consumption	4.87E+14	4.30E+14	-11.70%	4.65%	0.34	0.06	0.32
Oil Consumption	2.88E+14	2.69E+14	-6.60%	7.63%	0.09	0.07	0.47
Energy Demand in Municipality	2.86E+14	2.69E+14	-2.53%	0.07%	0.73	0.10	0.09

1 RMSPE is the root mean-squared percent error
2 Inequality statistics shows the fraction of mean-square-error. U^M measures the bias between simulated and actual data; U^S measures the degree of unequal variation between two datasets; U^C measures the degree of divergences between simulated and actual data in point-by-point estimation.

Table 4-5 Percentage of Coal Used for Power Generation under Different Weighting Schemes

Scenarios	Weighting Scheme	Percentage in 2030		
		Coal	Natural Gas	Oil
Only Considering Cost	w_1=1, w_2= w_3= w_4= w_5=0*	29.8%	50.20%	20.0%
Considering GHGs	w_1=0.8, w_2=0.2, w_3= w_4= w_5=0	13.4%	66.60%	20.0%
Considering GHGs and Water	w_1=0.6, w_2=0.2, w_3=0.2, w_4= w_5=0.5	10.6%	69.40%	20.0%

* w_1 to w_5 are the weighting factors for energy cost, greenhouse gas emission, water impacts, water intensity, water pollution, respectively.

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Table 4-6 Effectiveness of Energy Demand Management Options

Demand Management Options	Percentage Reduction from BAU					
	Energy Demand		GHG Emissions		Water Pollution	
	Without*	With*	Without	With	Without	With
Energy Price (50% Increase)	16.3%	16.3%	20%	37%	21%	55%
Energy Conservation Education	10.6%	10.6%	13%	32%	15%	51%
Rebates on Household Appliances	3.6%	3.6%	6%	26%	7%	47%

* Without and with represent the scenarios that without and with considering GHG emissions and water pollutions in choosing the fuels of power generation.

Table 4-7 Effectiveness of Energy Supply Management Options

Supply Management Options	Percentage Reduction from BAU		
	Non-renewable Energy	GHG Emissions	Water Pollution
Investment on Solar Energy Facilities	0.0019%	0.0017%	0.0019%
Incentives for Household Solar Panels	0.00027%	0.00024%	0.00026%

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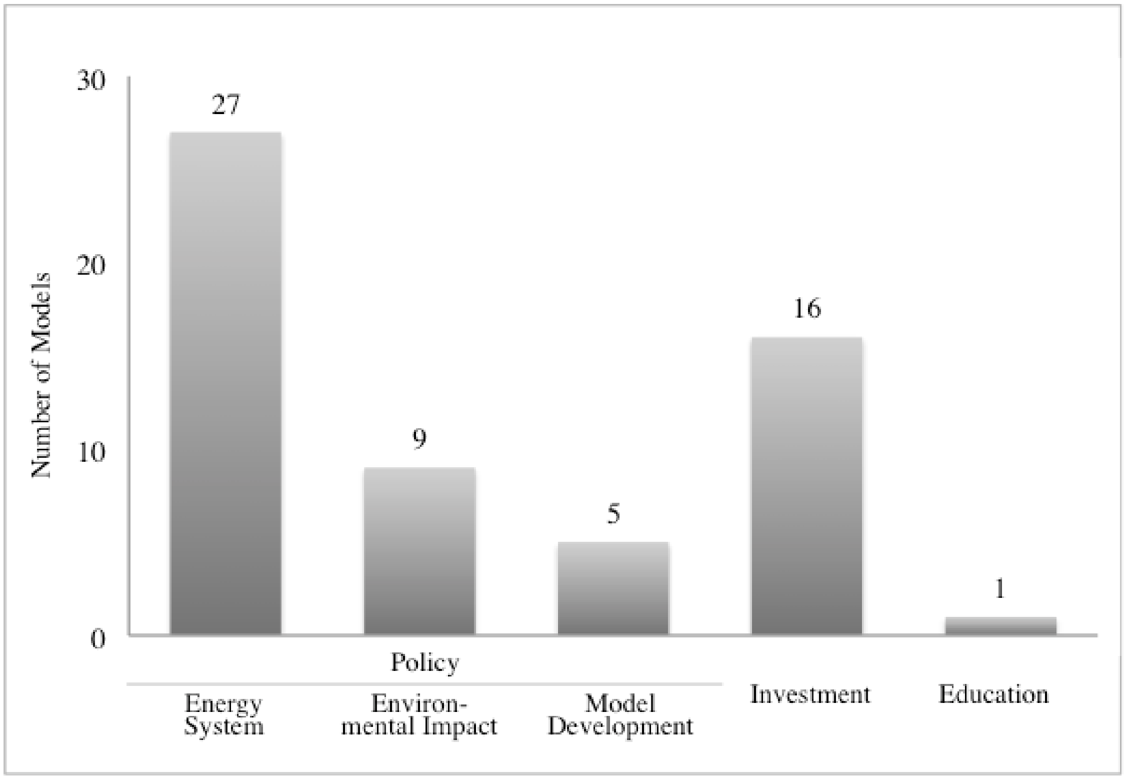

Figure 4-1 Reviews on Model Purposes of Energy System Dynamics Models

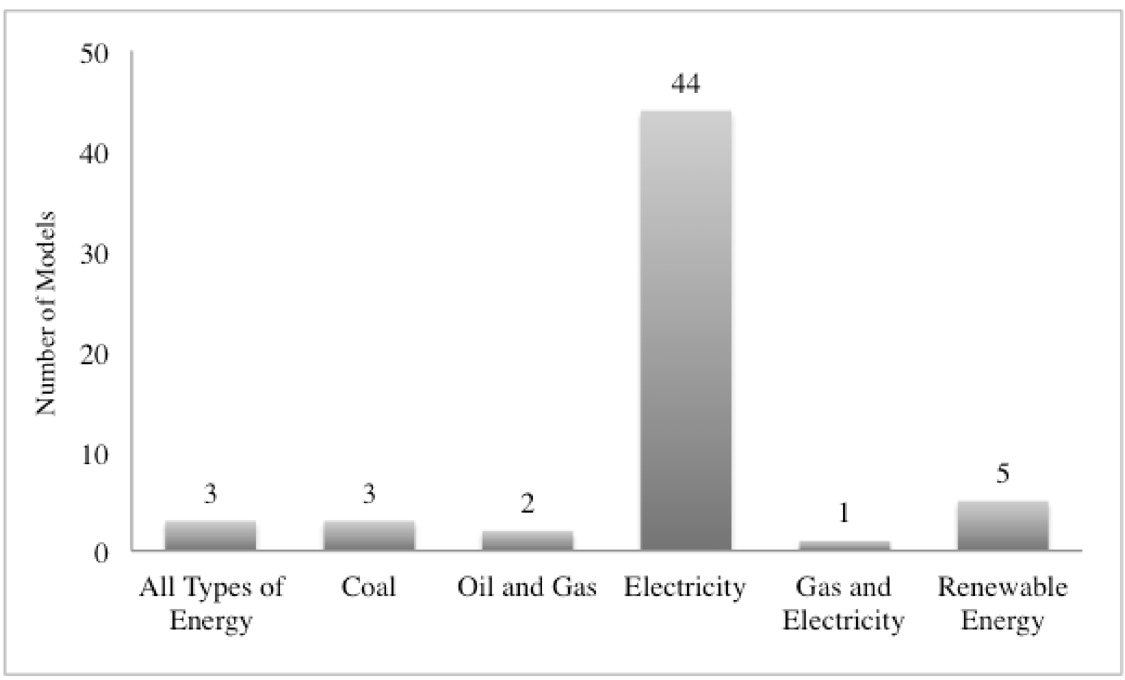

Figure 4-2 Reviews on Energy Supply of Energy System Dynamics Models

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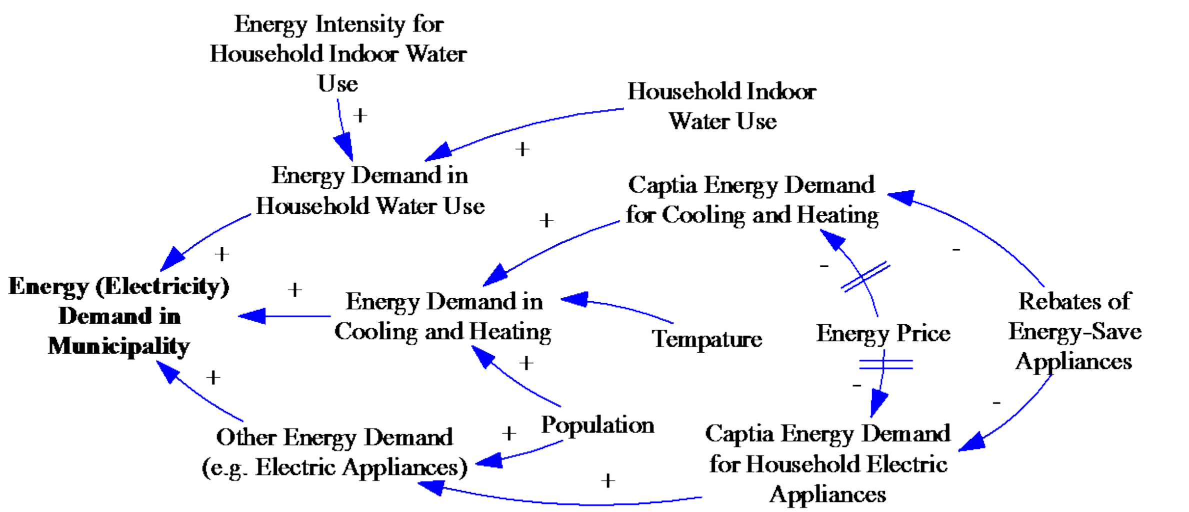

Figure 4-3 Causal Loop Diagram of Energy Demand in Municipality. The positive and negative signs represent reinforcing and balancing causal relationships. The two-line bar in the middle of a link represents a time delay.

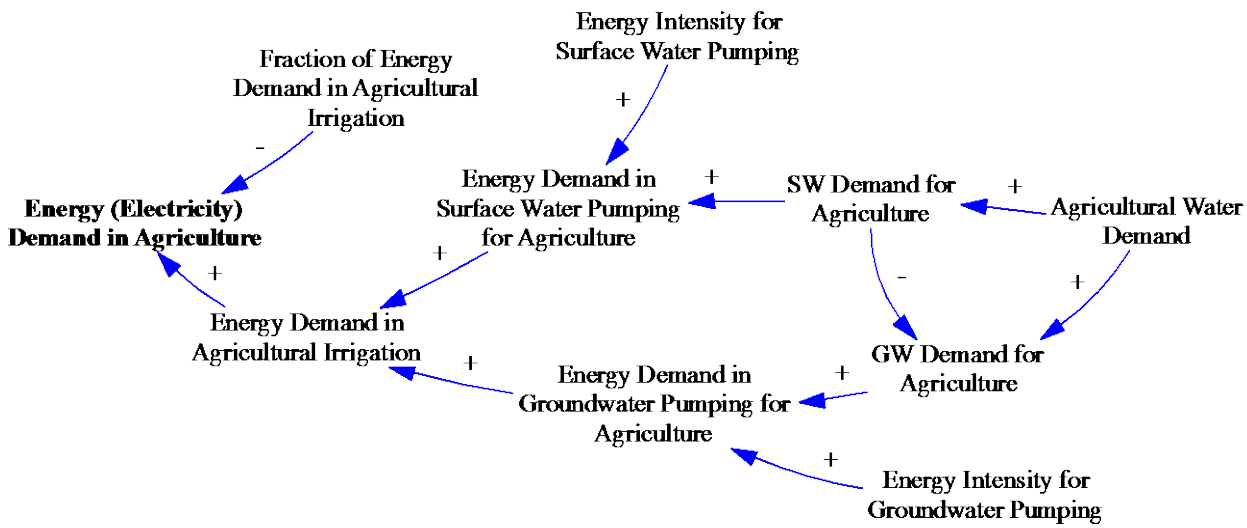

Figure 4-4 Causal Loop Diagram of Energy Demand in Agriculture. The positive and negative sign represent reinforcing and balancing causal relationships.

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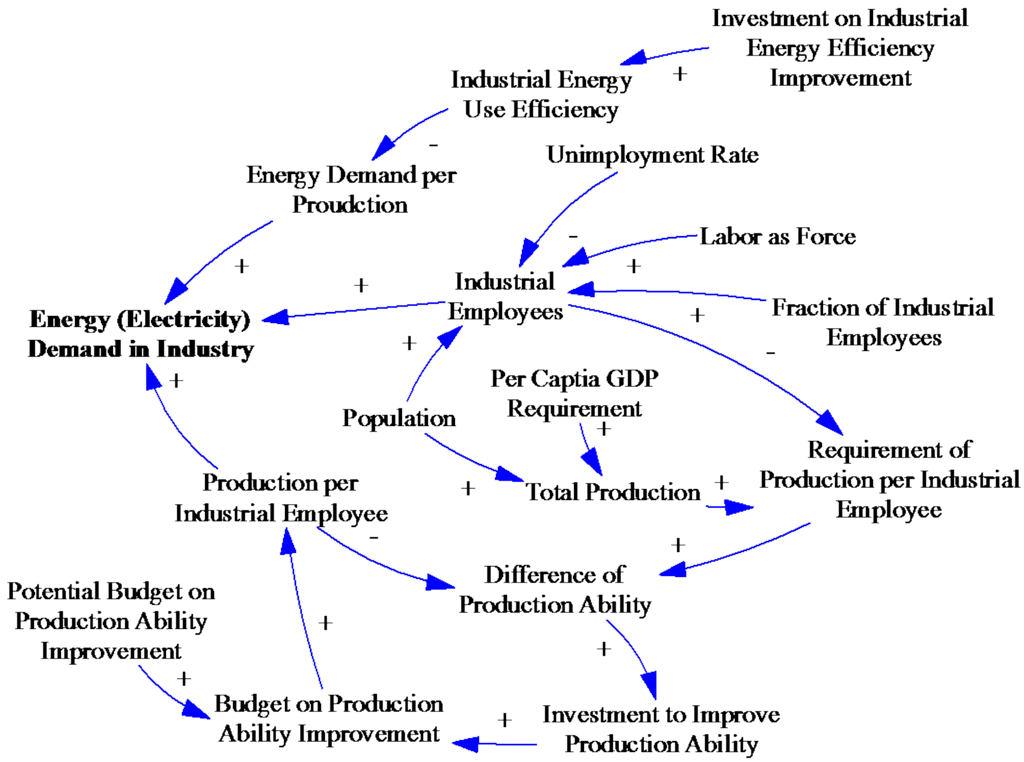

Figure 4-5 Causal Loop Diagram of Energy Demand in Industry. The positive and negative signs represent reinforcing and balancing causal relationships.

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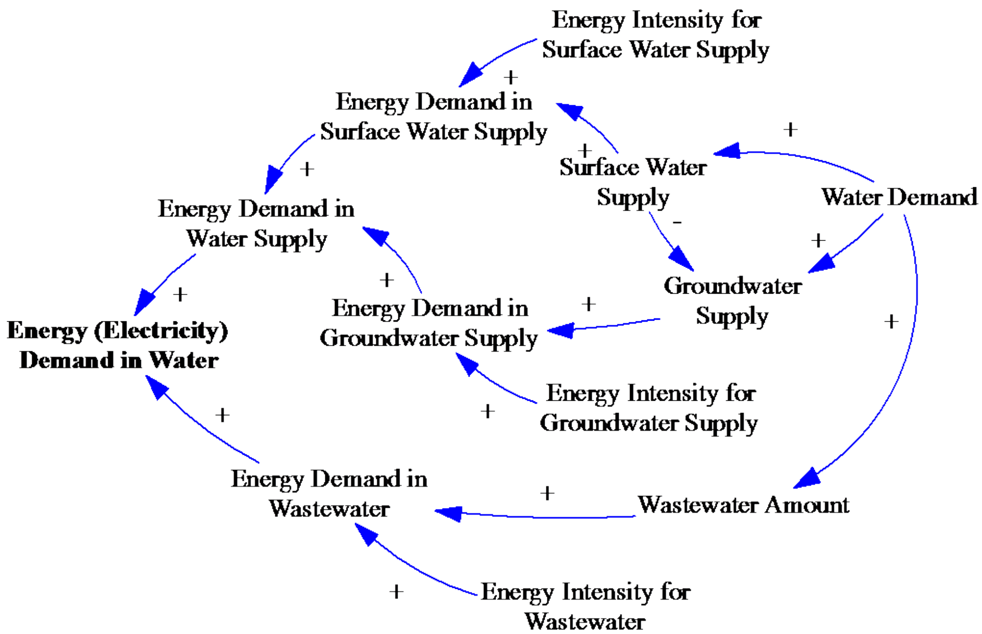

Figure 4-6 Causal Loop Diagram of Energy Demand in Water Sector. The positive and negative signs represent the reinforcing and balancing causal relationships.

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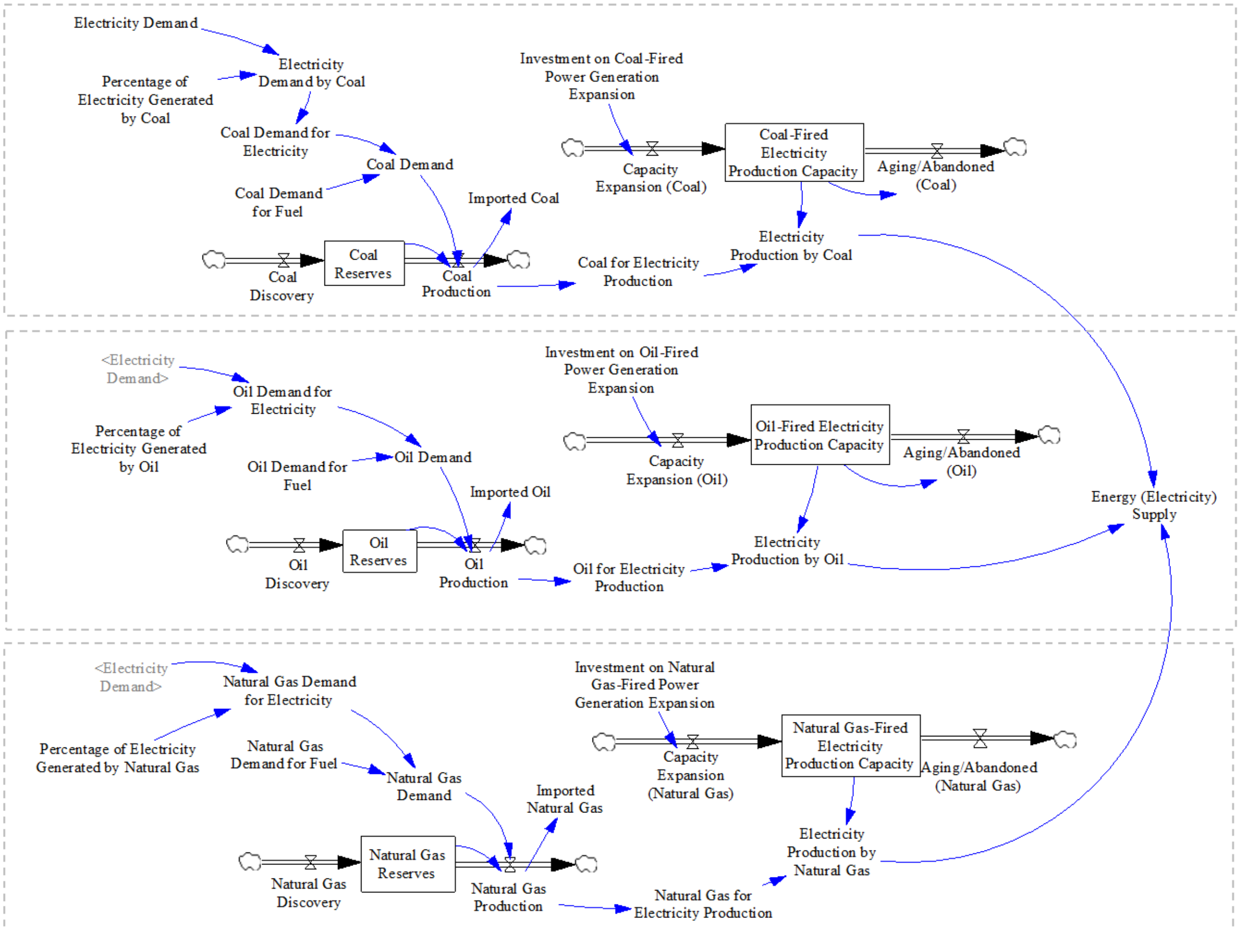

Figure 4-7 Stock Flow Diagram of Energy Supply. A variable with a rectangle is a stock. A variable with a pipe pointing into the stock is an inflow, and the variable with a pipe pointing out of the stock is an outflow. Clouds represent the sources and sinks for the flows.

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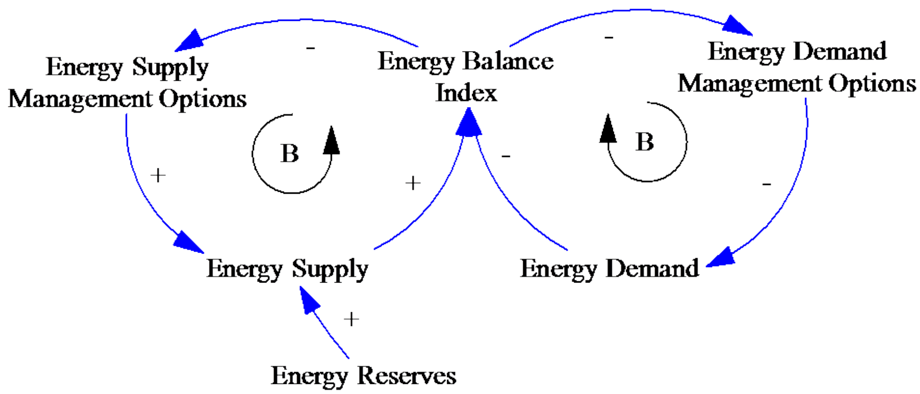
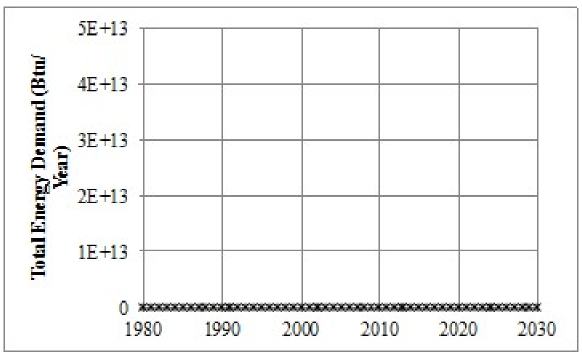
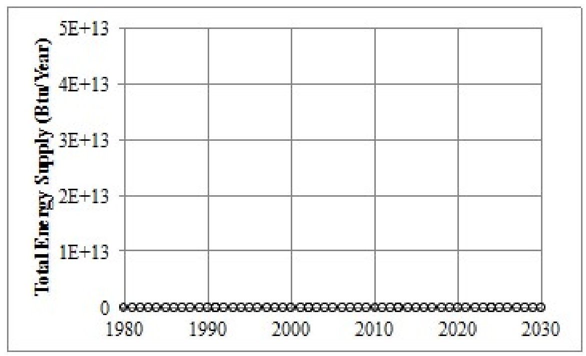


Figure 4-8 Interactions between Energy Supply and Demand. The positive and negative signs represent the reinforcing and balancing causal relationships. B represents the balancing feedback loop.



(a) Energy Demand with Zero Population



(b) Energy Supply with Zero Population

Figure 4-9 Extreme Condition Test of Energy Sub-model

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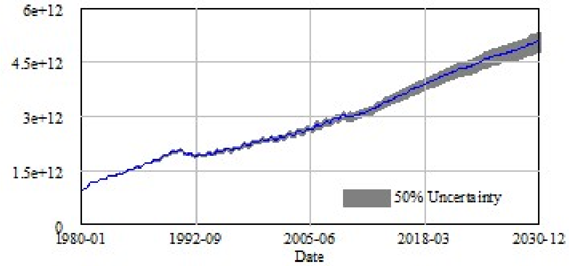
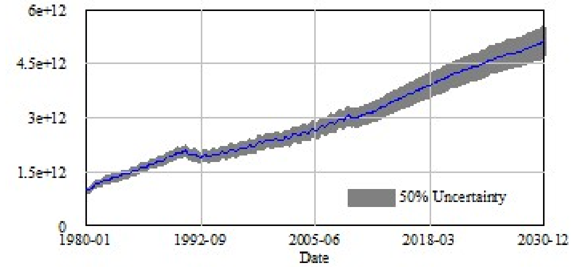
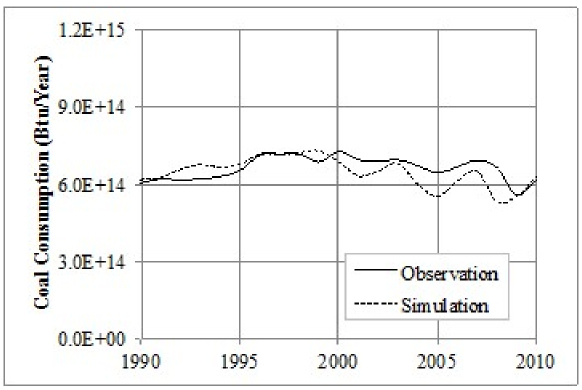


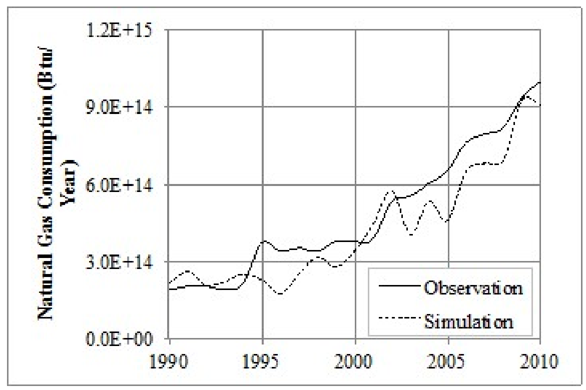


(a) Energy Supply to Budget (b) Energy Demand to Temperature

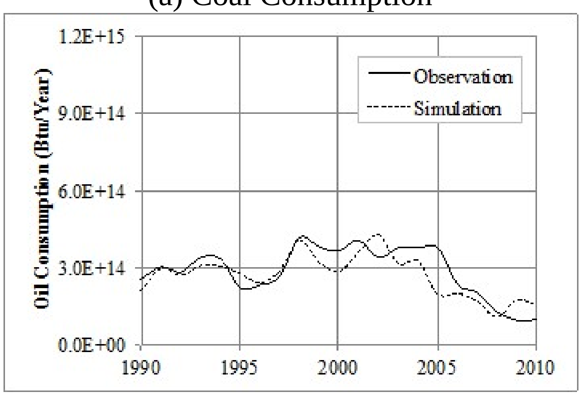
Figure 4-10 Sensitivity Analysis of Energy Sub-model



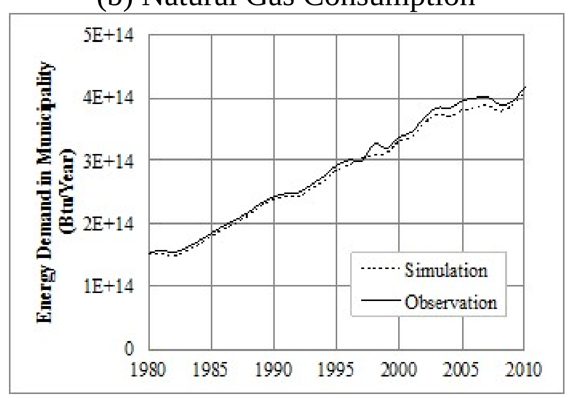
(a) Coal Consumption



(b) Natural Gas Consumption



(c) Oil Consumption



(d) Energy Demand in Municipality

Figure 4-11 Behavior Test of Energy Sub-model

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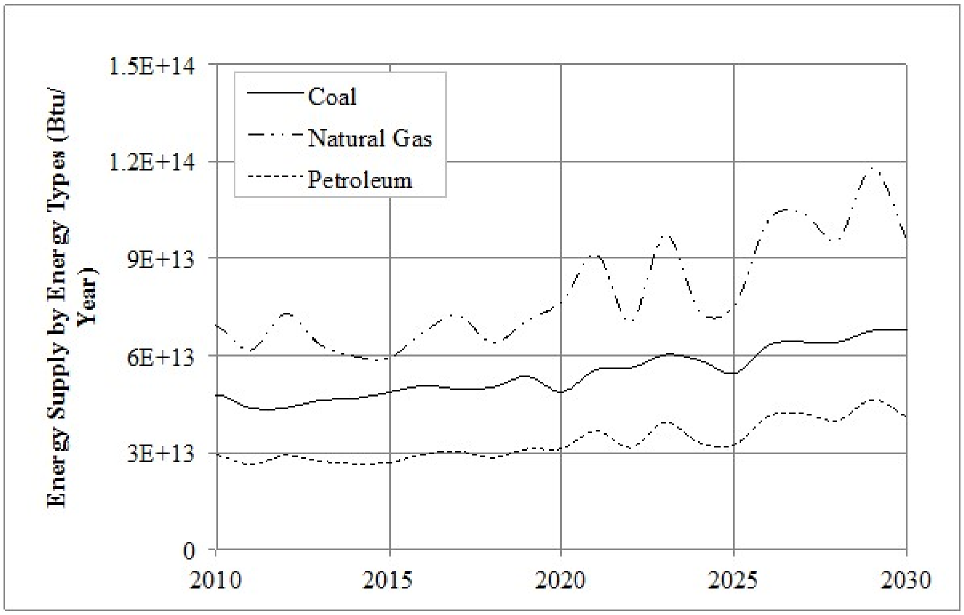
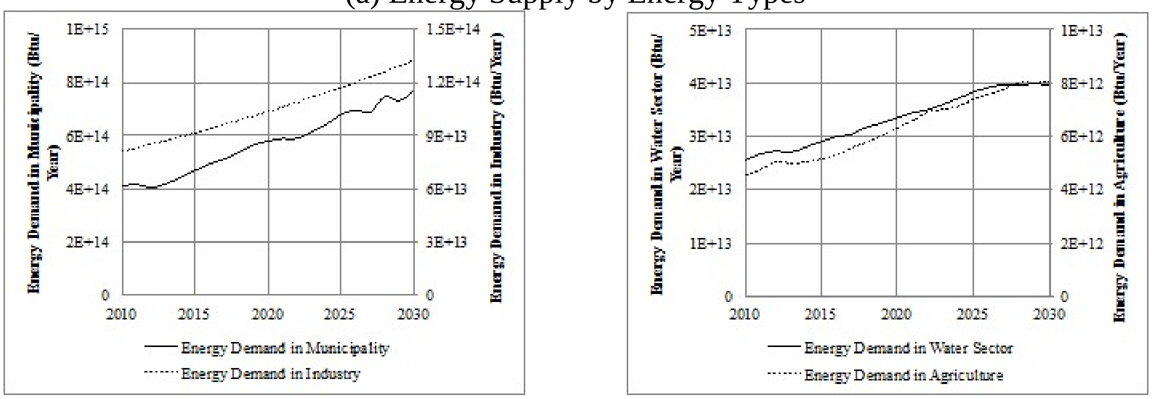


(a) Energy Supply by Energy Types



(b) Energy Demand by Users

Figure 4-12 Reference Behaviors of Energy Supply by Energy Types and Energy Demands by Users

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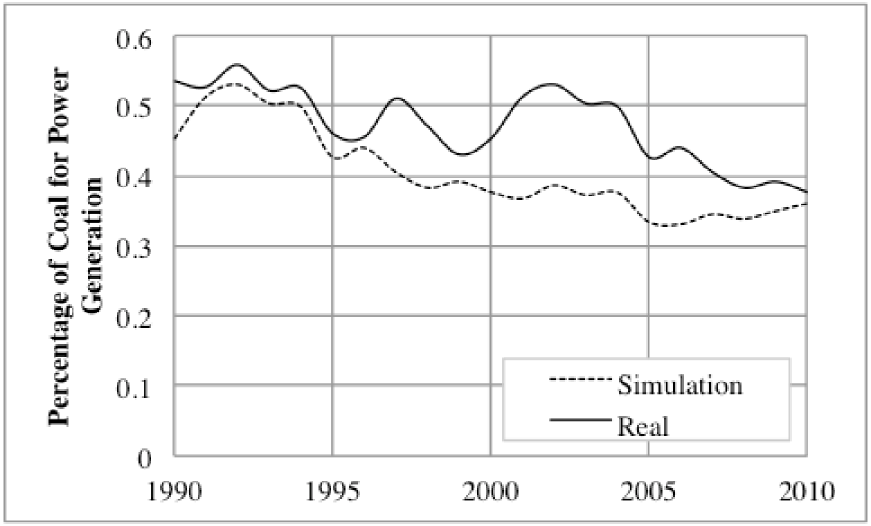

Figure 4-13 Percentage of Coal Used for Power Generation

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CHAPTER 5.

INTEGRATED WATER AND ENERGY MODEL

5.1. Introduction

5.1.1. Water and Energy Nexus

Water and energy are multifaceted issues with many factors influencing their supply and demand. The importance of water-energy nexus has been gradually recognized, especially since 2005 when the U.S. Department of Energy (DOE) held a series of workshops focusing on the regional interdependencies of water and energy (Pate et al., 2007). These nexus studies focus on: (a) the role of pricing, such as the impact of water price on energy use or the energy price on water use (Espey et al., 1997b; Hansen, 1996; Hobbs et al., 2001); (b) the interdependence of water and energy demands at utility level, such as the energy demand in water and wastewater treatment or water demand in power plant (deMonsabert and Liner, 1998; Hussey and Pittock, 2012; Lofman et al., 2002; Marsh, 2008; Marsh and Sharma, 2007; Perrone et al., 2011; Stillwell et al., 2011; Tidwell et al., 2009), and (c) water use or water footprint of biofuels (Chiu et al., 2009; De Fraiture et al., 2008; Delucchi, 2010; Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009; Gopalakrishnan et al., 2009; Yang et al., 2009). Few efforts, however, attempt to investigate the impact of the management options of one resource on the other resource, or examine the benefits of integrated water and energy management. The lack of systems thinking has already caused some issues in water and energy management (introduced in Chapter 1).

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System perspective is critical in water and energy management (Alcamo et al., 2007). However, as reviewed in Chapters 3 and 4, limited system dynamics (SD) models have considered energy as a separate water demand user as well as a constrain of water supply in water resource management; no SD models developed for energy management have incorporated water or the potential impact on water system (e.g., water level). The water model with incorporation of energy consumption and the energy model considering greenhouse gas emissions and water pollution were developed and introduced in Chapters 3 and 4, respectively. These models, however, are not dynamically linked together to investigate the impact of management options in one resource on the other. To link these two models together, the interactions between water and energy are identified based on previous studies and the feedback structures are recognized using system archetypes as introduced in the following section.

5.1.2. System Archetypes

A system archetype is a well-defined structure, which describes the common behavior of a system over time. It is helpful to reveal the generic behavior and gain insights into the underlying structure in system apart from the specific situation (Senge, 1997; Wolstenholme, 2003, 2004). There are twelve system archetypes as summarized in Table 5-1. The following section focuses on the archetypes used to identify the interactions between water and energy system.

5.2. Interactions between Water and Energy Systems

5.2.1. Reinforcing Growth: Water and Energy Demand

One fundamental archetype of water and energy system is reinforcing growth as shown in Figure 5-1a. The water supply increases with water demand and leads to the

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increase of energy demand in water (i.e., energy demand in water treatment and delivery). The increase of water supply also increases the amount of wastewater, which adds to the energy demand in wastewater treatment and delivery. The increase of energy demand in water leads to the increase of total energy demand, which requires more energy supply. The increase of energy supply requires more water in energy production, especially cooling water for power generation. It finally adds to the total water demand. This forms a reinforcing growth, which is the most fundamental relationship within water and energy demands. Water and energy demand are expected to continuously increase over time (Figure 5-1b). This interaction between water and energy has been supported by several studies (DOE, 2006a; Hightower et al., 2007; Hussey and Pittock, 2012; Marsh and Sharma, 2007; Pate et al., 2007; Perrone et al., 2011; Schnoor, 2011; Stillwell et al., 2011).

5.2.2. Reinforcing Growth: Price and Demand

The price and demand exhibits the structure of *Reinforcing Growth* as revealed in Figure 5-2. For example, the increase of water price causes the increase of water cost in energy supply, which in turn increases the total cost in energy supply as well as energy price. The increase of energy price will increase the total cost in water production due to the increase in the energy cost, which eventually increases the water price (Kalogirou, 2001; Zhenfang et al., 2004). This forms a reinforcing loop (R2 with bold links in red). As shown in Figure 5-2, the increase in water price results in the decrease of total water demand, which in turn reduces the total energy demand through R1 loop. The increase in water price also leads to the increase of energy price through R2 loop and causes the decrease of total energy demand, which then reduces the total water demand through R1 loop (i.e., water and energy

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demands). It implies that the increase of the water price or energy price leads to the decrease of both water and energy demands.

5.2.3. Limits to Growth: Water and Energy Supply

Limits to Growth consists of one reinforcing loop and one balancing loop as shown in Figure 5-3a. The increase of the system state leads to the increase of the growing action, which further adds to the system state. This reinforcing growth of the system state is limited by the slowing action, which decreases the system state. The similar structure is also recognized in the water and energy supply. Two *Limits to Growth* structures are combined together as shown in Figure 5-3c. As all the human activities are limited by the carrying capacity of the planet (Lovejoy, 1996; Meadows et al., 2004; Postel, 1994; Randers, 2012), the reinforcing growth of water and energy demands is constrained by water and energy availabilities. For example, the increase of water demand drives the water supply, but the supply is constrained by the physical water storage (B1). The storage is determined by the water availability, such as the carrying capacity (Daily and Ehrlich, 1996; Gong and Jin, 2009). On the other hand, the water supply is also constrained by the energy availability through the reinforcing feedback loop (R). The increase of water demand requires more energy in water sector (i.e., treating and delivering the water), which adds to the total energy demand. The amount of energy can be supplied is depended on the energy reserves (B2) (Henriques and Sadorsky, 2008; Kamat, 2007). Similarly, the energy supply is also limited by both energy availability and water availability (Koch and Vögele, 2009). As a result, the behavior of water and energy supplies are expected to present an S-shape growth for the system state as shown in Figure 5-3b.

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5.2.4. Fixes that Fail: Water and Energy Supply Options without Consideration of Each Other

Fixes that Fail consists of one balancing and one reinforcing loop as shown in Figure 5-4a. It describes a situation that a quick fix solution diminishes the system problem but may have unintended consequences and exacerbates the system problem as a reinforcing loop in a long term. Water and energy supply options without considering each other show the behavior of *Fixes that Fail*. Figure 5-4c shows that energy-intensive water supply option can relieve the pressure of water shortage in a short-term, but it fails (i.e., increase of water shortage) in a long-term due to the unintended consequences. For example, desalination as an energy-intensive water practice has been adopted to address water shortage (Cohen et al., 2004; DOE, 2006a; Mittal, 2010; Munoz et al., 2010). It increases the water supply, which reduces the water shortage (B1). However, due to the high-energy intensity, it results in additional energy demand in water sector. Through the reinforcing loop of water and energy demands, the additional energy demand in water sector increases the total water demand. Eventually, the water shortage becomes worse (R1). Besides, if fossil fuel is the dominant energy supply sources, the additional energy demand leads to the increase of the greenhouse gas emissions. This puts a threat on climate change, which in turn exacerbates water shortage (R2) (Frederick and Major, 1997; Lehman, 1998; Milly et al., 2005). Similarly, energy shortage solved by water-intensive energy practices will lead to more water and energy uses (Marsh, 2008; Stillwell et al., 2011). It eventually adds more pressure to energy shortage as shown in Figure 5-4d. Accordingly, the water and energy shortages are expected to decrease at the initial stage but become worse in a long term as shown in Figure 5-4b.

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5.2.5. Success to the Successful: Water and Energy Supply Options with Consideration of Each Other

Success to the Successful consists of two reinforcing loops as shown in Figure 5-5a. It describes a situation that the winner may win again, but the loser may lose again due to the reduction of resources. When A's result is better than B's, more resources are allocated to A instead of B. As resource increases, A's result improves, which leads to more resources allocated to A. This forms a reinforcing loop. Meanwhile, as resources allocated to B decrease, B's result decreases, which further reduces the resources to B. This also forms a reinforcing loop. Accordingly, the behavior of A keeps increasing while B keeps decreasing. This archetype is recognized by water and energy supply options with considering each other. Take the water supply options considering energy consumption for example (Figure 5-5c). Reclaimed water is less energy-intensive than desalination (Dolnicar and Schäfer, 2009; Stokes and Horvath, 2006), so reclaimed water requires less energy and puts less threat to energy shortage. Accordingly, it gains more preferences in the perspective of energy demand and more budgets, which in turn increases the use of reclaimed water. This forms a reinforcing feedback loop (R1). On the other hand, desalination is more energy-intensive and puts more threat to energy shortage, so it gains less preference and budgets. Eventually, the desalination supply keeps decreasing. This also forms a reinforcing loop (R2). Therefore, low energy-intensive water supply keeps increasing while high-energy intensive water supply keeps decreasing. Similarly, energy supply options with low water-intensity also gains continuous preference in low threat to water shortage (Figure 5-5d). As a result, the budgets on water and energy options considering each other are expected to increase, but the budget on options without considering each other are expected to decrease as shown (Figure 5-5b).

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5.3. Integrated Model Development

Based on the identified structure between water and energy systems described in Section 5.2, the water sub-model developed in Chapter 3 and the energy sub-model developed in Chapter 4 are linked together. The linkages between these two sub-models are depicted in Table 5-2.

5.4. Model Validation

5.4.1. Structure Test

The direct structure test for water sub-model was conducted in Chapter 3, and the direct structure test for energy sub-model was conducted in Chapter 4. The structure of water-energy interactions was tested by comparing the causal and mathematical relationships between variables with the available knowledge about real system. The causal relationships described in the causal loop diagrams are supported by previous studies as detailed in Sections 5.2.

5.4.2. Structure-Oriented Behavior Test

The structure-oriented behavior test in this study includes the extreme condition test and sensitivity analysis. The extreme condition examined the scenario with zero population within the study area. Figure 5-6 shows that water and energy demands become zero when population is zero, which align with the expectation.

The input variables considered in the sensitivity analysis include precipitation, temperature, water price, energy price, and budget for different management options. The output variables include surface water level, groundwater level, surface water quality, groundwater quality, sectoral water demands (i.e. agriculture, industry, municipality, and energy), energy storage, and sectoral energy demands (i.e. agriculture, industry, municipality, and water). The

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system outputs are most sensitive to precipitation. Table 5-3 provides the comparison of the sensitivities of the above outputs corresponding to precipitation. Water model in Chapter 3 is most sensitive to precipitation, and the energy model in Chapter 4 does not respond to precipitation; however, through the feedback loops between water and energy systems, sectoral energy demands in integrated model are also sensitive to precipitation. Energy demand in agriculture is most sensitive to precipitation, because around 90% of energy demand in agriculture is for pumping irrigation water (~90%) (USDA, 2013). For the similar reason, energy demand in water sector is also sensitivity to precipitation in the integrated model. Besides, the surface- and ground-water levels are more sensitive to precipitation in the integrated model compared with the water model due to the feedback loops of water and energy.

5.4.3. Behavior Test

The behavior test examined the behaviors of surface water level, municipal water withdrawal, agricultural water withdrawal, and energy supply. Table 5-4 shows that average errors between simulated and observed data are within 5%, except for energy supply. The reason causing the large errors in energy supply was explained in the Chapter 4. The root-mean-square errors (RMSPE) between simulated and observed data are within 10%. The majority of the errors are due to divergence in point-by-point prediction and the overall trends are well captured as shown in Figure 5-7.

5.5. Results and Discussions

5.5.1. Impacts of Management Options of One Resource on the Other

This section investigates the impacts of management options of one resource on the other. It tests the first hypothesis: management strategies for one resource may have the negative

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impacts on the other through complex linkages and feedback loops. The test is conducted on the integrated model. The effects of the water options on the energy side of the integrated model are examined along with the effects on the water side. Similarly, the effects of the energy strategies on the water side of the integrated model are also examined along with effects on the energy side. As indicated in Table 5-5, rebates on indoor water appliances, energy price, and water conservation education are effective to reduce both water and energy demand. Increase in water price is effective to reduce the water demand but has the unintended consequence of increasing the total energy demand. The other options, including rebates on outdoor water appliances, agricultural BMPs, lawn irrigation restriction, energy conservation education, and rebates on household electronic appliances, are effective to reduce the use of one resource but do not have the significant impacts on the other resource. The decreases of water and energy uses also result in reductions of environmental impacts.

5.5.1.1. Options Beneficial to Both Resources

Energy price is effective to reduce both energy demand (~16.3%) and water demand (~8%) in 2030 (Figure 5-8a). The price strategy decreases the household energy uses by 11.7%, including the water-related energy use (e.g., shower and bathing) (Chen et al., 2013; Retamal et al., 2009). Approximately 14% of household electricity is used for water heating in Florida, so the decrease of municipal energy demand reduces the municipal water demand by 9.6% (Figure 5-8b). Besides, the increase of energy price gradually reflects on the water and wastewater treatment cost. As the water price is not regulated by market, it does not spontaneously change with energy price. The influence of energy price on water system due to the change of the water price (the reinforcing loop R1 in Figure 5-2) is not significant until 2025.

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Options to reduce indoor water demand, such as rebates on indoor water appliances, are also effective to reduce both water demand (~10.60%) and energy demand (~2.40%). This option reduces the municipal water demand by 12.7%, which increases the surface water level by 1.2% (Figure 5-9a). This decrease directly reduces the energy demand in water sector by 12.1%, 1/3 of which is reduced from the energy demand in potable water treatment and delivery, and rest of which are from the energy demand in wastewater treatment and collection (Figure 5-9b). The reduction in indoor water demand also reduces the energy demand in municipality by 2.8% (Figure 5-9c), mainly from energy use for residential water heating. Combining the effects on energy demand in both water sector and municipality, rebates on indoor water appliances can decrease the total energy demand by 2.40%.

Additional budget on water conservation education is also effective to reduce the uses of both resources. On the water side, it reduces freshwater withdrawal by 12.6% and increases the surface water level by 1.1%. For the energy system, it increases the energy demand in water sector by 17.2% but decreases the energy demand in municipality by 1.2% (Figure 5-10). The increasing water conservation awareness increases the public acceptance of reclaimed water, and the reclaimed water supply is increased by 39.4% compared with the reference behavior. The increase of reclaimed water correspondingly increases the energy demand in water sector by 17.2%. On the other side, as stated in indoor water rebates, the decrease of water demand in municipality in turn reduces the energy demand in municipality. If the reduction is presented in the value, the energy demand in water sector increases by 1.1×10^{11} Btu, but the energy demand in municipality decreases by 4.6×10^{13} Btu. Overall, energy demand decreases by 0.31%.

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5.5.1.2. Options with Unintended Consequences

Price is an effective to reduce water or energy demand (Espey et al., 1997a; Martin and Kulakowski, 1991; Zhou et al., 2010), which are discussed in Chapters 3 and 4. Different from energy price, the increase of water price is beneficial on the water side but has unintended consequences on the energy side. A 10 times increase of water price is simulated in this study, which may reflect the true value of water (Biao et al., 2010; Brady and Yoder, 2013; Gibbons, 1986). The increase of water price leads to a 24.3% reduction of surface water withdrawal, which in turn increases the surface water level by 2.7%. The decrease of freshwater withdrawal, however, pushes the use of reclaimed water. The reclaimed water demand increases from 18.5 MGD to 204.5 MGD (~about 10 times). Assuming enough funding for capacity expansion is provided, the use of reclaimed water increases the energy demand in water sector from 1.3×10^{11} to 6.2×10^{12} (Figure 5-11) (~about 48 times higher), and the total energy demand increases by 2.48%.

5.5.1.3. Options Only Effective to One Resource

Options, including rebates on outdoor water appliances, agricultural BMPs, lawn irrigation restriction, are effective to reduce water demand but have no significant influence on energy demand (less than 0.05%). Most of outdoor water use is not collected and treated before discharge, which is also barely practical, so the reduction of outdoor water use cannot decrease the energy consumption in wastewater treatment. Besides, the energy used to pump irrigating water is negligible compared with other electric appliances at home, so it does not significantly impact on energy demand in municipality as rebates of indoor water appliances do. Energy demand in agriculture correspondingly decreases with water demand in agriculture; however, the percentage of energy demand in agriculture is lower than 1%, so the decrease cannot

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significantly influence the total energy demand. The reductions of GHG emissions associated with energy uses for these options range from 0~0.08%, which is also insignificant.

Similarly, options, such as energy conservation education, and rebates on household electronic appliances, are effective to reduce energy demand but not water demand. These two options can reduce total energy demand by 5.6% and to 16.6%, respectively. However, due to the location of the power plants in Tampa Bay, the increase of electricity does not significantly influence the freshwater withdrawal. Besides, the fuels used in power generation are not extracted within the boundary, so there is minor influence on the water quality due to the fossil fuel mining. Therefore, the impact of the feedback from energy to water system is reduced.

5.5.2. Impacts of Integrated Management Options

The population growth drives the increase of water and energy demands, but the water and energy supplies are limited by the availabilities. As a result, there will be shortages for both water and energy resources. Figure 5-12 shows the water and energy balance indices, which measure the difference between supply and demand (Eq. 3-13 and 4-9). The overall water balance index is lower than zero (47 out of 70 years for the simulation), which means there is a need for alternative water supply sources. The water balance index starts to decrease in 2039, and reaches to the minimum in 2052 (i.e. a maximum water shortage of 152.46 MGD). The non-renewable energy balance starts to decrease in 2034, and energy shortage happens from 2037 as no new fossil fuel reserves are discovered (Naill, 1976; Shafiee and Topal, 2009). The need for alternative energy sources to generate electricity keeps increasing and reaches to 5.54×10^{13} Btu in 2080.

The water and energy shortages are primarily caused by the increasing water and energy demands driven by population (Figure 5-13). It is also contributed by the reinforcing

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feedback structure between water and energy demands as identified in Section 5.2.1. In order to investigate this reinforcing structure without the influence of population, this study sets the population as a driver for one resource and investigates the impact of the reinforcing feedback structure on the other resource. Figure 5-14a shows the trend of the water demand when population is the driver only for energy system. The total energy demand increases by 7 times due to population growth. It leads to a 5 times increase (from 7.6 to 46.4 MGD) in water demand. Figure 5-14b shows the energy demand when population is the driver only for water system. The total water demand increases by 325% as population increases, and the energy demand in water sector increases by 592% (from 5.2×10^{11} to 3.6×10^{12} Btu/year). The increase of water demand also adds to the energy demand in municipality (household water heating). Overall, the total energy demand increases by 77%, from 3.1×10^{13} to 5.5×10^{13} Btu/year.

There are two ways to address the water and energy shortages: (a) decreasing the demand or (b) increasing the supply. The effects of demand management options have been discussed in Section 5.5.1. The following section focuses on the supply management options and investigates their effects to decrease the water and energy shortages (i.e., increase the balance indices) and environmental impacts. The supply management options include reclaimed water, seawater desalination, solar energy, and bioenergy. Reclaimed water is considered as an integrated supply option, since it is an alternative water supply with the consideration of energy intensity. Similarly, solar energy is also an integrated management option as it considers the water intensity and water pollution associated with energy supply. Seawater desalination and bioenergy are options to address the shortage of one resource without considering the other resource. Figure 5-15 shows the changes of percentages of

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water balance index, energy balance index, water pollution, and greenhouse gas emissions associated with these management options compared with the reference behavior. The reference behavior does not include any supply or demand management options. Traditional supply sources are considered in the reference behavior, such as surface water for water supply and fossil fuel for energy supply, and the environmental impacts are associated with the uses of these traditional supply sources.

As presented in Figure 5-15, the use of reclaimed water can increase the water balance index by 27.3% and reduce the water pollution by 11.8%. It can also increase the energy balance index by 0.1% and reduce the greenhouse gas emissions by 13.2%. Seawater desalination intends to increase the water supply and it does increase the water balance index in the short-term (from 2010 to 2024). However, the energy demand in water sector also increases, which results in an exponential increase in water demand for energy production due to the reinforcing feedback between water and energy. This option eventually leads to a decrease of the water balance index by 29.7% in 2080 compared with the reference behavior. The use of seawater desalination also has other unintended consequences in both water and energy systems. It decreases the energy balance index by 0.6% and causes 89.8% increase in water pollution and 14.5% increase in GHG emissions. That is because desalination consumes a large amount of energy, which is dominant by non-renewable fossil energy. The production of these fossil fuels results in the adverse environmental impacts.

Regarding to the energy supply management options, solar energy increases the energy balance index by more than 264 times and slightly decreases the water balance index (~0.02%). It also largely decreases the associated environmental impacts (42.4% for water pollution and 14781% for GHG emissions) due to replacement of using fossil fuel, while

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bioenergy causes shortages in both water and energy resources. It decreases the energy index by 140.2% and the water balance index by about 378 times. The water footprint for bioenergy is 260 times higher than solar energy (Gerbens-Leenes. 2012; Gerbens-Leenes and Hoekstra, 2012; Mekonnen and Hoekstra, 2011). The water used to produce the biomass feedstock causes non-point pollution (Clifton-Brown and Lewandowski, 2000), which increases the water pollution by 90% compared with reference behavior. The deterioration of water quality results in the increase of energy demand in water treatment and GHG emissions associated with the energy use. Overall, the use of bioenergy to address the energy shortage worsens both water and energy resources.

5.6. Chapter Summary

This chapter linked the water and energy models based on the feedback structures identified by system archetypes. The result reveals that some decisions to solve the problems of one resource result in the problems of the other resource. For example, the increase of water price is one of these, which decreases the water demand by 24.3% but leads to the increase of the energy demand by 1.5% due to the use of reclaimed water. Some management options are effective to reduce both water and energy demand, such as energy price, which reduces energy demand by 16.3% and water demand by 8%. Rebates on indoor water-efficient appliances are also effective to reduce both water and energy demands largely due to the household energy use in water heating. Some management options, including rebates on outdoor water appliances, agricultural BMPs, lawn irrigation restriction, energy conservation education, and rebates on household electronic appliances, are effective to reduce the use of one resource but do not have significant impact on the other resource.

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The result also shows that the increases in water and energy demands are primarily driven by the population growth and are also contributed by the reinforcing feedback structure between water and energy demands. As the demands increase, there are the needs to search for alternative supplies for both resources. This study finds that integrated management options can reduce the shortages of both water and energy resources and the environmental impacts, but decisions without considering each other may lead to more issues. Reclaimed water, a supply management option considering the energy resource, can increase the water balance index by 27.3% and the energy balance index by 0.14%; it can also reduce the water pollution by 11.8% and the greenhouse gas emissions by 13.2%. Seawater desalination, a water supply management option intends to increase the water supply and address the water shortage but eventually leads to an increase in the water shortage in long-term. It decreases the water balance index by 29.7% and causes 90% increase in water pollution and 14.5% increase in GHG emissions. Similarly, solar energy as an integrated energy supply option also shows an advantage in increasing both water and energy balance indices and reducing the environmental impacts.

The results are only valid within the defined system boundary under the assumptions made in the study. The causal relationships considered in this study center on the water and energy and other factors such as population and climate (i.e., precipitation, temperature) are considered exogenous to the modeled system. Therefore, the population and climate dynamics are not addressed in the study. In reality, population, climate, water, energy, food, and economy interact with each other. For example, when the water price increases dramatically (10 times simulated in this study), it will impact the population in the modeled area which will further affect agriculture and economic sectors. Such dynamics, however, are out of the scope of the study and not considered in the model developed. Although the integrated model is limited in

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that sense; it is useful to provide the insights of unintended consequences of some management options and examine the effectiveness of the management decisions from the system perspective (considering both water and energy systems). For instance, it allows the decision makers to investigate which management option is more effective to reduce the greenhouse gas emissions under the same investment, investing on energy-saving technology in water treatment plants from the water side or investing on less carbon intensive or renewable energy technology from the energy side.

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Table 5-1 Description of System Archetypes

Archetype	Description
Reinforcing Loop	One of the two fundamental structures of system archetypes. The system state keeps increasing or decreasing.
Balancing Loop	One of the two fundamental structures of system archetypes. The system state moves closely to the desired state.
Limits to Growth	The system state presents an S-shape growth.
Shifting the Burden	The system problem reoccurs over time, as the burden to solve the system problem is shifted from fundamental solution to symptomatic solution.
Eroding Goals	The system state meets the goal but the performance is lowered compared with the initial goal.
Escalation	Two entities put reinforcing efforts to achieve better performance than the other.
Success to the Successful	The entity with a better performance gains continuous preference in resource allocation and achieves better performance again.
Tragedy of Commons	The individual activity may cause an undesired outcome for the system over time.
Fixes that Fail	The system problem is solved at the initial stage but becomes worse in a long term.
Growth and Underinvestment	It is based on Limits to Growth. The growth of the system performance is limited by the investment on capacity.
Accidental Adversaries	The collaboration of two entities with a win-win goal may have the unintended consequences deteriorating both performances.
Attractiveness Principle	It is based on Limits to Growth. It indicates that reducing or removing the proper slowing actions will improve system performance effectively.

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Table 5-2 Linkages between Water and Energy Sub-models

Water Model	Integrated Model	Energy Model
Water supply	→ 1. Energy demand in surface water treatment and delivery 2. Energy demand in groundwater treatment and delivery	Energy demand in water
Wastewater discharge	→ 3. Energy demand in wastewater treatment and delivery	Energy demand in water
Water demand in energy & water availability (both quantity and quality)	← 4. Water used in fossil fuel extraction 5. Water used in power generation → 6. Impact of water availability on energy supply sources	Energy supply
Alternative water supply	→ 7. Energy demand in alternative water treatment and delivery ← 8. Impact of energy availability on the water supply sources	Energy demand in water & energy availability
Water price & water supply	→ 9. Water cost in energy production ← 10. Energy cost in water treatment	Energy price & energy supply

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Table 5-3 Sensitivities of the Model Outputs to Precipitation for Water Sub-model, Energy Sub-model, and Integrated Model

Output	Water Sub-model	Energy Sub-model	Integrated Model
Surface Water Level	1.84	NA	2.63
Groundwater Level	1.48	NA	1.75
Surface Water Quality	0.50	NA	0.64
Groundwater Quality	0.67	NA	0.67
Water Demand in Agriculture	0.60	NA	0.60
Water Demand in Industry	0.00	NA	0.00
Water Demand in Municipality	0.17	NA	0.17
Water Demand in Energy Sector	0.00	NA	0.00
Energy Storage	NA	0.00	0.00
Energy Demand in Agriculture	NA	0.00	3.00
Energy Demand in Industry	NA	0.00	0.00
Energy Demand in Municipality	NA	0.00	0.78
Energy Demand in Water Sector	NA	0.00	2.00

Table 5-4 Error Analysis of Behavior Test of Integrated Model

Variable	Average			RMSPE[1]	Inequality Statistics[2]		
	Observed	Simulated	Error		U^M	U^S	U^C
Surface Water Level (Feet)	21.60	21.73	0.60%	0.18%	0.02	0.47	0.28
Municipal Water Withdrawal (MDG)	135.01	132.65	-1.75%	1.35%	0.02	0.00	0.53
Agricultural Water Withdrawal (MGD)	78.98	82.73	4.75%	5.29%	0.04	0.21	0.40
Energy Supply (Trillion Btu/Year)	39.9	31.8	-20.30%	4.06%	0.88	0.10	0.01

1 RMSPE is the root mean-squared percent error

2 Inequality statistics shows the fraction of mean-square-error. U^M measures the bias between simulated and actual data; U^S measures the degree of unequal variation between two datasets; U^C measures the degree of divergences between simulated and actual data in point-by-point estimation.

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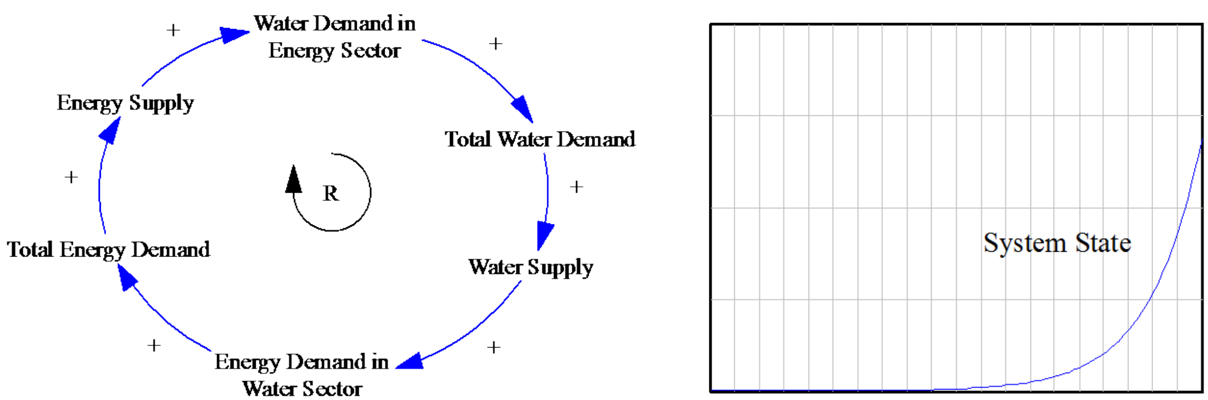
Table 5-5 Impacts of Demand Management Options of One Resource on the Other

Management Options	Percentage Change from BAU			
	Water Side		Energy Side	
	Water Demand	Water Pollution	Energy Demand	GHG Emission
Rebates on Indoor Water Appliances	-10.60	0.00	-2.40	-3.75
Rebates on Outdoor Water Appliances	-2.30	-4.46	-0.04	-0.06
Agricultural BMPs	-0.30	-0.88	0.00	0.00
Water Conservation Education	-12.60	-3.67	-0.31	-0.49
Water Loss Control	-0.70	0.00	-0.01	-0.02
Water Price (10 times increase)	-24.30	-4.71	1.53	2.38
Lawn Irrigation Restriction	-1.40	-2.72	-0.05	-0.08
Energy Price (50% increase)	-8.00	-1.55	-8.00	-25.44
Energy Conservation Education	0.00	0.00	-10.60	-16.55
Rebates on Household Electronic Appliances	0.00	0.00	-3.60	-5.62



(a) Structure (b) Generic Behavior

Figure 5-1 Reinforcing Growth of Water and Energy Demands. A positive sign represents a reinforcing causal relationship. R represents a reinforcing loop.

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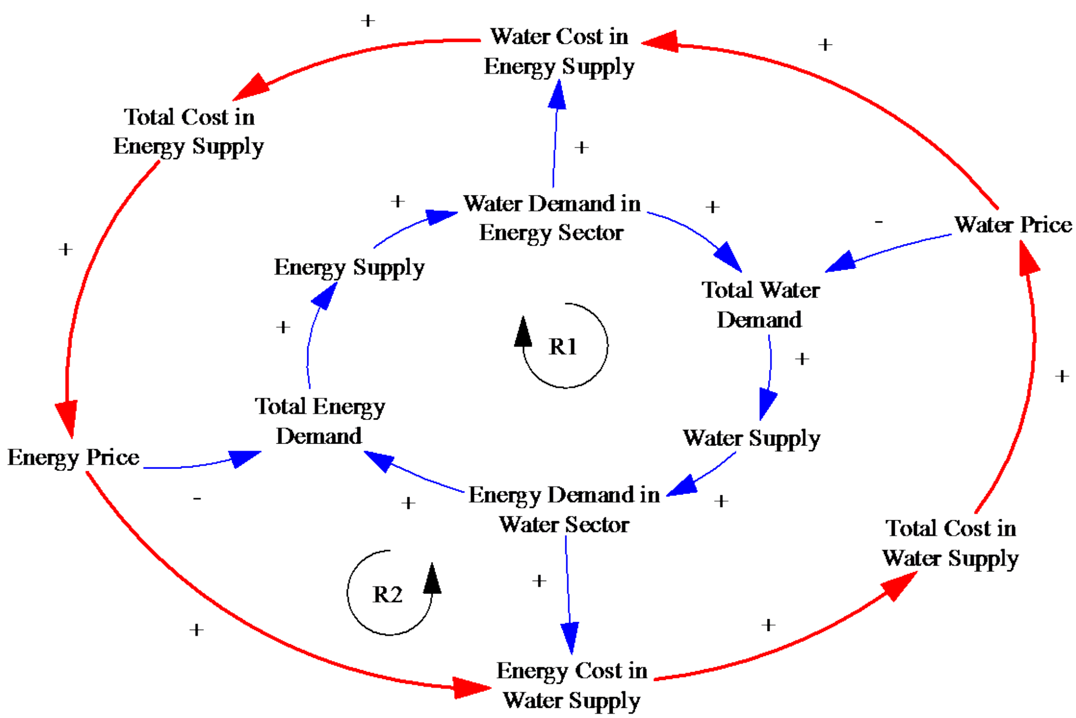

Figure 5-2 Reinforcing Growth of Price and Demands. A positive sign represents the reinforcing a causal relationship and a negative sign represents a balancing causal relationship. R1 represents the reinforcing loop of water and energy demands. R2 represents the reinforcing loop of demand and price.

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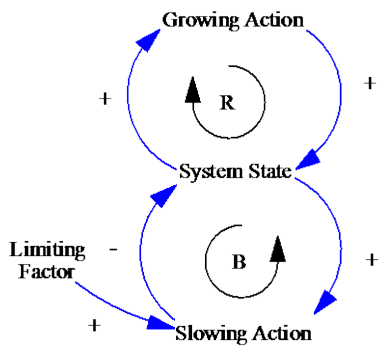
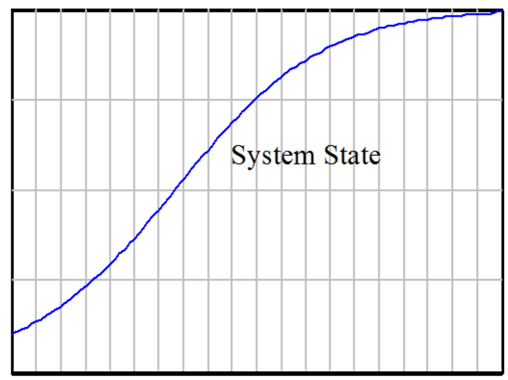
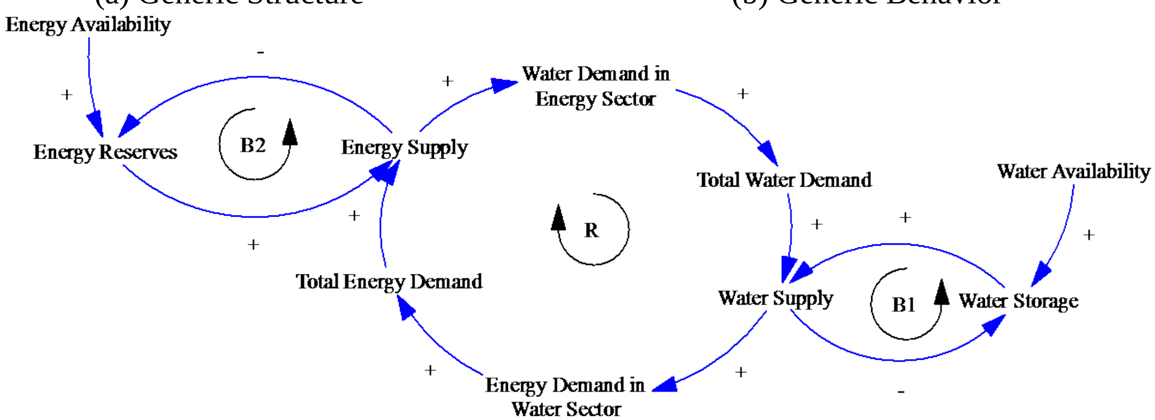


(a) Generic Structure



(b) Generic Behavior



(c) Limits to Growth of Water and Energy Supply

Figure 5-3 Limits to Growth of Water and Energy Supplies. The positive and negative signs represent the reinforcing and balancing causal relationships. R and B represent the reinforcing and balancing loops, respectively.

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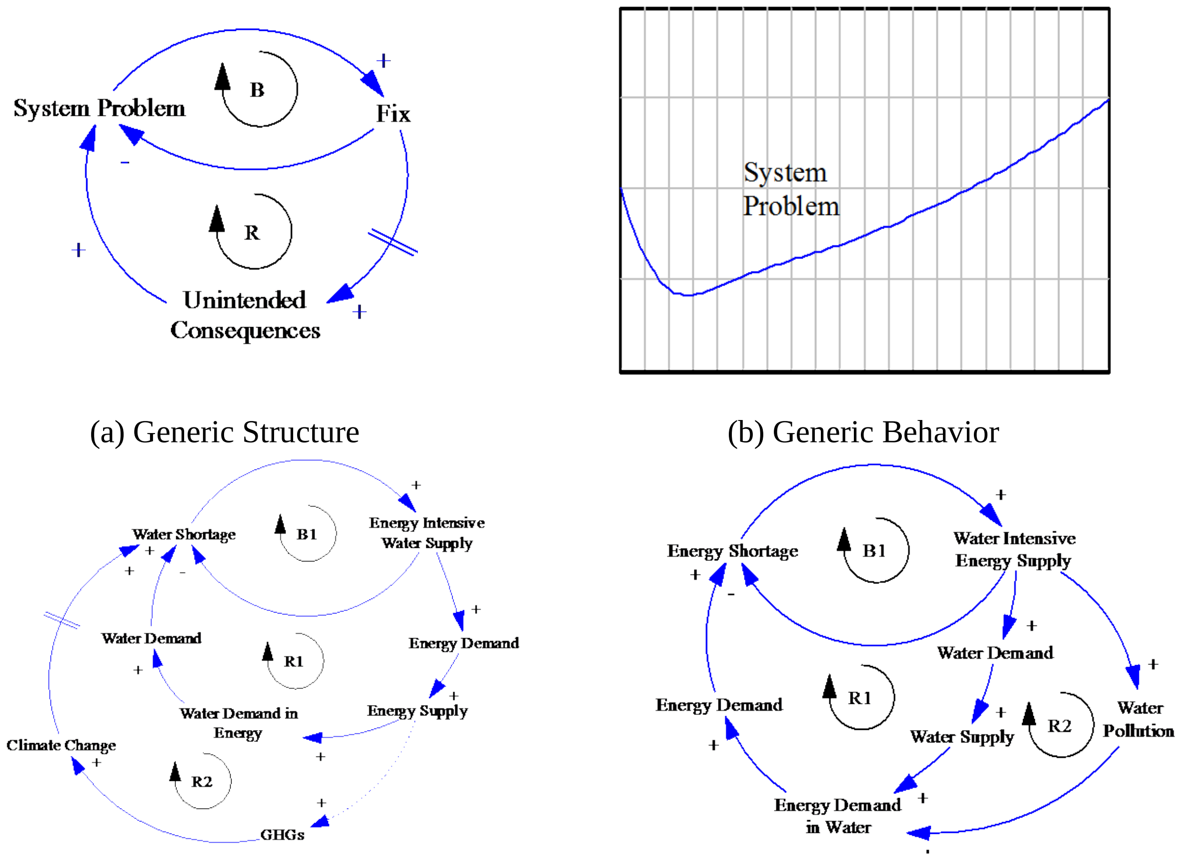

(a) Generic Structure

(b) Generic Behavior

(c) Water Supply Options with High Energy Intensity

(d) Energy Supply Options with High Water Intensity

Figure 5-4 Fixes that Fail of Supply Management Options without Considering Other. The positive and negative signs represent the reinforcing and balancing causal relationships. B and R represent the balancing and reinforcing loops, respectively. The two-line bar in the middle of the link represents time delay. The dashed arrow represents a conditional relationship.

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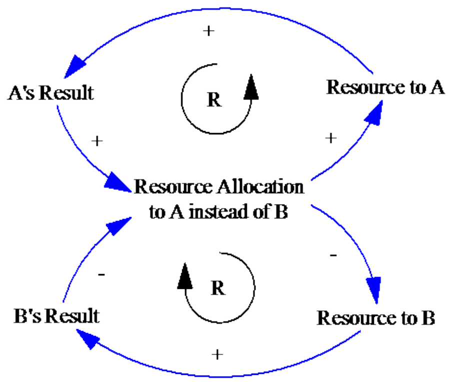
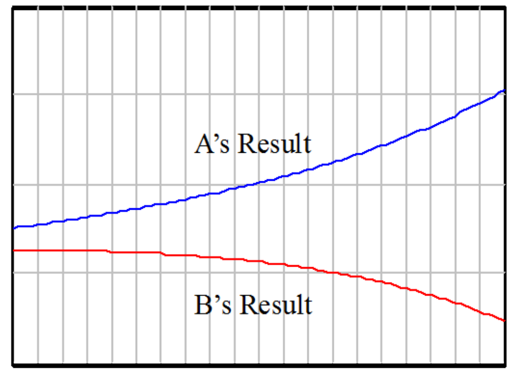
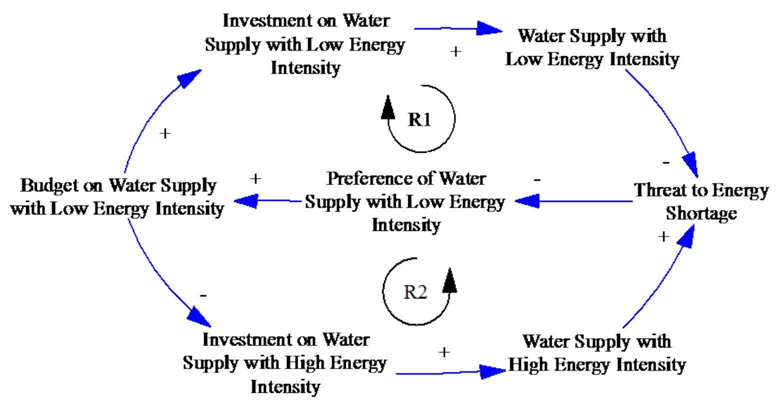


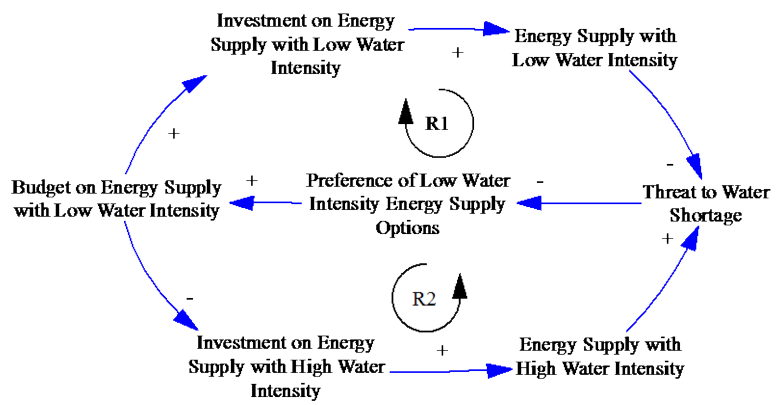
(a) Generic Structure



(b) Generic Behavior



(c) Water Supply Options with Low Energy Intensity



(d) Energy Supply Options with High Water Intensity

Figure 5-5 Success to the Successful of Supply Management Options Considering Other. The positive and negative signs represent the reinforcing and balancing causal relationships. R represents the balancing loop.

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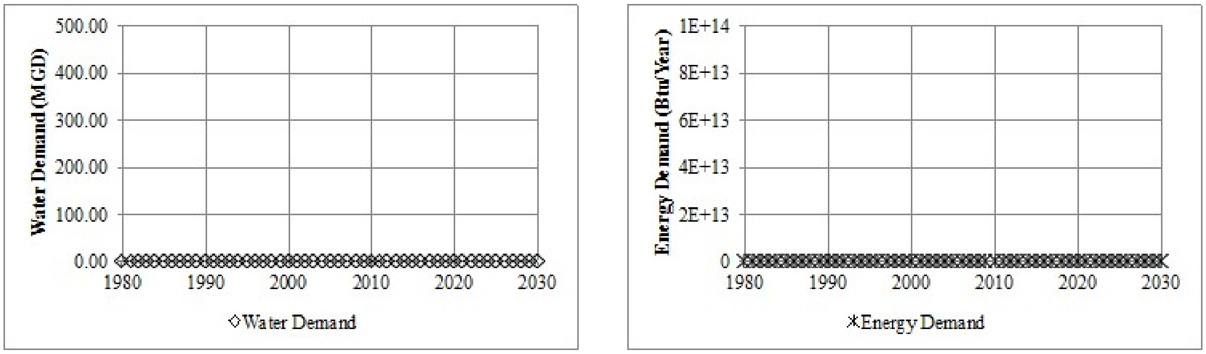
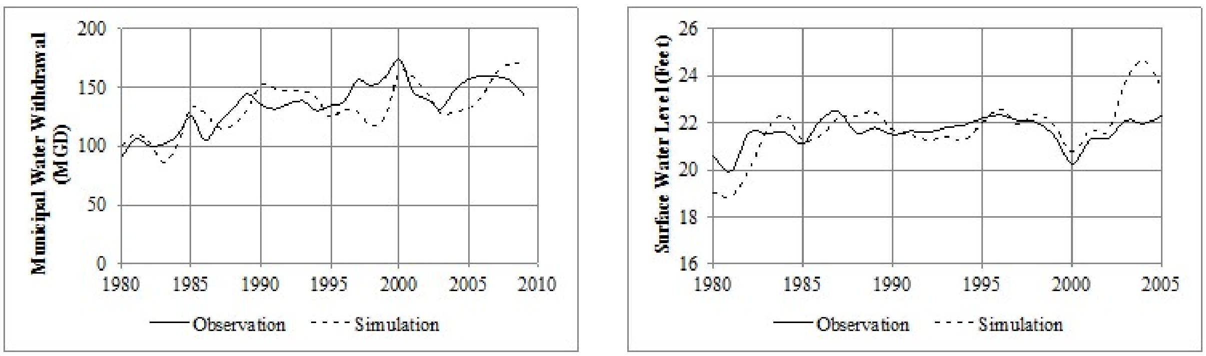
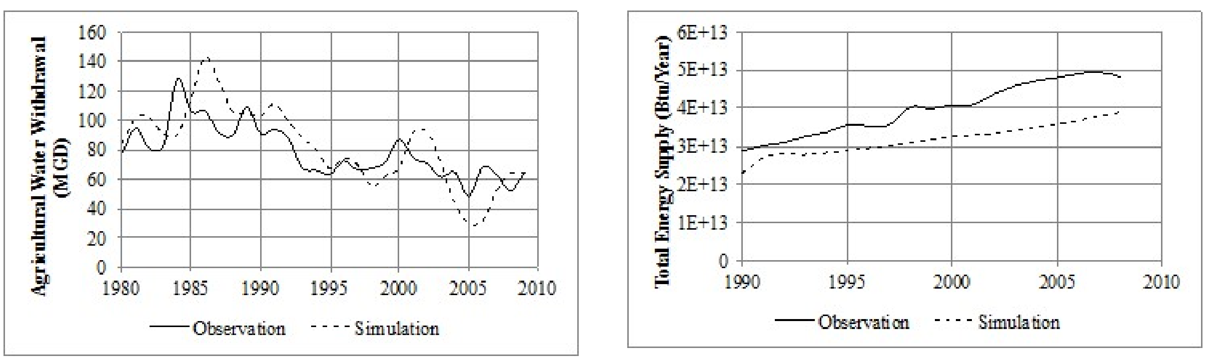


(a) Water Demand (b) Energy Demand

Figure 5-6 Extreme Condition of Zero Population for Integrated Model



(a) Surface Water Level (b) Municipal Water Withdrawal



(c) Agricultural Water Withdrawal (d) Total Energy Supply

Figure 5-7 Behavior Test of Integrated Model

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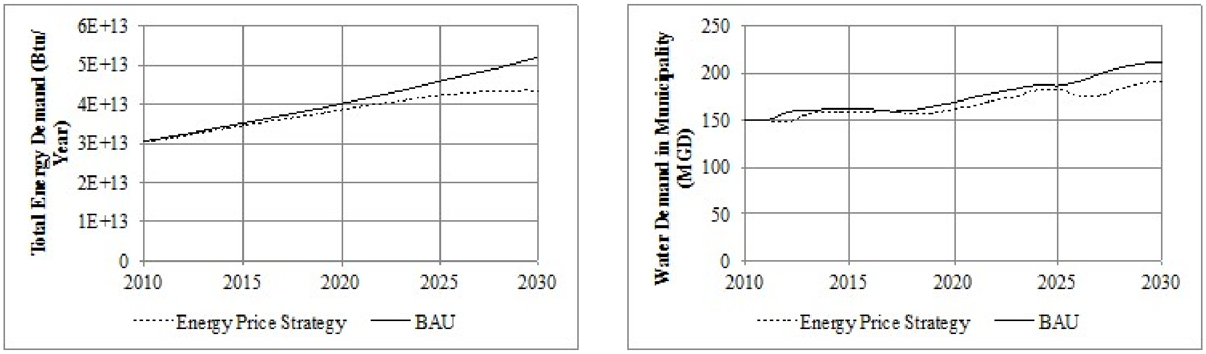
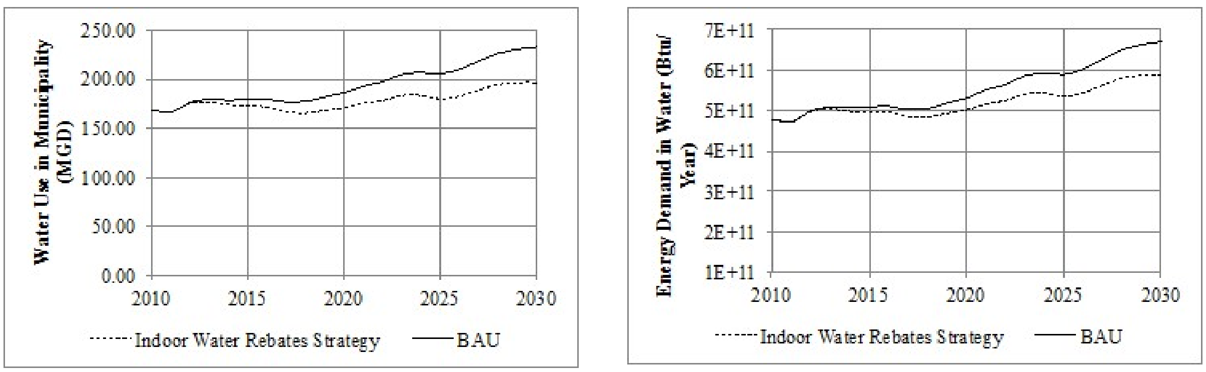
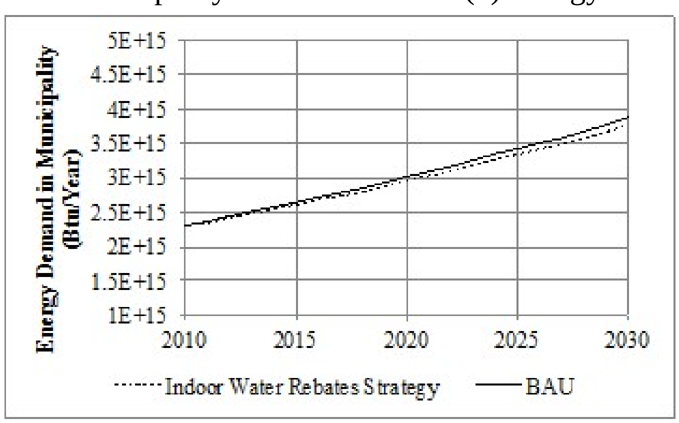


(a) Total Energy Demand (b) Water Demand in Municipality

Figure 5-8 Impact of Increasing Energy Price



(a) Water Use in Municiaplaity (b) Energy Demand in Water



(c) Energy Demand in Municipality

Figure 5-9 Impacts of Increasing Budget on Rebates on Indoor Water Appliances

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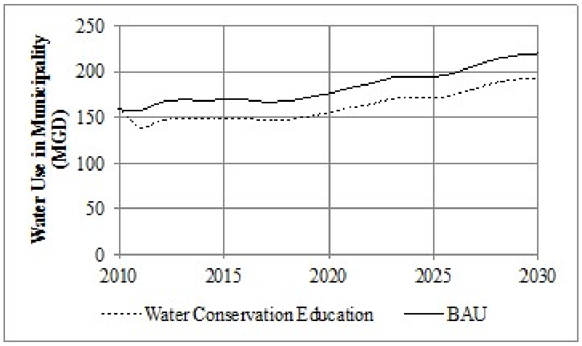
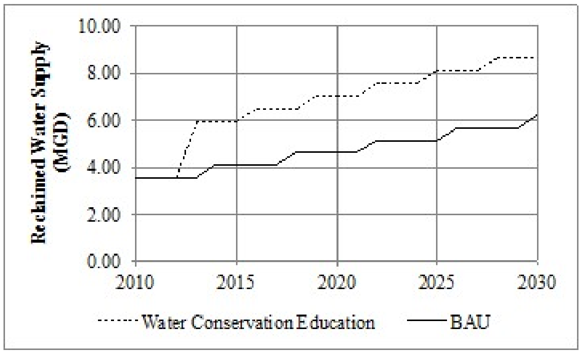
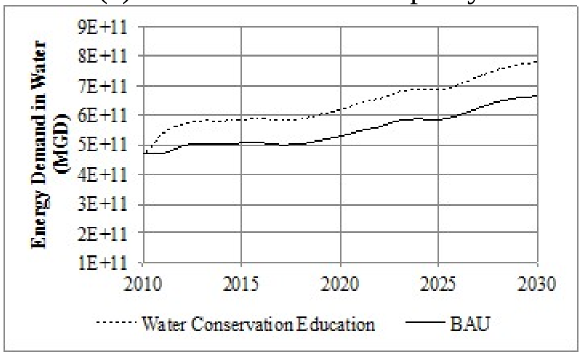


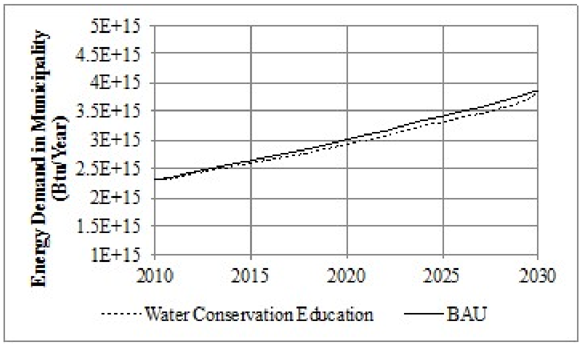
(a) Water Use in Municipality



(b) Reclaimed Water Supply



(c) Energy Demand in Water



(d) Energy Demand in Municipality

Figure 5-10 Impact of Increasing Budget on Water Conservation Education

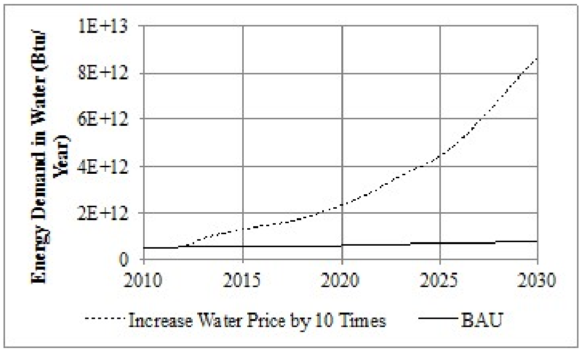


Figure 5-11 Impact of Increasing Water Price

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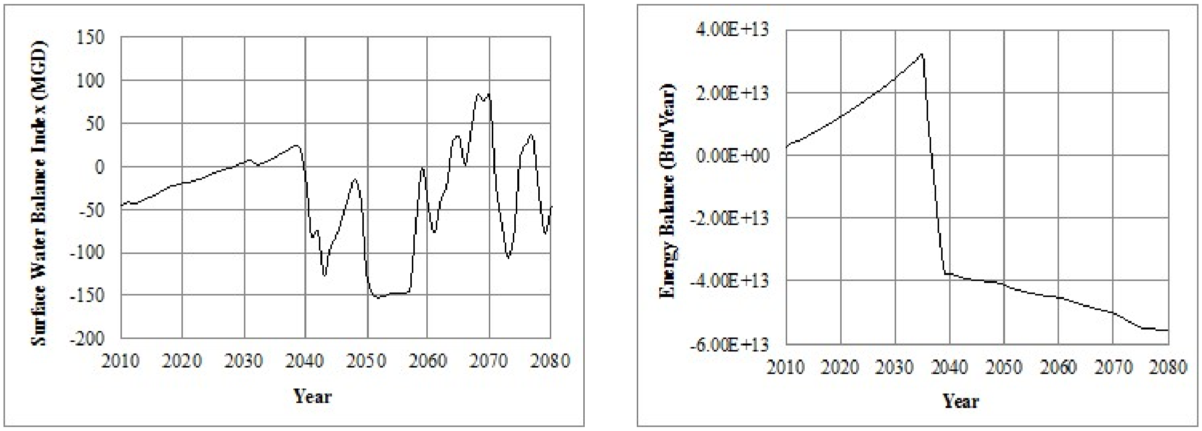
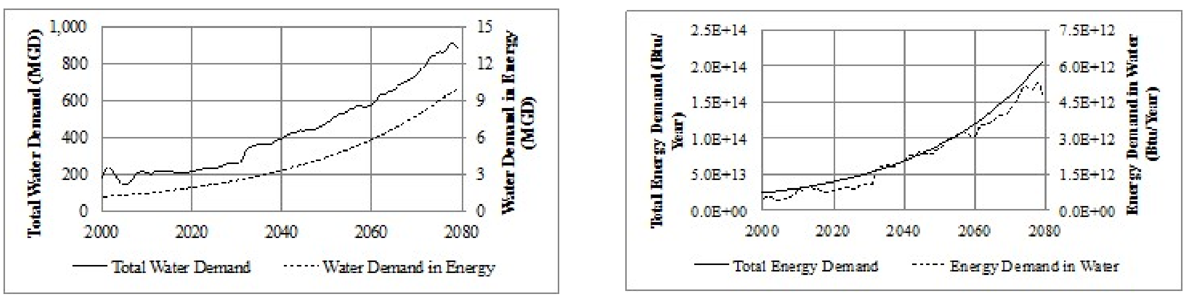


(a) Surface Water Balance Index (b) Energy Balance Index

Figure 5-12 Balance Index for Surface Water and Non-renewable Energy



(a) Total Water Demand and Water Demand in Energy

(b) Total Energy Demand and Energy Demand in Water

Figure 5-13 Behaviors of Water and Energy Demands Driven by Population

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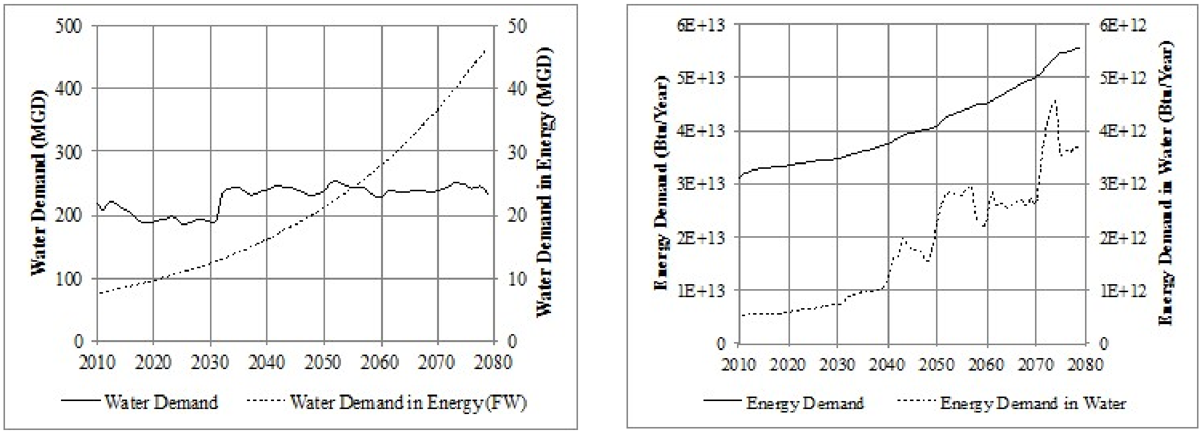

(a) Water Demand under the Reinforcing Feedback Loop of Energy Demand

(b) Energy Demand under the Reinforcing Feedback Loop of Water Demand

Figure 5-14 Reinforcing Feedback Behavior of Water and Energy Demands

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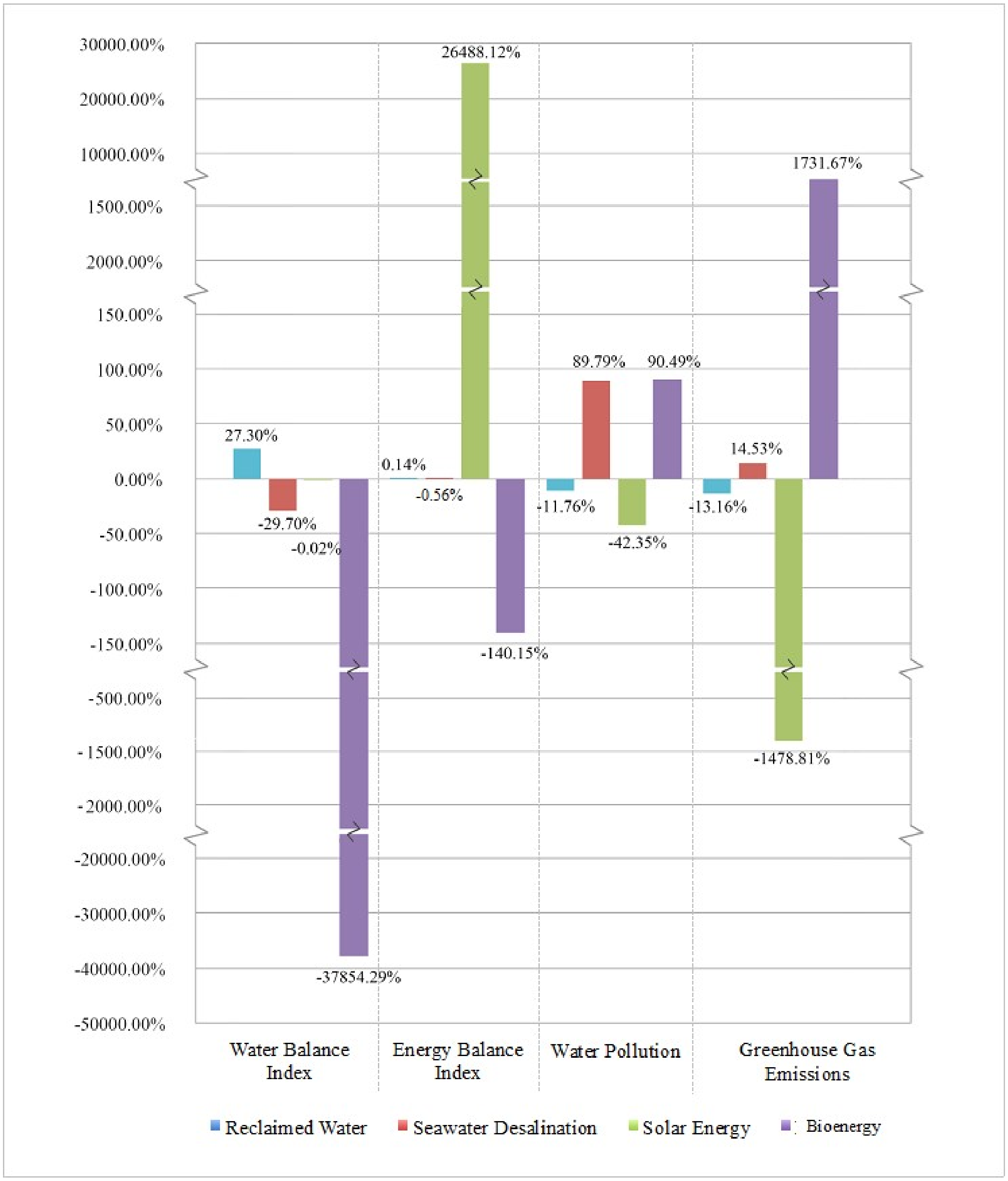

Figure 5-15 Water Balance Index, Energy Balance Index, Water Pollution, Greenhouse Gas Emission for the Supply Management Options

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CHAPTER 6.

CONCLUSIONS AND RECOMMENDATIONS

This study developed an integrated water and energy model to examine the management options for long-term regional water and energy resources management with consideration of their interactions through a system dynamics approach using Tampa Bay Region as the study site. The impacts of the management options of one resource on both systems are investigated. This study is helpful to understand the implications of water and energy interactions, and recognize the benefits of integrated water and energy management in terms of reducing resource uses and the environmental impacts while meeting the demands for both water and energy.

In order to investigate the interrelationship between water and energy systems, two sub-models (i.e., water sub-model and energy sub-model) were developed first. The water sub-model is composed of sectoral water demand (agriculture, industry, municipality, and energy sector), water supply (surface water, groundwater, reclaimed water, and water imports), and water quality and energy consumption associated with water supply. The result finds that surface water level increases by 1.32~1.39% when considering water quality and 1.10~1.30% with considering both water quality and energy consumption. There is a slight decrease in groundwater storage (0.02~0.08%) compared with the reference behavior. The result also reveals that water conservation education is the most effective option to reduce

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the freshwater withdrawals (~17.3%), followed by rebates on indoor water-efficient appliances (15.4%). Rebates on outdoor water-efficient appliances, increase in water rate, and water restriction are effective to reduce the outdoor water demand, but not the total withdrawals. Reclaimed water has no significant impacts on reducing freshwater withdrawal under current budget due to the high infrastructure cost and low public acceptance. Water loss control has the minimum effect on the reduction of freshwater withdrawals under current budget, but it has a high potential to conserve both water and energy. The implementation of minimum surface water level is effective to reduce the surface water withdrawal and maintain the water level, but it requires 26 MGD alternative water supply sources. To maintain the groundwater table to the surface at the distance of 20 feet, near 450 MGD of water is needed for groundwater recharge in 2030.

The energy sub-model consists of sectoral energy demand (agriculture, industry, municipality, and water sector), energy supply (coal, natural gas, oil, and electricity), and greenhouse gas (GHG) emissions and water pollution associated with energy supply. The result indicates that cost of fuels is the primary concern of determining the energy mix for power generation. The current electricity mix in the study area consists of 35.4% fuels from coal, 44.6% from natural gas, and 20% from oil. When considering the environmental impacts associated with energy supply, the percentage of coal reduces to 10.6%, and GHG emissions and water pollution can be reduced by 22% and 43% accordingly. The result also shows that energy price is the most effective to reduce the demand (~16.3%), followed by energy conservation education (~10.6%). Rebates on household appliances are the least effective option (~3.6%) due to consumers' low willingness to pay. Combining the supply decision incorporating environmental impacts and the demand option of energy price increase, the reductions of GHG emissions and

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water pollution can reach 37% and 55%, respectively. Solar energy has a high potential to reduce GHG emissions and water pollution, but current budget is too low. In order to increase the use of solar energy to 1%, at least half billion dollars needs to be invested in solar energy facilities.

The integrated model is developed by linking the water and energy sub-models based on the feedback structure between water and energy systems identified by the system archetypes. The result finds that some decisions to solve the problems of one resource result in the problems of the other resource. The increase of water price is one of these, which decreases the water demand by 24.3% but leads to the increase of the energy demand by 1.53% due to the use of reclaimed water. Rebates on indoor water-efficient appliances are effective to reduce both water and energy demands largely due to the household energy use in water heating. In addition, this study reveals that integrated management options can improve the uses of water and energy, but decisions without considering each other may lead to more issues. For example, reclaimed water, an integrated supply management option, can increase the water balance index by 27.3% and the energy balance index by 0.14%; it can also reduce the water pollution by 11.76% and the greenhouse gas emissions by 13.16%. Seawater desalination, a supply management option, intends to increase the water supply and address the water shortage but eventually leads to a decrease of water balance index by 29.7% in long-term. It also causes 89.79% increase in water pollution and 14.53% increase in GHG emissions. Similarly, solar energy as an integrated energy supply option shows an advantage in increasing both water and energy balance indices and reducing the environmental impacts.

This study is an initial attempt to link water and energy systems to explore integrated management options. It is limited by the data availability, assumptions for model simplification, and lack of consideration of climate change. The results are only valid within the defined system

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boundary under the assumptions made in the study. The causal relationships considered in this study center on the water and energy and other factors such as population and climate (i.e., precipitation, temperature) are considered exogenous to the modeled system. Therefore, the population and climate dynamics are not addressed in the study. Although the integrated model is limited in that sense; it is useful to provide the insights of unintended consequences of some management options and examine the effectiveness of the management decisions from the system perspective (considering both water and energy systems). The recommendations for future study include (a) employing a more accurate projection or representation of precipitation, (b) testing the energy model with local data, (c) considering water and energy allocation between different users under shortages, (d) examining the environmental impacts associated with bay water withdrawal for power generation, (e) investigating the water and energy use under climate change, and (f) involving stakeholders early in model development and continuous participation in policy analysis.

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APPENDICES

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Appendix A: Review of System Dynamics Models in Water Resources Management

Table A-1 Example Applications of System Dynamics in Water Resources Management

	Author and Year	Purpose	Supply			Demand				Quality	Validation			
			S 1	G 2	O 3	M 4	I 5	A 6	E 7		DS 8	SB 9	BV 10	BP 11
1	Anderson et al., 1975	Analyze the effects of different investment on water-based recreation on water quantity and quality of city located on a waterway	*			*	*			*				
2	Camara et al., 1986	Analyze the decisions to meet the increasing water demand	*	*		*	*	*						
3	Zhang and Liu, 1991	Assess the future water use under current economic development	*		*	*	*	*	*	*				
4	Ruth and Pieper, 1994	Develop a dynamic spatial model to simulate the effects of gradual sea level rise in coastal area	*			*	*	*				*		
5	Yu and Zeng, 1996	Analyze the impact of water demand on economic development	*	*		*		*						
6	Shawwash and Russell, 1996	Test the effects of different water supply options	*		*	*	*	*	*					
7	Ford, 1996	Analyze different polices and test the usefulness of the model	*	*		*	*							
8	Grigg, 1997	Analyze the impact of different decision on urban water supply systems	*			*	*	*						
9	Gao and Liu, 1997	Analyze the water balance under different scenarios	*	*	*	*	*					*		
10	Vezjak et al., 1998	Examine the effects of eutrophication on plankton seasonal dynamics	*			*	*	*	*	*		*	*	
11	Costanza and Ruth, 1998	Introduce the importance of SD for consensus building				*	*	*						

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Table A-1 (Continued)

	Author and Year	Purpose	Supply			Demand				Quality	Validation			
			S[1]	G 2	O 3	M 4	I 5	A 6	E 7		DS 8	SB 9	BV 10	BP 11
12	Simonovic and Fahmy, 1999	Analyze the effects of different water policies on water use and water quality	*	*	*	*	*	*	*	*				
13	Abbott and Stanley, 1999	Simulate recharge and flow interaction in a fractured bedrock aquifer		*		*	*	*						
14	Bender and Simonovic, 2000	Involve stakeholders for a hydroelectric development project	*			*	*	*						
15	Guo et al., 2001	Analyze the impacts of different economic strategy on water pollution	*			*				*		*		
16	Simonovic, 2002	Analyze the relationship between water use and socio-economic factors	*	*	*	*	*	*	*	*				
17	Sun et al., 2002	Analyze the impact of water use for economic development on water quality	*			*	*	*		*		*	*	
18	Li and Simonovic, 2002	Assess the main contribution of snowmelt to flooding				*	*	*				*	*	
19	Saysel et al., 2002	Analyze policies to help stakeholders understand the relationships between water, land, agricultural pollution, agricultural production and population	*	*		*	*	*	*	*		*		*
20	Xu et al., 2002	Analyze the water shortage (demand/supply) for each sub-water basins	*	*	*	*	*	*	*			*		
21	Stave, 2003	Analyze when demand exceeds supply under different options and increase the public understanding of water conservation	*			*								*
22	Tangirala et al., 2003	Assess total maximum daily load allocations for nutrient impaired stream.	*			*	*	*		*			*	

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Table A-1 (Continued)

	Author and Year	Purpose	Supply			Demand				Quality	Validation			
			S[1]	G[2]	O[3]	M[4]	I[5]	A[6]	E[7]		DS[8]	SB[9]	BV[10]	BP[11]
23	Simonovic and Rajasekaram, 2004	Analyze the relationship between water quantity, quality, and socio-economic factors	*	*	*	*	*	*		*				
24	Huerta, 2004	Assess the water allocation under conflict situation	*	*		*		*						
25	Fernandez and Selma, 2004	Analyze the policies to reduce water deficit	*	*	*	*		*		*	*	*	*	*
26	Tidwell et al., 2004	Analyze the effects of different water conservation polices	*	*	*	*	*	*	*					*
27	Ahmad and Simonovic, 2004	Analyze the economic damage of flooding				*	*	*						
28	Sehlke and Jacobson, 2005	Analyze the impacts of different decisions on water level	*	*		*		*						
29	Karamouz et al., 2005	Assess the water allocation with minimum water demand and water pollution	*			*	*	*		*				
30	Elshorbagy et al., 2005	Assess the ability of reconstructed watershed to provide common watershed functions	*			*	*	*					*	*
31	Ho et al., 2005	Assess the consequences of changes to water supply capacity, water treatment, and groundwater	*	*		*		*						
32	Chen et al., 2006	Analyze the effects of different decisions on supply and demand	*			*	*	*						
33	Leal Neto et al., 2006	Identify the investment priorities and policy analyses for pollution control	*			*	*	*		*				
34	Elshorbagy et al., 2007	Analyze the hydrological performance of a reconstructed watersheds for mining industry				*	*	*					*	*

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Table A-1 (Continued)

	Author and Year	Purpose	Supply			Demand				Quality	Validation			
			S[1]	G[2]	O[3]	M[4]	I[5]	A[6]	E[7]		DS[8]	SB[9]	BV[10]	BP[11]
35	Elmahdi et al., 2007	Determine the maximum water saving under different water prices with the constrains of supply capacity	*	*	*	*								
36	Ahmad et al., 2007	Investigate alternative options to minimize between the average natural flows and the average current flows	*	*		*								
37	Langsdale et al., 2007	Introduce climate change into integrated water resources planning and management	*	*	*	*	*	*						
38	Leaver and Unsworth, 2007	Represent the heat and mass transport in a geothermal spring	*	*	*	*		*		*			*	*
39	Bianchia and Montemaggiore, 2008	Integrate the balanced scorecard approach with system dynamics to improve the planning for a municipal water company				*	*	*						
40	Yang et al., 2008	Formulate a strategy to seek the balance between the financial cost and water shortage mitigation	*		*	*						*		
41	Tong and Dong, 2008	Analyze the effects of different water saving options	*	*		*	*	*	*				*	
42	Zhang et al., 2008	Analyze impacts of planning option on water quality	*			*				*		*	*	
43	Chung et al., 2008	Analyze the water storage under different options	*	*	*	*								
44	Feng et al., 2008	Evaluate the carrying capacity	*	*		*				*		*		*
45	Khan et al., 2009	Represent the hydrological process	*			*							*	
46	Langsdale et al., 2009	Incorporate stakeholder participation based on Langsdale's (2007) study	*	*		*	*	*						

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Table A-1 (Continued)

	Author and Year	Purpose	Supply			Demand				Quality	Validation			
			S[1]	G 2	O 3	M 4	I 5	A 6	E 7		DS 8	SB 9	BV 10	BP 11
47	Williams et al., 2009	Teach undergraduate students hydrologic literacy	*	*		*	*	*						
48	Prodanovic and Simonovic, 2009	Evaluate the vulnerability of water quantity to changing climatic and socio-economic conditions	*			*	*	*				*		
49	Madani and Mariño, 2009	Analyze different policies to reduce water demand and increase supply/demand ratio	*	*		*	*	*	*					*
50	Bagheri et al., 2010	Analyze the effect of water management polices to meet increasing demand after an earthquake	*	*		*	*	*			*	*	*	*
51	Adeniran, 2010	Assess the financial operation sustainability for a water plant	*			*	*	*	*					*
52	Gastélum et al., 2010	Analyze the economic benefits of short- and long-term water transfer options among the irrigated districts	*	*		*	*	*						
53	Bassi et al., 2010	Estimate the investment needed to sustainably supply needed water in global scale	*	*	*	*	*	*						
54	Bier, 2010	Educate college students to understand the structure and potential benefits of thermal water quality trading	*			*				*				
55	Ahmad and Prashar, 2010	Analyze the effect of water management options to reduce water demand to meet the ecological requirements	*	*		*	*	*	*			*	*	*
56	Zhang et al., 2010	Integrate SD with Multi Objective Programme to determine the optimal economic structure with the consideration of water quality	*			*	*	*		*			*	
57	Venkatesan et al., 2011	Evaluate the impacts of urban growth on salinity (TDS) discharge to the Colorado River	*		*	*	*	*		*				*

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Table A-1 (Continued)

	Author and Year	Purpose	Supply			Demand				Quality	Validation			
			S[1]	G[2]	O[3]	M[4]	I[5]	A[6]	E[7]		DS[8]	SB[9]	BV[10]	BP[11]
58	Davies and Simonovic, 2011	Analyze the effect of water management options to reduce water scarcity	*		*	*	*	*	*	*				
59	Qaiser et al., 2011	Evaluate outdoor water use with return flow credits under different water conservation policies	*		*	*	*	*	*		*	*	*	*
60	Qi and Chang, 2011	Forecast water demand under economic recession	*	*		*						*	*	
61	Rehan et al., 2011	Evaluate the financial sustainability for water and wastewater networks	*	*		*	*	*						
62	Shrestha et al., 2011	Compare the cost and carbon footprint between water transfer and desalination as two potential water supply options	*		*	*	*	*						
63	Wang et al., 2011	Analyze the effectiveness of water management policies to meet socio-economic and ecological requirements	*	*	*	*		*					*	
64	Sušnik et al., 2012	Assess water scarcity and determine the most sensitive variable to impact on the storage of aquifer	*	*		*		*				*		
65	Zarghami and Akbariyeh, 2012	Analyze the effect of water management options to reduce water shortage	*	*	*	*	*	*	*		*	*	*	*

[1] S represents surface water.
[2] G represents groundwater.
[3] O represents other water supply sources, including reclaimed water, desalination, water transfer, and rainwater.
[4] M represents municipal water use.
[5] I represents industrial water use.
[6] A represents agricultural water use.
[7] E represents water use in energy sector.

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Table A-1 (Continued)

[8] DS represents direct structure test.
[9] SB represents structure-oriented behavior test.
[10] BV represents behavior value test.
[11] BP represents behavior pattern test.

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Appendix B: Review of System Dynamics Models in Energy Resources Management

Table B-1 Example Applications of System Dynamics in Energy Resources Management

	Author and Year	Study Area	Purpose	Supply					EI[6]	BV[7]
				O[1]	NG[2]	C[3]	E[4]	R[5]		
1	Powell, 1990	Global	To discuss the major paradigms in world oil modeling	*	*					
2	Choucri, 1981	Global	To analyze the interaction between world oil supply and demand based on the economic and political influences	*	*					
3	Geraghty and Lyneis, 1983	Generic	To analyze the responses of external entities (consumers, regulators, and investors) to electric utility actions			*				
4	Coyle, 1985	Theoretical Application	To address the discrete events and theoretically apply to model coal mining industry			*				
5	Fan et al., 2007	Towns or Villages in China	To investigate the impact of the investment on state-owned mines and geological locations			*				*
6	Ford et al., 1989	Bonneville	To analyze the effects of conservation policies on utility performances (utility financial incentives, performance standards)				*			*
7	Smith et al., 1994	Medellin Metropolitan, Colombia	To investigate the relationships between industrial consumption (production lines and boilers) and economic development (investment and tariffs)				*			*

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Table B-1 (Continued)

	Author and Year	Study Area	Purpose	Supply					EI[6]	BV[7]
				O[1]	NG[2]	C[3]	E[4]	R[5]		
8	Bunn et al., 1992, 1993, 1994, 1995	U.K.	To analyze the new policy implications for the regulation of electric power industry.				*			*
9	Lyneis et al,, 1994	U.S.	To analyze the impacts of different pricing strategies on electricity market				*			
10	dos Santos, 2009	Brazil	To analyze the interactions between government, sugarcane industry, oil industry, car owners, and cars fleet by three exogenous variables (international sugar price, international petroleum and car demand)					*	*	*
11	Zhen, 1992	A Village in North China	To predict the energy supply and demand in rural villages					*	*	*
12	Naill, 1972, 1976	U.S.	To provide the basis for the evaluation of energy policy	*	*	*	*	*		
13	Fiddman, 1997, 1998	U.S.	To examine the relationship between environment, politics, economy, and society	*	*	*	*	*	*	
14	Osgood, 2003	Generic	To examine the use of renewable energy regarding to the policy	*	*	*	*	*		
15	Ochoa, 2007	Swiss	To examine the electricity market regarding to resource adequacy				*			*
16	Bassi, 2008	U.S.	To understand the energy issues					*	*	
17	Ochoa and Ackere, 2009	Swiss	To examine the electricity market regarding to resource adequacy				*			*
18	Bunn and Larson, 1992, 1994	England and Wales	To analyze the investment cycle in electricity generating capacity				*			*
19	Bunn et al., 1993	U.K.	To examine the risk of electricity market				*			*

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Table B-1 (Continued)

	Author and Year	Study Area	Purpose	Supply					EI[6]	BV[7]
				O[1]	NG[2]	C[3]	E[4]	R[5]		
20	Ford, 1983	Generic	To investigate the energy capacity expansion				*			
21	Dyner and Bunn, 1997	Columbia	To evaluate different political or regulatory incentives in Columbian electricity market				*			*
22	Ford, 1999	Western U.S.	To evaluate the cyclical investment in electricity generation units				*			
23	Larsen and Bunn, 1999	Generic	To examine the challenges of monopolistic to a competitive market				*			
24	Gary and Larsen, 2000	Generic	To compare SD models with equilibrium models in terms of reaching supply-demand equilibrium				*			
25	Dyner et al., 2001	Generic	To analyze different regulatory requirement for a stable market				*			
26	Ford, 2001	California	To examine the investment behavior in power plant construction				*			*
27	Qudrat-Ullah and Davidsen, 2001	Pakistan	To analyze the impact of policies on energy market				*			*
28	Arango et al., 2002	Colombia	To examine different investments in new generation units				*			*
29	Vogstad et al., 2004	The Nordic Countries	To investigate the short term impacts of energy policy in the Nordic electricity market				*		*	
30	Kadoya et al., 2005	New Jersey and New England	To evaluate the cause of cyclical investment behavior				*			*
31	Qudrat-Ullah, 2005	Pakistan	To examine the relationship between electricity supply, resources, and pollution				*		*	*
32	Olsina et al., 2006	Generic	To describe a mathematical background of cyclical investment mechanisms				*			

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Table B-1 (Continued)

	Author and Year	Study Area	Purpose	Supply					EI[6]	BV[7]
				O[1]	NG[2]	C[3]	E[4]	R[5]		
33	Arango, 2007	Colombia	To analyze the investment in power generation capacities in Colombia				*			*
34	Dimitrovski et al., 2007	Western Electric Coordinating Council	To investigate the best transmission grids performance under different regulations				*			
35	Dyner et al., 2007	Colombia	To examine the Columbian electricity market to identify the reliability charge mechanism				*			
36	Assili et al., 2008	Generic	To evaluate different capacity payment mechanisms				*			
37	He et al., 2008	Generic	To examine different regulatory instruments to avoid cyclical investment behavior				*			
38	Sanchez et al., 2008	Generic	To investigate the long-term investment associated with electricity use and capacity				*			
39	Acevedo and Aramburo, 2008	NA	To examine the relationship between investment and price				*			
40	Jager et al., 2009	Germany	To analyze the impact of policies (price, investment) on electricity market				*			*
41	Pereira and Saraiva, 2009	Generic	To provide the decision makers the maximum profits for infrastructure expansion				*			
42	Jalal and Bodger, 2010	New Zealand	To discover the cyclical investment behavior for New Zealand's electricity market				*			*
43	Tan et al., 2010	Generic	To analyze the investment alternatives as wind turbines				*			

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Table B-1 (Continued)

	Author and Year	Study Area	Purpose	Supply					EI[6]	BV[7]
				O[1]	NG[2]	C[3]	E[4]	R[5]		
44	Hasani and Hosseini, 2010	Generic	To investigate the mechanisms to ensure adequate generation capacity				*			
45	Bunn et al., 1997	U.K.	To analyze investment cycles in electricity generating capacity		*		*			*
46	Garcia-Alvarez et al., 2005	Spain	To investigate the bidding behavior of electric market				*			*
47	Vogstad, 2005	Northern Europe	To analyze the impact of energy policies (price, investment, technologies)				*			*
48	Ford, 2006	Western Electric Coordinating Council	To analyze the impact of carbon market on electricity system				*		*	
49	Ford et al., 2007	Northwestern U.S.	To evaluate the carbon emission with wind feed-in					*	*	*
50	Ford, 2008	Western Electric Coordinating Council	To examine the reduction in carbon dioxide emissions with electricity market				*		*	
51	Turk and Weijnen, 2002	Generic	To investigate the causal relationship and criteria of the reliability of the infrastructural system				*			
52	Botterud, 2003	Generic	To determine the uncertainties of different investment options				*			
53	Dimitrovski et al., 2004	Western U.S. and West Africa	To evaluate the relationship between investment and growth in electric power system				*			

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Table B-1 (Continued)

	Author and Year	Study Area	Purpose	Supply					EI[6]	BV[7]
				O[1]	NG[2]	C[3]	E[4]	R[5]		
54	Olsina, 2005	Generic	To investigate the energy security				*			
55	Franco et al., 2000, 2001	Colombia	To developed a training model for energy trading in Colombia				*			*

[1] O represents oil.
[2] NG represents natural gas.
[3] C represents coal.
[4] E represents electricity.
[5] R represents renewable energy.
[6] EI represents environmental impacts.
[7] BV represents behavior test of model validation.

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Appendix C: Variable Quantification

C.1. Population

Population= $\int$ (Population×Monthly Population Growth Rate)dt +Initial Population

Unit: People

$$\text{Initial Population}=\begin{cases}646939\text{, Hillsbrough County}\\ 728531\text{, Pinellas County}\\ 193661\text{, Pasco County}\end{cases}$$

Unit: People

$$\text{Monthly Population Growth Projection}=\begin{cases}\frac{0.028}{12}\text{,year}\leq 1990\\ \frac{0.018}{12}\text{,year}\leq 2000\\ \frac{0.021}{12}\text{,year}\leq 2010\\ \frac{0.02}{12}\text{,year}>2010\end{cases}$$

Unit: Fraction/Month

People per Household=4
Unit: People/Household

Projected Percentage of Industrial Employees=0.045
Unit: Industrial Employees/Total Employees

Ratio of Work Force=0.7
Unit: People Available to Work/Total Population

Unemployment Rate=0.1
Unit: Total Employees/Total Population

C.2. Water Demand

Indoor Water Demand=Indoor Water Demand Per Capita×Population
Unit: Gallon/Month

$$\text{Indoor Water Demand per Capita}=\frac{\text{Daily Indoor Water Demand per Capita}}{\text{Indoor Water Use Efficiency}}\times 30\times\left(1\text{-Reduction due to Water Price}\right)$$

Unit: Gallon/Month

Daily Indoor Water Demand per Capita=15
Unit: Gallon/Person-Day

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$$\text{Indoor Water Efficiency}=\frac{\text{Household Indoor Water Efficient Appliances}}{\text{Maximum Indoor Water Efficient Appliances}\times 0.95}$$

Unit: Fraction

Indoor Water Appliances Aging Rate = 2E-5
Unit: Fraction/Month

Maximum Indoor Water Efficient Appliances =

$$\text{Indoor Water Appliances per Household}\times\frac{\text{Initial Population}}{\text{People per Household}}$$

$$+\text{DELAY1}\left(\frac{\text{Population}-\text{Initial Population}}{\text{People per Household}}\times\text{Indoor Water Appliances per Household, 36}\right)\times 0.2$$

Unit: Number

Aged Indoor Water Appliances=Household Indoor Water Efficient Appliances
×Indoor Water Appliances Aging Rate
Unit: Number/Month

New Indoor Water Efficient Appliances=

$$\text{DELAY1I}\left(\frac{\text{Expenses on Indoor Water Appliances Rebates}}{\text{Budget on Every Household Indoor}}, 24, 0\right)$$

Number/Month

Household Indoor Water Efficient Appliances=

$$\int(\text{New Indoor Water Efficient Appliances}-\text{Aged Indoor Water Appliances})dt$$
$$+\text{Initial Indoor Water Efficient Appliances}$$

Unit: Number

$$\text{Initial Indoor Water Efficient Appliances}=\begin{cases}\text{452858, Hillsborough County}\\ \text{509972, Pinellas County}\\ \text{96831, Pasco County}\end{cases}$$

Unit: Number

Indoor Water Appliances per Household=4
Unit: Number/Month

Budget on Indoor Water Appliances per Household =150
Unit: Dollar/Number

Expenses on Indoor Water Appliances Rebates=

$$\begin{cases}\min\begin{pmatrix}\text{Potential Budget on Indoor Water Appliances Rebates,}\\ \text{Planned Budget on Indoor Water Appliances Rebates}\end{pmatrix}, 1980\le\text{year}\le 2010\\ \min\begin{pmatrix}\text{Potential Budget on Indoor Water Appliances Rebates,}\\ \text{Planned Budget on Indoor Water Appliances Rebates}\end{pmatrix}, \text{year}>2010\\ \quad+\text{Additional Budget on Indoor Water Appliances Rebates}\end{cases}$$

Unit: Dollar/Month

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Potential Budget on Indoor Water Appliances Rebates =500000/12
Unit: Dollar/Month

Outdoor Water Demand=Outdoor Water Demand per Capita×Population
Unit: Gallon/Month

New Indoor Water Efficient Appliances=

$$\text{DELAY1I}\left(\frac{\text{Expenses on Indoor Water Appliances Rebates}}{\text{Budget on Every Household Indoor}}, 24, 0\right)$$

Number/Month

Outdoor Water Demand per Capita=

$$\frac{\text{Net Water Requirement for Lawn} \times \text{Lawn per Person} \times \text{Turf Coverage per Unit}}{\text{Outdoor Water Efficiency}} \times (1 - \text{Reduction due to Water Price}) \times (1 - \text{Reduction due to Restrictions})$$

Unit: Gallon/Person-Month

$$\text{Reduction due to Irrigation Restriction} = \begin{cases} 0, & \text{year} < 2002 \\ \text{Irrigation Restriction Lookup Function}, & \text{year} \geq 2002 \end{cases}$$

Unit: Fraction/Month

Irrigation Restriction Lookup Function=
WITH LOOKUP (Maximum Weekly Irrigation Times,
([(0,0)-1000,40)],(0,1),(1,0.5), (2,0.3),(3,0),(10,0)))
Unit: Fraction

$$\text{Net Water Requirement for Lawn} = \begin{cases} 0, & \text{Net Precipiation} \geq \text{Crop ET} \\ \text{Crop ET} - \text{Net Precipiation}, & \text{Net Precipiation} < \text{Crop ET} \end{cases}$$

Unit: Inch/Crop

Turf ET Coefficient=1.05
Unit: Dimensionless

Agricultural Crop ET=1.35
Unit: Dimensionless

Household Outdoor Water Efficient Appliances=

$$\int (\text{New Outdoor Water Efficient Appliances} - \text{Aged Outdoor Water Appliances})\,dt + \text{Initial Outdoor Water Efficient Appliances}$$

Unit: Number

Effective Precipitation =Precipitation Rate×Effective Precipitation Ratio
Unit: Inch/Month

Effective Precipitation Ratio =0.7
Unit: Fraction

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Outdoor Water Appliances Aging Rate=1E-5
Unit: Fraction/Month

$$\text{Initial Outdoor Water Efficient Appliances}=\begin{cases}32347, \text{Hillsborough County}\\ 36427, \text{Pinellas County}\\ 5810, \text{Pasco County}\end{cases}$$

Unit: Number

Aged Outdoor Water Appliances=Household Outdoor Water Efficient Appliances ×Outdoor Water Appliances Aging Rate
Unit: Number/Month

New Outdoor Water Efficient Appliances=

$$\text{DELAY1I}\left(\frac{\text{Expenses on Outdoor Water Appliances Rebates}}{\text{Budget on Outdoor Appliances per Household}}, 18, 0\right)$$

Unit: Number/Month

Expenses on Outdoor Water Appliances Rebates=

$$\begin{cases}\min\left(\begin{matrix}\text{Potential Budget on Outdoor Water Appliances Rebates,}\\ \text{Planned Budget on Outdoor Water Appliances Rebates}\end{matrix}\right), 1980\leq\text{year}\leq 2010\\ \min\left(\begin{matrix}\text{Potential Budget on Outdoor Water Appliances Rebates,}\\ \text{Planned Budget on Outdoor Water Appliances Rebates}\end{matrix}\right), \text{year}>2010\\ \quad +\text{Additional Budget on Outdoor Water Appliances Rebates}\end{cases}$$

Unit: Dollar/Month

New Outdoor Water Efficient Appliances=

$$\text{DELAY1I}\left(\frac{\text{Expenses on Outdoor Water Appliances Rebates}}{\text{Budget on Outdoor Appliances per Household}}, 18, 0\right)$$

Unit: Number/Month

Budget on Outdoor Appliances per Household=200
Unit: Dollar/Number

Maximum Outdoor Water Efficient Appliances =

$$\text{Outdoor Water Appliances per Household} \times \frac{\text{Initial Population}}{\text{People per Household}}$$

$$+\text{DELAY1}\left(\frac{\text{Population} - \text{Initial Population}}{\text{People per Household}} \times \text{Outdoor Water Appliances per Household}, 36\right)\times 0.3$$

Unit: Number

Potential Budget on Outdoor Water Appliances Rebates =500000/12
Unit: Dollar/Month

$$\text{Water Demand in Agriculture}=\frac{\text{Net Crop Requirement} \times \text{Irrigated Land} \times \text{Crop Coverage}}{\text{Agricultural Irrigation Efficiency}}$$

Unit: Gallon/Month

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Agricultural Irrigation Efficiency=

$$\frac{(\text{Irrigated Land-Irrigated Land with BMPs})\times 0.5+\text{Irrigated Land with BMPs}\times 0.95)}{\text{Irrigated Land}}$$

Unit: Fraction

Expenses on Irrigated Land BMPs=

$$\begin{cases} \min\begin{pmatrix}\text{Potential Budget on Irrigated Land BMPs,}\\ \text{Planned Budget on Irrigated Land BMPs}\end{pmatrix}, \text{year}<2010 \\ \min\begin{pmatrix}\text{Potential Budget on Irrigated Land BMPs,}\\ \text{Planned Budget on Irrigated Land BMPs}\end{pmatrix}, \text{year}\geq 2010 \\ \quad +\text{Additional Budget on Irrigated Land BMPs} \end{cases}$$

Unit: Dollar/Month

$$\text{Crop Coverage}=\begin{cases}0.3, \text{year}<1990\\ 0.5, \text{year}\geq 1990\end{cases}$$

Unit: Fraction

Expenses on Unit Irrigated Land BMPs=5000
Unit: Dollar/Acre

Irrigated Land=

$$\int\left(\text{Irrigated Land Development} - \text{Conversion of Irrigated to Residential Land}\right)dt$$
$$+\text{Initial Irrigated Land}$$

Unit: Acre

$$\text{Initial Irrigated Land}=\begin{cases}65000, \text{Hillsborough County}\\ 1762, \text{Pinellas County}\\ 97982, \text{Pasco County}\end{cases}$$

Unit: Acre

Irrigated Land Development=

$$\begin{cases} 0, \text{Irrigated Land}>\text{Minimum Irrigated Land} \\ \text{DELAY3}\left(\frac{\text{Minimum Irrigated Land-Irrigated Land}}{\text{Time to Restore Irrigated Land}}, 6\right), \text{Otherwise}\end{cases}$$

Unit: Acre/Month

$$\text{Irrigated Land with BMPs}=\int(\text{New Land with BMPs-Land Loss})dt$$
$$+\text{Initial Irrigated Land with BMPs}$$

Unit: Acre

$$\text{Initial Irrigated Land with BMPs}=\begin{cases}6500, \text{Hillsborough County}\\ 176, \text{Pinellas County}\\ 9798, \text{Pasco County}\end{cases}$$

Unit: Acre

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Maximum Land with BMPs=Irrigated Land, Initial Irrigated Land × 0.8
+ DELAY3 ((Irrigated Land-Initial Irrigated Land) ×0.3, 36)
Unit: Acre

C.3. Water Supply

Surface Water Storage =

$$\int\begin{pmatrix}\text{Precipitation + Runoff + Surface Water Discharge}\\ \text{+Surface Water Inflow–Evaporation-Infiltration from Surface Water}\\ \text{-Surface Water Outflow-Surface Water Withdrawal}\end{pmatrix}dt$$

+Initial Surface Water Level×Surface Water Area ×2.09e08)

Unit: Gallon

Surface Water Availability=

$$\begin{cases}\text{0, Surface Water Level<Minimum Surface Water Level}\\ \text{Surface Water Level-Minimum Surface Water Level)}\times\dfrac{\text{Surface Water Area}\times 2.09\text{e}08}{\text{Time for Supply}}\text{, Otherwise}\end{cases}$$

Unit: Gallon/Month

Surface Water Withdrawal=min(Surface Water Availability, Surface Water Demand)
Unit: Gallon/Month

$$\text{Groundwater Storage=}\int\begin{pmatrix}\text{Groundwater Inflow + Groundwater Recharge}\\ \text{+ Percolation + Seawater Intrusion}\\ \text{– Groundwater Outflow – Groundwater Withdrawal}\end{pmatrix}dt$$

+Aquifer Area×1500×2.09e08)

Unit: Gallon

Ground Water Availability=

$$\begin{cases}\text{0,Minimum Groundwater Table>Groundwater Table to Surface}\\ \text{(Minimum Groundwater Table-Groundwater Table to Surface)}\times\dfrac{\text{Aquifer Area}\times 2.09\text{e}08}{\text{Time for Supply}}\text{,Otherwise}\end{cases}$$

Unit: Gallon/Month

Groundwater Withdrawal=min(Ground Water Availability, Ground Water Demand)
Unit: Gallon/Month

$$\text{Infiltration from Precipitation=min}\begin{pmatrix}\text{Difference between Soil Storage and Capacity/1,}\\ \text{Precipitation Reaching Soil}\end{pmatrix}$$

Unit: Gallon/Month

Difference between Soil Storage and Capacity=
Soil Water Saturation Capacity-Soil Water Storage
Unit: Gallon

Precipitation Reaching Soil=Precipitation Rate ×(1-Interception Ratio) × Permeable Land
Unit: Gallon/Month

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Depth of Soil Layer=80
Unit: Inch

Field Capacity=Depth of Soil Layer×Field Capacity Fraction×Soil Area
Unit: Gallon/Month

Field Capacity Fraction=0.3
Unit: Fraction

Field Capacity=Depth of Soil Layer× Field Capacity Fraction×Soil Area
Unit: Gallon/Month

Field Capacity Fraction=0.1
Unit: Fraction

Percolation=max(Percolation Surplus, 0)
Unit: Gallon/Month

Percolation Surplus=Soil Water Storage-Field Capacity
Unit: Gallon/Month

$$\text{Soil Water Storage}=\int \left(\begin{matrix}\text{Infiltration from Precipitation} + \text{Infiltration from Surface Water} \\ - \text{Percolation} - \text{Soil Evapotranspiration}\end{matrix}\right) dt$$
$$+\text{Initial Soil Water Storage}$$
Unit: Gallon

Initial Soil Water Storage=0.5×Soil Water Saturation Capacity
Unit: Gallon/Month

Seawater Intrusion=
$$\begin{cases} 0, \text{Seawater Level} < \text{Groundwater Table to Surface} \\ \text{DELAY3}\left(\begin{matrix}(\text{Seawater Level-Groundwater Table to Surface}) \\ \times \text{Intrusion Area}, 24\end{matrix}\right), \text{Otherwise}\end{cases}$$
Unit: Gallon/Month

Soil Water Saturation Capacity=Soil Water Saturation Capacity Fraction
×Depth of Soil Layer×Soil Area
Unit: Gallon/Month

Soil Water Saturation Capacity Fraction=0.5
Unit: Inch/Inch

$$\text{Reclaimed Water Expansion}=\text{DELAY3}\left(\frac{\text{Expenses on Reclaimed Water Expansion}}{\text{Unit Cost for Reclaimed Water Expansion}}, 24\right)$$
Unit: Gallon/Month

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Reclaimed Water Capacity= $\int$(Reclaimed Water Expansion)dt
Unit: Gallon

Reclaimed Water Expansion= DELAY3 $\left(\frac{\text{Expenses on Reclaimed Water Expansion}}{\text{Unit Cost for Reclaimed Water Expansion}}, 24\right)$
Unit: Gallon/Month

Reclaimed Water Supply=min(Reclaimed Water Demand, Reclaimed Water Capacity)
Unit: Gallon/Month

Potential Reclaimed Water Demand=People with Reclaimed Water Acceptance ×Reclaimed Water Demand per Capita
Unit: Gallon/Month

C.4. Energy Demand

Energy Demand in Cooling and Heating=Population×Perceived Temperature ×Unit Municipal Electricity Demand
Unit: Btu/Month

Energy Demand in Household Water Use=700×Indoor Water Demand
Unit: Btu/Month

Captia Production=min(1547.76×$(1+0.22)^n$, 2500)
Unit: Dollar/Person

Electricity Demand in Agriculture= $\frac{\text{Energy Demand in Agricultural Water}}{\text{Fraction in Agriculture}}$
Units: Btu/Month

Fraction in Agriculture=0.9
Unit: Fraction

Electricity Demand in Industry=Estimated Unit Electricity Demand for Industry ×Industrial Production×Industrial Employees
Units: Btu/Month

Electricity Demand in Municipality=Population×Perceived Temperature ×Unit Municipal Electricity Demand
Units: Btu/Month

Energy Intensity for Groundwater Supplied to Municipality=(9.15e-06+0.00121)×3412.14 +Raw GW Pumping Energy Intensity× $\frac{\text{Groundwater Table to Surface}}{\text{Average Groundwater Table to Surface}}$
Units: Btu/Gallon

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Perceived Temperature=DELAY INFORMATION(Temperature, 12)
Unit: Degree F

$$\text{Energy Intensity for Surface Water Supplied to Municipality}=(9.53\text{e-}06+0.00121)\times 3412.14 + \text{Raw SW Pumping Energy Intensity}\times\frac{\text{Surface Water Level}}{\text{Average SurfaceWater Level}}$$

Units: Btu/Gallon

Energy Intensity for Wastewater Treatment=143.31
Units: Btu/Gallon

Wastewater=0.7×Water Demand in Municipality
Units: Gallon/Month

C.5. Energy Supply

$$\text{Energy Production}=\min\left(\begin{array}{c}\text{Energy Demand,}\\ \text{Energy Availability/Time for Energy Supply}\end{array}\right)$$

Unit: Btu/Month

Time for Energy Supply=36
Units: Month

Energy Availability=1e+16
Units: Btu

Alternative Energy Supply=max(Energy Demand-Energy Production, 0)
Unit: Btu/Month

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Appendix D: Historical Precipitation, Reference Evapotranspiration, and Temperature

Table D-1 Historical Precipitation (Unit: Inch/Month)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1980	2.61	2.20	3.39	3.79	6.01	4.33	8.68	7.50	4.27	0.98	3.63	0.65	48.04
1981	0.50	4.98	1.65	0.05	2.06	7.42	6.21	11.35	7.08	1.23	0.90	3.21	46.64
1982	2.42	3.02	5.52	3.49	5.78	9.22	8.89	7.29	8.84	2.57	1.31	0.92	59.27
1983	2.14	9.09	8.80	2.47	2.38	7.84	7.01	8.47	8.50	2.51	2.54	6.57	68.32
1984	1.79	3.53	2.16	3.06	3.67	4.63	9.91	6.11	4.33	1.00	2.16	0.21	42.56
1985	2.09	1.88	2.11	1.01	1.05	8.55	8.22	10.19	6.15	3.22	1.40	1.50	47.37
1986	3.13	2.37	4.63	1.13	2.26	10.24	7.41	8.82	3.31	4.36	1.16	2.76	51.58
1987	3.16	2.13	12.20	0.26	6.14	5.86	7.78	5.95	5.52	2.34	4.77	0.31	56.42
1988	3.59	1.99	5.33	1.83	2.00	3.66	6.01	10.19	15.06	0.58	7.04	1.20	58.48
1989	3.03	0.16	2.09	1.53	0.94	8.47	7.37	5.50	7.77	1.37	1.98	4.66	44.87
1990	0.42	3.85	1.24	1.49	2.36	6.53	9.23	6.07	2.61	3.41	1.24	0.30	38.75
1991	3.20	0.74	5.17	3.93	7.58	6.54	11.40	7.35	2.28	1.43	0.53	0.80	50.95
1992	1.48	4.86	1.56	3.64	0.70	12.09	3.99	10.21	5.47	2.81	2.40	0.68	49.89
1993	5.77	2.55	4.48	2.50	2.77	4.22	4.92	7.40	6.46	4.05	0.76	1.39	47.27
1994	4.16	1.01	1.63	3.74	1.67	8.65	8.49	9.16	10.65	3.60	1.03	2.24	56.03
1995	3.43	1.83	1.77	2.13	1.68	8.56	10.49	10.77	5.18	6.80	1.83	0.82	55.29
1996	5.22	2.58	5.44	3.24	2.87	7.40	4.36	4.06	5.65	3.49	0.79	2.76	47.86
1997	1.40	0.76	1.93	6.68	2.48	5.16	8.23	6.27	12.18	4.98	4.02	13.67	67.76
1998	4.26	9.95	6.82	0.43	2.07	2.29	8.78	6.19	12.92	0.76	1.93	0.95	57.35
1999	3.69	0.30	0.89	1.15	4.54	9.38	6.43	9.32	6.17	3.27	2.28	1.54	48.96
2000	1.20	0.34	0.74	0.83	0.16	6.63	7.93	6.55	7.61	0.23	1.21	0.67	34.10
2001	0.63	0.50	7.14	0.04	0.53	8.00	10.09	5.79	11.72	1.58	0.19	1.15	47.36
2002	1.77	3.30	0.74	2.76	2.51	10.52	7.50	9.89	5.95	3.38	2.91	16.07	67.30

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Table D-1 (Continued)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
2003	0.06	3.23	4.58	3.50	2.99	15.06	5.61	9.79	5.33	1.29	1.33	1.94	54.71
2004	4.06	4.04	1.45	4.57	2.17	10.46	11.40	12.92	14.64	1.34	1.68	1.78	70.51
2005	1.53	2.23	4.33	3.51	4.41	12.71	9.10	7.36	3.04	4.51	2.15	1.43	56.31
2006	1.07	4.30	0.12	0.65	1.99	7.33	8.45	7.83	6.85	1.20	1.92	2.55	44.26
2007	2.16	2.06	0.61	2.63	0.64	7.05	8.18	8.01	5.19	5.65	0.14	1.39	43.71
2008	3.56	2.73	3.49	3.94	0.93	8.05	9.49	6.95	1.77	2.12	0.99	1.07	45.09
2009	2.03	0.74	1.05	1.51	10.02	7.94	8.94	7.58	7.07	1.65	2.11	3.00	53.64
2010	3.66	2.38	6.79	4.08	2.49	5.82	7.20	10.43	2.90	0.09	1.59	0.62	48.05
2011	5.55	0.69	8.43	1.52	1.51	5.01	8.86	10.52	5.84	4.55	0.79	0.34	53.61
Average	2.65	2.70	3.70	2.41	2.86	7.68	8.02	8.18	6.82	2.57	1.90	2.47	51.95
Minimum	0.06	0.16	0.12	0.04	0.16	2.29	3.99	4.06	1.77	0.09	0.14	0.21	34.10
Maximum	5.77	9.95	12.20	6.68	10.02	15.06	11.40	12.92	15.06	6.80	7.04	16.07	70.51
Standard Deviation	1.49	2.23	2.89	1.55	2.21	2.74	1.82	2.04	3.48	1.67	1.40	3.53	8.54

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Table D-2 Historical Reference Evapotranspiration (Unit: Inch/Month)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1999	2.48	3.08	4.03	4.8	5.27	6	5.89	4.65	3.6	3.72	2.7	2.17	48.39
2000	2.17	3.19	4.34	5.1	5.89	4.8	5.89	5.27	4.2	3.41	2.7	1.86	48.82
2001	2.17	3.08	3.72	5.1	6.2	6	5.58	5.58	4.5	3.72	2.7	2.17	50.52
2002	2.48	2.8	4.65	5.1	6.2	5.7	5.27	5.27	3.9	3.72	2.7	2.17	49.96
2003	2.17	2.8	4.03	5.1	6.51	5.7	5.58	5.27	4.5	3.72	2.4	1.86	49.64
2004	1.86	2.32	3.72	4.5	5.58	4.8	5.27	4.65	3.9	3.1	2.1	1.55	43.35
2005	1.86	2.52	3.1	4.5	5.89	5.7	5.58	4.65	4.5	3.41	2.4	1.55	45.66
2006	1.86	2.24	3.72	4.8	5.27	4.5	5.89	5.27	4.5	3.1	2.1	1.55	44.80
2007	1.86	2.24	3.72	4.5	5.27	5.7	5.58	5.27	4.5	3.41	2.1	1.86	46.01
2008	1.86	2.32	3.41	4.5	5.27	5.4	5.27	5.58	4.5	3.1	2.1	1.86	45.17
2009	1.86	2.52	3.72	4.5	5.58	5.4	4.34	4.65	4.5	3.1	1.8	1.55	43.52
2010	1.55	1.96	3.1	4.8	4.96	5.4	4.96	4.96	4.2	3.72	2.1	1.55	43.26
2011	1.55	2.52	3.41	4.8	5.89	6	5.58	4.96	4.5	3.41	2.1	1.24	45.96
Average	1.98	2.58	3.74	4.78	5.68	5.47	5.44	5.08	4.29	3.43	2.31	1.76	46.54
Minimum	1.55	1.96	3.10	4.50	4.96	4.50	4.34	4.65	3.60	3.10	1.80	1.24	39.30
Maximum	2.48	3.19	4.65	5.10	6.51	6.00	5.89	5.58	4.50	3.72	2.70	2.17	52.49
Standard Deviation	0.29	0.36	0.43	0.25	0.44	0.47	0.41	0.33	0.30	0.26	0.30	0.28	4.13

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Table D-3 Historical Temperature (Unit: °F)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1980	58.4	55	65.9	69	75.4	80	82.6	82.3	80.6	71.9	64.3	56.3	70.1
1981	49.5	59.2	61.6	71.7	74.1	82.2	82.7	81	78	72.8	63.1	57.4	69.4
1982	57.6	64.8	67.2	70.5	74.2	80.5	81.3	81.2	78.3	72.2	68.1	64	71.7
1983	55.4	58	61.3	66.2	74.4	78.8	82.1	82.2	78.1	73.7	63.9	58.9	69.4
1984	55.6	59.6	63.3	68.3	75.1	78.4	80	81	78	74.3	63.4	64.8	70.1
1985	52.8	60.2	66.9	69.6	75.9	81	80.6	81.3	78.5	77	70.9	56.6	70.9
1986	57	63.2	63.6	67.6	75.1	80.7	82	81.2	80.2	74.1	72.4	63.2	71.7
1987	56.5	59.9	64.3	65.1	75.5	80.7	82.2	82.8	79.5	68.4	66.5	61.6	70.2
1988	55.1	57.2	63.1	69.7	73.1	79.1	80.8	81.5	80.4	70.4	67.9	59.4	69.8
1989	64.3	61.8	67.2	69.7	75.4	80.1	81.5	81.7	79.8	72.2	66	52.8	71
1990	62.9	66	67	69.2	77	80.6	81.8	82.2	80.1	74.3	66.5	63.4	72.6
1991	62.3	61.8	66.3	73.4	78.4	80	81.8	81.7	79.8	72.9	62.7	62.2	71.9
1992	56.7	61.9	64	68	72.7	80	82.6	80.6	79.5	70.8	67.3	61.1	70.4
1993	63.9	58.4	62.5	66.2	73.9	80.5	82.6	82.4	80.1	73.3	65.8	56.9	70.5
1994	57.2	64	66.1	72.2	75.8	80.6	80.6	80.4	78.4	73.5	69.7	62.1	71.7
1995	56.9	59	66.7	70.5	78.3	79.2	82.2	82.4	79.9	75	63	57.5	70.9
1996	56.6	58.7	60.4	67.8	76.9	79.2	82.2	80.7	79.1	72.1	65.1	60.2	69.9
1997	59.6	64.2	70.6	68.4	74.8	78.8	81.9	81.6	79.8	72.2	63.8	59.1	71.2
1998	60.6	60	62.1	69.6	77.3	83.9	83.5	82.6	80.3	75.2	69.7	65	72.5
1999	60.9	62	62.5	72.6	74.5	79.2	82.1	83	78.8	73.4	66	59.5	71.2
2000	58.9	60.6	67	68.2	77.2	80.4	82.2	81.7	79.6	71	63.7	57.1	70.6
2001	53.1	65.1	64.2	70	74.7	80.1	81.2	81.3	77.6	71.5	68	64.4	70.9
2002	59.3	59.6	66.7	73.6	76.6	79.6	81.5	81.2	81.1	76.3	63.2	57.5	71.4
2003	52.4	61.5	70.2	69.5	78.2	80.1	81.3	81	78.9	73.4	68.7	56.4	71
2004	56.9	59.4	65.8	67.5	76.1	81.3	81.8	81.4	79.9	74.5	67.3	58	70.8
2005	60	60.6	62.9	66.6	74.2	79.8	83.1	83.1	80.6	73.5	67.1	56.9	70.7

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Table D-3 (Continued)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN UAL
2006	60.6	58.2	64.6	72.3	75.4	80.3	81.7	82.5	79.2	71.9	63.4	64.3	71.2
2007	61.3	58	66.2	68.2	74.7	79.8	82	83.5	80.3	76.1	64.7	64.3	71.6
2008	58.1	62.9	64.4	69.2	75.9	80.5	81	81.2	79.6	71.3	61.4	62	70.6
2009	57.4	57.8	65.5	69.7	76.7	81.8	81.6	82	84.4	75.2	66	60.5	71.1
2010	52.4	52.3	58.7	69.5	78.3	83	83.3	83.6	81.1	72.2	64.9	50	69.1
2011	55.1	61.7	66.5	73	76	81.9	82.4	83.6	79.7	70.6	66.7	63.7	71.7
2012	59.3	63.9	70.2	71.1	77.4	79.4	82.2	81.6	79.5	73.3	62.3	62.2	71.8
Average	58.3	60.0	64.8	69.7	75.5	79.9	81.3	81.4	79.4	72.8	65.0	59.5	70.6
Minimum	49.1	51.0	56.5	65.1	72.5	77.4	79.6	79.9	76.9	68.4	59.0	50.0	68.5
Maximum	68.9	67.9	70.7	75.4	78.6	83.9	83.5	83.6	84.4	78.5	72.4	68.9	72.6
Standard Deviation	3.8	3.6	3.0	2.0	1.4	1.1	0.8	0.8	1.1	2.0	2.6	3.4	0.8

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Yilin Zhuang graduated from Tongji University (China) with a Bachelor of Science degree in Environmental Science and Master Degree in Environmental Engineering. She enrolled the doctoral program in Environmental Engineering in University of South Florida in 2009 and worked as a research assistant. Yilin is also a member of System Dynamics Society and working as a volunteer for Tampa Bay Estuary Program.

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