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A system dynamics approach to water resources planning and management in South Florida

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A SYSTEM DYNAMICS APPROACH TO WATER RESOURCES PLANNING AND MANAGEMENT IN SOUTH FLORIDA

by

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ABSTRACT

A System Dynamics Approach to Water Resources planning and Management in South Florida

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The primary aim of this research is to test a number of policy options to reduce water consumption in agricultural and municipal sectors, and quantify its impact on environmental supply. A System Dynamics model is developed to evaluate the sustainability of agricultural, municipal, and environmental water demands in South Florida. Performance criteria of vulnerability, resilience, and reliability, are used to measure the success of the policies. In addition, scenarios with varying precipitation and population growth rates are generated to account for uncertainty.

The status-quo simulations run from 1970 to 2050 show a reduction in environmental flows after 2010. That can deteriorate the water resources and adversely impact water availability. Intervention scenarios show that conservation causes a significant improvement in environmental flows. However, agricultural interventions prove to be more successful as compared to municipal interventions in reducing the stress on the water resources.

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CHAPTER 1

INTRODUCTION

Water availability is an essential part of growth and development of human settlements. Throughout history, most major cities have developed along rivers and lakes to ensure easy availability of fresh water. Water bodies not only provided for the water requirements of the settlements but also acted as means of disposal of wastes. Eventually, the explosive growth of human population in all parts of the world led to an enormous pressure on the available limited water resources.

The world's demand for water has more than tripled since 1950 (Postel, 1997). The world population has grown from 2.5 billion in 1950 to 4.4 billion in 1980 and exceeded 6.6 billion in 2007. It is expected to approach 8 billion in 2025, 9.3 billion in 2050 and eventually stabilize between 10.5 and 11 billions (UNDESA, 2002). This overwhelming population growth has led to a surge in the demand for freshwater, which is difficult to be fulfilled at present and would be nearly impossible to fulfill in the future. The only way out of this predicament is to develop new sources of water or implement measures to reduce unnecessary consumption.

Much of water resources planning and research in the last century has been concentrated on obtaining more water. However, since the global water stocks are limited, there is an upper limit to the amount of water that can be drawn in order to fulfill the ever growing requirements. Therefore, there is a pressing need that the future water resources research be concentrated on conservation, efficient management, and equitable allocation of water.

1.1 Research Motivation

Water is required for almost all human activities such as drinking, cooking, hygiene, household use, irrigation, landscaping, industries etc. Therefore, all spheres of human life are adversely affected due to lack of water. Many parts of the world are experiencing varying degrees of water shortage. It is estimated that approximately 2.4 billion people are living in water stressed regions, which is approximately 40% of the total world population (Oki and Kanae 2006). The problem is particularly difficult for regions experiencing a rapid population growth. The water requirements of these regions increase for two reasons. In addition to the direct water requirement of the people, which grows proportionate to the population, the food production also has to be increased, thus, increasing not only municipal but also irrigation water requirement.

The amount of water used at a particular location depends upon a variety of factors such as population, socioeconomic conditions, physiographic and climatic features, etc. Combinations of these factors determine the amount of water use and future growths. It is estimated that agriculture alone uses 87% of the global freshwater withdrawals (Postel 1992). However, the efficiency of application of irrigation water is low throughout the world and only 50% of it reaches the crop (van der Leeden et al 1990). Although it is difficult to eliminate wastage, it is possible to make irrigation practices efficient through techniques such as micro irrigation.

With rapidly growing population, many regions in the world are finding it difficult to sustain requirements of its inhabitants. This problem is particularly severe in regions with high population density. Some studies estimate a basic per capita water requirement of 14 gallon per day (gpd) (Gleick 1996). The in water availability per capita per day varies considerably. On one hand, for several underdeveloped regions in the world, the per capita water availability may be as low as 2-3 gpd. On the other hand, for many urban areas in industrialized nations, per capita water consumption may be as high as 200 gpd.

A number of urbanized regions throughout the world are facing the challenging task of meeting the enormous water demands of the residents. Increasing population growth rates result in increasing demands for water. Such regions of localized high demands can result in overexploitation of the water resources in the vicinity. However, there is an upper limit to the water that can be drawn without stressing the water resources. As demands for water increase, it is becoming critical to share water resources between human and ecological needs. Ignoring the need for environmental flows may result in serious and even irreversible damage to the ecology.

Environmental flows is water provided for the environment to sustain, and where necessary, restore ecological processes and biodiversity of water dependent ecosystems (DEWR 2007). Loss of ecosystem services as a result of reducing environmental flows can have detrimental effects on the ecology. To maintain these and other ecosystem services, water needs to be allocated to sustaining the ecology of rivers, and wetlands. The realization that environmental water requirements need to be taken into consideration, in plans for developing water resources, is emerging rapidly.

Natural systems, having a large number of components, are inherently complex. They have several feedback loops and time delays built into their structure. Thus, a change or an intervention, introduced into one of the component processes of a system, may have repercussions which are removed from its cause in both time and space. Our minds are not capable of efficiently keeping track of changes occurring at locations and time remote from the point of intervention. Therefore, water management and policy making for sustainable management of water demands in growing regions usually requires the support of simulation models. The growing demands of freshwater resources create an urgent need to link research with improved water management. Accurate estimation of demands and assessment of water resources could help to allocate water more efficiently between various competing uses. This study estimates the two major types of demands i.e., agricultural and municipal. It also generates water availability trends and inflows to the water bodies.

This research creates a Decision Support (DS) model for a representative region with a balanced distribution of agricultural and urban areas, and high rates of water consumption. This model captures the interaction among population growth, land use changes, various competing demands, and water availability in the area of interest.

This model generates population growth and land use changes internally. It also generates various water demands for the desired planning horizon. It subsequently provides an estimate of the magnitude of water surplus or deficit to maintain the environmental flows. Based on this estimate, water conservation measures can be tested for their effectiveness in reducing the water demands and relieving the stress from the water resources.

Various water conservation measures and policy options are considered in this research to reduce unnecessary and wasteful water use. A simple way of reducing the pressure on the water sources is to reduce wasteful consumption and make water use more efficient in both agricultural and municipal sectors. Several mandatory and non-mandatory policies could be implemented by the governing bodies in order to accomplish this purpose. Some of the potential water saving policies are tested in this study for their effectiveness in reducing consumption.

At present only 14-15% of the agricultural acreage in the world uses sprinkler irrigation, and only 1% of the total cultivated area in the world uses micro irrigation. So far, high installation and maintenance cost have been a major discouragement to the adoption of these irrigation techniques (Postel 2001). The use of micro irrigation could reduce water consumption by a significant amount. It has been shown in a number of studies that the use of micro irrigation can reduce water consumption by 12% to 29% per crop while increasing the yield by 20 to 30% simultaneously (Shreshtha and Gopalakrishna1993, Waykar 2003). A reduction in agricultural demand can produce notable increase in available water for environmental purposes.

Municipal water sector is another avenue which presents a considerable scope of economizing water use. It is shown in a number of studies that the use of smart indoor fittings and modern landscaping techniques can significantly reduce unnecessary water use by 25% to 42% (Nelson 1994, Testa 1993, Sovocool 2005). It is of interest to quantify the savings that could be achieved by the adoption of these measures and their subsequent impact on the environmental flows in the water bodies.

1.2 Research Objectives

The overall objective of this research is to determine the sustainability of the water withdrawal for agricultural and municipal use, without compromising the environmental demands. To achieve this objective, water demands as well as the water availability are determined. The comparison between water demands and availability determines the extent of the water shortage for fulfilling the environmental demands. For the purpose of generating trends of the water availability, it is essential to know the inflows, outflows, and demands. Therefore, a water budget for surfacewater and the groundwater resources is developed in this research.

The model does not attempt to accurately predict the water demands and availability but tries to reproduce the general trends of growth of demands, in direction and magnitude. In order to explore the options available to the policy makers, several policies leading to water conservation are tested for their efficacy. Brief outlines of the water saving measures that are tested are as follows:

In the municipal water sector, a number of measures and policy options are explored in order to reduce water consumption. Use of pricing as a tool, to encourage consumers to reduce consumption is studied. Savings achieved due to the use of smart appliances are also examined. Gardening techniques such as xeriscaping are also studied as means to save water outdoors.

In the agricultural water sector, the use of micro irrigation is tested for water conservation. Since, a number of studies have shown that adoption of micro irrigation increases crop yields by 20-30%, it would be worthwhile to consider the option of reducing crop acreage in conjunction with micro irrigation. In addition, substitution of water intensive crops with crops having low water requirement is evaluated as a means to conserve water.

Another major focus of this study is to understand how variations in population growth affect water demands and availability and its subsequent effect on the environmental flows. In addition to the scenarios generated under normal temporal precipitation distribution, the model also generates the demands and water availability for scenarios under varying rainfall distribution. The demands generated from these scenarios are tested against water availability to provides an estimate of the magnitude of the shortage. The following research questions are identified for this research.

1. How would water systems respond to future population growth?
2. What are the promising policies to reduce water demand in the agricultural and municipal sectors?
3. What would be the impacts of rainfall variations on the overall water demands and availability?

In order to accomplish the above mentioned research objectives, the model developed in this research undergoes the following sequence of steps towards the completion of the model.

Task 1. Develop a dynamic simulation model that captures population growth and land use changes and, based upon them, estimates the agricultural and municipal demands.

Task 2. Calibrate and validate the model using historic data. Generate water availability using precipitation as an inflow, compare water demands with availability and estimating the amount of water available to meet environmental demands.

Task 3. Test the following policies to reduce water consumption in the agricultural and municipal sectors and quantifying the savings achieved.

a. Policies tested in agricultural sector include

    i. reduction in agricultural acreage,

    ii. micro irrigation, and

    iii. crop substitution.

b. Policies tested in municipal sector include

    i. low flow appliances,

    ii. xeriscaping, and

    iii. pricing.

Compare different policies on the basis of increase in the water available for environmental demand.

Task 4. Perform sensitivity analysis on population growth.

Task 5. Assess the impact of different rainfall scenarios to incorporate the impacts of climate variability on the system.

To test the applicability of the model to real world situations, a study area of South Florida Water Management District (SFWMD) was chosen for model implementation. Chapter 2 discusses the study area and System Dynamics (SD) modeling approach in water resources management. Chapter 3 explains the development and formulation of the model and Chapter 4 presents and discusses the calibration, and results obtained from model simulations. Chapter 5 lists the conclusions of this research and recommendations for extending it.

CHAPTER 2

LITERATURE REVIEW

This chapter focuses on the prevailing conditions of water availability, growing demands in South Florida, existing literature on the subject, and System Dynamics as a modeling approach. Section 2.1 discusses the study area, its historic growth and climatic conditions. Section 2.2 describes the physical features within South Florida that play a major role in driving the water availability and demands. Section 2.3 discusses the recent developments, environmental issues and legislations that have led to the framing of Minimum Flow Levels (MFLs) for South Florida's water bodies. Sections 2.4 and 2.5 provide the description of agricultural and municipal water use patterns in South Florida and scope for efficiency and improvement. Section 2.6 describes the current water use patterns and the distribution of water uses and withdrawals. Finally, section 2.7 provides a review of the models that are currently in use in the study area and the method adopted for this research.

2.1 Study Area

South Florida Water Management District (SFWMD) is geographically defined by water. It is a single, complex watershed bounded by sea on three sides. It overlies two very prolific aquifers, and hosts a very fragile ecosystem. It is home rapidly growing cities of Miami Dade, Palm Beach, Fort Lauderdale, and other densely populated urban areas on the south east coast. The region also contributes considerably to the nation's production of sugarcane and citrus fruits. All these factors contribute towards the region's distinct characteristics of being water rich and yet not having enough water.

Figure 2.1 shows the monthly rainfall and standard deviation for South Florida. Rainfall in South Florida has a high spatial and temporal variation. Annual maximum rainfall in the south eastern coastal regions is 60 inches whereas it 45 inches in the central parts. Two thirds of annual rainfall is deposited during the wet months from May to October.

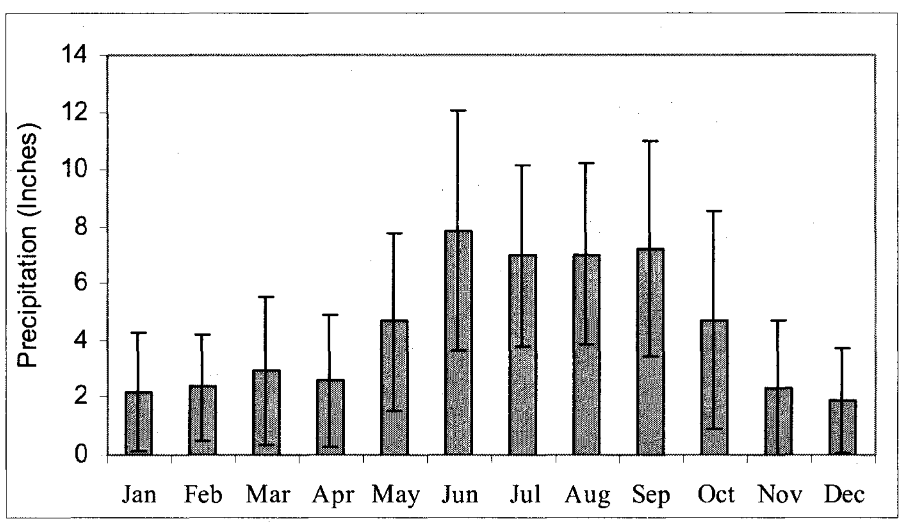

Figure 2.1 Average Monthly rainfall for South Florida (Alaa 2000).

In 1900, Florida was the smallest state in terms of population east of Mississippi with a population of 528,542 inhabitants. By 2000, its population grew to 15,982,378 and stands at over 19 million in 2007. Growth rates during the twentieth century ranged between 20% and 80% per decade, considerably above the 10-20 % growth rates experienced by the United States as a whole (Smith, 2005). The largest growth was experienced by the southern counties of Dade, Palm Beach, and Broward. These counties and others, making a total of eleven counties, contained fully or partially within SFWMD boundaries, have had one of the fastest growth rates in the state.

According to Census 2000, almost 7 million people, approximately half of Florida's total population, live in South Florida (Florida Consensus Estimating Conference, 2000). The region's population is expected to grow to 12 million by 2050 (USACE and SFWMD, 1999). Currently, almost 85% of South Florida's population resides in urban areas and majority of the projected growth is expected to be in these areas (Lenze, 1994). While the Lower East Coast (Palm Beach, Broward, Miami-Dade, and Monroe Counties) comprises only 9.5% of the State's land area, it is home to 31% of Florida's population (USACE and SFWMD, 1999). Almost half of South Florida's future growth is projected for the Lower East Coast. It is expected to grow by 72% from just over 4 million in 1990 to nearly 7 million by 2050 (G.E.C., 1996). Burchell et al. (1999) report that the five counties of southeast Florida will grow faster than 28 states in the US in population and faster than 34 states in employment. By contrast, Glades, Hendry, Highlands, Martin, Okeechobee, and St. Lucie Counties, predominantly agricultural economies contain only 3% of the region's population (USACE and SFWMD, 1999). The Lower West Coast region (Collier, Lee, most of Hendry, and parts of Charlotte and Glades Counties) is also growing at a very fast pace. In 1990, the estimated population of the region was 632,000. It is expected to increase to 1 and 1.4 million by 2010 and 2050, respectively. The population of the Upper East Coast region (Martin, St. Lucie and portions of Okeechobee County) is expected to more than double by 2050. However, this will only comprise about 5% of South Florida region's population (USACE and SFWMD, 1999).

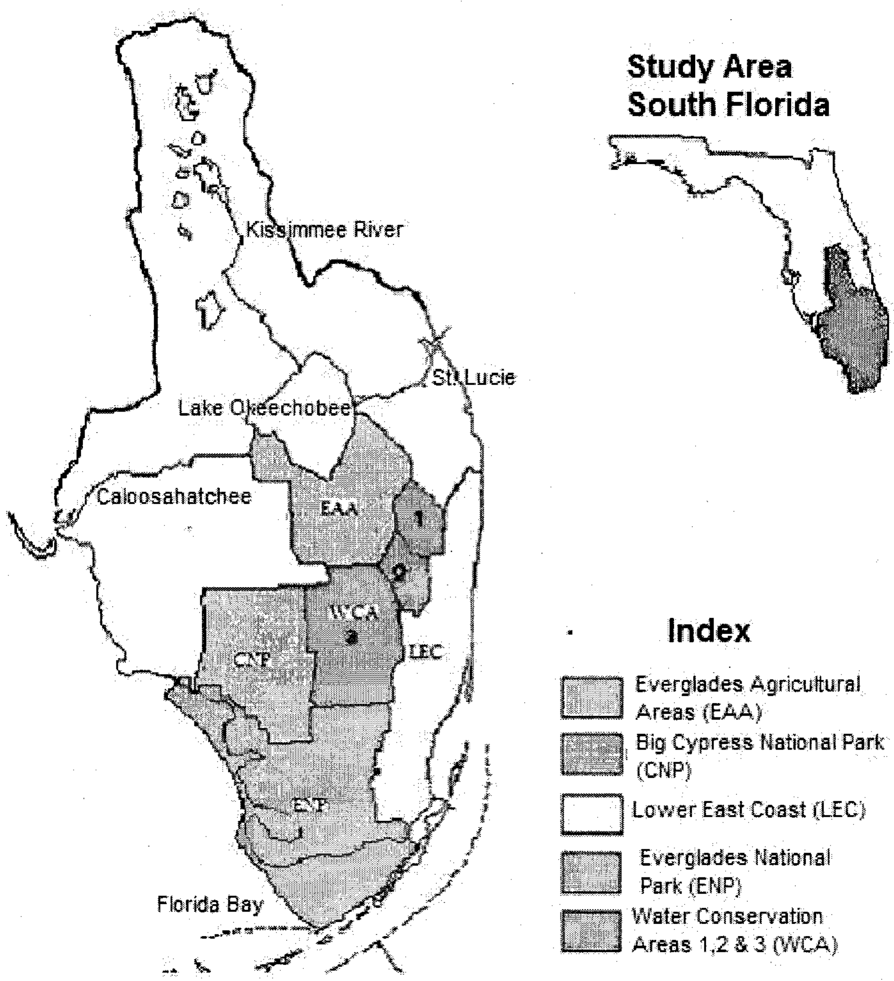

Figure 2.2 Features of South Florida Water Management District.

Agriculture, one of the major economic resources of South Florida, is concentrated in the interior of the region. The dairy and beef cattle farming is primarily located north of Lake Okeechobee, sugar cane in the Everglades Agricultural Area immediately south of Lake Okeechobee and citrus in the non-coastal southwest and northeast parts of the region. Water demands for agricultural sector has steadily increased in the past due to expansion of agricultural areas, but not much growth is expected in the future due to a lack of availability of land for cultivation. The favorable and moderate climate of South Florida allows a large number of crops to be grown all year round. This was not so in the pre-development era because land was prone to inundation all year round. The agricultural development at a large scale started in the 1920s when large tracts of peat soil in the northern everglades were drained for agriculture. Presently, agriculture is concentrated primarily in the northern Everglades immediately south of Lake Okeechobee, flatlands west of Lake Okeechobee, and along Lower East Coast. The chief crops grown in the district include sugarcane, citrus fruits, fruit orchards and small regions under other row crops.

South Florida has been constantly changing over the last century. The extraordinary growth of population made it a hub of economic activity. However, it created an enormous thirst for potable and municipal water. The extremely favorable climate of South Florida enabled it to be a major center of agricultural and farming areas and a major tourist attraction but it brought about a huge demand for irrigation water to be supplied at specific locations at specific points of time which do not necessarily coincide with the periods of easy availability of water.

Figure 2.3 shows the land use changes that occurred in South Florida over the last century. Historically Everglades extended from the southern rim of Lake Okeechobee up to the southernmost tip of the peninsula. A large portion of the Everglades is now Everglades Agricultural Areas or is intersected by a number of canals hindering the free movement of water.

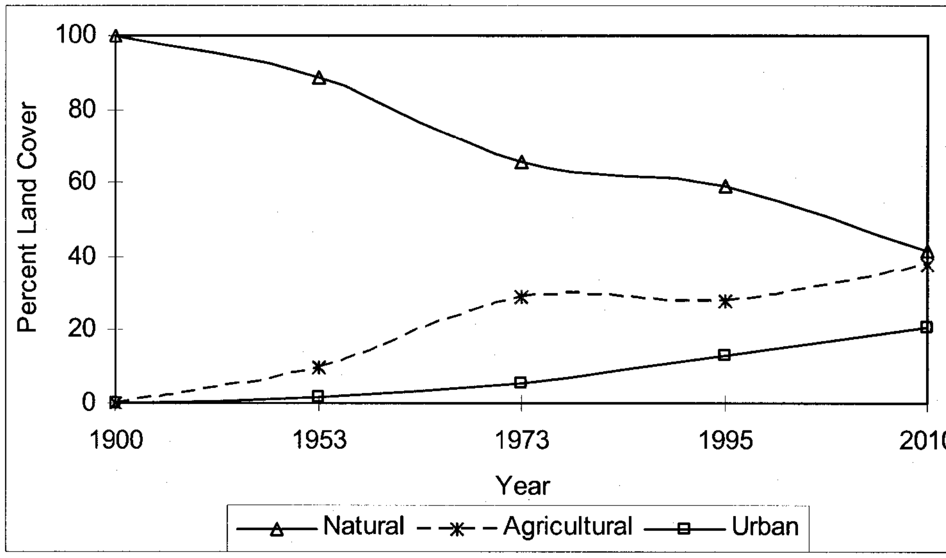

Figure 2.3 Changes in land use in South Florida (SFWMD 1999).

Urbanization in South Florida began in the lower east coast along the Atlantic Coastal Ridge where the elevation is higher as compared to inland areas. Its proximity to the sea made trade and marine transport possible. Some land was also made available for urbanization further inland after the development of the agricultural areas, flood control structures and draining of the Everglades.

Urbanization poses a number of problems and obstacles in the natural course of water cycle. Due to changes in land use and development of paved surfaces and buildings, a large portion of pervious surface is rendered impervious which causes the infiltration to drop. Additionally, to cater the freshwater demands of the residents, groundwater is pumped out of the aquifers, which further drops the groundwater levels.

Specific to South Florida is the problem of saltwater intrusion. The land in order to stay habitable requires canals for drainage; these canals lower the water table and allow sea water to infiltrate. During the prolonged droughts of the 1930's and 1940's, seawater moved inland along canals and infiltrated aquifers. At the end of the 1945 dry season, seawater intrusion had affected large segments of the Biscayne aquifer, and several of Miami's municipal supply wells yielded salty water. Water levels in southern Dade County and in the eastern part of Everglades National Park were as low as 2 ft below sea level (Parker et al, 1955). Lowering of groundwater levels below sea levels creates a negative head which allows seawater to intrude into the aquifer. Uncontrolled drainage in southeastern Florida has been stopped since then by the installation of control structures near the outlets of most drainage canals. These structures controlled the recurring problems of seawater intrusion and excessively low water levels. During the rainy season, the controls are opened to release water for flood prevention in the urban and agricultural areas, and during the dry season, they are closed to prevent over drainage and to retard seawater intrusion.

2.2 Features of the South Florida

In order to understand the working of the complete system, it is necessary to understand its component and their behavior. South Florida historically comprised of a chain of natural bodies such as the Kissimmee River, Lake Okeechobee, and The Everglades. Now it is an intricate web of natural and manmade features which interact with each other in numerous ways. Before going into the method and modeling section in Chapter 3, the natural and manmade features of the SFWMD are described in the following sections.

Figure 2.2 shows the details of the SFWMD's surface features. The Kissimmee River drains into Lake Okeechobee. Caloosahatchee River and the St. Lucie Canal are the lake's outlets to the sea on the western and eastern sides respectively. The Everglades

Agricultural Areas (EAA) which lies immediately south of Lake Okeechobee, are a major source of sugar for the US. The Water Conservation Areas (WCAs) lying south of the EAA serve as a storage for surplus water and also act as a natural reserves for the remnants of the everglades. The Lower East Coast (LEC) is the region with the highest population density in the district. It is situated on a ridge between the Atlantic to the east and the low-lying everglades to the west. The Everglades National Park (ENP) lies at the southernmost part of the Floridan peninsula and comprise of tropical and subtropical environment of the natural Everglades. The next few sections of the manuscript are devoted to describe the features of South Florida in detail

2.2.1 Kissimmee River

The Kissimmee River originates in the Osceola County in south central Florida as the outflow from Lake Tohopekaliga. It passes through Lake Cypress, Lake Hatchineha, and Lake Kissimmee on its way to Lake Okeechobee. The river originally was 134 miles in length before it was channelized and straightened (SFWMD 2007). It has a watershed of about 3000 square miles and forms the headwaters of the Kissimmee-Okeechobee-Everglades ecosystem.

The Kissimmee River and floodplain have been highly altered from their original conditions by the construction of a major canal and water control impoundments. The Kissimmee River was originally a meandering river and floodplain, with numerous oxbows extending south from Lake Kissimmee to the north end of Lake Okeechobee. In the 1960s, the U.S. Army Corps of Engineers (USACE) channelized the river into a 56-mile canal by removing the oxbows and meanders in the river to improve flood protection within the watershed. Now a series of combined locks and spillways divides the

Kissimmee River into five pools (pools A–E). A regulation schedule controls water levels in each of these pools.

Efforts are underway at present to restore the river and its headwaters to achieve a more natural flow and improve water level conditions in the river and floodplain. Designed to restore 43 miles of the river, the Kissimmee River Restoration Project is redirecting flows through the historic river channel and restoring the ecological functions of the river/floodplain system. The project is expected to restore 27,000 acres of floodplain wetlands and would benefit over 320 species of fish and wildlife, including the endangered wood stork, snail kite, and southern bald eagle. Environmental studies on the river are establishing a baseline for tracking expected changes and responses to the ecosystem as restoration projects move forward.

2.2.2 Lake Okeechobee

Lake Okeechobee, which is also called the "liquid heart" of South Florida's water supply and flood control system, covers 730 square miles. It represents the second largest fresh water lake located wholly within the continental United States. The name Okeechobee comes from Hitchiti words "Oki" meaning "Big" and "Chubi" meaning "Water". The name Okeechobee thus literally means Big Water.

The lake is shallow with a mean depth of only 9 feet, and has a surface water storage capacity of over 1 trillion gallons or 300,000 ac-ft. The lake levels are maintained within 13 to 15 ft NGVD (National Geodetic Vertical Datum) through a detailed regulation schedule. The lake supports an extensive littoral zone of roughly 150 square miles that provides important feeding and nesting habitat for fish, wading birds, migratory waterfowl, and the endangered Everglades snail kite. The lake also supports a viable commercial fishing industry (SFWMD 2003).

Lake Okeechobee is the primary and biggest source of surface water in the district. The major tributaries to the lake are Kissimmee River and Taylor Creek. Caloosahatchee River and St. Lucie River drain the lake into the sea. Kissimmee River and other streams combined together bring about 1.6 million ac-ft/yr of water into the lake and Caloosahatchee River and St. Lucie Canal combined together discharge approximately 416,000 ac-ft/yr of water into the sea. Besides the surface water flows, precipitation also contributes a major share (about 40%) of the total inflow into the lake (SFWMM). The evapotranspiration takes away 55 inches of water from the lake.

Lake Okeechobee provides irrigation water for over 1000 square mile EAA located south of the lake and represents a critical supplemental water supply for the Everglades during dry periods. The lake is a direct source of drinking water for a number of lakeside cities and towns and also serves as a water supply source for urban areas located along the Lower East Coast of Florida in times of high demands. Given these often-competing demands on the lake, management of this water resource is a major challenge.

2.2.3 Everglades Agricultural Area

Agriculture began in the everglades, immediately south of Lake Okeechobee, after the drainage projects. Through Central and South Florida (C&SF) Project of 1948 a large area of the northern Everglades was converted into agricultural areas and this was a major justification for the expense incurred for the drainage of the Everglades. What was once an unbroken expanse of sawgrass and marsh was fragmented and detached from its source, Lake Okeechobee. About 700,000 acres of the original everglades were converted into agricultural areas, which is about 27% of the total area of historic everglades.

Sugarcane is the major crop grown in the EAA. Besides this, winter vegetables crops are also grown to some extent. Almost all of the sugarcane grown in Florida comes from the EAA. The sugarcane cultivation is so localized to the EAAs that a visitor may never encounter a sugarcane field in rest of Florida. Approximately 70% of the commercial acreage of sugarcane is located in the Palm Beach county and the remaining in the adjoining counties of Hendry, Glades and Martin. The EAA contributes about 51.3% of all cane sugar produced in the US (Baucum et al, 2006). Agricultural activities in The EAA account for a significant portion of the agricultural water demand in the district.

2.2.4 Biscayne Aquifer

The district overlies two major aquifer systems, Biscayne and Floridan Aquifer Systems. However, the chief source of water supply in the South Eastern Florida is the Biscayne Aquifer. The great depth of the Floridan Aquifer and its salinity make tapping the Floridan Aquifer unsustainable. The Floridan aquifer however, is used for wastewater injection (McPherson and Halley. 1996). The SFWMD relies on groundwater sources to fulfill 92% of its municipal water demand and about 62% of its agricultural demand.

The Biscayne aquifer underlies an area of about 4,000 square miles and is the principal source of water for all of Dade and Broward Counties and the southeastern part of Palm Beach County in southern Florida (Figure 2.4). It is the biggest source of water for Boca Raton, Pompano Beach, Fort Lauderdale, Hollywood, Hialeah, Miami, Miami Beach, Homestead, and Florida Keys.

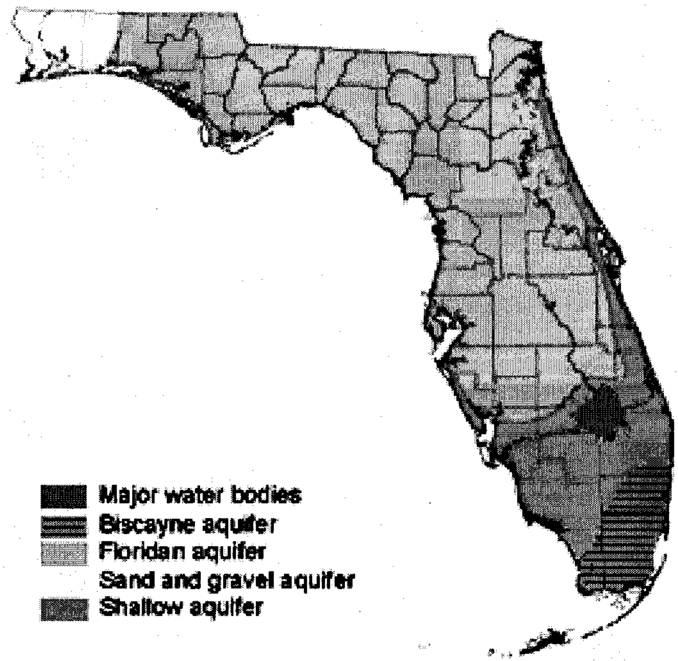

Figure 2.4 Areal extent of aquifers in Florida (Source USGS).

Biscayne aquifer is highly susceptible to contamination due to its permeability and shallow depth. The aquifer is classified as a sole source of water supply by the EPA. Water in the Biscayne aquifer is under unconfined, or water-table, conditions and the water table fluctuates in direct and rapid response to variations in precipitation. The aquifer material is especially porous under the Biscayne Bay and is highly saline. Some of this saltwater has migrated inland in response to the lowering of inland ground-water levels. The lowering of the groundwater is particularly noticeable adjacent to canals constructed for drainage of low-lying areas and near large well fields.

Major fluctuations ranging from 2 to 8 feet per year, depending primarily on variations in precipitation and pumpage can be observed in the aquifer annually. In coastal areas, this lowering of water table can lead to saltwater intrusion. The hydraulic connection between the canals and the aquifer results in benefits as well as problems. An obvious benefit is the ability of the canals to rapidly remove excess surface and ground water, thereby preventing flooding in low-lying interior areas. A subtle benefit is the ability to move water from inland parts of the aquifer to coastal areas through the canals, allowing groundwater levels near the coast to remain high enough to retard saltwater intrusion during periods of less than normal precipitation. However, due to the direct hydraulic connection between the canals and groundwater aquifer contamination by any pollutants in the canal water can be both rapid and widespread. In addition, the canals provide channels by which saltwater can encroach into the aquifer for considerable distances inland during periods of low water levels. The latter problem has been greatly alleviated by the construction of large-scale canal control structures near the coastal ends of the major canals.

2.2.5 Water Conservation Areas

South of Lake Okeechobee and the EAA, the C&SF Project compartmentalized the Everglades into WCAs 1, 2A, 2B, 3A and 3B (Figure 2.2) located within Palm Beach, Broward, and Miami-Dade counties. These five surface water impoundments covering an approximate area of 1,371 square miles, were developed to provide flood control, water storage, and wildlife conservation benefits for the region. Managed as surface water reservoirs, the WCAs have a combined storage capacity of 1,882,000 ac-ft. Outside the ENP, WCAs contain the region's last remnants of the original sawgrass marshes, wet prairies and hardwood swamps. Water Conservation Areas 2B and 3B also serve the purpose of recharging and maintaining groundwater levels in coastal areas to the east (Light and Dineen 1994). The WCAs were designed to accomplish the following seven objectives.

1. Receive and store agricultural runoff from the EAA.
2. Prevent the water accumulated in the Everglades from flowing into the urban areas of the south east coast.
3. Recharge the regional groundwater and keep saltwater intrusion at bay.
4. Store and convey water for agricultural and municipal demand, and to maintain the minimum flows in the ENP.
5. Enhance fish, wildlife and recreation.
6. Receive regulatory discharges from Lake Okeechobee during wet season.
7. Mitigate the effect of tides induced by hurricanes on marsh vegetation in the system.

2.2.6 Everglades National Park

Everglades National Park (Figure 2.2) is the largest subtropical wilderness in the United States. The park contains temperate and tropical plant communities including sawgrass prairies, mangrove and cypress swamps, pinelands and hardwood hammocks, as well as marine and estuarine environments. Known for its abundant bird life, the park has large wading bird colonies of various species, such as the roseate spoonbill, wood stork, great blue heron and a variety of egrets. Rich in wildlife, the park is host to rare and endangered species, including the American crocodile, Florida panther, and West Indian manatee. Everglades National Park was the first national park to be established to preserve purely biological resources—to protect the particular and primitive natural conditions of the subtropical Everglades ecosystem. The park is designated as an International Biosphere Reserve, a World Heritage Site, and a Wetland of International Importance, in recognition of its significance to all the people of the world (Ogden and

Davis 1994).

Flows from WCA-3A and WCA-3B enter the northern boundaries of Everglades National Park through a series of water management structures and culverts located under Tamiami Trail (US 41). Much of this water enters the park and flows in a southwest arc through Shark River Slough to Whitewater Bay and the Ten Thousand Islands area. Some of the water entering the park is diverted to the east into the South Miami-Dade Conveyance System and enters the park via the L-31N Canal and Taylor Slough. Water also enters from the C-111 Canal, where it flows south into northeastern Florida Bay.

2.2.7 Lower East Coast Service Area

The Lower East Coast (LEC) Planning Area in the SFWMD covers approximately 6,100 square miles and includes essentially all of Miami-Dade, Broward and Palm Beach counties, most of Monroe County, and eastern portions of Hendry and Collier counties (Figure 2.2). The LEC Planning Area encompasses a sprawling, fast-growing urban complex that, according to the 2000 Census, provided homes for more than 5 million people, primarily along the coast. The major water consuming areas in the LEC have been divided into three service areas, Lower East Coast Service Areas 1, 2, and 3.

The Lower East Coast Service Area 1 (LECSA-1) includes the portion of Palm Beach County east of WCA-1 and a small portion of Broward County. The service area includes the West Palm Beach Canal (C-51) and Hillsboro basins. This service area is heavily urbanized and has experienced rapid growth for several decades. A large amount of agriculture, principally winter vegetables, citrus, and nurseries, are located in the western portions of the service area.

The Lower East Coast Service Area 2 (LECSA-2) includes portion of Broward

County east of the WCAs and south of the Hillsboro Canal Basin and the C-9 Canal Basin in northern Miami. The LECSA-2 is heavily urbanized and has experienced rapid growth for several decades. While the rate of growth is slowing, the increasing population results in significant increases in demand for potable water.

Lower East Coast Service Area 3 (LECSA-3) includes portion of Miami-Dade County east of WCA-3B and Everglades National Park, as well as the Florida Keys. The Florida Keys are included in LECSA-3 because their primary source of drinking water is the Florida Keys Aqueduct Authority Wellfield located near Florida City. Water demand in the LECSA-3 is generated primarily by a mixture of urban and agricultural land uses. Population is expected to grow and displace some of the agriculture in southern Miami-Dade County. The citrus, winter vegetables and tropical fruit farming in southern Miami-Dade County represents the second-largest agricultural area in south Florida.

The agricultural and municipal demands are very unevenly distributed throughout the district. On one hand, bulk of agricultural water is consumed in the interiors of the district. On the other, most of the municipal demand comes from the lower east coast. This research in later chapters suggests measures to improve efficiency in both these sectors. Therefore, before suggesting changes, it is imperative that one has a thorough understanding of the agricultural practices and policies related to municipal water sector. The sections 2.4 and 2.5 study the policy options that are in use in other parts of the world and those which can be exercised in SFWMD.

Having understood some of the water resources and management related problems in South Florida, one can understand the deep connection between growth and the dwindling water resources. Population and agricultural growth causes more water to be drawn from the surface water bodies. This leaves them with less water than they require for maintaining their ecological functions. However, the Florida legislature mandates the water management districts in the state to define MFLs for their water bodies and ensure that those levels are maintained. The following section describes the situations leading to the framing of those legislations and their impact on the water management policies followed by the districts.

2.3 Legislations

Prior to the Florida Water Resources Act of 1972, water in the state as well as the district was managed in a very disjointed and unorganized manner. The state adhered to the Eastern US Water Law, which meant that anyone who had his property directly adjoining the water body could use the water as long as the use was considered reasonable. The uncertainty in what constitutes a reasonable use led to a large number of litigations to define reasonable use of water (Maloney et al., 1972). In that era not much emphasis was given to allocation of water to meet the requirements of the water bodies.

The SFWMD is charged by the Florida Legislature with managing the water use in South Florida. An important task in this charge is the planning for future water demands in specific geographic regions within the district. The water supply planning activities were first required of the state's water management districts following the adoption of the 'Florida Water Resources Act' of 1972 (Florida Statutes, Chapter 373). This act theorizes that the proper water allocation could best be accomplished within a statewide, coordinated planning framework.

The overall mission of the SFWMD can be summarized as follows. It is derived from the state Comprehensive plan, which states that Florida shall assure the availability of an adequate supply of water for all reasonable, beneficial, and competing uses. The state is also expected to maintain the functions of natural systems and the overall present level of surface and ground water quality. In addition, the state shall also restore the water bodies which did not meet the water quality standard (Florida Council of 100, 2003).

SFWMD attempts to achieve these goals by balancing the following six principal Water Use Directives embodied in the Florida law (SFWMD, 1991).

1. Prevent uneconomical, impractical, or unreasonable uses of the water resources.
2. Promote economic development of the water resources consistent with other directives and uses.
3. Protect and enhance environmental resources while providing appropriate levels of service for drainage, flood control, water storage, and water supply.
4. Maximize levels of service for legal users, consistent with other directives.
5. Preserve and enhance the quality of the state's ground and surface waters.
6. Develop and maintain resource monitoring networks and applied research programs (such as forecasting models) required to predict the quantity and quality of water available for reasonable-beneficial uses.

In order to address the challenge of ensuring the state's water supply, Florida Legislature enacted the Water Protection and Sustainability Program in 2005. This program was subsequently signed into a law by Gov. Jeb Bush. This program encourages cooperation between municipalities, counties, and the state's five water management districts for the protection and development of water supplies. More specifically, the law requires the regional water supply planning function of water management districts to promote alternative water supply projects to reduce the use of traditional ground and surface water supplies. The Alternative Water Supply Sources in the law, are defined as

1. Reclaimed water,
2. Saltwater and brackish water,
3. Surface water captured predominately during wet-weather flows,
4. Sources made available through the addition of new storage capacity,
5. Stormwater, and
6. Any other source designated as non traditional in a regional water supply plan.

In South Florida, most of the population is concentrated in small areas of large population density. This highly localized demand coupled with low surface water levels caused concerns to the state, which in 1997 led to the legislation called the 1997 Water Act. This act required the Water Management Districts (WMDs) to promote the availability of sufficient water for all existing and future reasonable beneficial uses and natural systems (F.S. 373.016 [2][d]). This legislation was important because aimed at increasing the water availability in the state as well as prevented the conflict between the interests of the consumptive users against each other as well as against the natural systems (Matthews and Nieto, 1998).

The 1997 Water Act required the Water Management Districts to set up MFLs for all waterbodies within their jurisdiction to maintain the environment and ecosystem of the region. These minimum flows are maintained while managing the system in accordance to the laws laid out by the Florida Legislature to protect the environment from 'harm' which has been defined as below.

Harm: the temporary loss of water resource functions, as defined for consumptive use permitting in Chapter 40E-2, F.A.C., which results from a change in surface or ground water hydrology and takes a period of one to two years of average rainfall conditions to recover.

Significant Harm: the temporary loss of water resource functions, which result from a change in surface or ground water hydrology, that takes more than two years to recover, but which is considered less severe than serious harm.

Serious Harm: the long-term loss of water resource functions, as addressed in Chapters 40E-21 and 40E-22, F.A.C., resulting from a change in surface or ground water hydrology (40E-8, FAC).

In this research, MFLs are computed on the basis of water consumption and availability. to ensure the MFLs in case of water shortage in the future and to avoid harm to the district's water bodies.

2.4 Agricultural Water

During the past few decades more than three quarters of the increase in demand for water in the world came from increases in agricultural yield, mainly as a result of the Green Revolution (FAO, 2002). Thus, many of the solutions to water shortage and environmental security problems come from within agriculture. The development and management of water supplies impact food security, ecosystems, and the services ecosystems provide. To achieve water security and ecosystem protection, water resource management requires a different perspective that focuses on both water efficiency and the value obtained from the use of water.

A general perception is that increasing efficiency in agriculture is the solution to the water crisis. Irrigation efficiency is concerned with the amount of diverted water that reaches the crops, and the amount wasted down the drain (Rijsberman and Molden, 2001). According to an estimate only 45% of applied irrigation water is actually used by the crop. The rest is lost: 15% from the irrigation system, another 15% lost in distributing water within the farm, and another 25% lost when the water is applied on the farmer's field (FAO, 1995). However, not all the water besides the consumptive use is actually lost from a systemic perspective. In some situations the water which flows over one field, but is not used for evapotranspiration and plant growth, simply flows onto the next field, or returns to canals or replenishes the underlying aquifer. If all water in a system is consumed by crops, factories, and households, nothing will be left over for environmental purposes such as flushing salts, maintaining wetlands, or for other ecosystem sustenance. Therefore, it is difficult to know how much of the water not used by crops is actually being lost. The real wastage comes from not being as productive as possible with the water that is consumed currently in agriculture (Rijsberman and Molden, 2001).

Micro irrigation, also commonly known as drip irrigation or trickle irrigation is a method which minimizes the water and fertilizer requirements for a crop due to its nature of allowing water to trickle slowly into the root zone of a plant. The most widely used version of this method is the dripping emitter which emits water drop by drop into the root zone. This method creates almost no runoff and also minimizes evaporation losses and is therefore, the most efficient of all irrigation methods currently available. Micro irrigation may also involve attachments called micro-spray heads instead of dripping emitters which spray the water over a relatively larger area and are useful for trees and orchards such as citrus, which is cultivated widely in addition to sugarcane in South

Florida. In 2000 almost all of the sugarcane plantations used flood irrigation and 79% of citrus orchards used micro irrigation (Marella, 2000).

Apart from water and fertilizer efficiency, micro irrigation also affords a large number of other advantages to the farmers. It allows for a greater control over the maintenance of soil moisture level depending upon the requirements, therefore, resulting in a higher yield because of greater control over the growing environment. Since there is virtually no runoff, it also ensures that the surface water bodies do not receive fertilizers and nutrients from the agricultural runoff. However, this method also has certain limitations which might be an obstacle for small scale farmers to adopt it. For example, the installation cost for this method is relatively high and may discourage some potential users. Also for crops like sugarcane, the tubes have to be removed before each harvest and laid again after the next plantation.

In South Florida micro irrigation is used for majority of citrus orchards however, the use of micro irrigation in sugarcane plantations is virtually absent (Marella 2000). The use of micro irrigation is increasing worldwide for most major crop types including sugarcane. The use of micro irrigation in sugarcane cultivation is shown to have lowered the water consumption by 12% and increased the yield by 20% in Hawaii (Shreshtha 1993). Indian Institute for Sugarcane Research pegs the savings due to micro irrigation at 29% over furrow irrigation (Waykar 2003). The advantages offered by micro irrigation make it a very promising prospect for South Florida as a viable alternative to flood or furrow irrigation for sugarcane plantations. In addition, to further economize water consumption, the use of drip irrigation may also be extended to the remaining 21% of the citrus orchards that are currently under conventional irrigation systems.

2.5 Municipal Water

People in urban areas have an easy access to clean potable water to meet their daily needs at a very low price. Thus, water is treated by most as a granted commodity and not much effort goes into conservation. The benefits of water conservation at homes, if taken up seriously, will be felt not only by the nation as a whole but by individual customers as well. It is estimated that an average American household spends approximately $500 on water and sewer bills and by making a few simple changes in lifestyle, approximately $170 can be saved per year. If all households in the US were fitted with low flow appliances, it is estimated that the total amount of water saved in the country in one year would be in the range of 3 trillion gallons worth $18 billion per year (WaterSense, USEPA).

Water management has traditionally been an engineering problem rather than a management one. Water supply managers tend not to use pricing as a tool to reduce water demand, instead relying on low flow appliances or restrictions to achieve this end. However, these approaches in practice often have a lower success rate than expected because of behavioral response of the customers. For example, customers may take longer showers, wash hands for a longer duration, flush the toilet twice for low flow appliances, or water the lawns longer for day of the week or time of the day restrictions (Olmstead & Stavins, 2007). The use of price as an allocation mechanism is limited by the fact that water is generally considered as a basic necessity, even a right, not an economic good (Berk et al., 1980).

Various studies suggest that pricing has a significant impact on the domestic water consumption. The description of residential demand as price inelastic is a technical definition; it simply means that one percent increase in price results in a less than one percent decrease in consumption. In other words, consumers respond to higher prices, but at a rate less than proportionate to the price increase (Renwick et al., 1998).

Conservation or water demand management is making efficient the use of water at the point of consumption. Measures such as outdoor water use restrictions during times of shortage do not play a major role in conserving water in the long run. The solutions that can be considered to be effective in the municipal sector in the long run include changes in the pricing, retrofitting homes with low flow appliances, encouraging new housing developments to adopt low flow appliances, etc. In agricultural sector, adopting micro irrigation, and using less water intensive crops can reduce long term water demands. Other intangible conservation measures can include changing the behavioral patterns of the consumers and sensitizing them towards the advantages of water conservation. These intangible conservation measures play a significant role in reducing water demands in the long run but are difficult to quantify directly. In this study, only those measures are evaluated which result in a direct quantifiable reduction in water consumption.

In most urban areas, outdoor domestic water demand is a major component of the total domestic demand. This demand includes the water consumed for lawn irrigation, landscaping, swimming pools, etc. Besides encouraging consumers to save water and adopt smart appliances for irrigating their lawns, the water management agencies can also set up regulations and restrictions to prevent unnecessary use of precious potable water. Xeriscape is defined in Subsection 373.185(1)(b), F.S.: Xeriscape or Florida-friendly landscape means quality landscapes that conserve water and protect the environment and are adaptable to local conditions and which are drought tolerant. The principles of Xeriscape include planning and design, appropriate choice of plants, soil analysis which may include the use of solid waste compost, efficient irrigation, practical use of turf, appropriate use of mulches, and proper maintenance. A number of studies conducted on Xeriscaping suggested that it led to water saving between 25 to 42% (Nelson 1994, Testa 1993, and Sovocool 2005).

Water use restrictions can play an important role not only in reducing water use during times of shortage but also as a permanent measure to reduce water consumption throughout the year. These restrictions are usually imposed upon outdoor water uses such as irrigating lawns, washing cars etc. By imposing permanent restrictions on outdoor water use, considerable amount of municipal water can be conserved. People tend to over irrigate their lawns by two or more times the water required by the plants, this leads to a considerable wastage of water (Maheshwari 2006).

2.6 Water Withdrawal Trends

The largest amount of freshwater in the state of Florida is withdrawn by SFWMD, which accounted for nearly 49% of all freshwater withdrawals in the state (Figure 2.5). In 2000, SFWMD withdrew 4731 MGD or 5.3 million ac-ft of freshwater from surface and groundwater sources. In addition, about 3952 million gallons per day (MGD) or 4.4 million ac-ft of saline water was also withdrawn and utilized for power generation. Figure 2.6 shows the total amount of water including saline water withdrawn by SFWMD.

In 2000 SFWMD was the largest supplier of public water in the state. It draws 42% of its freshwater from the surface sources and 58% from the groundwater sources (Figure

2.7). Approximately 63% of the agricultural water supply in the state was also made by SFWMD, again making it the largest supplier of agricultural water in the state. For the agricultural water supply, the SFWMD relies on surface water to fulfill 38% of its demand and the rest from groundwater sources (Figure 2.8). However for fulfilling its municipal demands, the SFWMD relies primarily on groundwater sources Figure 2.9.

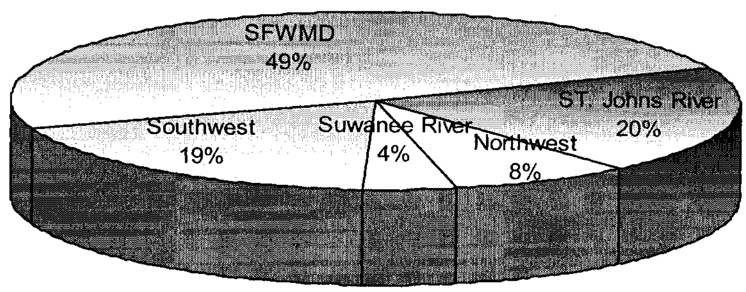

Figure 2.5 Fresh water withdrawals in FL by the WMDs in 2000.

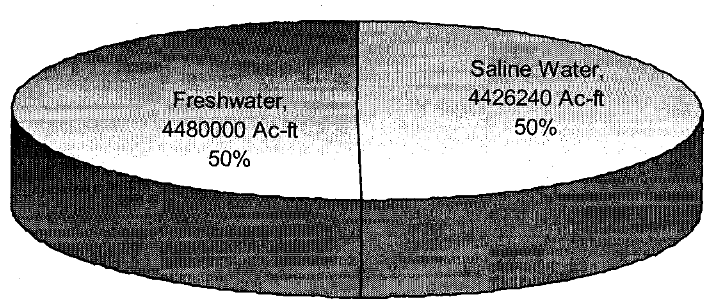

Figure 2.6 Total water withdrawals including saline water by SFWMD in 2000.

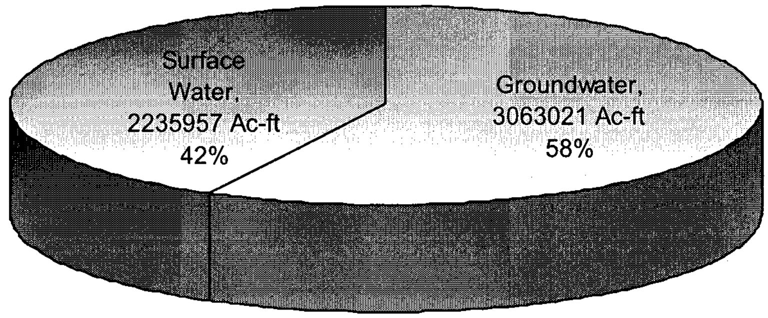

Figure 2.7 Freshwater withdrawals by SFWMD in 2000.

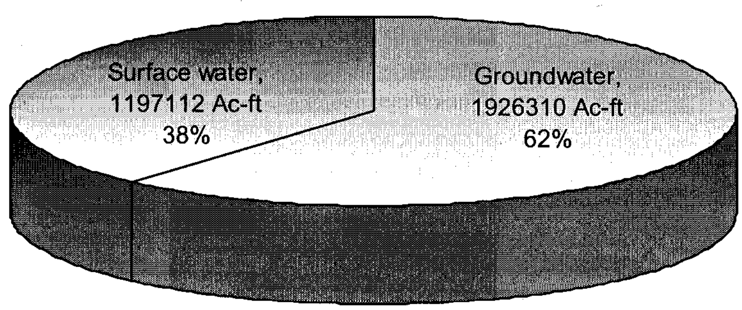

Figure 2.8 Agricultural water withdrawals in SFWMD by source in 2000

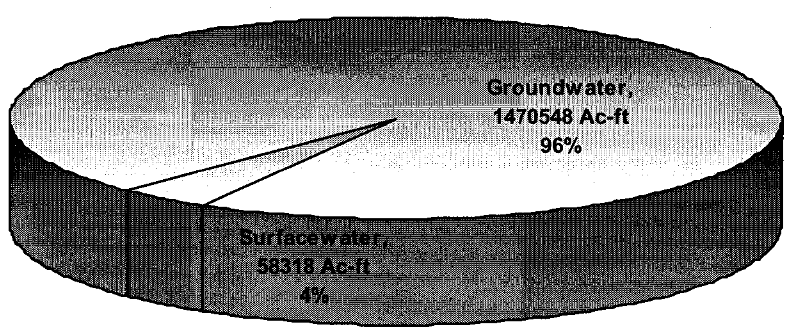

Figure 2.9 Municipal water withdrawals in SFWMD by source in 2000

2.7 Existing Models

There are a number of models related to groundwater, surface water, land use, and hydrological processes in use in the district. A few notable examples of such models are South Florida Water Management Model (SFWMM), Natural System Model (NSM), Regional Simulation Model (RSM), and MODFLOW Packages.

SFWMM plays an important role for SFWMD in water resources management and planning. It simulates the effect of rainfall and evapotranspiration on ground and surface water. It can also predict the hydrological response of the natural system to proposed alterations to the hydrological infrastructure. This model is being used in Comprehensive Everglades Restoration Project in guiding the restoration efforts.

The NSM simulates the pre-drainage response to the current hydrological conditions. Therefore, it is often used for comparing the results from SFWMM simulations. Vegetation, topography, and river courses used by NSM are based on pre-drainage conditions. Recent climatic data is used to simulate the pre-drainage hydrologic response to current hydrologic input allowing for meaningful comparisons between a SFWMM simulation of a managed system alternative and the pre-drainage natural system simulated by the NSM. RSM simulates the coupled movement and distribution of groundwater and surface water throughout the model domain using a Hydrologic Simulation Engine to simulate the natural hydrology and a Management Simulation Engine to provide a wide range of operational capabilities.

These models, however, do not include the future population growths, land use changes, water demands, and effect of climate variability within the model in an explicit and interconnected manner. These factors influence the demands as well as availability of water in the district. Hence, in order to evaluate the policy changes to be made in the future, it is necessary that the changes in the above mentioned parameters be generated within the model to more effectively capture the feedbacks they have on the system. For example, these models have to depend on independent demographic models to forecast the population growths and use these forecasts to estimate the future municipal demands. But we know from past experiences that as population increases, many other factors such as a reduction in per capita consumption, decline in agriculture etc. come into play and change the overall water demand. The present model generates the population growth, land use changes, and changes in water consumption practices within the model; therefore, it is effective in dealing with the changes in one factor when another is tweaked.

2.8 System Dynamics

System Dynamics (SD) is a simulation modeling approach available to hydrologic modelers to integrate the principles of hydrology, management, and economics into a single dynamic model. Systems Thinking and System Dynamics have found wide application in business management, policy making, and study of the behavior of natural systems. J. W Forrester is considered to be the father of Systems Theory. He came up with Systems Theory by applying the principles of feedback control in electrical engineering to other systems. Since its inception in the 60's, System Dynamics is being seen as a tool for modeling systems with behavior too complex for usual mental modeling. The Systems Thinking is based on the tenet that natural systems usually have time delays and internal feedback loops that alter the behavior of entire system. The underlying difference between SD and other modeling tools is the study of stocks and flows as individual entities which affect each other through feedback loops and together they produce effects and display certain properties which can not be attributed to any of the individual processes making up a system.

The stocks in SD are defined as variables which accumulate or deplete over time and flows are defined as inputs or outlets that increase or decrease the stock. The converters modify the flows through information links and in turn modify the stocks. A number of mathematical and statistical functions can be used to describe the relation between the converters and flows resulting in the interaction pattern simillar to the natural system.

System dynamics models can be divided into several sectors in order to reduce the complexity of a model and make it more manageable. These sectors can be modified independently but they still communicate with each other through information links. A model divided into sectors allows the modelers to look into different working parts of a model individually and makes the model more manageable. A modeler uses his judgment while deciding where to draw a boundary around a particular sector in his model. Usually, all the related converters, flows, and stocks are included in one single sector which makes it easier to isolate a particular component of the model for changes.

Over the years a number of studies in the area of water resources planning and management, and environmental sciences have been conducted using SD. This is because of the growing need to explore a large number and variety of policy options in the planning process and decision making. System Dynamics provides the planners with the ability to reproduce the structure of a natural system in a simulation model and run the simulations to a desired future time horizon, as well as weight the outcomes and results achieved as a result of adoption of the possible policy options. Even in the modern age of science and industrialization, social policy decisions are based on incompletely communicated mental models. Which means that even the modeler could not examine and scrutinize the assumptions and reasoning behind his model (Meadows 1985). Therefore, any logic behind the formulation of social policies is unclear to most people affected by the policy (Meadows and Robinson, 1985).

Dynamic feedback relationships between physical characteristics of water balance and population growth; development of agriculture and industry; technological development; and use of other resources; are not captured explicitly by many other modeling techniques. Therefore, the utility of these models for understanding the impact of water on world development at the global scale is quite limited (Simonovic, 2002).

A few notable examples of models for regional water resources management include Kao et al. (2005) who modeled the effect of growing population on water availability in Taiwan. Simonovic and Fahmy (1999) illustrated the use of system dynamics in structuring water resources policy for Nile River Basin in Egypt. Stave (2003), describes the structure of water supply system for the city of Las Vegas and how public education and awareness can help in water conservation in an already arid area. Tidwell et al. (2004) developed a model to assist in community based planning for water resources in the Middle Rio-Grande Basin in New Mexico and educating as well as engaging the public in the complex decision making processes involved. Simonovic and Ahmad (2005) developed a SD model to simulate human behavior during emergency evacuation orders for floods. Ahmad and Simonovic (2006) used Artificial Neural Networks and SD to develop a Decision Support for Management of Floods, which performs three functions for flood management i.e. selection of flood damage reduction options, flood forecasting, and operation of flood control structures. Rajasekaram and Nandalal (2005) developed a decision support model for resolving water allocation conflicts in a typical multipurpose reservoir.

Besides these, some models on a larger scale i.e., country or world level have also been developed by Simonovic (2003), wherein the future development of world is modeled as WorldWater keeping the water shortage specifically in view. The study revealed that, contrary to the predictions of other models, water is one of the limiting factors that needs consideration in global modeling of future world development and that pollution of water is the most important future issues on a global scale (Simonovic 2003). An offshoot of the same model, the CanadaWater, modeled the development of Canada keeping in view the water availability in Canada. (Simonovic and Rajasekaram 2004).

SD has also found application in describing hydrological processes such as in Li and Simonovic (2002). They use SD for simulating flood generation due to snowmelt associated with hydrological processes in North American Prairies. Previous such models did not explicitly represent the internal hydrologic dynamics and the impact of climatic factors on them. The input included all calibrated parameters such as temperature, precipitation and a set of initial values for the state variables. A number of precipitation storage sectors or Stocks were defined, these were: snow storage sector, canopy storage sector, surface soil storage sector, subsurface soil storage sector, groundwater storage sector, and runoff recession. This hydrological model shows that the simulated streamflow is influenced by the variation in temperature and precipitation as well as the moisture interaction between the surface, subsurface and the groundwater storages.

Saysel and Barlas (2001) conducted a study on South-eastern Anatolian Project in semiarid south-eastern Turkey to represent the effects of salinization and water availability on regional crop yields. The project alters the dynamics of agricultural production and land use through decreasing income levels for certain crop selections. The variables employed in the study were root zone salinity, watertable level, rootzone salinity increase, rootzone salinity decrease, watertable increase, watertable decrease discharge, and watertable decrease intrusion. The model was run for different scenarios, such as when irrigation is abandoned, for excessive irrigation, when agricultural land is progressively increased, and it predicted the effect of all these on the salinity of the land. The dynamic salinization model provides description of the long-term process of salt accumulation in lowlands under continuous irrigation practice, where irrigated lands are annually increased. Model analysis revealed three critical processes of rootzone salinity related to drainage, groundwater discharge and groundwater intrusion.

Ahmad and Simonovic (2004) developed Spatial System Dynamics providing an opportunity to integrate System Dynamics with GIS and improve upon the deficiencies of SD in representing spatial processes. This was achieved by dynamic data exchange between the two. A model of the Red River Basin, Canada was illustrated as a case study. It simulated the flow of the river in the floodplain and captured the operations of the flood control structures, calculating the damages due to floods. For the purpose of modeling, a cell to cell routing approach was adopted. The model was developed in two main sectors, flow routing, and damages. The flow routing sector describes the movement of water from cell to cell which depends upon relative elevation of the cells, slops, presence of dykes, and storage capacity of cells. More than 24 rules, governing the flow through the floodplain, were described in this sector. The stage damage curves for various cross sections were used to calculate the damages to the buildings in the damages sector. The physical processes that we are often interested in modeling are functions of both time and space. There is a continuous feedback between the two and system performance is influenced by change of condition in space as well as time. Thus Spatial System Dynamics proves to be a better tool for modeling such problems.

Ahmad and Simonovic (2000) describe an outline for a general framework for reservoir operation using SD approach. Reservoir operating rules were developed for high flood years and impacts on flood management capacity were explored by simulating a gated spillway in addition to an existing unregulated spillway on the Shellmouth Reservoir on Assiniboine River, Canada. In addition, the study evaluated alternative operating rules by changing the reservoir storage allocation, the reservoir levels at the start of the flood season, and the reservoir outflows. The causal loop for the model illustrates the relationship between inflow, upstream flooding, reservoir capacity, reservoir area, reservoir level, releases, flood storage zone, water for other uses, and downstream flooding. Time steps of one day were adopted for the model and five historic high flood years were used for simulation. The data sets considered for reservoir simulation model included reservoir volume and area curves; daily inflow, water levels, operating rules, spillway and conduit rating curves, relationship between depth of water and area flooded, additional flows joining the Assiniboine downstream, and evaporation and seepage losses. The simulations revealed that with revised operating rules, for four out of five major historic high flow years, the reservoir could have been operated without causing any flooding on the downstream or the upstream side and for the 100 year flood event there was a reduction in the flooding by 40%. It was suggested that the installation of gates on the Shellmouth dam would considerable ease the reservoir operations especially during high flow years.

Xu, et al., (2002) develop a SD model for water resources planning to analyze the sustainability of water resources in the Yellow River basin in China to future climate change, population growth, and industrial development. The Water Resources System

Dynamics model (WRSD) of the Yellow River was developed to explore a wide range of scenarios for the area. The WRSD model was created within STELLA using a planning period of 30 years and 1 year time steps. The input data included precipitation, streamflow, in stream flow requirements, industrial growth rate, per capita water use, population growth rate etc. The various scenarios modeled included business as usual, climate change, lowering of groundwater flows, irrigation improvements, increase in irrigated areas, water recycling and an integrated scenario. A total of ten scenarios for future water demand increases were analyzed to evaluate the sustainability of water supply in the yellow river basin. The study recommended that recycling of wastewater would go a long way in reducing the burden on the limited water resources. It also advocated a reduction in irrigation to increase the in-stream flow.

Ewers (2005) combined the elements of hydrology and economics in order to develop a model to facilitate the reallocation of water keeping in mind the value of the use and to achieve a greater efficiency in water use in San Juan Basin, located in the northwestern portion of New Mexico with extensions into Colorado, Utah and Arizona. Another motive of this study was to maintain the water level in the Navajo reservoir at a minimum elevation of 5990 ft for proper operation of irrigation canals. The model inspected various scenarios based upon water uses in the water supply, agricultural, energy production, and municipal sectors. The model employed monthly time steps and encompassed a time horizon from 1976 to 2045. For simplicity groundwater and its interaction with surface water was not modeled since major water usage in the basin is surface water. The major inflows considered were from the various tributaries to the San Juan River. The outflows included agricultural, municipal, and endangered species demands. The simulation results for varying intensities of droughts and for increased energy production scenario were represented in the paper. The author recommends further work on calibration of the model using historic gauge data, introducing a user interface for the model to make it more convenient for stakeholders, parameterizing river losses and leakages, and furthering the energy generation scenario.

Gao and Liu (1997) establish a SD model through systematic analysis of the regional water resources system in Hanzhong Basin, China. Based on the SD model, different exploitation scenarios are set up, and the optimal scenario and related exploitation policy are determined by multi-scenario multi-objective appraisal. The authors considered 33 variables while building the SD model, these include: Relationship between water supply and demand, water saving pressure for the supply, water availability etc. Based upon the amount of investment of water resources and industrial growth, the research came up with five different scenarios: planning scenario, status quo scenario, high scenario, middle scenario, and the low scenario which represent a decreasing rate of investment of water resources and industrial growth. The study revealed that the Middle Scenario, corresponding to a rate of investment of water resources and industrial growth of 10% each, yields the optimal rate of exploitation of the water resources.

Zarghami and Salavitabar (2006) develop a model for integrated urban water management in Tehran, Iran. The city's water authority supplied about 1000 million cubic meters of fresh water in 2004 out of which 40% came from groundwater sources, during droughts however, the contribution of groundwater rises to about 50%. The other sources include Karaj, Latyan and Lar dams which contributed about 674 million cubic meters of fresh water. Due to an increase in population and per capita consumption of water, the demands are expected to outstrip the supplies sooner or later, therefore, necessitating proper management of the region's water resources. The variables studied in this model are groundwater, surface water, water demand, shortage, and budget for water management. The model was simulated using historic data from the years 1990-2000. Tehran's SD model simulated a water shortage in the near future. It also predicted that extension of wastewater collection and treatment system will promote water supply and this will reduce the water shortage. Water saving fixtures at homes, extension of wastewater collection and treatment system were also presented as possible solutions to promote water supply and reduce the water shortage.

Guo et al., (2001) develop an environmental system dynamics model (ErhaiSD) for environmental planning and management in the Lake Erhai Basin, China. Interactions among a number of system components within a time frame of 15 years beginning from 1996, were examined dynamically. The main concerns included water pollution in Xier River due to industrial wastewater discharge and eutrophication in Lake Erhai due to nutrient discharges from non-point pollution sources. For modeling, the variables included in the study were population, industry, pollution control, and water-quality. The study predicted the growths in population, economy, changes in pollution, and water quality and quantity. The study proposed some steps for pollution abatement in the basin. The predictions for population, land use, agricultural water consumption and lake level had errors less than 3% but for industrial activities they were as high as 40%. Besides the base run, three additional alternatives were also considered. Alternative 1 offered a balance between environmental and economic objectives, alternative 2 promoted industrial growth at a cost to the environment, and alternative 3 emphasized on water pollution control which would probably result in a reduced economic development.

Elshorbagy et al., (2005) developed a SD model to assess the sustainability of reclamation of disturbed watersheds due to the mining of oil sands in Northern Alberta, Canada which leaves behind large pitstailing facilities, and overburden in which the natural hydrology of the surface and groundwater has been changed completely. The model accounts for the different components of the water balance in the reconstructed watershed. It identifies the ability of the watershed to allow revegetation and, seeks a solution for minimization of undesirable deep percolation of water to underlying layers. The various stocks defined for the system were peat storage, snow storage, till storage, and shale storage. Climatological factors such as temperature determine the snowmelt, rainfall and snowmelt determined the amount of water available for infiltration and soil moisture affects, in the form of feedback, the amount of infiltrating water. The difference between the amount of water available and infiltrating water was represented as channel storage. The model suggested that the proposed cover could be successful in restoring two of the major watershed functions of runoff and infiltration. Certain inconsistencies were observed between the observed and simulated values which can be attributed to the limitations of the measuring instruments.

Sehlke and Jacobson (2005) developed a SD model for transboundary river systems such as the Bear River Basin in northwest USA. The model examined how SD can link the various components of a hydrologic system into a model that can help explain the behavior of the system and test various management strategies. The Bear River basin is turning from primarily an agriculture dominant area into a mix of agricultural and suburban area, connected to this change are problems such as an increase in water demand, water quality issues etc. Besides the river makes five crossings between the three states and the aquifers connected are also interstate, this poses a number of management problems for the allocation of water. This research integrates climatic factors, hydrological processes, and management parameters into a dynamic simulation model. The structure includes precipitation, evapotranspiration, storage, ground water flows, surface water flows, and water use and residence times. The model could predict the availability of water during particular times of the year at any point along the hydrologic system. The model could also estimate the amount of water flowing past each gauge station and allocations to the different users in the system..

System Dynamics models are not usually predictive in nature because they do not provide with point predictions. But they are either descriptive in nature and give an insight into the working of a system or they are predictive to the extent of giving an insight into the behavior of the natural systems and improve the understanding of the system (Ford 1999). A descriptive model looks in hindsight and answers questions such as the cause of an observed problem. A predictive model allows the understanding of future trends and helps in identifying leverage points on which to apply pressure in order to move the system in a desired direction (Hughes 1999).

The present model and research use the concepts of hydrology and water resources management in systems approach to not only obtain the future trends in water consumption and availability, but also improve the understanding of the internal workings of a complex hydrological system. The laws and the legislations, leading to the formulation of the districtwide water management plans and MFLs, provide a framework within which this study is conducted. A further study of the models used by SFWMD, for forming its water management policies, provides the direction for this study. SD, which is increasingly being used in a wide variety of problems in all major disciplines of study, is selected as the modeling tool because of its capability to include a diversity of data in a single model. The details of model formation and the individual sectors are discussed in Chapter 3.

CHAPTER 3

METHOD

In this chapter, the details of the Decision Support (DS) model and its component sectors are discussed. The model framework is developed using SD and the different components of the system are modeled in individual sectors within the model. In this study Structural Thinking Experiential Learning Laboratory (STELLA®) by "I See Systems" is used for modeling the water resources of South Florida. The model uses a time horizon from 1970 to 2050 with a monthly time step. The period between 1970 and 2000 is used for calibration and the remaining is used for projections. This chapter begins with a brief description of the modeling software STELLA®, and in the subsequent sections describes the model structure and component sectors of the model.

3.1 STELLA®

The model is created using the software STELLA®, which is an object oriented modeling software based on SD approach. It has a three level working environment. The lowermost level contains the equations that govern the working of the model. The middle level is the map level in which the model structure is drawn. The top level is the user interface where the controls for the inputs to the model can be provided. STELLA® provides a number of tools such as slider inputs, switch selections, graphical and tabular display etc. to make the model interactive and interesting to the user. Figure 3.1 shows the user interface constructed for the present model on STELLA®.

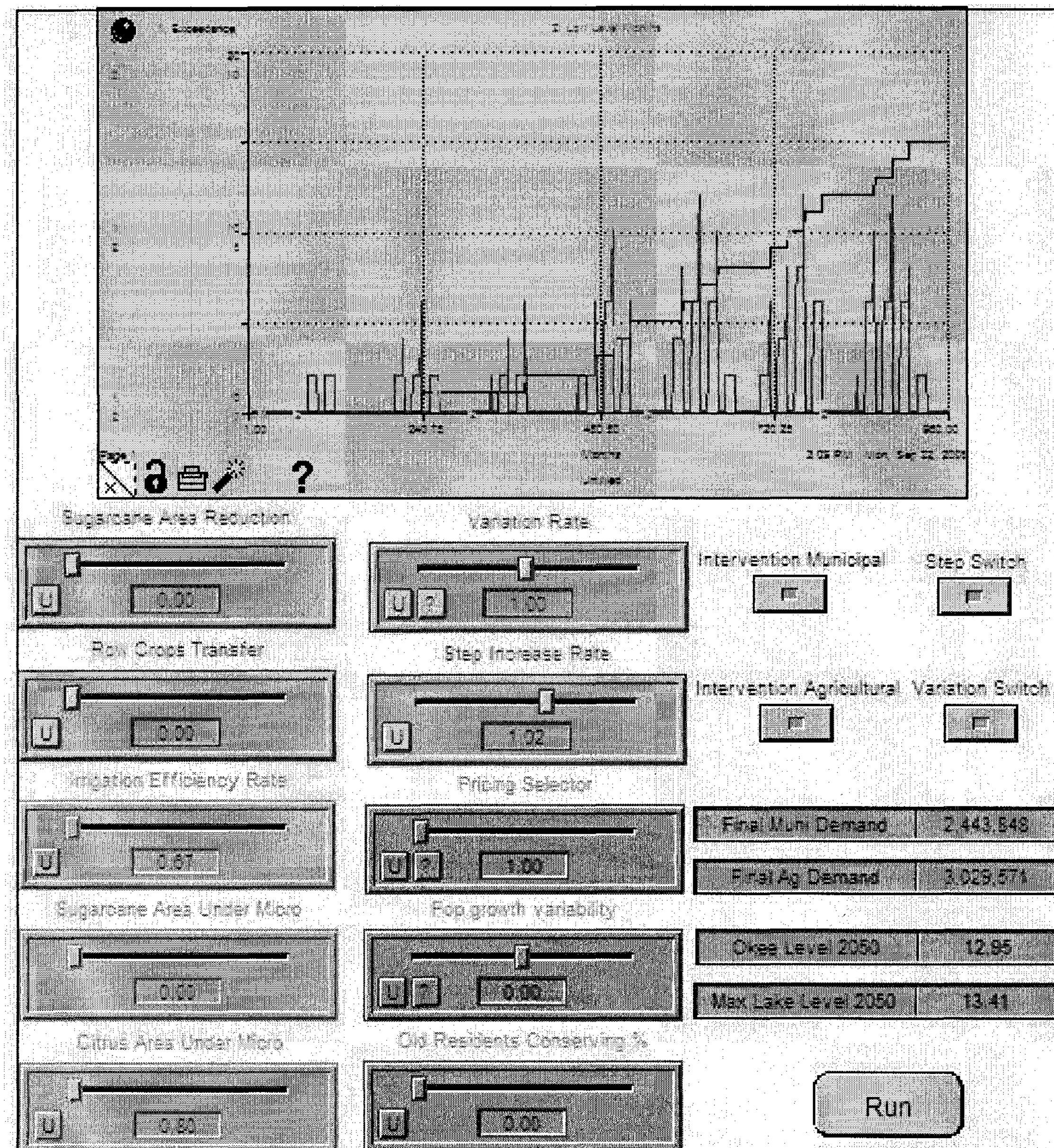

Figure 3.1 User interface for the model in STELLA®.

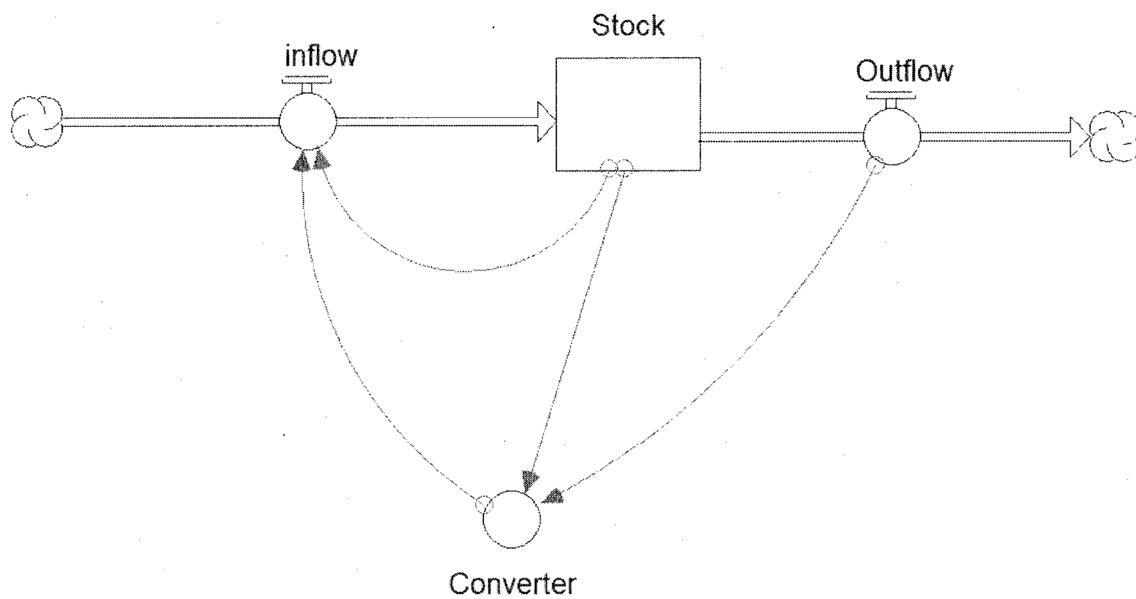

Figure 3.2 Building blocks in STELLA®.

In the map level, four basic building blocks are available to draw the structure of a model. Figure 3.2 demonstrates the use of the four building blocks in STELLA®. Stocks, represented by rectangles, are accumulations which increase or deplete over time. Flows cause the stocks to increase or deplete and are represented by arrows moving into or out of the stocks. Converters define the inputs to the model, hold constant values, and do algebraic operations. Connectors are the arrows which link the stocks to converters, converters to flows, converters to converters, flows to converters and carry out the role of passing information between the blocks they connect in the direction of the arrow.

3.2 Model Sectors

The present model is a water budget for Lake Okeechobee and Biscayne Aquifer. It contains seven sectors directly or indirectly connected and influencing each other in more than one way as shown in Figure 3.3. Figure 3.3 shows the interaction between the major components of the model. Similar figures representing different model sectors in this chapter only provide a visual representation of the structure of the sector. A number of converters and connectors have been removed for simplicity and the figures display only the major components of the sector. The model consists of the following seven sectors, each of which is described in detail in this chapter.

1. Population
2. Land Use
3. Surface Water
4. Ground Water
5. Agricultural Demand
6. Municipal Demand
7. Environmental Demand

3.2.1 Population

Population is one of the major driving factors behind the amount of municipal water consumed in the region. The district has seen a significant population growth since the beginning of simulation period in 1970. This growth translates into an equivalent increase in water consumption. The population growth rate used for water demand forecasts is one which is in agreement with the forecasts of the US Census Bureau. However, using a deterministic approach towards modeling can significantly reduce the applicability of the model under varying circumstances. Therefore, the present model allows for changing the rate at which the population grows.

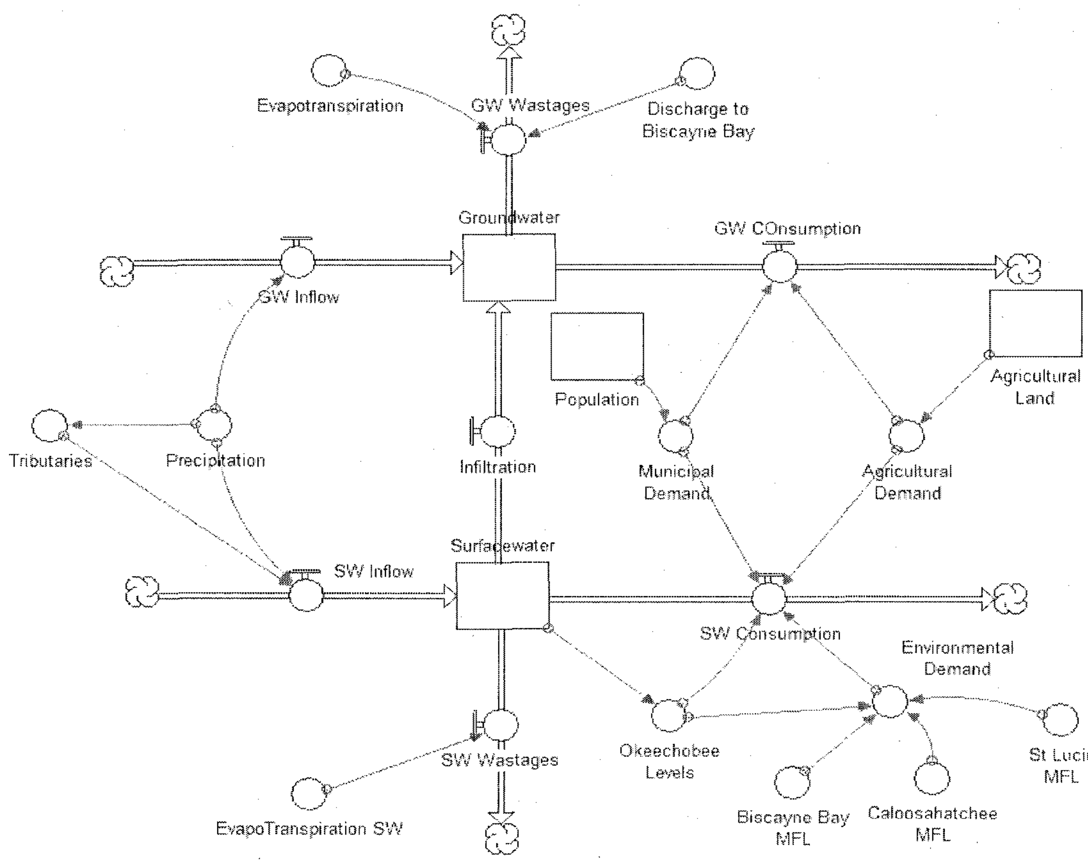

Figure 3.3 Basic structure of the model.

The population at any time *(t)* is given by

$$P(t) = P(t - dt) + (P_{gr} - P_{dc})dt \tag{3.1}$$

where

$P(t)$ = Population at time 't',

P_{gr} = Population growth in time (dt),

P_{dc} = Population decline in time (dt), and

In SFWMD the population in 1970 was 2.59 million and is expected to grow to 12 million by 2050. Population in three out of the sixteen counties i.e., Charlotte, Polk, and Orange is excluded from the because only a small part of these fall within the boundaries of SFWMD. The population in the counties of SFWMD is shown in Table 3.1.

Table 3.1 Population of South Florida by county in 1970 and 2000 (US Census).

County	Population in 1970	Population in 2000
Broward	620,100	1,623,018
Collier	38,040	251,377
Glades	3,669	10,576
Hendry	11,859	36,210
Highlands	29,507	87,366
Lee	105,216	440,888
Martin	28,035	126,731
Miami-Dade	1,267,792	2,253,779
Monroe	52,586	79,589
Okeechobee	11,233	35,910
Osceola	25,267	172,493
Palm Beach	348,753	1,131,191
St. Lucie	50,836	192,695
Total	2,592,893	6,441,823

The inflows and outflows to and from the population are due to births, immigration, deaths, and emigrations. The immigration rate, emigration rate, death rate, and birth rate are derived from a study on Florida's population growth and demographics (Smith 2005). The shift of populations within the district are assumed not to impact the overall water consumption, therefore, are not accounted for. The inflow to the population, which represents the population growth, is given by

$$P_{gr} = B + I \quad 3.2)$$

where

P_{gr} = Population Growth,

B = Number of births, and

I = Number of immigrations.

The outflow from the total population, which is the decline in population is given by

$$P_{dc} = D + E \quad (3.3)$$

where

P_{dc}= Population Decline,

D = Number of deaths, and

E = Number of emigrations.

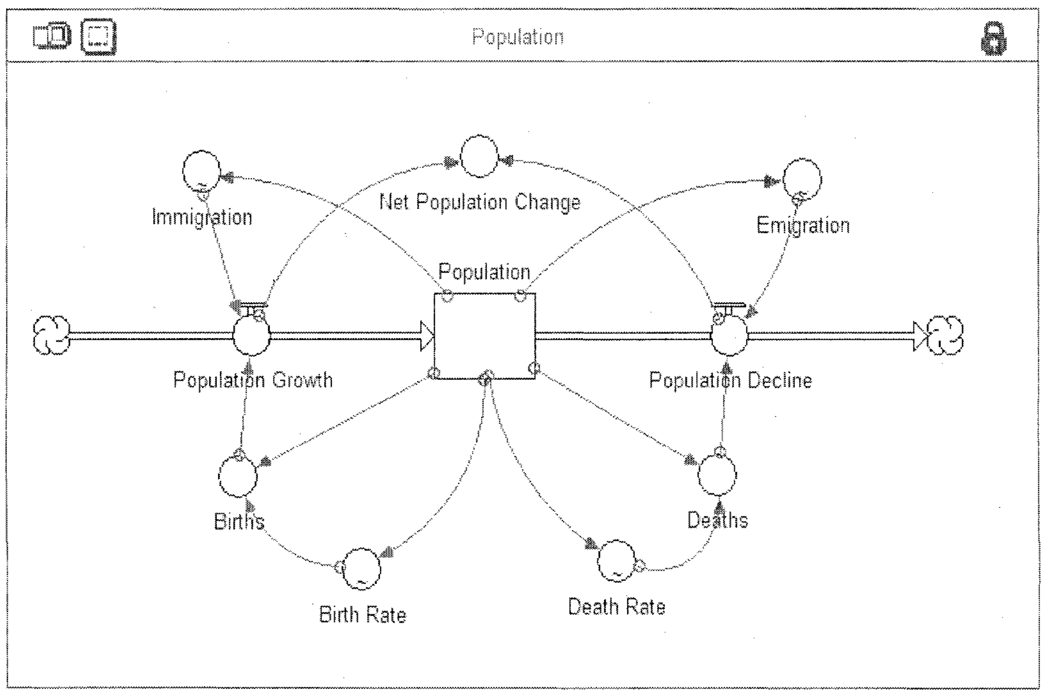

Figure 3.4 Basic structure of the population sector.

Figure 3.4 shows a representation of the population sector. The inflows and outflows are affected by the feedback from the population. Birth rate, death rate, immigrations, and emigrations influence the population and in turn are influenced by the population.

3.2.2 Land Use

For the planning horizon of fifty years, the land use in the district is expected to undergo considerable changes. These changes are capable of bringing about a significant increase in water consumption as well as the relative distribution of water demand among various competing uses. In this sector, majority of shifts in land use are assumed to be from the natural to agricultural, natural to urban, and agricultural to urban land uses. This is a very reasonable assumption since the growing population virtually rules out any changes in the reverse direction. The amount of natural land at any time *(t)* is given by the equation

$$L_N(t) = L_N(t-dt) - [(P_{gr} \times F/2) + C_{Ag}] \qquad (3.4)$$

where,

L_N = Natural land,

P_{gr} = Population growth in time interval (dt),

F = Urbanization factor, and

C_{Ag}= Conversion to agricultural land in time (dt).

The amount of agricultural land in the district at any time (t) is calculated using the equation

$$L_{Ag}(t) = L_{Ag}(t-dt) + (C_{Ag}) - (P_{gr} \times F/2) \qquad 3.5)$$

where,

L_{Ag}= Agricultural land,

C_{Ag}= Conversion of natural land into agricultural land in time (dt),

P_{gr} = Population growth in time interval (dt), and

F = Urbanization factor.

The land use data for the years 1988 and 2030, obtained from SFWMD website GIS catalog (www.sfwmd.gov), is used for modeling the changes. The distribution of land among various uses considered at the beginning of simulation period is as follows; 66% natural, 29% agricultural, and 5% urban (SFWMD 1999).

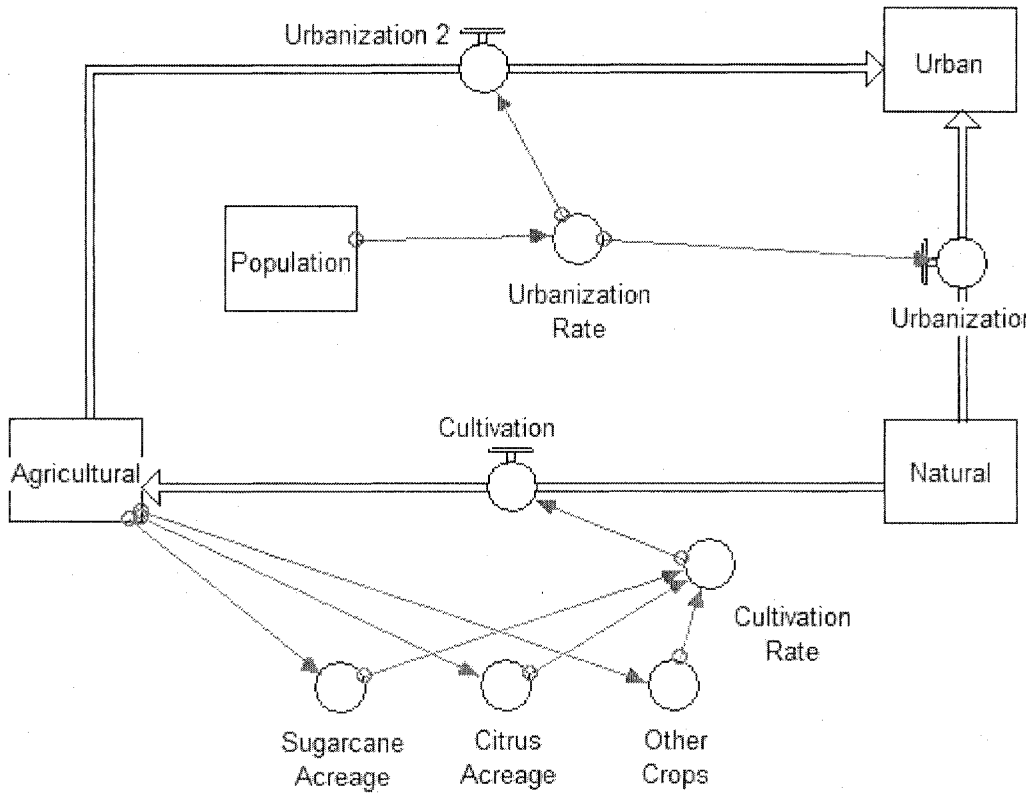

Figure 3.5 Basic structure of the land use sector.

Figure 3.5 shows the basic structure of the land use sector in the model. It consists of three stocks representing the three broad categories of land uses i.e., natural, agricultural, and urban land. An Urbanization converter is used to transfer land from the agricultural and natural land to the urban land use. This factor converts a fixed amount of agricultural and natural land into urban land for every added person to the total population. The allocation rate decreases with time and takes into account, the reduction in available land and population density. The urbanization factor is derived from a study conducted to determine the rate of urbanization of Florida due to increasing population (Zwick 2006). It is estimated that with the existing development patterns, in the five Southeast Florida counties, an additional 311,155 acres would be required between 1995 and 2020, with 92% of that being used to accommodate residential development. Most of this land would come from lands presently used for agriculture (Burchell et al., 1999). Initially, when more land is available for expansion, the rate of land use conversion per person is higher but subsequently lowers as urbanization increases and reaches towards a saturation point. The rate of conversion of natural land into agricultural land is determined using historical trends beginning 1970 to 2000 and the future projected growth in agricultural area is obtained from the SFWMD land use and land cover maps. The amount of the urban land in the model is estimated using the equation

$$L_u(t) = L_u(t - dt) + (P_{gr} \times F) \quad (3.6)$$

where,

L_u = Urban land use,

P_{gr} = Population growth in time interval (dt), and

F = Urbanization factor.

In order to test the policies of crop substitution, and acreage reduction, a provision is made to allow the transfer of land under sugarcane cultivation to other crop types. This provision was made only for sugarcane because of the very high water requirement of sugarcane crops. The model allows the selection of the annual rate at which the area under sugarcane is transferred to other crops. The land released from sugarcane cultivation can then be distributed among the other crop types in the region.

3.2.3 Ground Water

Figure 3.6 shows the idealized cross section of the Biscayne aquifer. It can be approximated as a wedge having its thicker end towards the east and uniformly reducing in thickness inland. In the calculations for the capacity of Biscayne Aquifer, the bottom face of the aquifer is assumed to have a uniform gradient sloping down towards east.

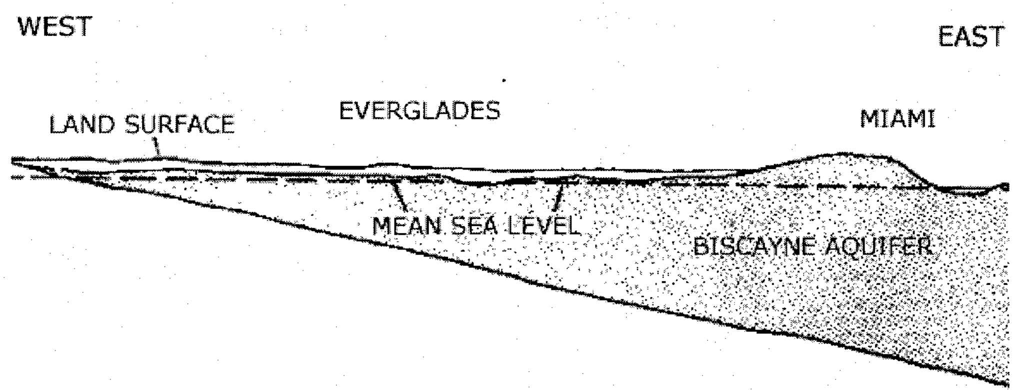

Figure 3.6 Idealized cross section of the Biscayne Aquifer (Parker, 1951).

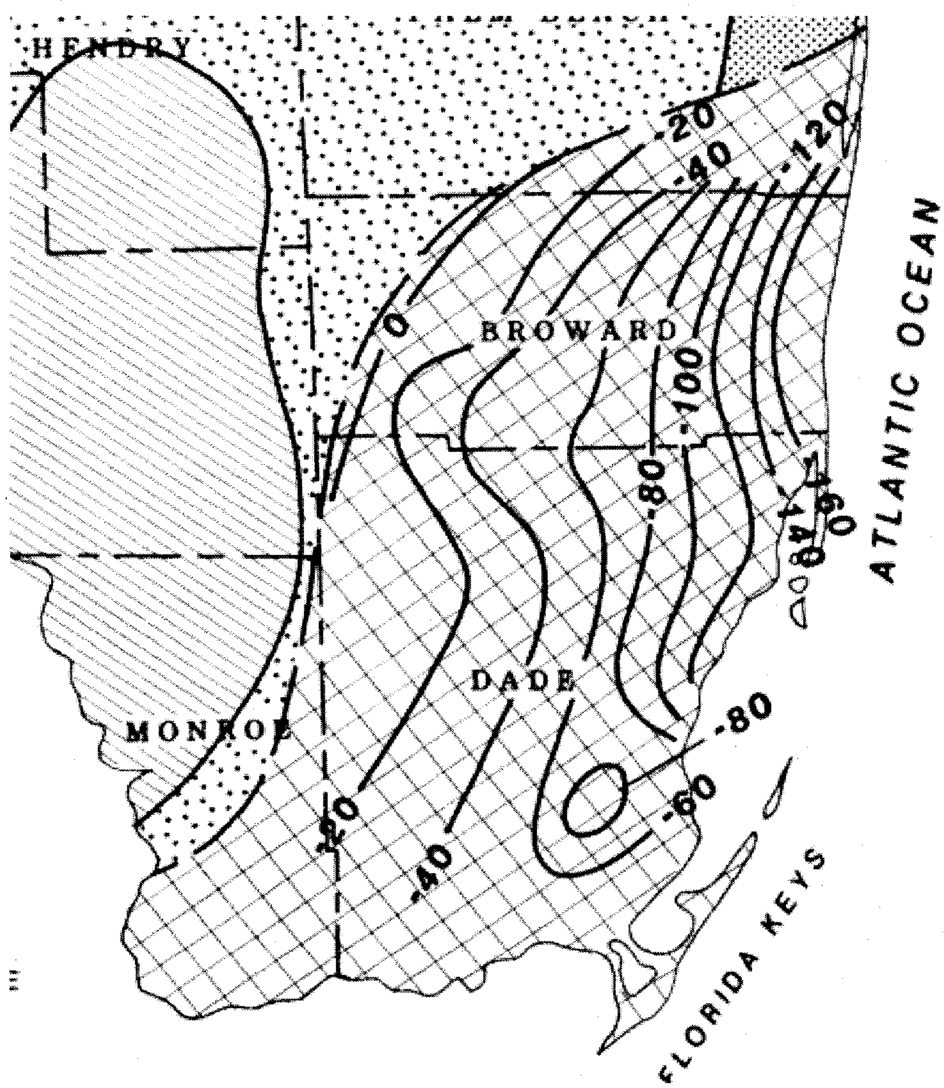

Figure 3.7 Depth of base of the Biscayne Aquifer below sea level (Klein, 1975).

Figure 3.7 shows the depth of the Biscayne Aquifer below sea level. This figure was used to calculate the capacity of the Biscayne Aquifer as shown in Table 3.2. Column 1 contains the range of depth of the base of the Biscayne Aquifer below the sea level. Column 3 contains the number of cells lying between the corresponding contour intervals in the table. The total area of the Biscayne Aquifer at the surface is roughly equal to 4000 sq miles and on the figure it is covered by a total of 412 cells. Thus area of one cell is equal to 9.7 sq miles. The volume of aquifer material is calculated by multiplying the area between the contours with the average depth. To calculate the effective water storage in the aquifer, the total volume of the aquifer is multiplied by the storage coefficient.

Storage coefficient is defined as the volume of water released from a vertical prism of having a base of unit area and a height equal to the thickness of the aquifer when the piezometric surface falls one unit of height. The mean storage coefficient for the Biscayne Aquifer is approximately 0.2 (Klein 1978). Thus, the Biscayne aquifer can hold approximately 28 million ac-ft of water. The stage storage curve for the Biscayne Aquifer is shown in Figure 3.8. The model assumes that the ratio of withdrawals of groundwater and surface water remain constant at the present value and groundwater is able to meet its share of the total water withdrawals. The Groundwater at a time (t) is calculated using

$$GW(t) = GW(t - dt) + R - (C + W) \tag{3.7}$$

where

GW(t) = The volume of water contained in the aquifer at time (t),

R = Recharge in the time interval *(dt),*

C = Consumption in the time interval *(dt), and*

W = Wastages in the time interval *(dt).*

Table 3.2 Calculation for capacity of Biscayne Aquifer.

Contour Interval	Average Depth (ft)	Number of cells	Area Between Contours (sq miles)	Area Between Contours (Acres)	Volume Between Contours (Ac-ft)
0 – 20	10	110	1068.10	683,584	6,835,840
20 – 40	30	76	737.96	472,294	14,168,832
40 – 60	50	85	825.35	528,224	26,411,200
60 – 80	70	45	436.95	279,648	19,575,360
80 – 100	90	26	252.46	161,574	14,541,696
100 – 20	110	25	242.75	155,360	17,089,600
120 – 140	130	20	194.20	124,288	16,157,440
140 – 160	150	11	106.81	68,358	10,253,760
160 – 180	170	14	135.94	87,001	14,790,272
SUM		412	4000.52	2560,332	139,824,000
Average Storage Coefficient for Biscayne Aquifer					0.2
Volume of water contained in the Biscayne Aquifer (Ac-ft)					27,964,800

The Biscayne Aquifer is one of the most productive aquifers in the world and comprises of highly permeable limestone and sandstone formations. Since the aquifer lies at such shallow depths, it is easily recharged by precipitation occurring over it. The recharge primarily comes from percolation of precipitation, irrigation water, and the infiltration from the surface water bodies.

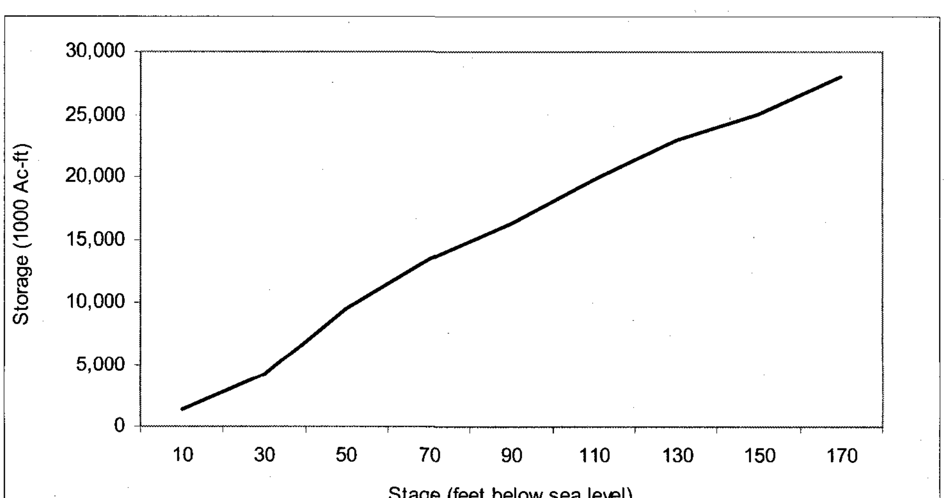

Figure 3.8 Stage storage curve for the Biscayne Aquifer.

The recharge into the groundwater is obtained using

$$R = (C_I \times P) + R_{Ag} + I_{WCA} \quad (3.8)$$

Where

C_I = Coefficient of infiltration,

P = Precipitation,

R_{Ag}= Recharge from agricultural water use, and

I_{WCA}= Infiltration from WCAs

The major outflows from the Biscayne Aquifer include groundwater withdrawals for irrigation, municipal supply, evapotranspiration, and seepage into the Bay of Biscayne. Unlike most other aquifers, the Biscayne aquifer lies at very shallow depths under water table conditions, usually within the rootzone levels and sometimes at the surface. Therefore, a significant portion of water that infiltrates into the aquifer is evapotranspired by the vegetation (USGS, Groundwater Atlas of the United States 1990). The wastages from the Biscayne Aquifer are calculated using

$$W = Et + D \quad (3.9)$$

where,

Et = Evapotranspiration losses, and

D = Subsurface discharge to Biscayne Bay and canals.

Consumption is the amount of water withdrawn from the Biscayne Aquifer by SFWMD for agricultural and municipal uses. Approximately 62% of agricultural and 96% of municipal water requirements is drawn from the aquifer. The consumptive withdrawals from the groundwater are calculated using,

$$C = (0.96 \times Mu) + (0.62 \times Ag) \quad 3.10)$$

Where

Mu = Municipal demand,

Ag = Agricultural demand.

The Biscayne aquifer loses a considerable amount of water into the Biscayne Bay and also through evapotranspiration since it lies at a very shallow depth. Both these components are added up to determine the wastages from the Biscayne Aquifer (Klein, 1978). It is estimated that 20 inches of the approximately 60 inches of annual rainfall in Dade County is lost directly by evaporation, about 20 inches is lost by evapotranspiration after infiltration, 16 to 18 inches is discharged by canals and by coastal seepage, and the remainder is utilized by man (Sherwood, 1973). Thus, nearly 50 % of the rainfall that infiltrates the Biscayne aquifer is discharged to the ocean, a reflection of the high degree of connection between the aquifer and the canal system.

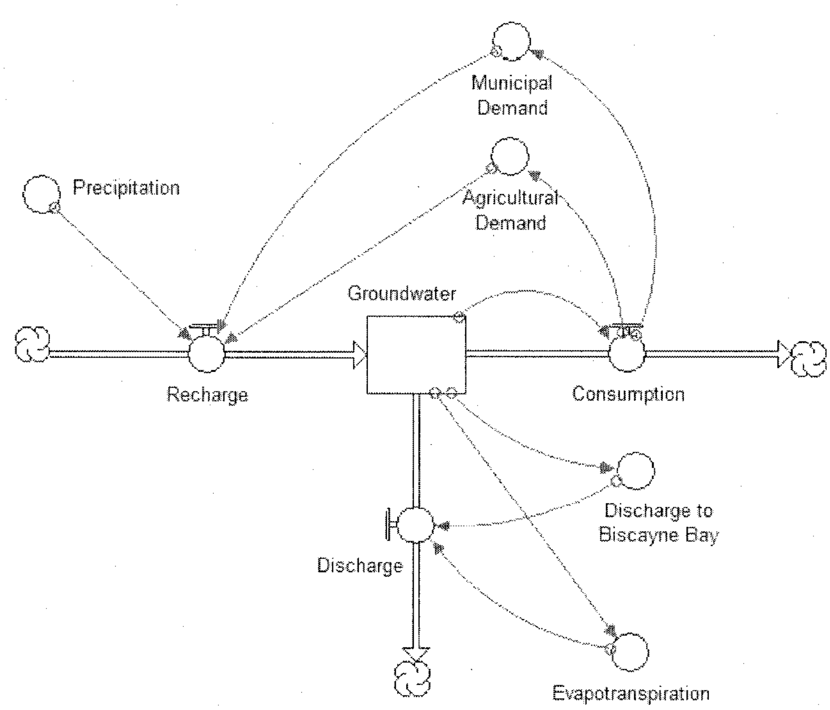

Figure 3.9 Basic structure of the groundwater sector

Figure 3.9 shows the basic structure of the groundwater sector. The volume calculated in Table 3.2 gives the initial value of the stock for the groundwater sector. This value gives the total potential water storage in the Biscayne Aquifer and is acted upon by inflows and outflows, which increase and decrease its value over time.

3.2.4 Surface Water

After Lake Michigan, Lake Okeechobee is the second largest freshwater lake in the mainland US. It has a surface area of approximately 730 square miles and an average depth of 9 feet. The stage area storage curve for the lake is shown in Figure 3.10. The lake has a total storage capacity of over 6 million ac-ft when full at a stage of 20 ft but the water levels are regulated within 13 ft to 15 ft. This is done in order to ensure the safety of the Herbert Hoover Dyke surrounding the lake and to maintain the extensive littoral zones around the lake in a healthy condition.

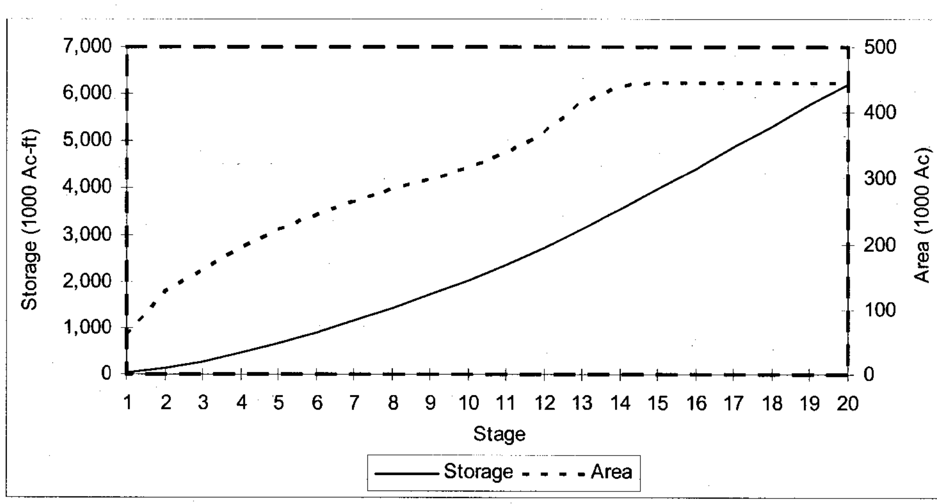

Figure 3.10 Stage-Area-Storage curve for Lake Okeechobee.

Lake Okeechobee is the primary stock in the surface water sector, and its volume is dependent on inflows, outflows, and wastages. Figure 3.11 shows the basic structure of the surfacewater sector. The inflow into Lake Okeechobee primarily comprises of rainfall occurring over the lake, and the runoff from kissimmee River basin. The surface water stock in the lake at a time (t) is calculated using

$$SW(t) = SW(t-dt) + I - (C + W) \qquad 3.11$$

where

S$W(t)$ = The volume of water contained in the lake at time (t),

I = Inflow in the time interval *(dt),*

C = Consumption in the time interval *(dt),* and

W = Wastages in the time interval *(dt.).*

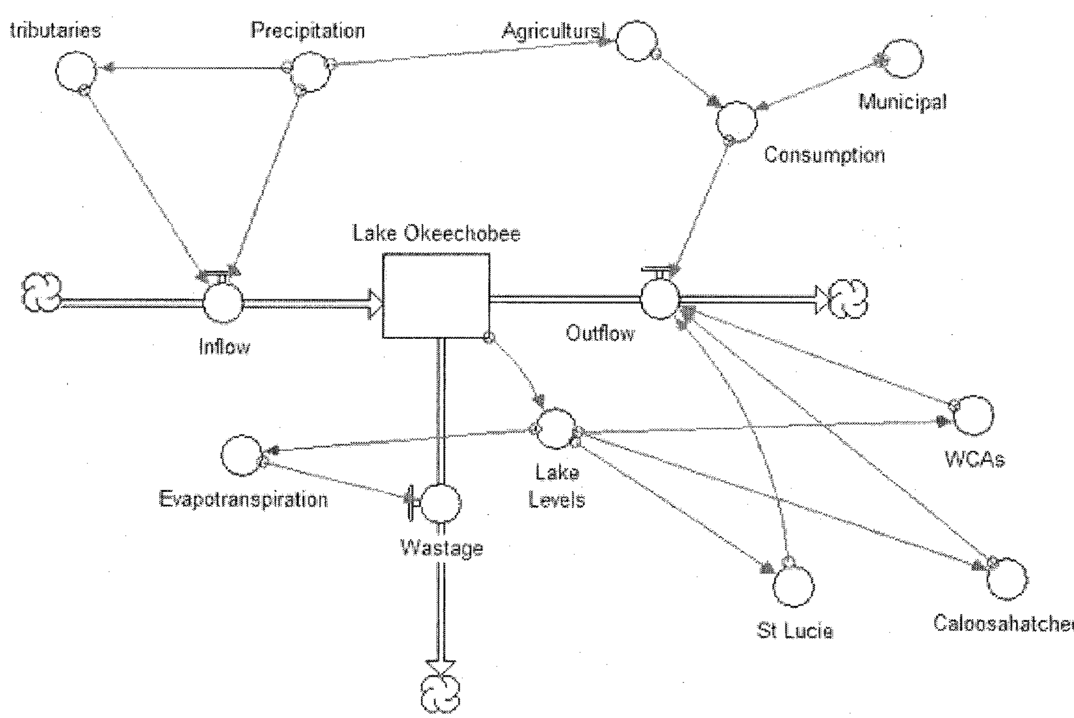

Figure 3.11 Basic structure of the surface water sector.

The inflow into the lake comprises of precipitation occurring directly over the lake, and the precipitation occurring in the Kissimmee basin, which is converted into effective runoff in kissimmee River using runoff coefficients (

Table 3.3) obtained from GIS Data from SFWMD website. The contributions from kissimmee River, minor tributaries such as Taylor Creek, Fisheating Creek etc. in the model are lumped under the inflow from the tributaries. The rainfall amount that is used for the modeling is the average of precipitation from 1914 to 2000. Actual rainfall is not used for modeling the status quo because large temporal variations in rainfall amounts tend to overshadow the general trends which this study is interested in. These are later varied in rainfall variability scenarios to account for changing rainfall amounts. The inflows to the lake are calculated using the equation

$$I = (C \times P \times A_{Kissimmee}) + (P \times A_{Okee}) \quad (3.12)$$

Where,

P = Average annual precipitation.

I = Inflow to the Lake

C = Runoff coefficient for Kissimmee River basin,

$A_{Kissimme}$ = Area of Kissimmee River basin, and

A_{Okee} = Area of Lake Okeechobee.

Table 3.3 Runoff coefficients for Kissimmee River Basin.

Percentage of total area	Runoff Coefficient
0.35	0.15
92.25	0.28
7.40	0.07

The outflows from the lake include the agricultural and municipal consumptions, and environmental flows. The water levels in Lake Okeechobee are maintained through regulatory and non regulatory releases. The regulatory releases are made according to a calendar based schedule established by USACE and SFWMD in order to ensure the peripheral integrity of the levee constructed around the lake. The schedule is designed to have minimum impact on the ecology of the downstream systems at the same time meeting the flood control requirements. Regulatory releases can be made through the St. Lucie canal and Caloosahatchee River to the sea, or to the WCAs. The flow into the WCAs and the discharge in the distributaries is regulated according to Water Supply and Environmental (WSE) Regulation Schedule shown in Figure 3.12 & Table 3.4. The WSE regulation follows the protocol shown in Figure 3.13. Non regulatory discharges are made in order to serve a variety of purposes such as irrigation, municipal water supply, prevention of saltwater intrusion, and maintaining MFLs. In addition to the regulatory and non regulatory discharges, some water escapes Lake Okeechobee through evaporation which also has been accounted for as wastage. The value of evapotranspiration depth from the surface of the lake, was adopted as 56 inches. This value is based on the historic records from 1965 to 2000 (SFWMM, 2005). The outflows which are a sum of consumption and losses are calculated using the equation

$$O = [(0.04 \times Mu) + (0.38Ag)] + (Et \times A_{Okee}) + (Env) \qquad 3.13)$$

where,

O = Outflows from the lake,

Mu = Municipal demand,

Ag = Agricultural demand,

Et = Evapotranspiration from the lake,

A_{Okee}= Area of Lake Okeechobee and

Env= Environmental flows to St. Lucie, Caloosahatchee, and WCAs.

The lake also is a source of agricultural water for the EAAs lying immediately south of its rim. Approximately 38% of agricultural and irrigation water in the district is obtained from the lake, the rest being drawn from groundwater sources. Apart from agricultural water, the lake also supplies a small fraction of the district's municipal water demand especially for the towns located close to the lake in Lake Okeechobee Service Area. Lake Okeechobee and the surface water sources account for approximately 4% of the district's municipal demand.

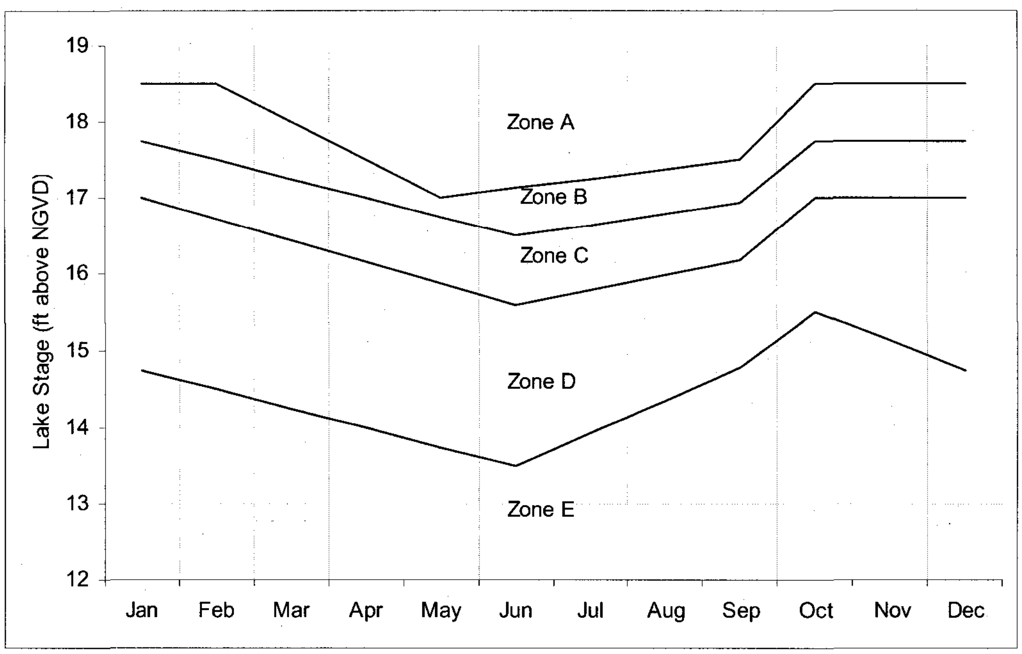

Figure 3.12 Okeechobee WSE regulation schedule.

Table 3.4 Okeechobee WSE regulation schedule.

Zone	Flow to WCAs	Caloosahatchee River	St. Lucie Canal
A	Max Practicable	Up to Max Capacity at S-77	Up to Max Capacity at S-80
B	Max Practicable	6,500 cfs at S-77	3,500 cfs at S-80
C	Max Practicable	Up to 4,500 cfs at S-77	Up to 2,500 cfs at S-80
D	Max Practicable	Max Non-Harmful Discharge to estuary when stage rising	Max Non-Harmful Discharge to estuary when stage rising
E	No Regulatory Discharge	No Regulatory Discharge	No Regulatory Discharge

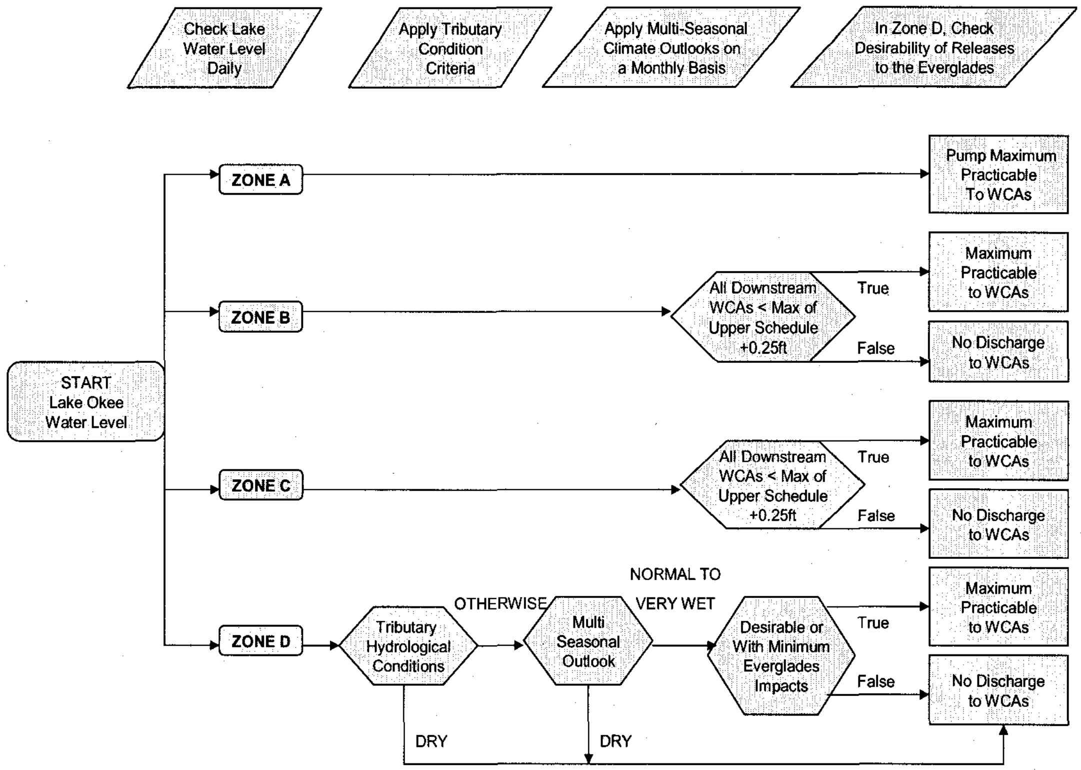

Figure 3.13 Lake Okeechobee operational guideline tree.

3.2.5 Municipal Water Demand

The major urban centers of the LEC, i.e., Miami Dade, Palm Beach, Broward counties are the biggest consumers of municipal water in the district. The average per capita water consumption per day, which has stayed more or less constant since 1970 at 170 gpd, is used as a base demand (SAFE, 1995). This figure of 170 gpd is the total consumption in the region divided by the number of inhabitants and besides domestic consumption also includes public, industrial, and commercial water uses. The division of municipal water use in the different sectors is shown in the Figure 3.14 (Marella, 2000). The biggest consumer of municipal water is the domestic sector followed by commercial and public water uses. The water conservation techniques in the model are applied to only the domestic indoor and domestic outdoor uses.

The Figure 3.15 shows the structure of the municipal demand sector in the model. The Domestic demand is further split into indoor and outdoor uses and the indoor use undergoes yet another division into the various uses such as bath/showers, faucets, laundry, kitchen etc. (Table 3.5). This division of indoor water is necessary in order to apply the effect of low flow appliances in each of the water uses independently.

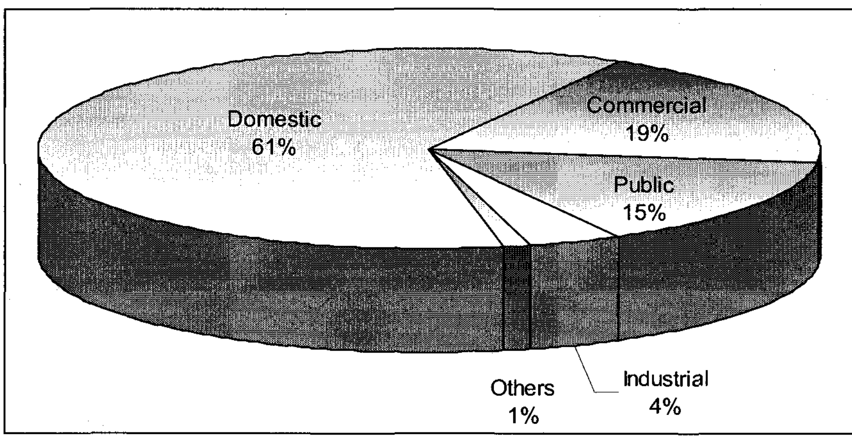

Figure 3.14 Division of municipal water among indoor uses.

The policy options intended to be tested in this sector affect both the indoor as well as the outdoor domestic water use. The reduction in water consumption due to the use of low flow appliances is tested in indoor domestic use. The model also tests the use of mandatory low flow appliance fittings in all homes built after 2010. Besides, the model shows the effect on water consumption when a fraction of existing homes adopt retrofitting to low flow appliances. This fraction can be varied using a slider provided in the user interface in the model.

The outdoor domestic municipal water demand is evaluated in response to permanent and long term water use restrictions. These restrictions may involve restricting the number of days in a week during which the lawns may be irrigated. Alternately the governing bodies may also encourage or mandate for the adoption of Xeriscaping which requires little water for maintenance. Many water management districts adopt the policy of restricted outdoor water use but this option is exercised only in times of water shortage. This model examines the effect of such water use restrictions on a long term basis along with other conservation policies for domestic water use. Approximately 58% of the total municipal demand in the urban areas is consumed for outdoor water uses such as landscape irrigation (Mayer, 1995). This figure also includes the outdoor water uses by public places and institutions, commercial establishments, and industrial buildings. This approximately 30% of the domestic or residential water is used for irrigation and other outdoor water uses at homes.

Table 3.5 Division of indoor domestic water use.

Use	Percentage
Laundry	22
Faucet	16
Shower/Bath	19
Leakages	14
Toilet	26
Others	3

Price of a commodity has a direct relation to the rate of consumption of that commodity. This assertion also holds true for water consumption. Low prices of water do not encourage conservation hence the consumers tend to use water less cautiously causing the consumption to go up. However in case of necessities such as water, the consumption does not vary linearly with the rate of change in pricing. The reason for this being that after a certain amount of economy has been brought about and after the wastages have been reduced to a minimum, further savings can not be brought about so easily. The relation between the price of a commodity and its consumption is called 'price elasticity'. Price elasticity for domestic water consumption according to a number of studies varies from -0.15 to -0.52 (Nieswiadomy 1992, Nieswiadomy and Molina 1989, Billings 1987, Moncur 1987, Agthe et al. 1986, Renwick et al. 1998, and Olmstead et al 2007). For US customers, the price elasticity has been estimated to be in the range of -0.33 (Olmstead et al 2007). A price elasticity of -0.30 is adopted for this model. This implies that an increase of 100% in the price of municipal water reduces the demand by 30%.

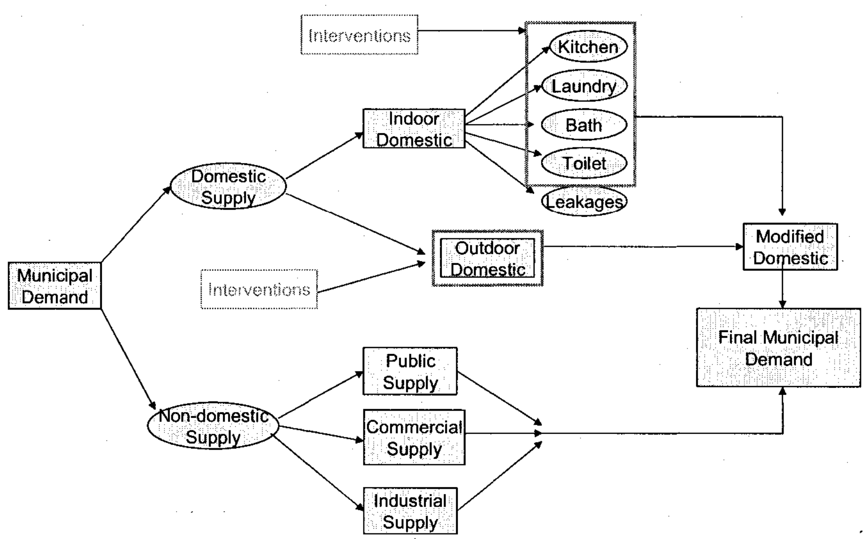

Figure 3.15 Flow chart for the municipal demand sector.

3.2.6 Agricultural Water Demand

The agricultural water demand in the model is calculated using the crop acreage data from land use datasets from SFWMD website (www.sfwmd.gov). The crop acreage is multiplied with the irrigation depth requirement for the corresponding crop, thus, obtaining the water requirement. The water requirements for all the crops are added to obtain the total agricultural water demand in the district. The policies considered in this sector include crop substitution, increasing the use of micro irrigation, and reducing the agricultural land.

Sugarcane cultivation has a major share in the total agricultural land in the district. Approximately four hundred thousand acres of land is devoted to sugarcane cultivation. The water requirement for sugarcane is relatively high as compared to other crops in the region. Since the water requirement for other crop types is lower than that for sugarcane, therefore the total water consumption is expected to reduce if a part of the sugarcane acreage is transferred to other crop types. In order to test this policy, a converter is provided in the sector. This allows choosing the rate at which the land can be transferred from sugarcane to other crop types. This land is then distributed into the other crop types i.e., citrus orchards, row crops, field crops, and other orchards.

Presently, in South Florida, sugarcane plantations do not use micro irrigation. In order to explore the use of micro irrigation in sugarcane and determine the savings out of it, the model allows for adoption of micro irrigation in sugarcane plantations. Apart from introducing micro irrigation to sugarcane cultivation, the study also explores the effect of expanding the use of micro irrigation in citrus orchards. Varying proportions of sugarcane and citrus acreage can be selected for micro irrigation using a converter.

Almost all the land under sugarcane cultivation is irrigated through flood irrigation which has an efficiency of 50%. For the citrus orchards, in 2000, 79% of the land was irrigated using micro irrigation which has a high irrigation efficiency of 85% to 95% (Shreshtha and Gopalakrishna, 1993). Therefore, the overall efficiency for the irrigation of citrus orchards is higher than that for sugarcane plantations. The combined irrigation efficiency for both sugarcane and citrus stood at 66% in 2000. Table 3.6 shows the calculations for the efficiency of application of irrigation water in the district, for the year 2000. Weighted efficiency of the irrigation method is calculated individually for the citrus and sugarcane crops. These are then added to obtain the efficiency of irrigation for citrus orchards and sugarcane plantations separately. The efficiencies for the two are then added proportionally to their acreage to obtain the overall irrigation efficiency in the district.

Table 3.6 Irrigation efficiency for citrus and sugarcane.

Year 2000	Area	Weightage	Efficiency	Weighted Efficiency
Sugarcane Total Area (Acres)	404,123			
Area Under Micro Irrigation	0	0.0000	85%	00%
Area under Sprinkler Irrigation	72	0.0002	70%	0.01%
Area under flood irrigation	404,051	0.9998	50%	49.99
		Sugarcane Efficiency		50%
Citrus Total Area (Acres)	520,617			
Area Under Micro Irrigation	410,836	0.7891	85%	67.08%
Area under Sprinkler Irrigation	42,015	0.0807	70%	5.65%
Area under flood irrigation	67,762	0.1302	50%	6.51%
		Citrus Efficiency		79.23%
		Combined Efficiency		66.46%

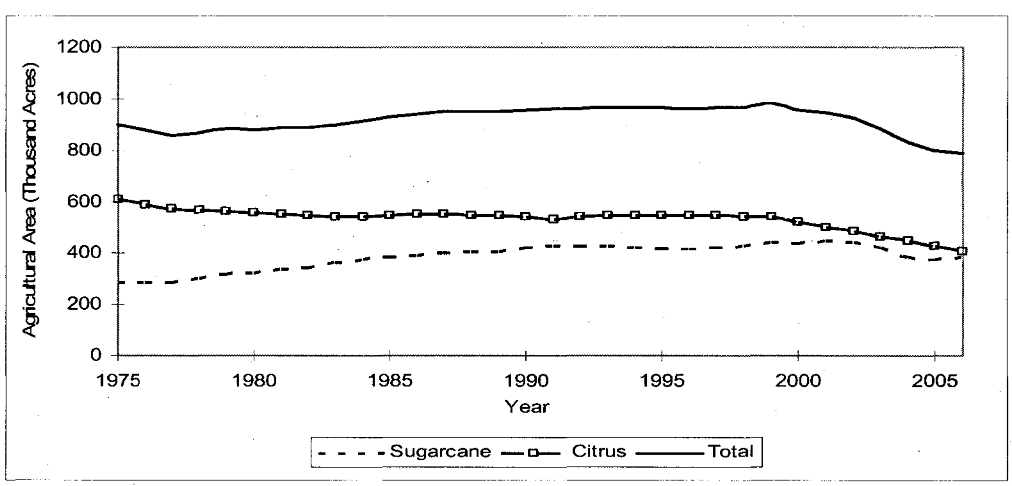

Figure 3.16 Cultivated areas for major crops.

Figure 3.16 shows the acreage of major crops in South Florida over a period of 35 years from 1975 to 2005. The policy option testing the reduction in agricultural area uses the same converter that was used for testing crop substitution. In this case the acreage under the crop is reduced by the desired amount without allocating it to another crop. Figure 3.17 shows the basic structure of the agricultural sector in the model. The converters representing irrigation efficiency, micro irrigation, and rainfall are connected to the monthly irrigation requirements of the crops. These converters determine the depth of irrigation water required by the crops. The precipitation is included in the calculation to account for the soil moisture which reduces the irrigation requirement for a crop. The irrigation requirements are then multiplied by the corresponding acreage to obtain the agricultural demands for a particular crop type using the relation

$$IR = A \times (ET - 0.3 \times P) / \eta \qquad (3.14)$$

where,

IR = Irrigation requirement of a crop,

A = Crop acreage,

ET = Crop evapotranspiration or consumptive use,

P = Precipitation, and

η = Efficiency of application of irrigation water.

3.2.7 Environmental Water Demand

This sector is incorporated in the model to ensure that the withdrawal of the agricultural and municipal demands from surface and groundwater bodies does not cause any adverse effects on the environmental flows. The WCAs are treated as the central stock in this sector. Only the water requirements for the normal functioning of the everglades, WCAs, and Biscayne Bay are considered in this sector. The environmental demands of Lake Okeechobee, Caloosahatchee River, and St. Lucie Estuary are included in the surface water sector in Lake Okeechobee outflow regulation schedules. Table 3.7 shows the violation conditions for environmental water demands for the water bodies.

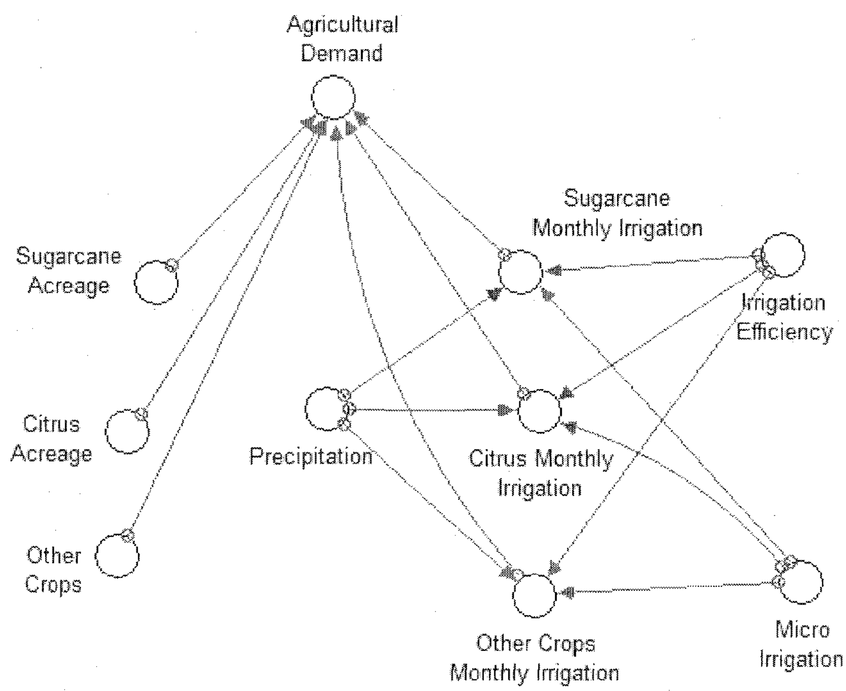

Figure 3.17 Structure of the agricultural water demand sector.

Table 3.7 Violation condition of environmental water requirements

Water Body	Violation condition
Lake Okeechobee	Average three monthly water levels below 11 ft NGVD
Caloosahatchee River	Annual flow less than 217,200 ac-ft
Flow to WCAs	Annual flow less than 105,000 ac-ft
St. Lucie River	Annual Flow less than 20,272 ac-ft

The WCAs serve a variety of purposes including storage, flood control, augmenting water supplies, maintaining groundwater level and wildlife habitat. The combined storage capacity of the three WCAs is about 1.88 million ac-ft and the water stored is used to supplement the municipal and agricultural demands in the LEC region (NAS, 2005). The volume of water contained in the WCAs at any time (t) is given by,

$$WCA(t) = WCA(t-dt) + [P + F + D] - [Et + C + I + Env] \qquad (3.15)$$

where,

WCA(t)	= Volume of Water stored in the WCAs at time (t),
P	= Precipitation occurring over the entire WCA area,
F	= Flow from Lake Okeechobee,
D	= Drainage from surrounding areas,
Et	= Evapotranspiration losses,
C	= Water withdrawals for consumption,
I	= Infiltration, and
Env	= Environmental flows to Biscayne Bay and Everglades.

Figure 3.18 shows the structure of the environmental sector in the model. It receives water from Lake Okeechobee, and drainage from the surrounding areas. The biggest contributor, however, is the direct precipitation occurring over the WCAs. The WCAs release environmental flows to the ENP and the Biscayne Bay in addition to providing for a small fraction of agricultural and municipal demands. The WCAs overlie a large part of Biscayne Aquifer therefore, they also serve an important purpose of maintaining the water levels in Biscayne Aquifer.

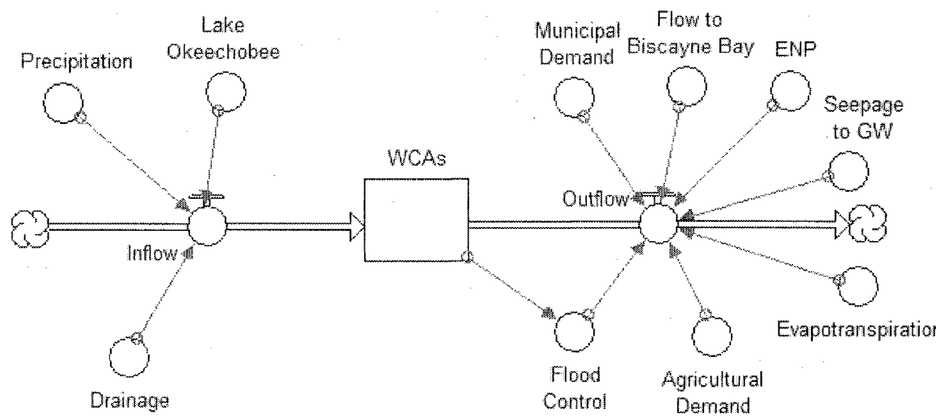

Figure 3.18 Structure of the environmental sector.

3.2.8 Performance Evaluation

This sector evaluates the ability of Lake Okeechobee to perform under various scenarios by developing three criteria for evaluating its performance. These criteria were proposed by Hashimoto et al (1982) to develop measures, based on which alternative policy options can be selected for reservoir operation. The criteria are reliability, resilience, and vulnerability. Each of these three criteria is described in this section.

Reliability is a concept widely used in water resources planning. It can be explained as the system's resistance to failure. Alternately, it is the probability that the system is in a satisfactory state at any given time. Figure 3.19 shows the structure of the sector used for calculating reliability. For the optimum performance of Lake Okeechobee at all fronts, a minimum level of 11 feet NGVD is required. In order to calculate the reliability of Lake Okeechobee for various scenarios, this level is considered as the threshold between failure and satisfactory states. Reliability can provide an estimate of the percentage of time for which Lake Okeechobee can be relied upon to fulfill water supply and ecological functions. The model determines the number of months for which the lake levels have been satisfactory and subsequently obtains a ratio between the number of satisfactory months and total number of months. Reliability may vary between 0 and 1. A larger value implies that the reservoir is more reliable and vice versa. Mathematically, reliability can be calculated using

$$\alpha = P(S)/T \qquad (3.16)$$

where

α = reliability,

$P(S)$ = probability of the system being in a satisfactory state, and

T = total time duration.

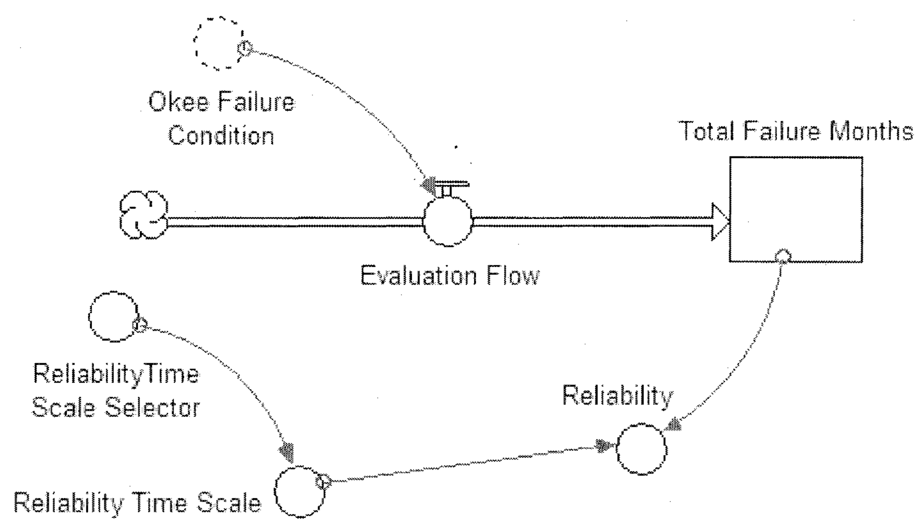

Figure 3.19 Model structure to calculate reliability.

This definition of reliability does not describe the intensity of failure, which is taken into account by vulnerability. In practice, it is uneconomical to build systems that are so large that failures are completely eliminated. Therefore, it is essential to determine the extent of the damage a failure event can cause. Vulnerability is defined as the intensity of a failure event. Even if the probability of failure is low, it should be ensured that the consequences of a failure event are not very severe. Figure 3.20 shows the structure for vulnerability calculation in the model. For this research, the depth by which the lake levels falls below the 11 feet mark is considered to be the intensity of failure. The model determines the depth by which the lake levels fail each time the levels are below 11 feet NGVD. The failure depth is then averaged over the total number of failure months. Vulnerability can take a value from 0 (not vulnerable) to any number (higher value represents a greater vulnerability). The vulnerability of a system can be calculated using,

$$\beta = \frac{\sum_{1}^{N} I}{N} \tag{3.17}$$

where

β = Vulnerability of a system,

I = Intensity of failure, and

N = Number of failures over a given time period.

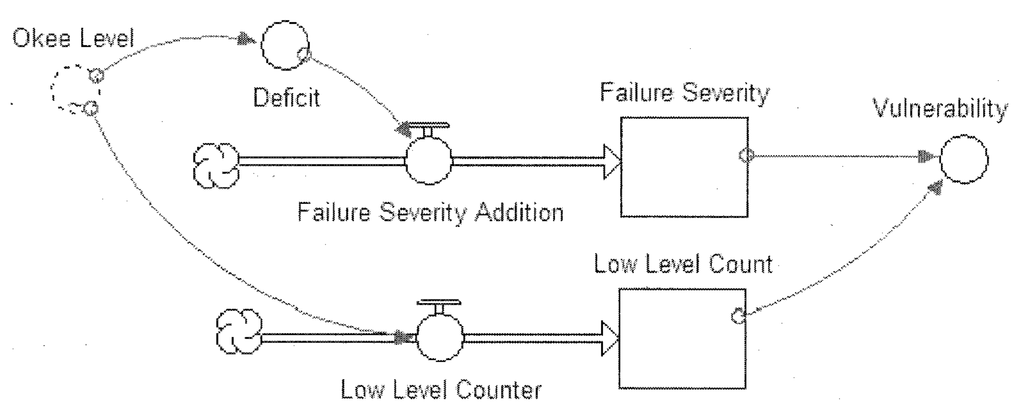

Figure 3.20 Model structure to calculate vulnerability.

Resilience is the virtue of a system to recover from a collapse. If failures are severe, the recovery will be slow hence, the resilience would be low. Mathematically, if t is the time taken by a system to recover from a state of failure then resilience can be defined as $1/t$. Figure 3.21 shows the structure for calculating resilience of Lake Okeechobee in the model. It counts the number of months for which the lake levels stay below 11 feet NGVD once a failure has occurred. Number of transitions between failure and satisfactory states is also counted. The ratio of these two gives the resilience of Lake Okeechobee which is the time taken by the lake to recover from a failure state.

$$1/\chi = \frac{\sum_1^N T}{N} \tag{3.18}$$

where

χ = Resilience,

T = Duration of failure, and

N = Number of failure events.

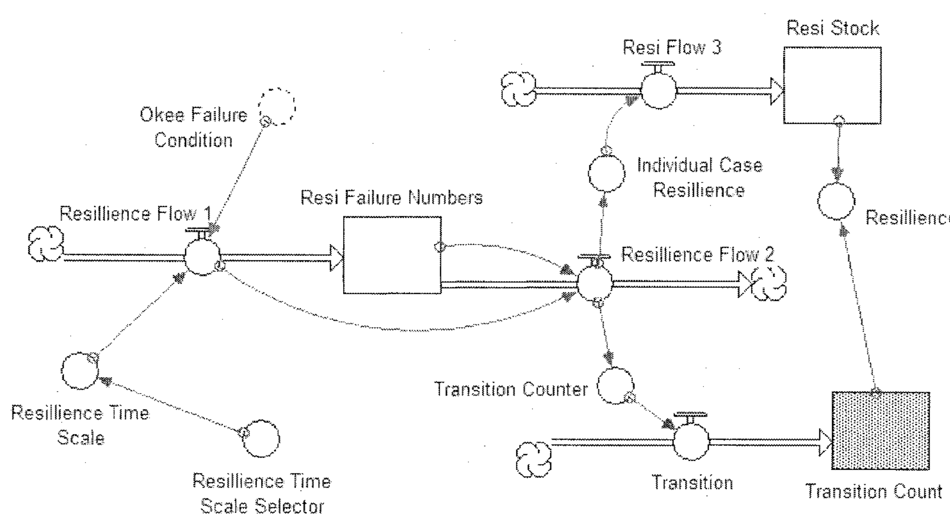

Figure 3.21 Model structure to calculate resilience.

Chapter 4 describes the calibration of the model followed by the projections obtained for the various scenarios tested in the model. In addition, several rainfall scenarios are also tested. The chapter also describes the effect of the policy options and rainfall scenarios on the environmental water supply in the district.

CHAPTER 4

RESULTS

The model described in chapter 3 is developed to help the decision makers and water supply managers evaluate equitable allocation to the three competing demands of agricultural, municipal, and environmental sectors. It achieves this goal by testing measures to conserve water in the agricultural and municipal sectors, thereby ensuring adequate water supply to the environmental sector. Conservation of water and development of new sources are the two measures using which the problem of water shortage can be overcome. This study explores the use of water conservation as an approach to resolve water shortage.

A “status quo” scenario is simulated in section 4.2 to provide a baseline for comparison and evaluation of the results achieved by the water conservation policy options. All the policy options tested in this research come into effect in 2010. Two separate scenarios are set up to economize the agricultural and municipal demands in sections 4.3 and 4.4 respectively. Each scenario is a collection of sub scenarios for simulating the effect of the multiple policy decisions affecting the two sectors. In addition to water conservation options, the effects of limiting population growth and natural variations in precipitation rates are also presented in this chapter in sections 4.6 and 4.7 respectively.

4.1 Calibration

A system dynamics model tries to replicate the modeled processes in a manner as close as possible to the actual process. Therefore, in order to achieve the best possible results it is essential that model behavior follows the behavior of the process in the real system. Any deviations from the natural model behavior may cause the model to produce incorrect results. Therefore, any model which is expected to look into the future behavior of environmental systems must undergo the process of calibration. To detect the flaws in a System Dynamics model various methods can be used, for example, 'direct structure tests' wherein the model equations are matched against their counterparts in the real world, 'Sensitivity analysis test' can be employed to see the variation in the value of a particular parameter i.e., a stock or a flow with varying values of an influencing factor. 'Extreme condition test', which is an indirect structural test, evaluates the model behavior under extraordinary circumstances of extreme inputs and comparing the model behavior to the anticipated behavior of the actual system (Saysel 2001).

The time horizon of this research is from 1970 to 2050 with a monthly time step. Entire South Florida is treated as a single unit for forecasting population growth, land use changes, and water demands. For calibrating land use changes and water demands, data from 1975 to 2000 is used. For population growth however, data from 1970 to 2030 is used. Calibration, as applied to this model is the process by which certain model parameters are changed until a reasonable match is obtained between model output and historical data.

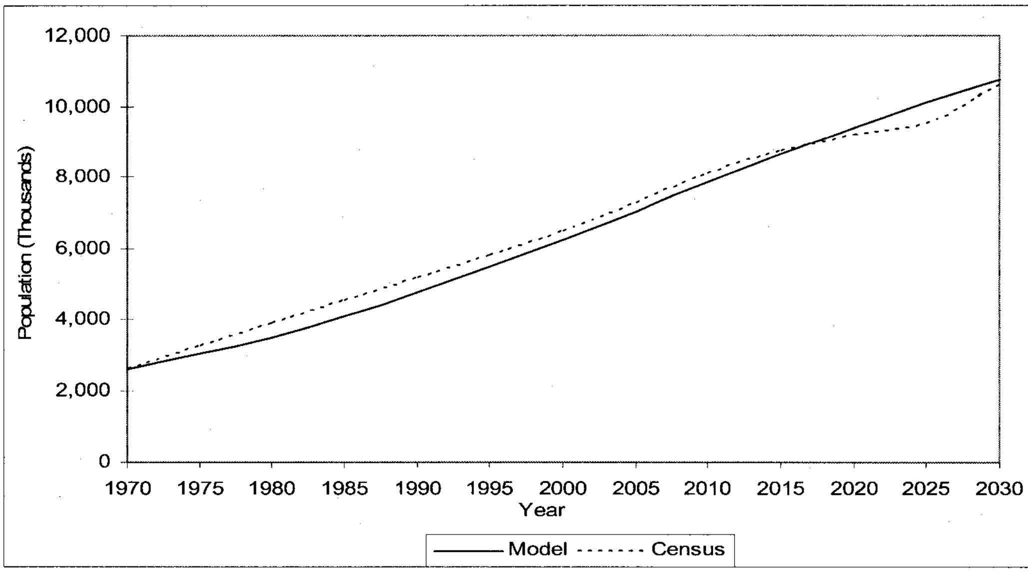

Figure 4.1 Calibration for population growth.

A comparison of the graph plotted for the simulated and projected population growths in the region from 1970 to 2030 is given in Figure 4.1. According to the US census bureau, the population of SFWMD is expected to grow from about 2.6 million in 1970 to over 10.5 million by 2030 following an 'S' shaped growth with a rapid growth in the initial phases which slows down subsequently. The model is able to reproduce the population growth successfully following nearly the same pattern as suggested by the US Census.

The growth of the municipal demand replicates the growth of population since the average daily per capita demand in the district has remained more or less constant at 170gpd. Therefore, the growth of the municipal demand as simulated by the model was expected to match the actual trends (Figure 4.2).

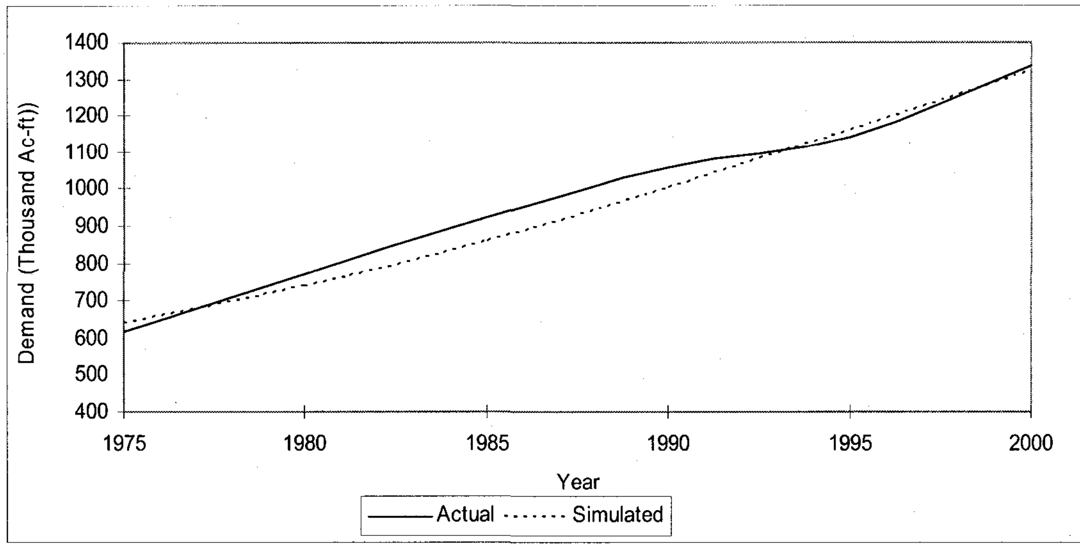

Figure 4.2 Calibration for municipal demand.

Figure 4.3 and Figure 4.4 show the calibration results for the growth of citrus and sugarcane acreage respectively. The data for historical growth for the agricultural acreage was obtained from United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS) for the counties of South Florida for the years 1975 to 2000. To match the changes in agricultural land use, the rate of conversion of natural land to agricultural land is varied until an accurate match within 5% error is obtained. In order to calibrate the agricultural water demand, soil moisture content was varied to obtain a closely matching curve. Figure 4.5 shows the calibration of the agricultural water demand in SFWMD. The data ranges from the year 1975 to 2000.

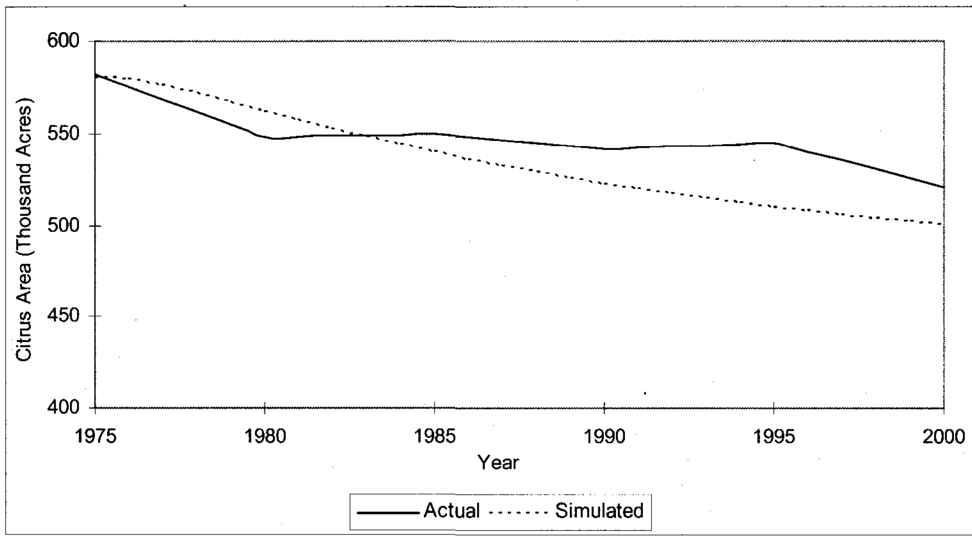

Figure 4.3 Calibration results for citrus acreage.

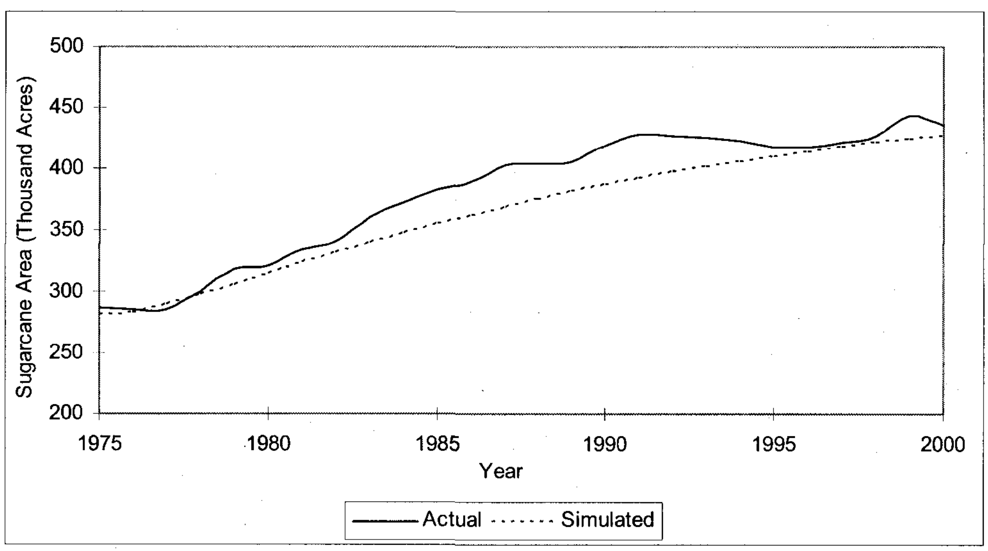

Figure 4.4 Calibration results for sugarcane acreage.

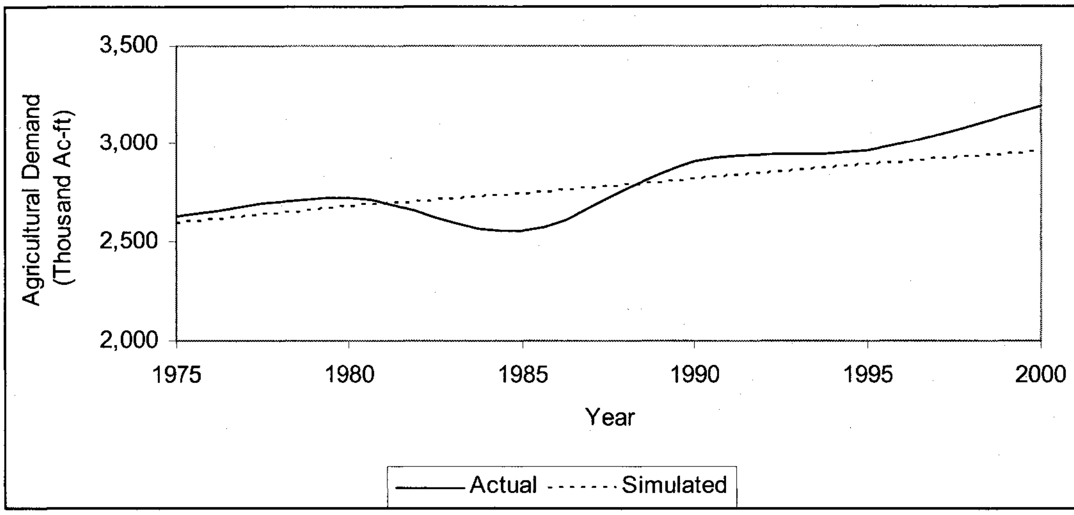

Figure 4.5 Calibration results for agricultural demand.

After calibrating the growth of the variables which govern the water consumption in the model, it is necessary to check if the model is able to reproduce Lake Okeechobee water levels as well. Since the model uses average monthly precipitation and evapotranspiration rates in the district, therefore, not much similarity can be expected in the model generated water levels and actual lake levels. The calibration for the lake levels, therefore, is done using actual precipitation data from 1970 to 2005, on a gauging station over the lake. In order to match the simulated levels with the historical lake levels, the flood control discharges were varied. The calibration results for the annual average Lake Okeechobee levels between 1970 and 2005 are shown in Figure 4.6.

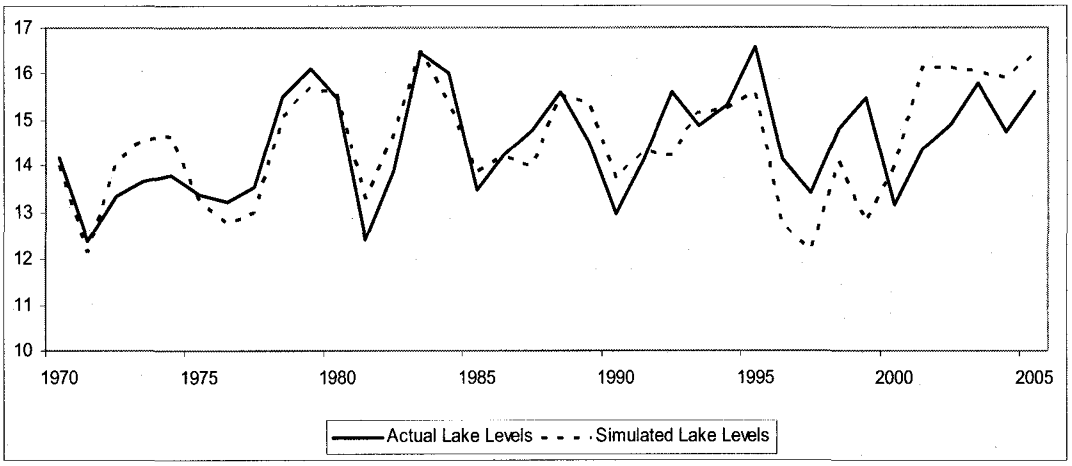

Figure 4.6 Calibration for Lake Okeechobee water levels

The summary for the calibration results for the model are given in Table 4.1. The table shows the correlation between the actual and simulated values of the respective variables between the years 1975 and 2000 for population, municipal demand, agricultural land uses under citrus orchards and sugarcane plantations, and agricultural water demand. The calibration for population, however, was done for the period between 1970 and 2030 because of availability of census data and projections for all counties of SFWMD for that period. The data consists of actual census stats for the period between 1970 and 2005 and population projections for the counties between 2005 and 2030.

Table 4.1 Calibration results summary

Variable	(Correlation Coefficient)	RMS Error
Population	0.99	2.10%
Municipal Demand	0.99	2.83%
Citrus Acreage	0.88	3.56%
Sugarcane Acreage	0.97	3.69%
Agricultural Demand	0.86	4.92%
Okeechobee Water Levels	0.71	7.45%

The next section discusses the policy options tested in order to reduce agricultural and municipal demands. It also shows the water savings achieved in each sector due to the corresponding policies and their impact on fulfillment of environmental water availability.

4.2 Scenario 1: Status Quo

The status quo scenario works under the assumption that the population grows at the expected growth rate and increases to 12 million by 2050. No conservation measures are adopted in the agricultural or the municipal sectors to economize water consumption. Precipitation and evapotranspiration rates are also assumed to follow the historic average values. The simulations run under this scenario reveal that the water consumption in both the sectors, agricultural and municipal, increase over the planning horizon.

Figure 4.7 shows the variation of annual agricultural demand from 1970 to 2050. The annual agricultural demand increases from 2.6 million ac-ft/yr in 1970 to 3.02 million ac-ft/yr in 2050, this is an increase of 16.15%. Between 2008 and 2050, the agriculture demand increases by 1.4%. Maximum agricultural demand in the district is observed in 2035, when it reaches 3.04 million ac-ft/yr. The growth is rapid initially but flattened subsequently due to a limited amount of land available for conversion into agricultural land. After 2035, the amount of agricultural area decreases due to conversion into residential and urban land uses. That results in a proportional decrease in water consumption as well.

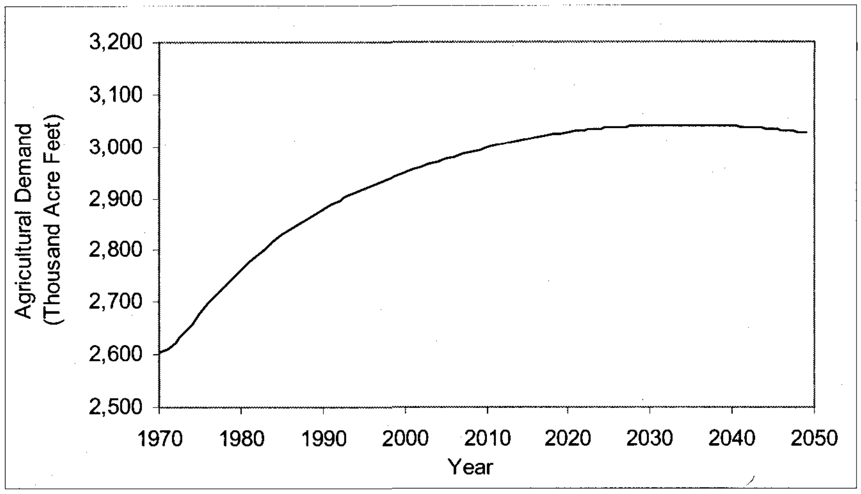

Figure 4.7 Annual agricultural demand (Status Quo).

Figure 4.8 shows the variation of annual municipal demand in SFWMD from 1970 to 2050. It increases from 0.5 million ac-ft/yr to 2.45 million ac-ft. i.e., a 390% increase in demand. Between 2008 and 2050, the municipal demand grows by 1.04 million ac-ft, which is a growth of 71%. Since the daily per capita demand of municipal water does not vary significantly, therefore, the growth of municipal demand closely replicates the growth in population.

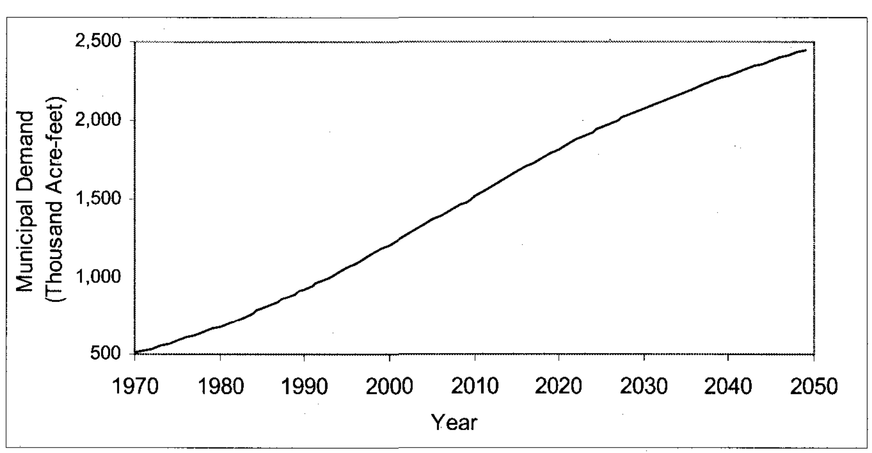

Figure 4.8 Annual municipal demand (Status Quo).

Figure 4.9 shows the Lake Okeechobee water levels for the status quo scenario. The plot shows annual minimum, maximum, and average water levels in the lake. The increase in the agricultural and municipal demands causes the average annual Okeechobee Levels to drop to 11.85 ft NGVD by 2050. The annual minimum levels however are even more alarming. The average monthly lake level in May, when the water level in the lake is minimum, dropped to 10.5 ft NGVD in 2050. The lake levels dropping to such low levels in summers can have a detrimental effect on the aquatic ecosystem in and around the Lake Okeechobee. Additionally, water requirements for all the competing uses agricultural, municipal, and environmental sectors would be difficult to fulfill.

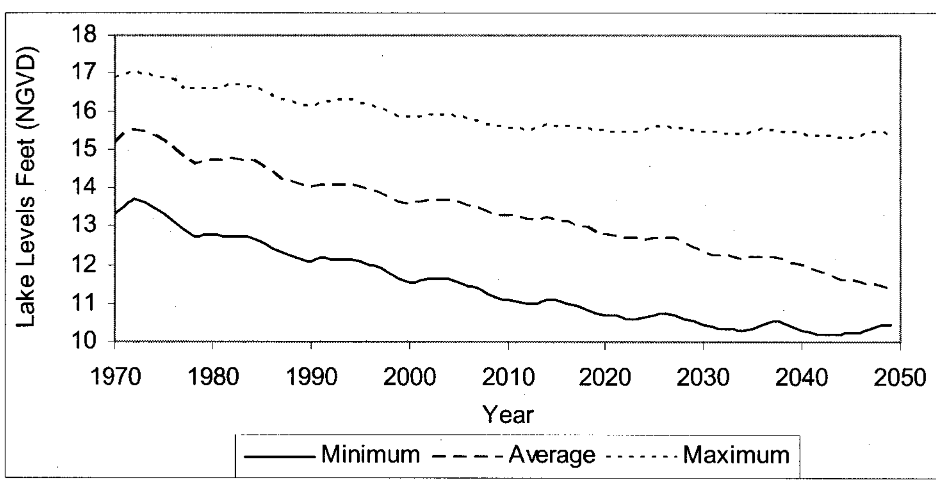

Figure 4.9 Annual Okeechobee water levels (Status Quo).

The effect of falling lake levels is observed in the environmental water demand fulfillment. The number of instances when the environmental demands were not met increased significantly between 2010 and 2050. 13 exceedances are observed for Lake Okeechobee water levels between 2010 and 2050. The flows to the WCAs, Caloosahatchee River, and the St. Lucie Canal are below their designated environmental demands 15, 16, and 14 times respectively. The similar shapes of the graphs for the flows in Caloosahatchee River (Figure 4.10), the discharge to the WCA's (Figure 4.11), and St. Lucie Canal (Figure 4.12) is due to Lake Okeechobee Regulation Schedule. This schedule releases regulatory flows when the water level rises above Zone E and stops the flows as soon as the levels drop. The duration of the flows, therefore, is equal for all discharges but the magnitudes vary.

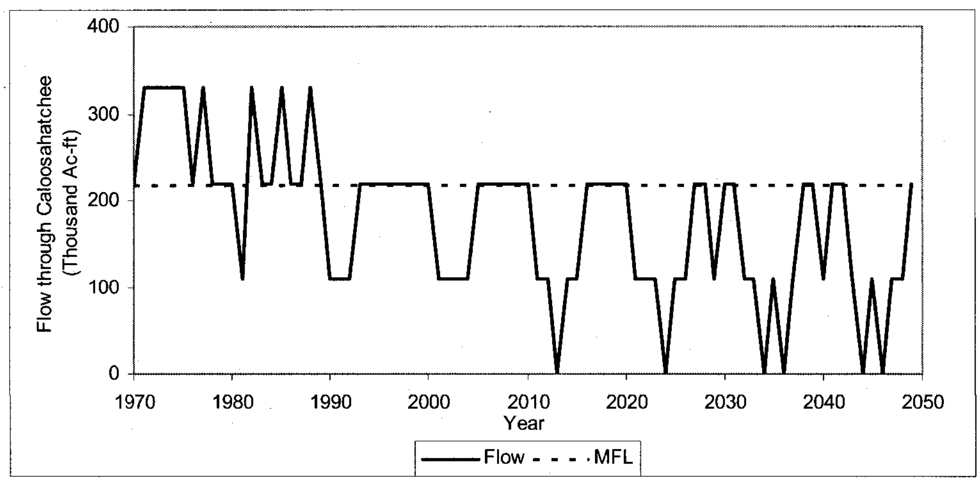

Figure 4.10 Annual flow through Caloosahatchee (Status Quo).

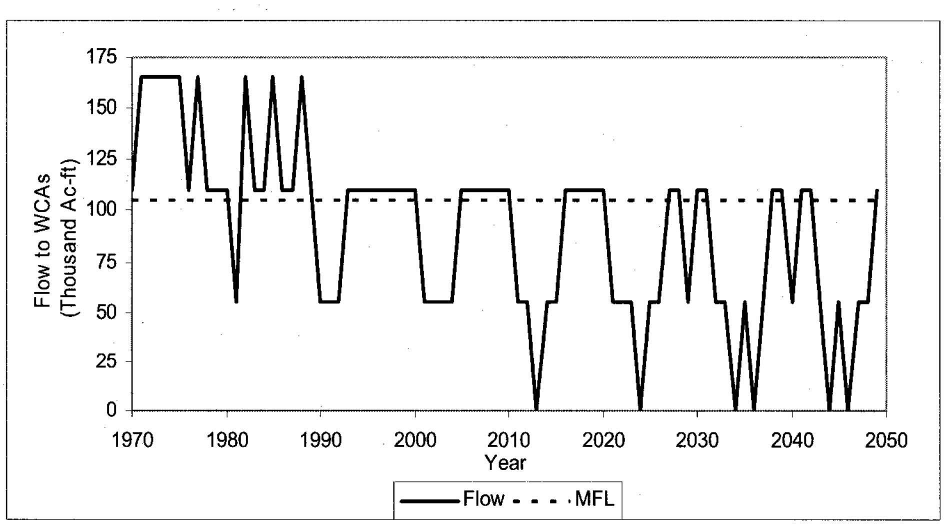

Figure 4.11 Annual flow to the WCAs (Status Quo).

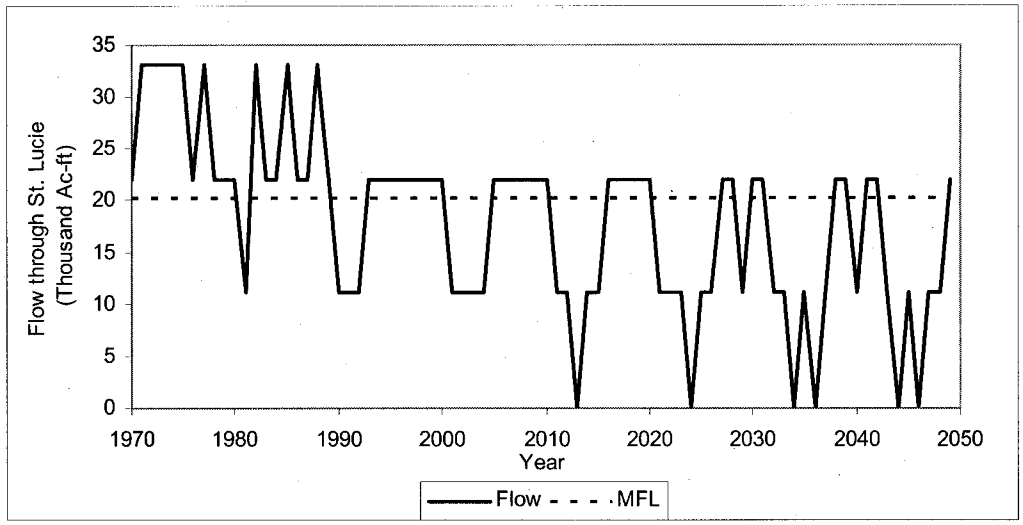

Figure 4.12 Annual flow through St. Lucie Canal (Status Quo).

4.3 Scenario 2: Agricultural Intervention

The Agricultural Intervention scenario explores measures which can be implemented in order to reduce the unnecessary use of agricultural water and ultimately reduce consumption. This would allow more water to flow in surface water bodies to meet the environmental demands. The measures tested in this study include micro irrigation, crop substitution, and reduction in acreage. The details of the policy options are summarized in Table 4.2.

Table 4.2 Policy options tested in the agricultural intervention scenario.

Policy	Policy	Details
1.	Reduction in Acreage	Reduction in agricultural area under sugarcane by 20%
2.	Micro Irrigation	Increasing the acreage under micro irrigation from 80% to 90% for citrus and from 0% to 20% for Sugarcane
3.	Crop Substitution	Substituting 20% sugarcane acreage with row crops
4.	Combination	Combination of policies 2 and 3

4.3.1 Reduction in Acreage

The total agricultural acreage in SFWMD in 2000 exceeded 750,000 acres. A simplistic approach to reduce agricultural water demand is by reducing the cultivated area. Although exercising this option would result in economic repercussions but it can be a feasible option to be explored under extreme conditions of water shortage. A reduction in agricultural areas may also be a natural outcome of urban expansion which results in conversion of agricultural land into urban land uses.

Figure 4.13 shows the decrease in agricultural water demand with 10% and 20% reduction in sugarcane acreage in the district. The corresponding reductions in agricultural demands are 4.5% and 9.1% respectively of total agricultural demand. The reduction in terms of volume is 136,000 ac-ft/yr per 10% reduction in sugarcane acreage.

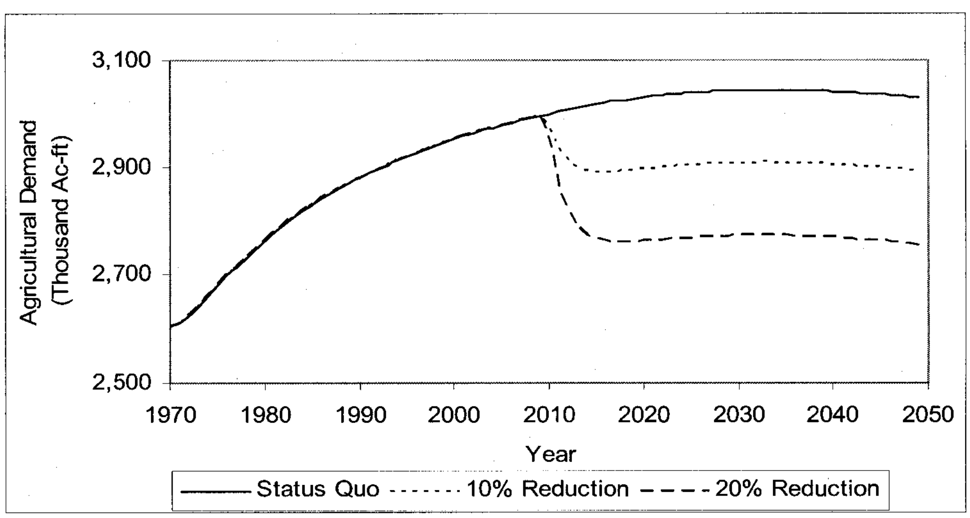

Figure 4.13 Variation in agricultural demand with decreasing sugarcane acreage.

4.3.2 Micro Irrigation

Conversion of existing seepage irrigated crops to microirrigation can be a significant source of water savings. Approximately 6 billion gallons, 18000 acre feet per year, or 15.8 million gallons per day of water can be conserved by converting 25,000 acres of cropland from flood irrigation with 50% efficiency to microirrigation with 85% efficiency.

Given the large volumes of water used for irrigation by agriculture, water conservation is often extremely cost effective compared to the costs of developing additional water supplies. It is estimated by the Institute of Food and Agricultural Sciences (IFAS), University of Florida that the initial cost to install a microirrigation system for citrus is $1,000 per acre, and that the system would have estimated annual maintenance costs of $25 per acre per year (IFAS 1993).

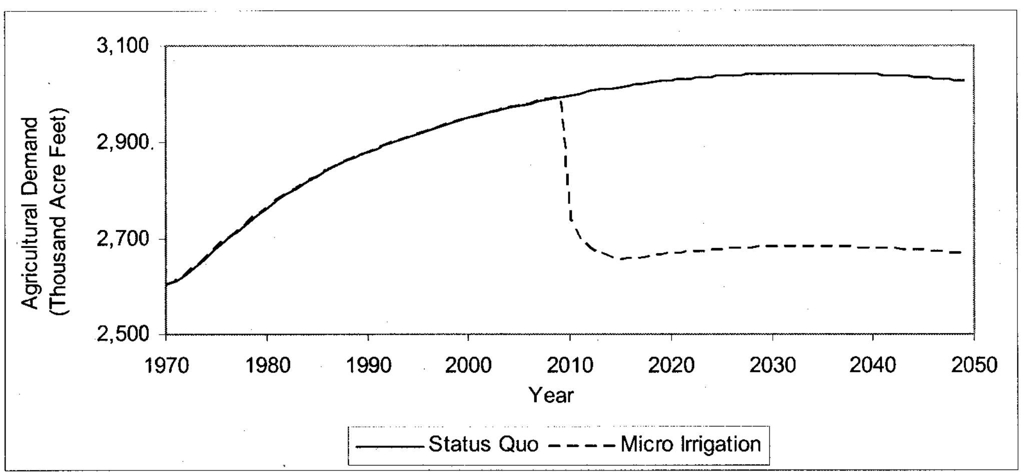

Figure 4.14 Variation in agricultural demand with increasing micro irrigation.

Figure 4.14 shows the reduction in agricultural water demand due to adoption of micro irrigation in 20% of the acreage under sugarcane plantations and increasing the extent of micro irrigation in citrus orchards from the present value of 80% to 90%. Both these combined together result in a saving of 11.88% which translates into 360 thousand ac/ft of agricultural water per year by 2050.

Model simulations for varying overall irrigation efficiencies are shown in Figure 4.15. The agricultural water demand dropped from 3.03 million ac-ft/year to 2.88 million ac-ft/year due to an increase of 2% in overall irrigation efficiency. Figure 4.16 shows the variation of Lake Okeechobee levels for varying irrigation efficiencies. An increase in irrigation efficiency from 67% to 68% causes the annual average lake levels to rise by a fourth of a foot. Another 1% increase in efficiency has a relatively smaller impact on the final levels. The lake levels at the end of simulation period for status quo, 68%, and 69% irrigation efficiencies were 12.0 ft, 12.26 ft, and 12.37 ft respectively. It raises the lake levels by just a tenth of a foot but it reduces the amplitude of fluctuations in the lake level. This is because of Lake Okeechobee regulation schedules, which drain the lake at a faster rate when the levels are high.

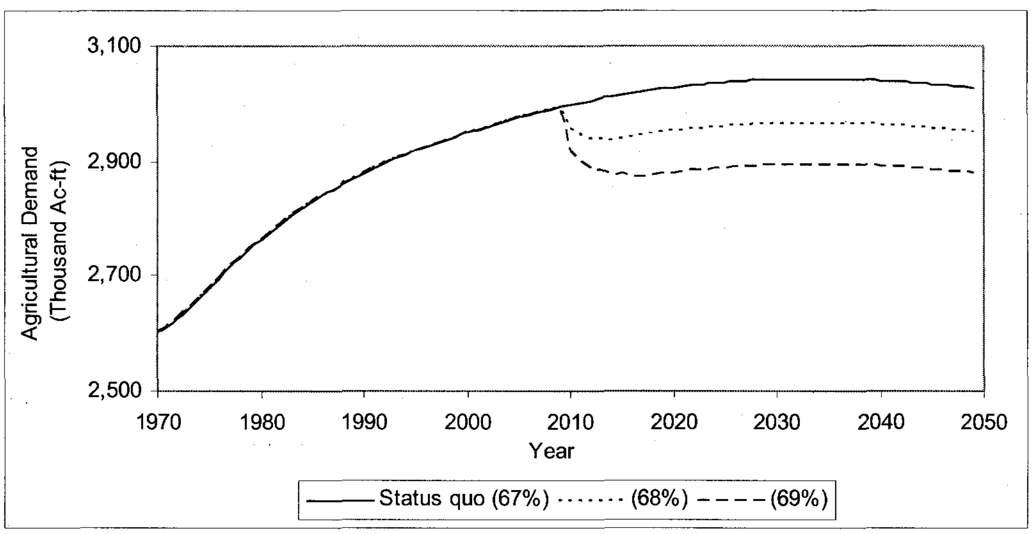

Figure 4.15 Variation of agricultural demand with varying irrigation efficiency.

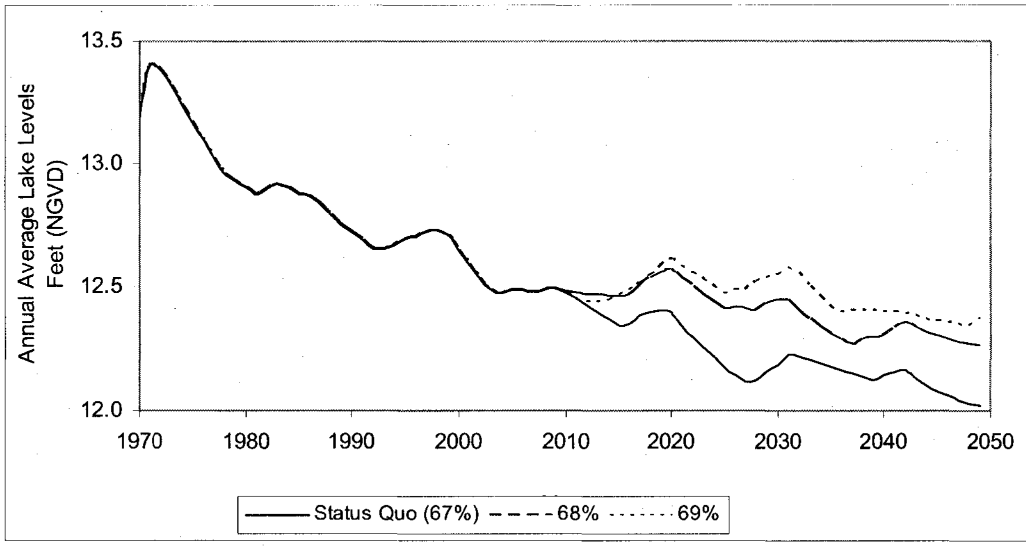

Figure 4.16 Annual average Lake Okeechobee levels with irrigation efficiency.

4.3.3 Crop Substitution

Sugarcane and citrus crops cover the largest portions of agricultural area and require the maximum amount of water per harvest. By changing the relative distribution of the crops or by allotting parts of acreage under sugarcane and citrus plantations to other crops, the total water demand can be reduced while maintaining the total agricultural area. For the simulations, the sugarcane acreage is chosen for reduction because of the water intensive nature of the sugarcane crop. 20% of the area under sugarcane is allotted to row crops which use significantly less water than sugarcane thus, reducing the overall demand.

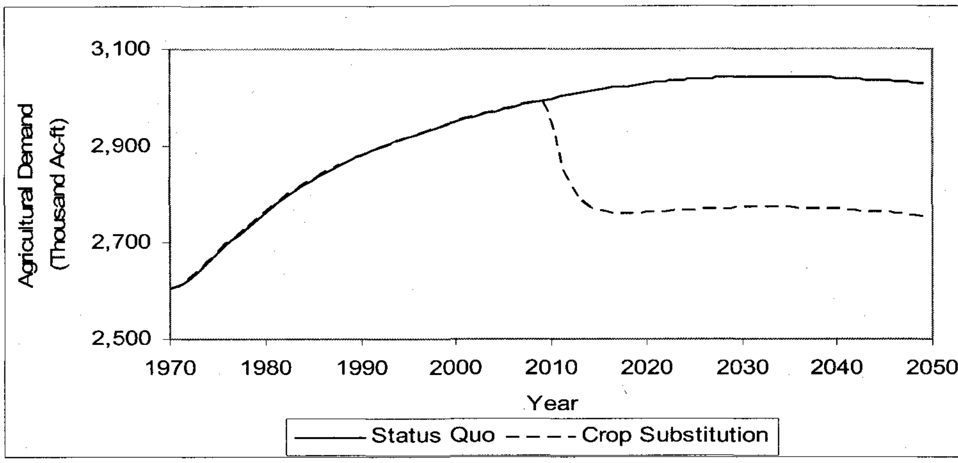

Figure 4.17 Change in agricultural demand due to crop substitution.

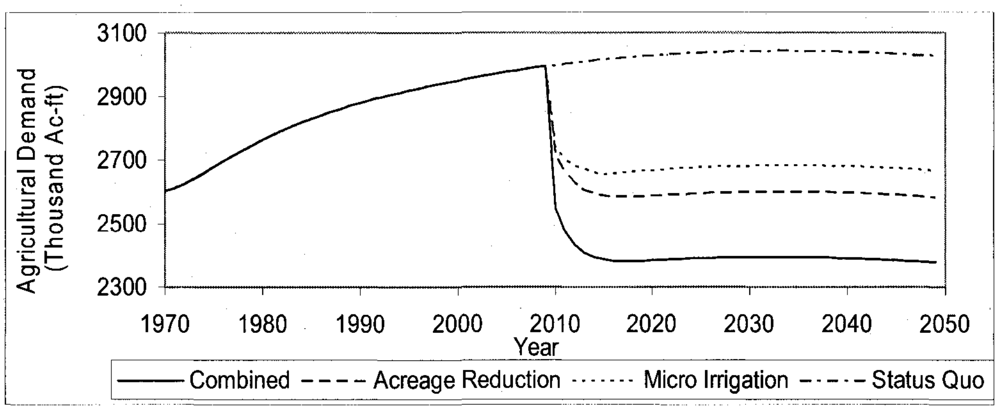

Figure 4.18 Savings due to various options in agricultural intervention scenario.

Figure 4.17 shows the reduction in agricultural water demand due to crop substitution. A 12% reduction in annual demand is observed by the year 2050 which is equal to 365 thousand ac-ft of water annually. Figure 4.18 shows the variation of annual agricultural demand for the various sub scenarios within agricultural intervention scenario. The combined saving achieved by crop substitution and micro irrigation stands at 21.48%. The water savings achieved by each method are summarized in Table 4.3 and Table 4.4 shows the extent of intervention required to achieve a 10% reduction in agricultural water and maximum achievable conservation using the corresponding policy.

Table 4.3 Comparison of sub scenarios for agricultural intervention.

Sub Scenario	Demand in 2050 (1000 Ac-ft/yr)	Change in demand in 2050 (1000 Ac-ft)	Saving in (2050) (%)
Status Quo	3,027	--	--
Combined	2,377	-650	21.48
Acreage Reduction	2,584	-443	14.65
Micro Irrigation	2,668	-359	11.88
Substitution	2,887	-140	4.64

Table 4.4 Maximum achievable conservation from agricultural interventions.

Policy	Change for 10% Reduction	Max Reduction Achievable	Comments
Acreage Reduction	21%	47.20%	436000 Acres in 2000
Micro Irrigation (Sugarcane)	41%	24.20%	0% in 2000
Micro Irrigation (Citrus)	Not Achievable	7.50%	70% in 2000
Substitution	57%	17.54%	436000 Acres in 2000

4.4 Scenario 3: Municipal Intervention

The municipal demand, as seen from the results of the status quo simulation, increases substantially from 2000 to 2050. Therefore, there is a pressing need to reorient the water management policies in an integrated manner. Efficient urban water management policies have to achieve an appropriate balance between developing capacity of water supply as well as conservation. The traditional engineering approach to municipal water management has sought to increase water supply, which has led to overexploitation of the water resources, and undervaluation of water supply.

The municipal intervention scenario tests policies to decrease the municipal demand through conservation. These policies include use of low flow appliances, price changes, and reducing outdoor water consumption through Xeriscaping. The details of the sub scenarios adopted in this policy option are provided in Table 4.5.

Table 4.5 Sub scenarios of municipal intervention.

Policy	Details
Low flow appliances	Mandatory low flow appliances in homes constructed after 2010
Low flow appliances	Retrofit of 20% old homes
Xeriscaping	Permanent restrictions on outdoor water use beginning 2010.
Price Increase	A 30% increase in the price of municipal water beginning 2010

4.4.1 Low Flow Appliances

The municipal demand sector in the model allows testing the use of low flow appliances in new housing developments after a particular date as well as retrofitting old homes. In this scenario, the date of intervention is set at 2010. In addition to mandatory use of low flow appliances in new developments, twenty percent of the homes built before 2010 are also retrofitted. The savings are applied independently for each of the domestic water use component such as in the kitchen, bath, toilets, laundry, outdoor irrigation, etc.

Figure 4.19 shows the change in municipal demand due to the adoption of low flow appliances. The figure shows the savings achieved by the policy of mandatory use of low flow appliances in all new housing developments after 2010. Additionally it also shows the saving achieved by mandatory use of low flow appliances in new homes as well as twenty percent of old homes retrofit with low flow appliances. The water consumption due to the adoption of mandatory low flow appliances for new housing developments drops from 2.45 million ac-ft to 2.29 million ac-ft, a saving of 6.2%. Retrofit of twenty percent of the old homes resulted in an additional 1.98% of annual water saving and combined together, both these measures resulted in a saving of 183 thousand ac-ft/year or 8.19% of total municipal demand.

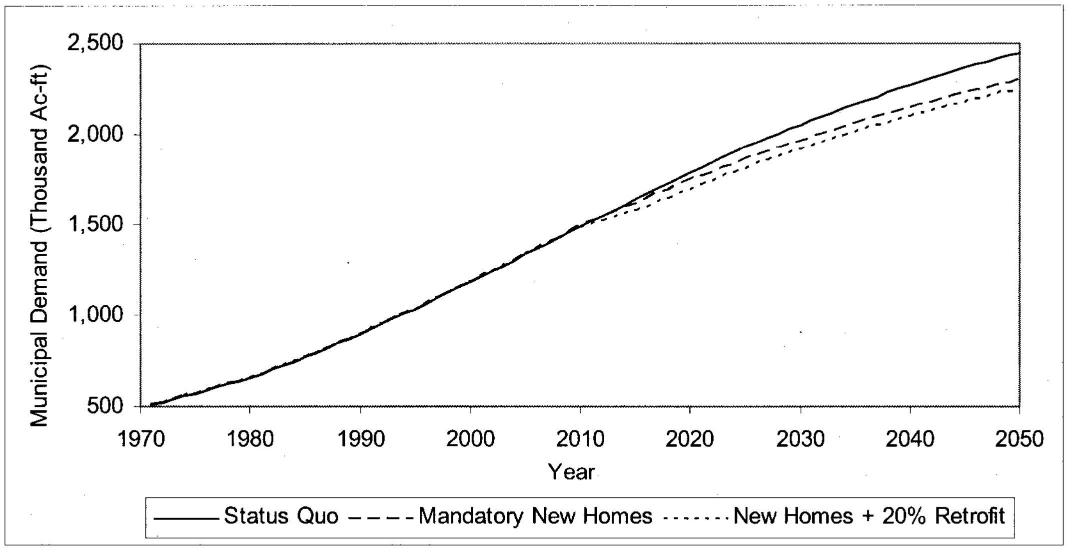

Figure 4.19 Annual municipal demand with introduction of low flow appliances.

4.4.2 Xeriscaping

This section explores the use of mandatory restriction on the use of water for outdoor uses by means of converting existing lawns into Xeriscapes and mandating their use for all new housing developments. Reduction of outdoor water use discussed in this section is not suggested as a short term solution or as seasonal restrictions, but as a long term and permanent reduction in outdoor water use by adopting modern irrigation and landscaping techniques such as Xeriscaping.

Figure 4.20 shows the change in municipal demand due to adoption of outdoor water use restrictions. The model simulations show that a 4.57% water saving can be achieved by implementing the outdoor water use restrictions on all homes. This saving amounts to 112 thousand ac-ft in the year 2050.

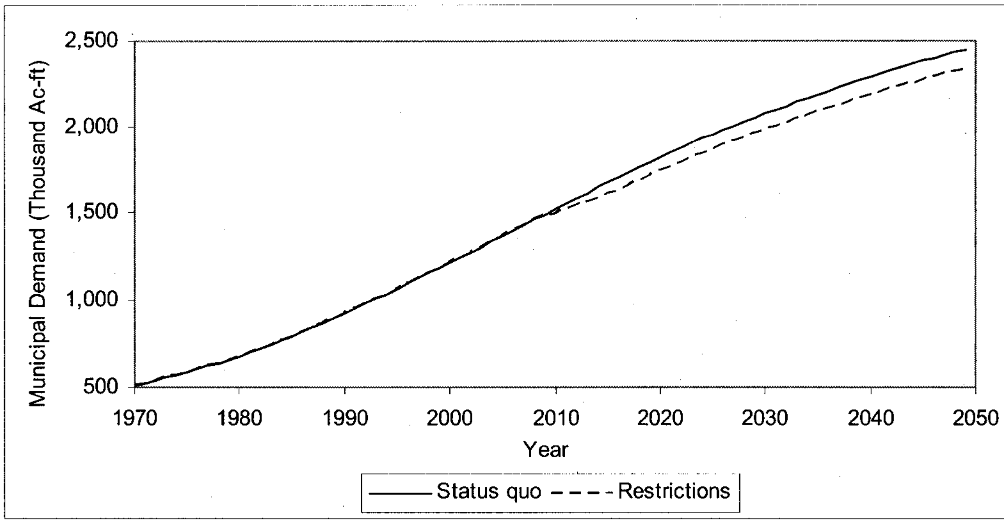

Figure 4.20 Municipal demand for outdoor water use restrictions.

4.4.3 Pricing

A price elasticity of -0.30 is adopted for this model. This implies that an increase of 100% in the price of municipal water reduces the demand by 30%. A simplifying assumption about the nature of savings is made in the model. It assumes that the price elasticity determined in California in 1998 would be valid in Florida in 2010. No adjustment for inflation rates is made to account for the changes in the value of money during the interval.

An increase in the price of municipal water resulted in a decrease in water consumption in the municipal sector. Figure 4.21 shows the variation of municipal demand with price. The model is run for water prices varying between values ranging from status quo price to an increase of 40%. The reduction in consumption is 1.83% for every 10% increase in the price. The reduction in municipal demand in terms of volume of water saved is 45 thousand ac-ft/yr in 2050 for every 10% increase in the price of municipal water.

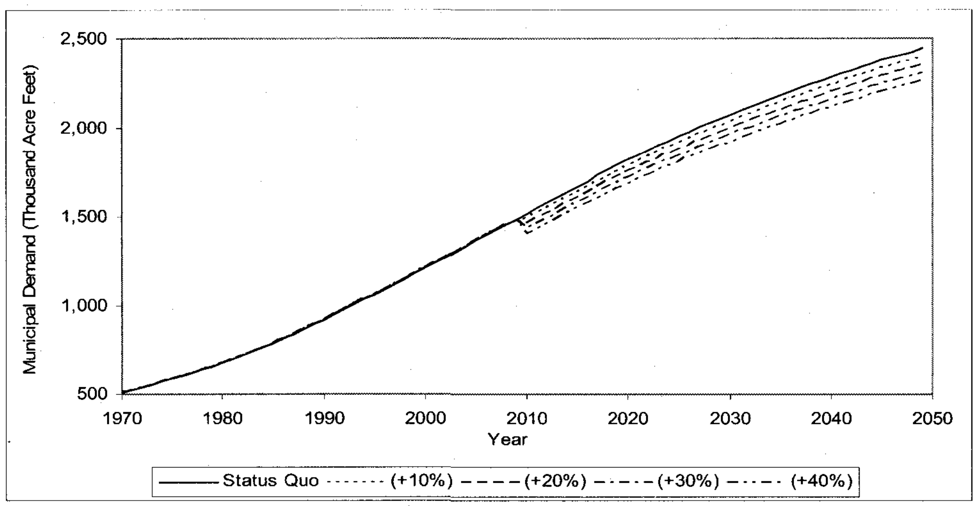

Figure 4.21 Variation of municipal demand with a price increase of 0 to 40%.

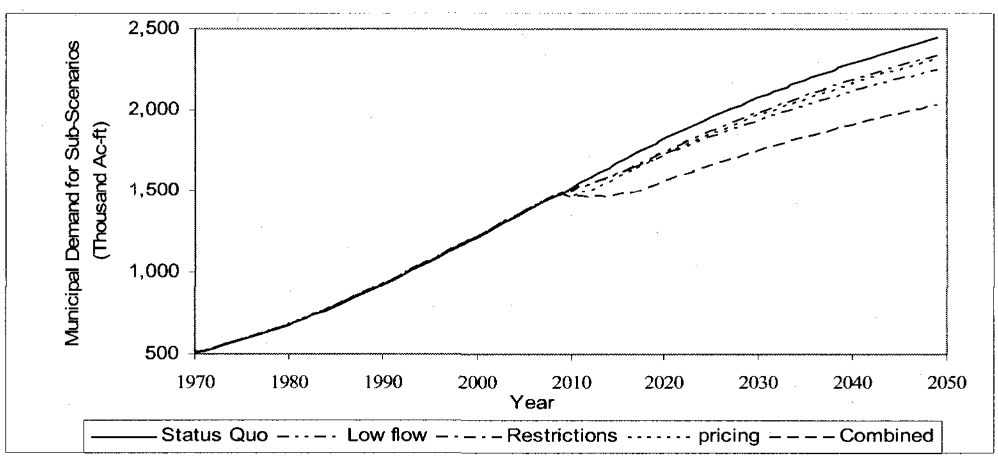

Figure 4.22 Comparative graph for water savings due to different policies.

The comparison of the policies aimed at reducing municipal demand is given in Figure 4.22. The component policies of the municipal intervention scenario result in savings as shown in Table 4.6. A combined maximum saving of 16.12% can be achieved if all the component policy options are adopted simultaneously.

Table 4.6 Comparison of policies scenarios to reduce municipal demand.

Policy	Demand in 2050 (1000 Ac-ft)	Change in demand in 2050 (1000 Ac-ft)	Saving (%)
Status Quo	2,155	--	--
Combined	1,808	-347	16.12
Pricing	1,948	-207	9.63
Low flow Appliances	2,002	-153	7.12
Outdoor Restrictions	2,057	-98	4.57

4.5 Impacts on Environmental Supply

According to Lake Okeechobee regulation schedule (Figure 3.12), municipal and agricultural demands are fulfilled in preference to environmental flows. The environmental flows consist of flows to the WCAs and discharges through the distributaries which also serve the purpose of maintaining the ecology of the everglades and the coastal estuaries respectively. Thus 'failure' is defined as a year when annual amount of water released to the WCAs, St. Lucie River, and Caloosahatchee River is less than 105,000 ac-ft, 20,272 ac-ft, and 217,000 ac-ft of water respectively.

The simulations revealed that for Lake Okeechobee environmental flows exceedances occur 13 times in 40 years of simulation under the status quo scenario. For Caloosahatchee, and WCAs and St. Lucie River the number of violations are 15, 16, and 14 times respectively. In case of agricultural interventions, it is observed that the number of failures drop significantly. However, since the municipal sector draws very little water from the surface water sources, therefore, the impact of municipal interventions on the surface water availability and environmental flows is very little and the combined effect of all municipal interventions resulted in that number to drop very slightly.

Figure 4.23, Figure 4.24, and Figure 4.25 show the annual flow discharge to Caloosahatchee River, WCAs, and the St. Lucie Canal respectively for the agricultural intervention scenario. Figure 4.26, Figure 4.27, and Figure 4.28 show the annual flow discharge to Caloosahatchee River, WCAs, and the St. Lucie Canal respectively for the municipal intervention Scenario.

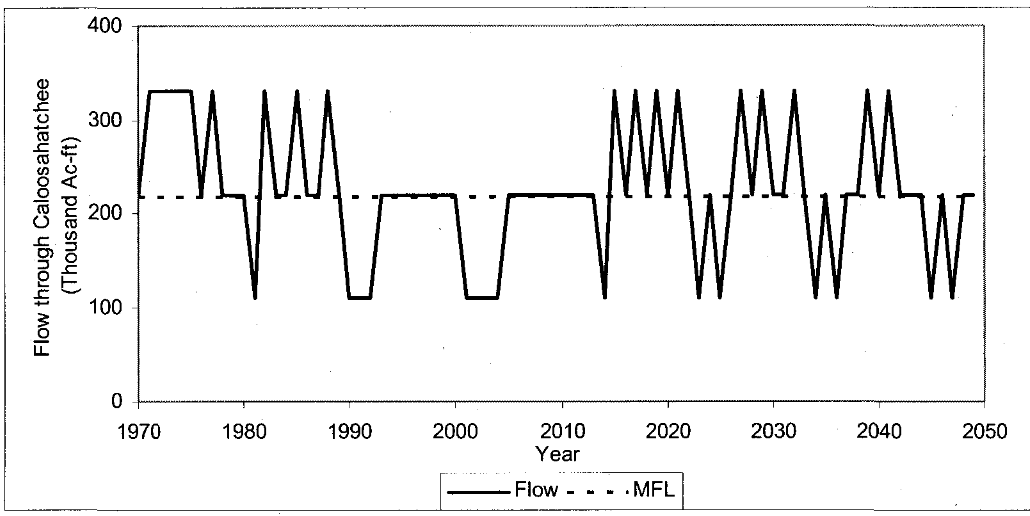

Figure 4.23 Annual flow in Caloosahatchee River (Agricultural Intervention).

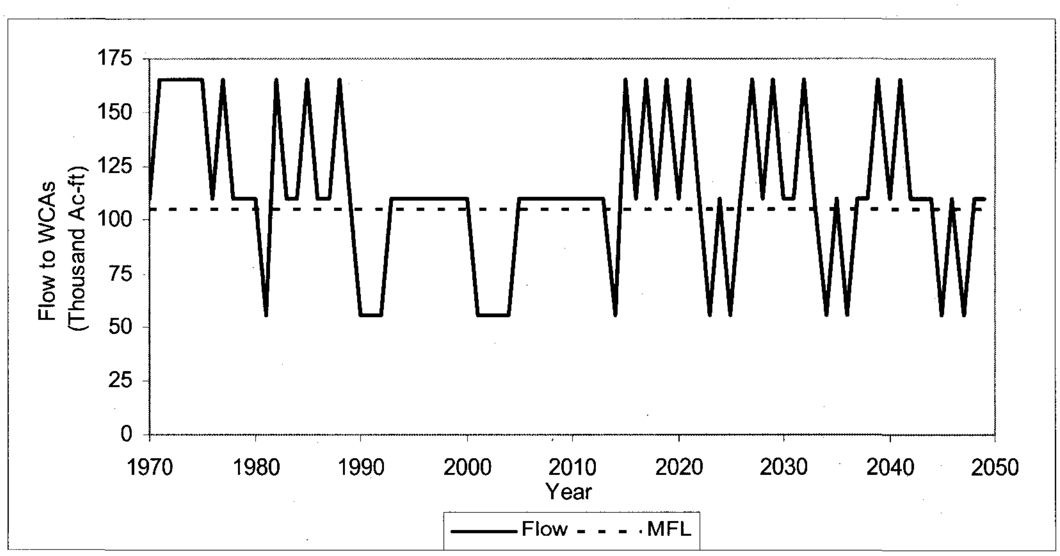

Figure 4.24 Annual flow to WCAs (Agricultural Intervention).

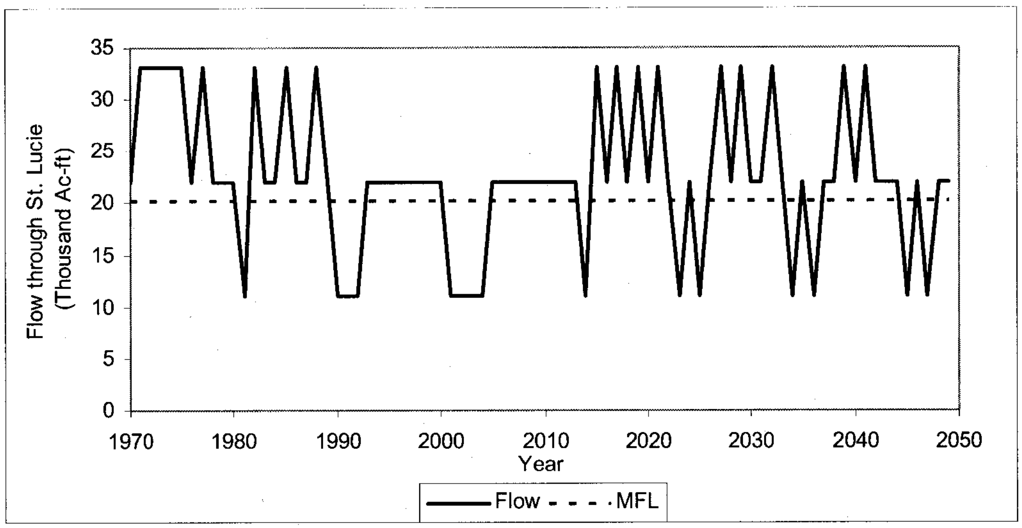

Figure 4.25 Annual flow in St. Lucie Canal (Agricultural Intervention).

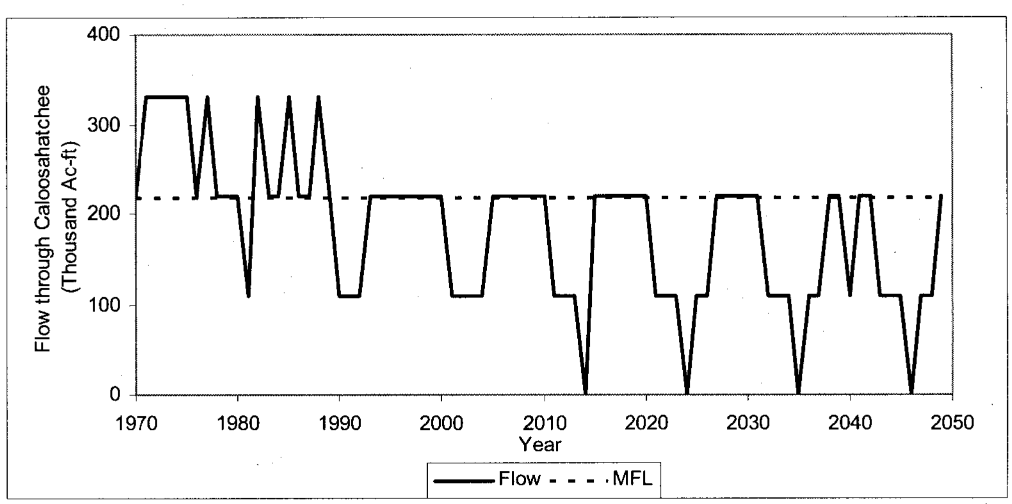

Figure 4.26 Flow through Caloosahatchee (Municipal Intervention).

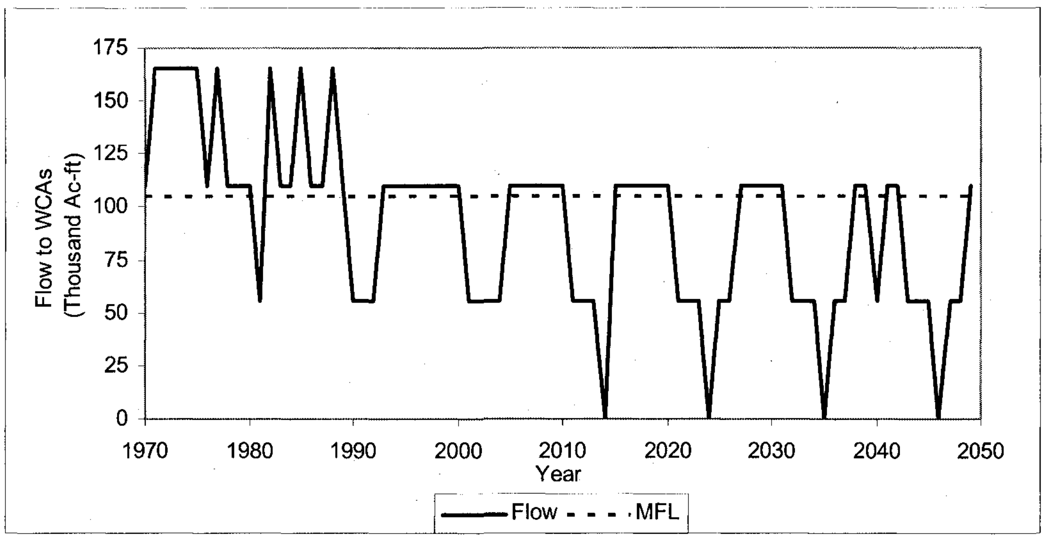

Figure 4.27 Annual flow to WCAs (Municipal Intervention).

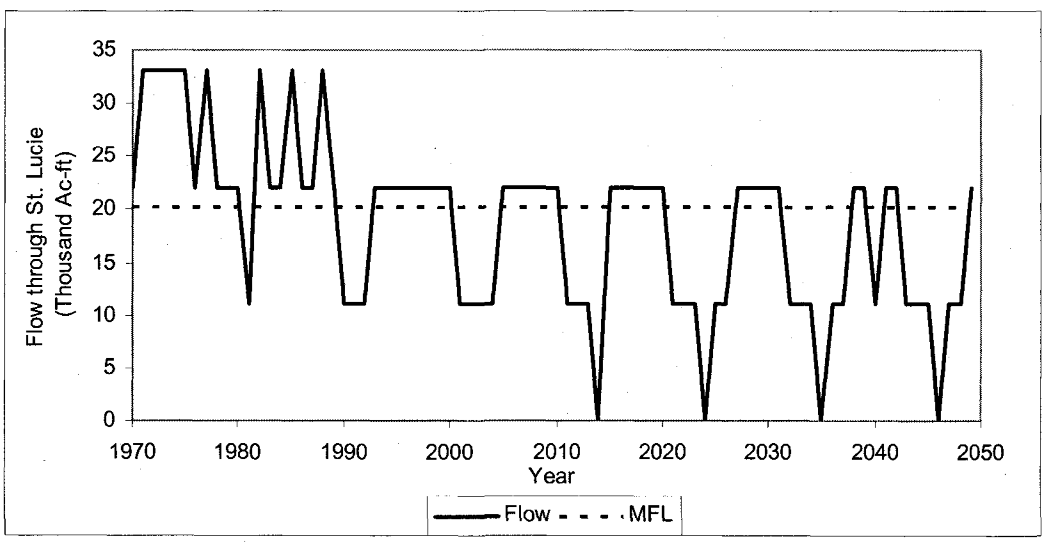

Figure 4.28 Annual flow in St. Lucie Canal (Municipal Intervention)

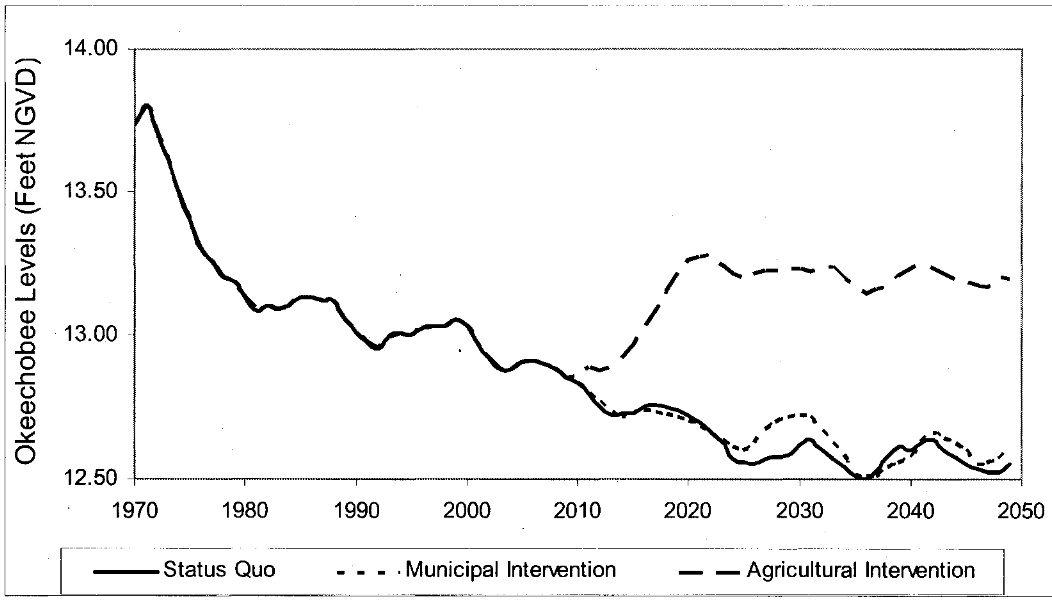

Figure 4.29 Lake levels for status quo, agricultural, and municipal scenarios.

Figure 4.29 shows the change in annual average Lake Okeechobee levels due to agricultural and municipal interventions. The lake levels in 2050 for status quo, agricultural, and municipal intervention scenario are 12.55, 12.60, and 13.70 feet NGVD respectively. The municipal interventions have a negligible effect on the lake levels but agricultural interventions raise the lake levels significantly.

4.6 Variable Population Growth

The population growth has a significant impact on the total and municipal water demands in the district. The increase in municipal demand, as a result of population growth, is 107% from 2000 to 2050 under the status quo scenario. However, in case if the region experiences a growth greater than for the status quo scenario, then it will require an additional amount of water in the municipal sector. This additional amount of water will have an impact on the district's surface water bodies. This section quantifies the effect of population growth on the municipal demands and the fulfillment of environmental demands of the district's water bodies.

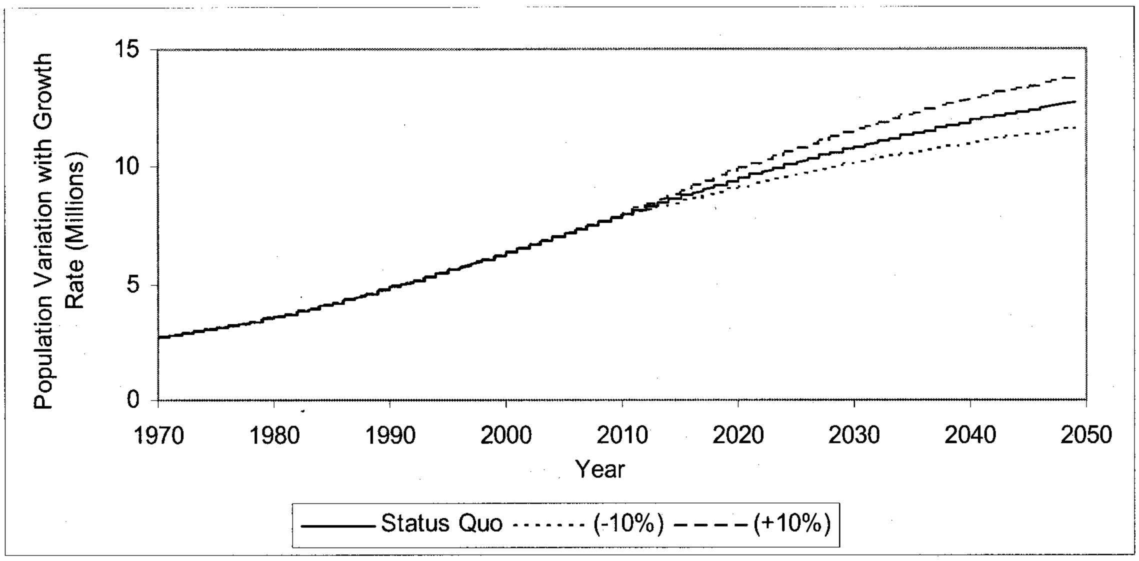

Figure 4.30 Population estimate for varying growth rates.

Model simulations adopting a population growth rate of 10% above that for the status quo scenario show that an additional one million people are added to the district's population by 2050. The total population in the region will increase by an additional 7.85% for an increase of 10% in the population growth rate. Figure 4.30 shows the growth of population in SFWMD if the population growth rates for the district vary from the estimated rate by ±10%.

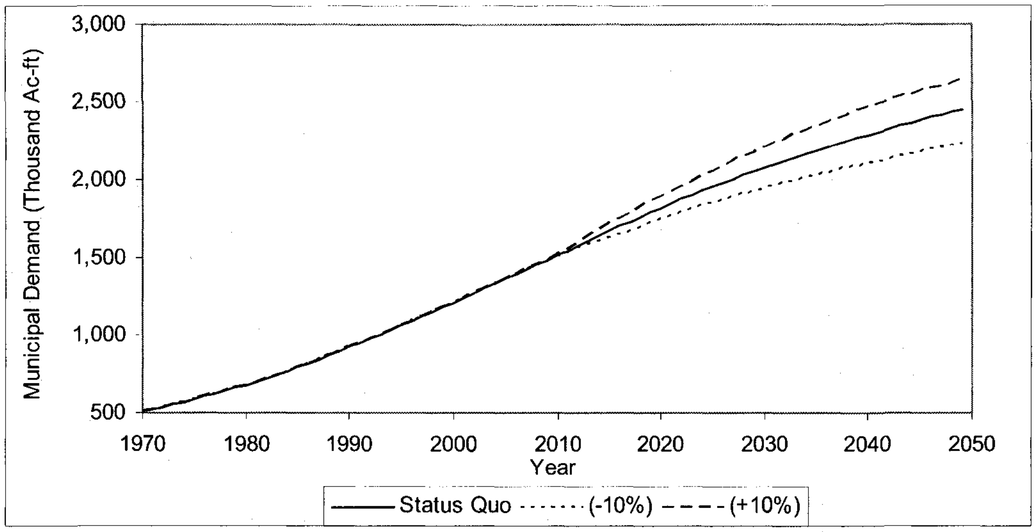

Figure 4.31 Municipal demand for varying population growth rates.

In Figure 4.31 the growth of municipal water demand with varying growth rates is shown. The growth rates vary by $\pm$ 10% above and below the status quo scenario for the period between 2010 and 2050. The population figures for status quo, increase of 10% in growth rate, and decrease of 10% in growth rate are 12.7 million, 13.7 million, and 11.6 million respectively. The municipal demand for an accelerated growth rate increases to 2.64 million ac-ft/yr as compared to 2.44 million ac-ft/yr for status quo growth rate. Thus a 10% increase in population growth rate over the period between 2010 and 2050 led to an increase in the annual municipal in 2050 by 7.85%. Similarly, in case of population growth rates that are 10% under the status quo growth rates, the reduction in municipal demand in 2050 is 8.8% or 200,000 ac-ft/year.

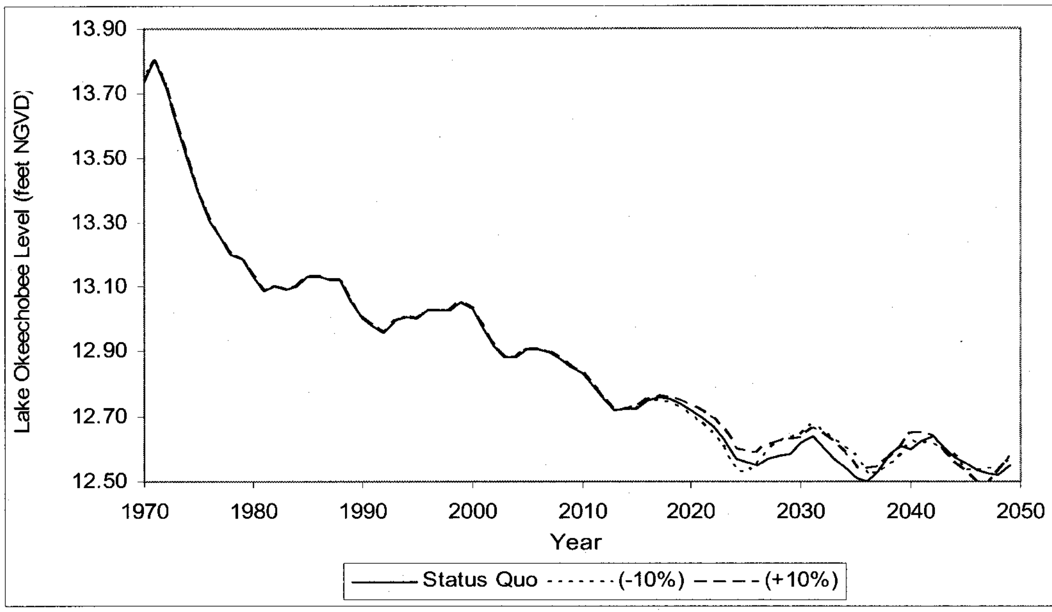

Figure 4.32 Lake Okeechobee levels for varying population growth rates.

A change in population growth rate is seen to have a negligible impact on water levels in Lake Okeechobee. This is because of the fact that the population growth only impacts the municipal water demand in the district and municipal sector draws very little water from Lake Okeechobee. Figure 4.32 shows the annual average Lake Okeechobee levels for the population growth rates 10% above and below status quo. The final levels for status quo, +10%, and -10% growth rates are 12.55, 12.48, 12.81 feet NGVD respectively.

The effect of varying population growth on environmental flows to St. Lucie, Caloosahatchee, and WCAs is shown in Figure 4.33, Figure 4.34, and Figure 4.35 respectively. Changing the population growth rates has a negligible impact on the district's environmental flows. Although a 10% decrease in population growth rate decreases the municipal demand by 8.85% but this reduction in demand does not have a noteworthy reduction in the number of environmental flow failures. The number of failures for the status quo scenario for the three water bodies is 15, 16, and 14 times respectively. An increase of 10% in growth rates has no effect on the number of failures but a decrease of 10% in population growth rate reduces the number of failures to 14, 15, and 13 times respectively.

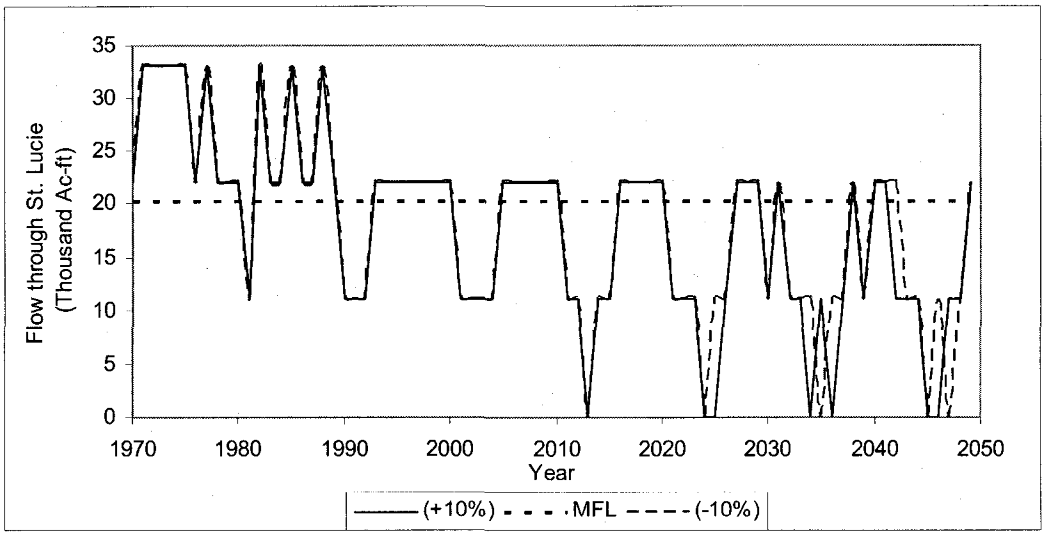

Figure 4.33 Flow through St. Lucie for varying population

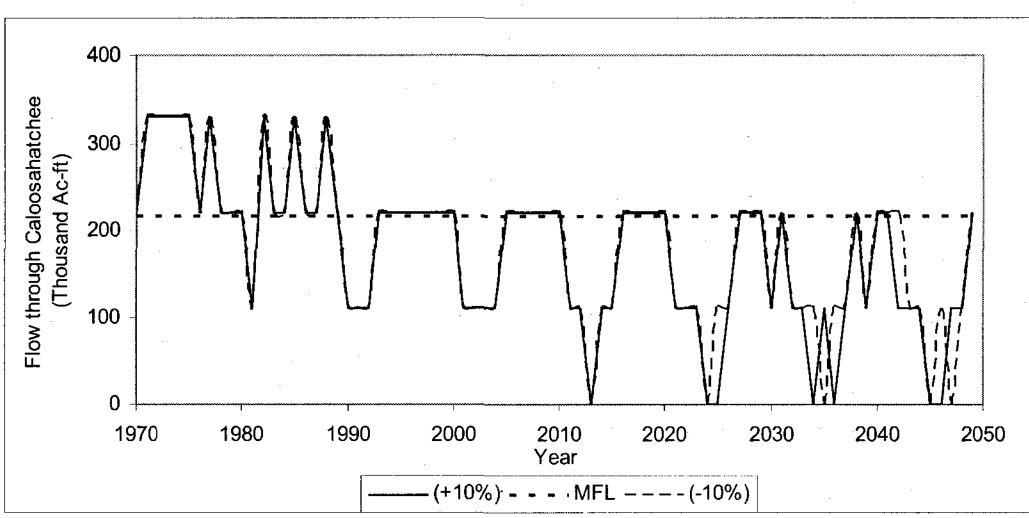

Figure 4.34 Flow through Caloosahatchee for varying population.

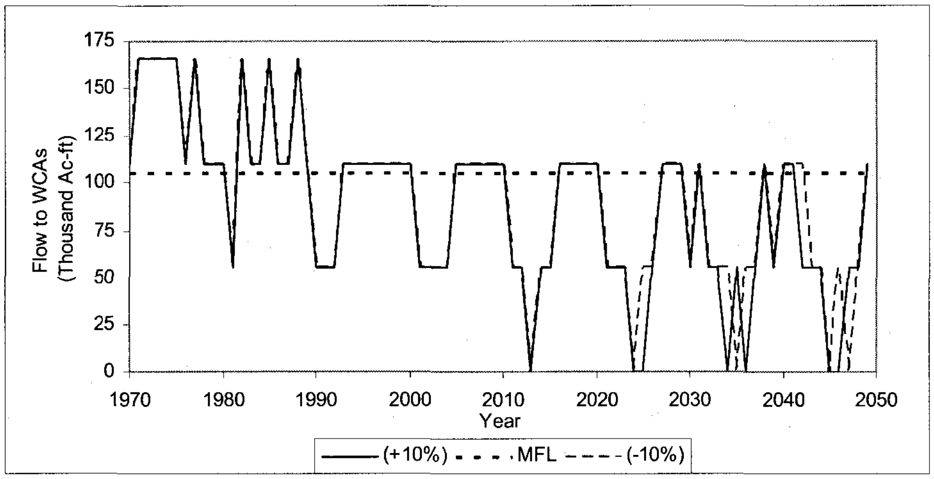

Figure 4.35 Flow to WCAs for varying population.

4.7 Rainfall Variability

The model so far is run using long term average monthly precipitation amounts. The advantage this assumption offers is that it provides consistent trends throughout the timeline of the model and afforded a better view of the direction in which the changes are occurring. This is important for analysis of the results, because large annual variations in precipitation amounts tend to overshadow the long term trends in water availability and consumption. However, for a planning period that extends 40 years into the future, the results obtained would be quite inadequate if climatic variability is not taken into consideration. Thus a variable is introduced to incorporate the desired changes in the rainfall amounts over the planning horizon extending beyond the year 2010.

Table 4.7 Description of rainfall scenarios

Scenario	Description
Status Quo	Historic average rainfall from1970 to 2000 (N inches)
Wetter than normal	Random generation of rainfall (N to 1.1N)
Drier than normal	Random generation of rainfall (N to 0.9N)
Prolonged drought	10 year low rainfall from (2020 to 2030)

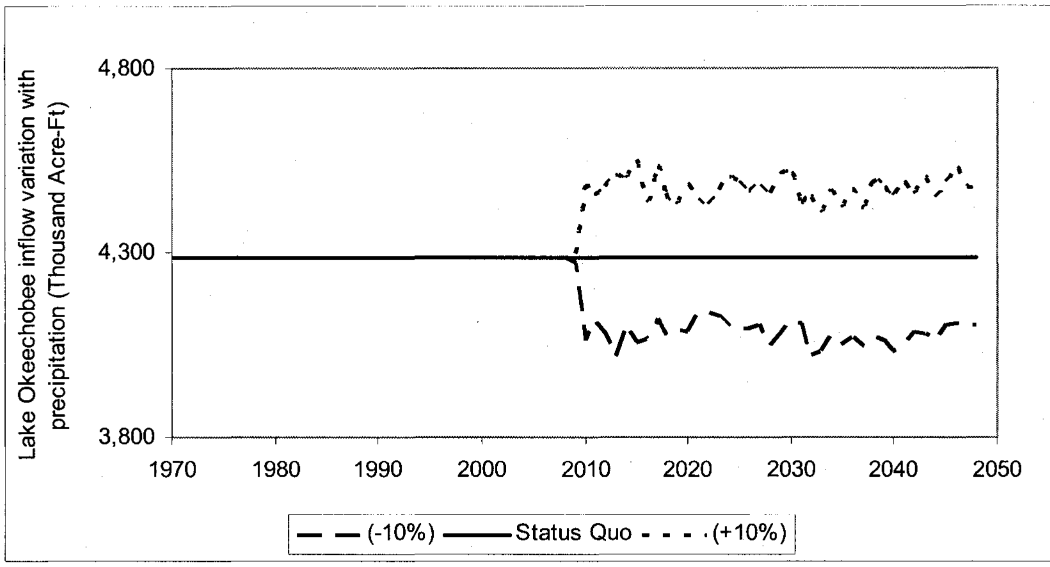

Figure 4.36 Variation of inflow into Lake Okeechobee with precipitation.

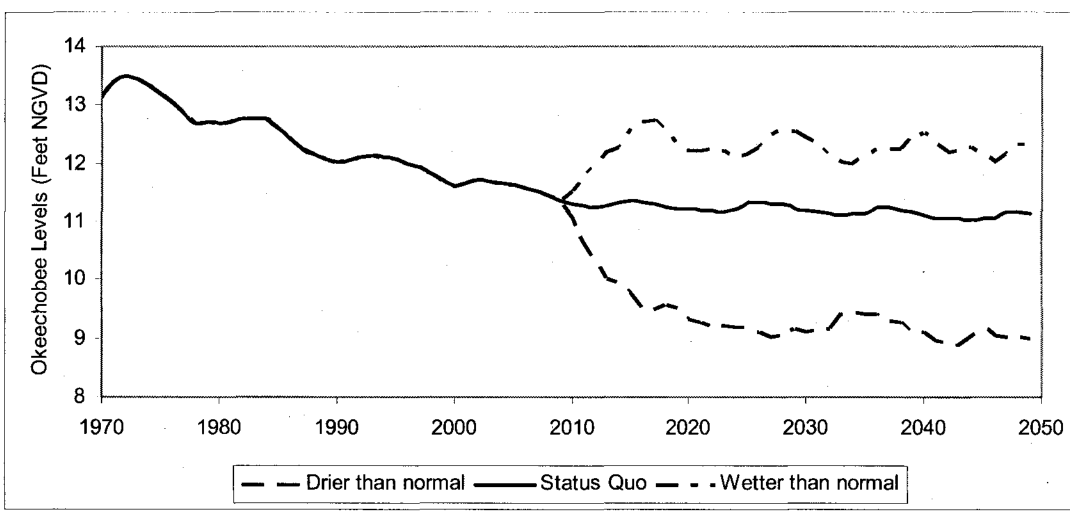

Figure 4.37 Variation of Lake Okeechobee levels with varying precipitation rates.

Any variation in the amount of rainfall experienced by the district will also reflect on Lake Okeechobee levels. The impact of rainfall variation on Lake Okeechobee levels will be two fold. On one hand, it would change the demands and on the other hand it will also change the inflows received by the lake. The impact of change in precipitation amount on the demands is in the opposite direction, i.e., an increase in rainfall would result in a decrease in the agricultural demand and vice versa. The inflows to the lake on the other hand are impacted in a positive direction i.e., with an increase in the precipitation amount, the inflows also increase (Figure 4.36). The increase in the inflows can be attributed to an increased runoff as well as an increase in the precipitation occurring directly over the lake. For status quo, wetter than normal, and drier than normal scenarios the inflow into Lake Okeechobee from its tributaries is 43,000 ac-ft, 45,000 ac-ft, and 41,000 ac-ft respectively. Figure 4.37 shows the variation of Lake Okeechobee levels with varying precipitation depths. The annual rainfall depths in the period beyond 2010 are decreased or increased by 10% and the corresponding annual average lake levels are plotted in the figure.

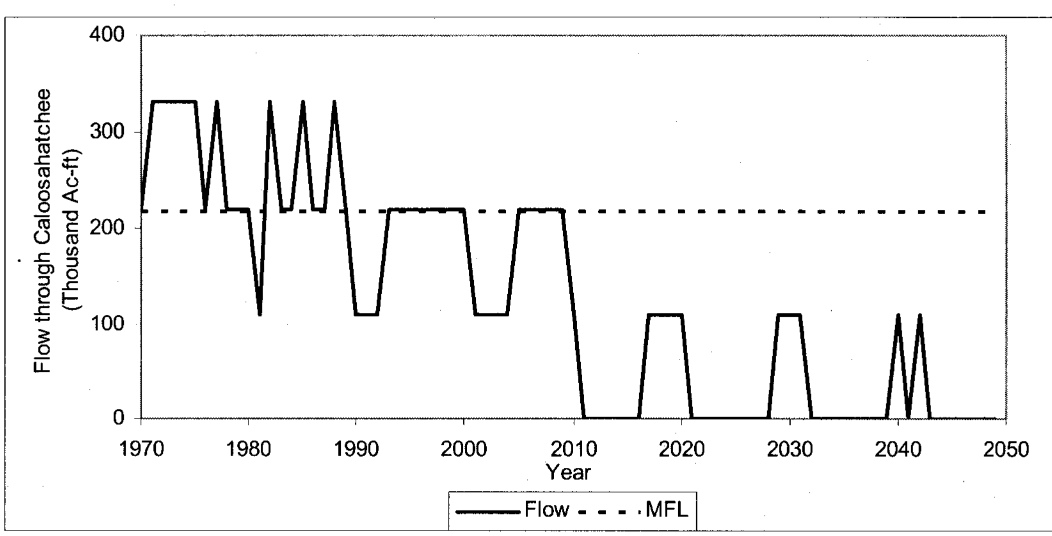

Figure 4.38 Annual flows to Caloosahatchee River for dryer than normal years.

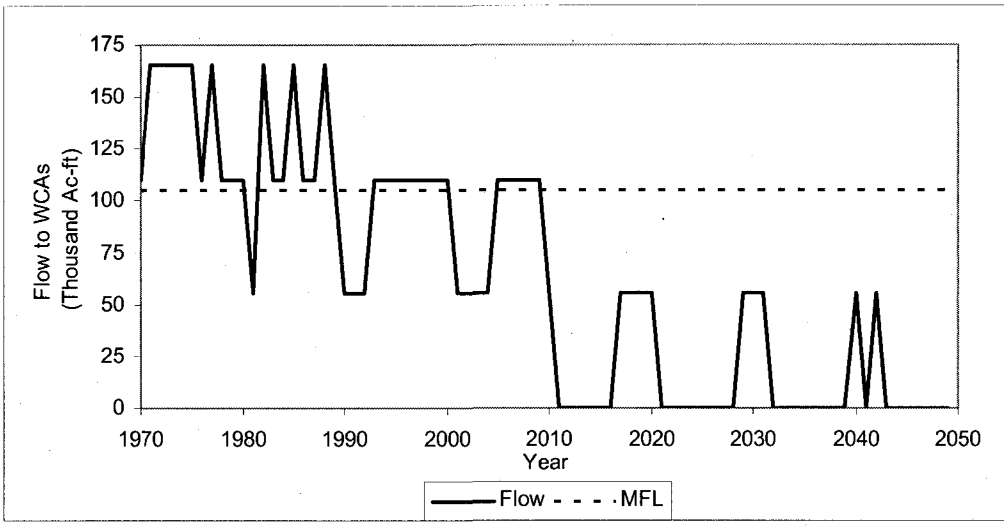

Figure 4.39 Annual flows to WCAs for dryer than normal years.

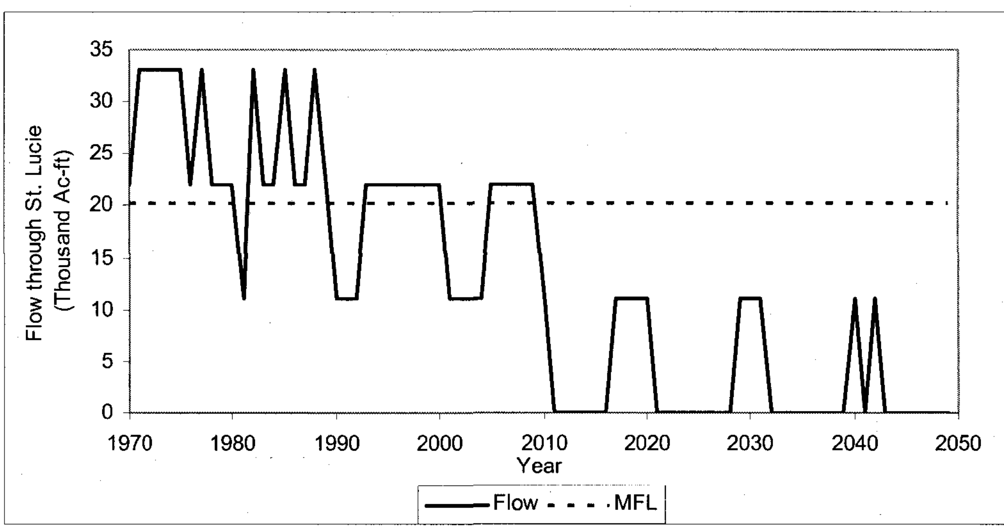

Figure 4.40 Flow through St. Lucie Canal for dryer than normal years.

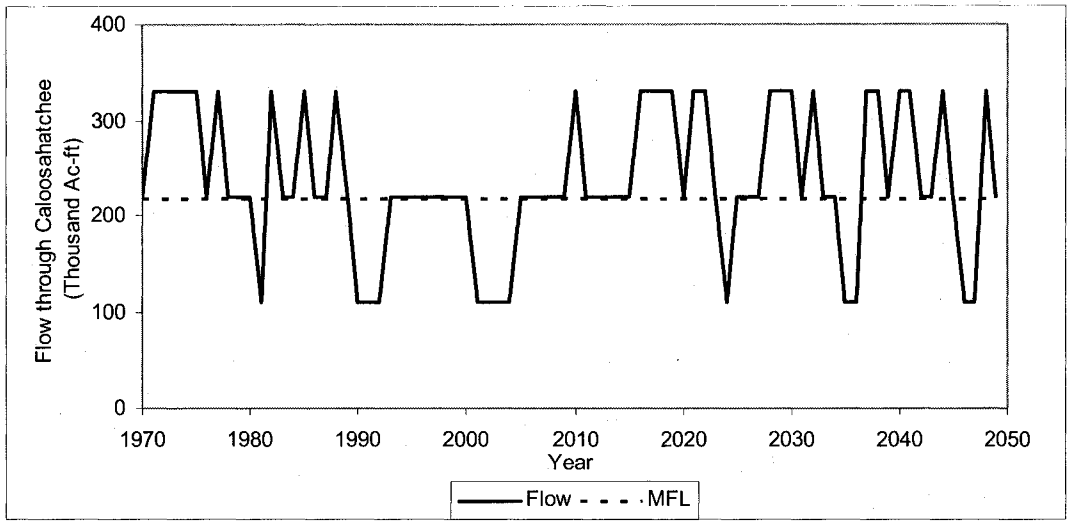

Figure 4.41 Annual flow in Caloosahatchee River for wetter than normal years

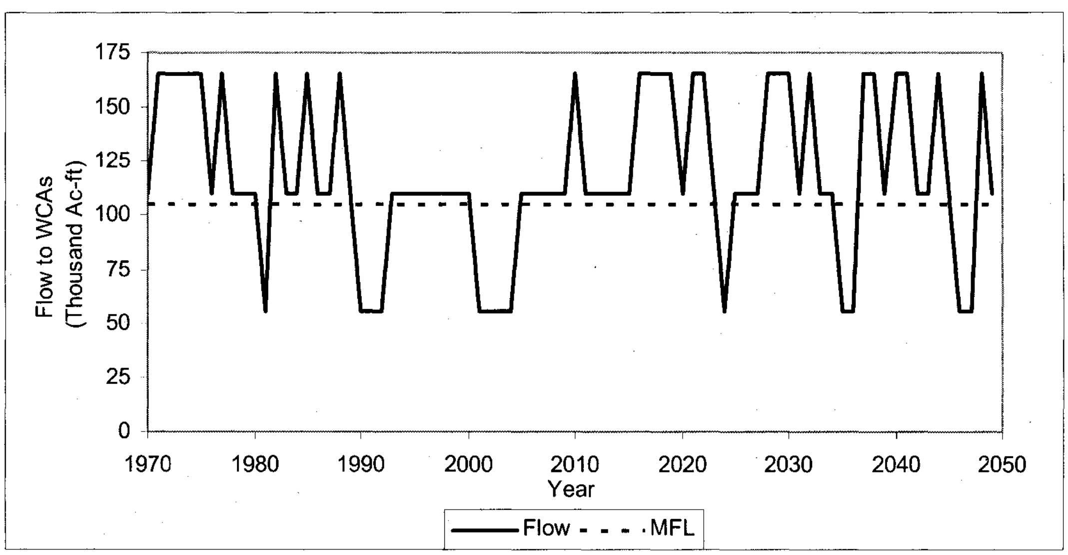

Figure 4.42 Annual flow to the WCAs for wetter than normal years.

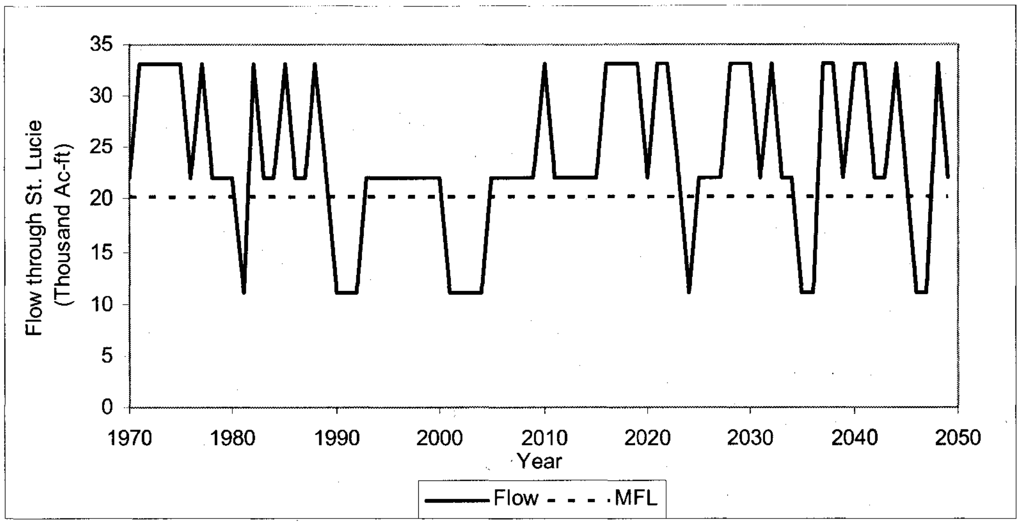

Figure 4.43 Annual flow through St. Lucie Canal for wetter than normal years.

Table 3.7 explains the environmental flow failure criteria adopted for the model. The threshold for MFL violation in Lake Okeechobee is lowering of water levels in the lake below 11 feet NGVD. For Caloosahatchee River, the MFLs are guided by the following two conditions. (a) 30-day average salinity concentration exceeds 10 parts per thousand at the Ft. Myers salinity station and, (b) single, daily average salinity exceeds a concentration of 20 parts per thousand at the Ft. Myers salinity station. The WCAs are expected to release 105,000 ac-ft of water to the Biscayne Bay, this requirement is derived from Lake Okeechobee. The St. Lucie River, which drains the lake to the east, has a MFL requirement of 28 cfs. This flow which is also based upon salinity measurement levels in the river, translates into 20,272 Ac-ft of water annually. Table 4.8 tabulates the number of years during which the model fails to meet the environmental flow requirement of the corresponding water body.

Table 4.8 Number of failures of environmental flows observed for the different scenarios.

Scenario	Okeechobee Levels	Flow to WCAs	Caloosahatchee River	St. Lucie Estuary
Status Quo	13	15	16	14
Municipal Intervention	8	12	14	12
Agricultural Intervention	2	6	6	6
Normal Rainfall	13	15	16	14
Wetter than normal	2	5	5	5
Drier than normal	40	39	39	38
Prolonged drought	41	18	23	12

Table 4.9 Rainfall statistics for SFWMD (Alaa 2000).

	Monthly Rainfall (inches)	
	Average	Std Dev
Jan	2.01	2.05
Feb	2.36	1.85
Mar	2.95	2.56
Apr	2.60	2.32
May	4.65	3.15
Jun	7.83	4.13
Jul	6.97	3.19
Aug	7.05	3.19
Sep	7.24	3.78
Oct	4.72	3.82
Nov	2.28	2.36
Dec	1.89	1.81

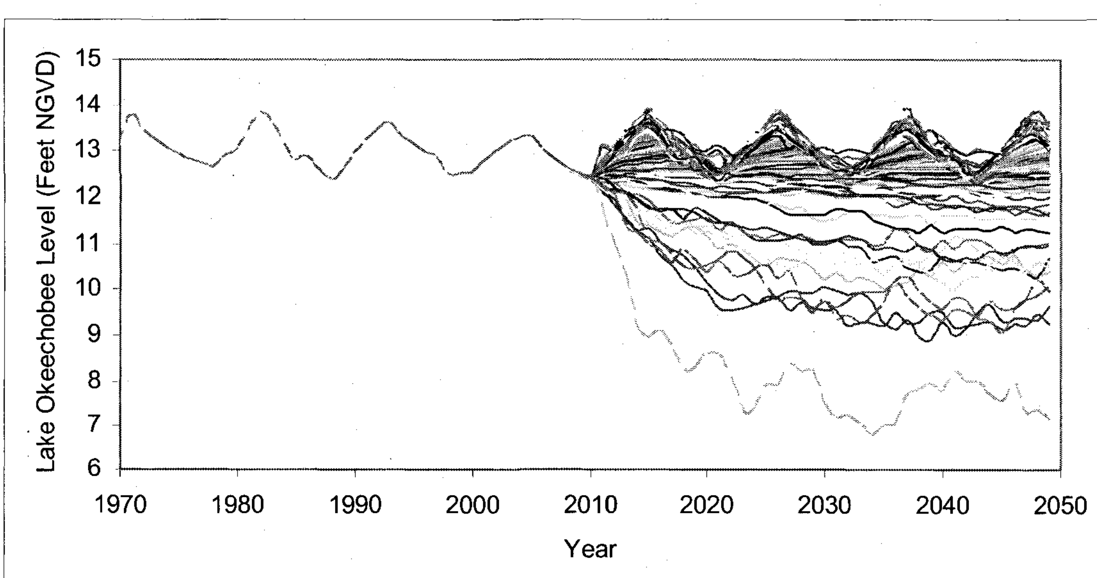

Figure 4.44 100 runs from Monte Carlo Simulations.

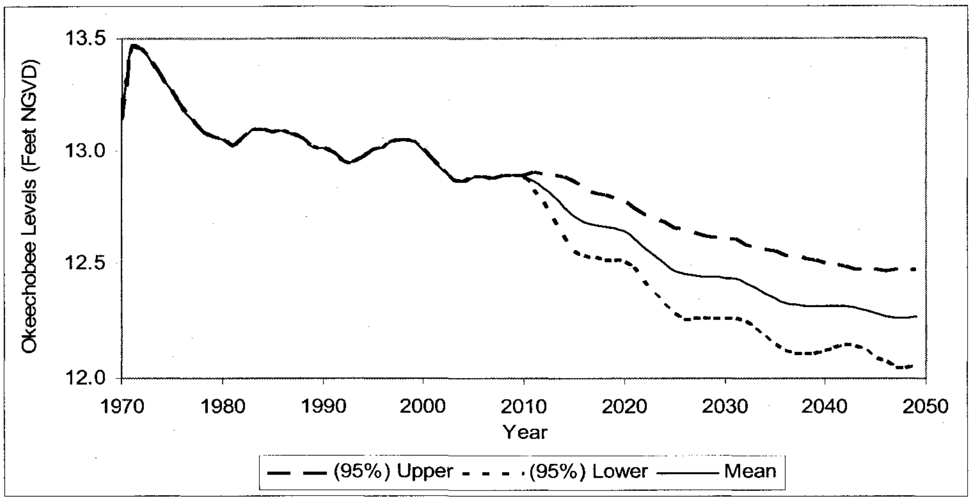

Figure 4.45 Annual average lake levels with 95% confidence limits.

Monte Carlo simulations are run on the model for the status quo scenario to generate the lake levels within 95% confidence limits. Rainfall is randomly generated from a distribution data (Table 4.9) and the results from a 1000 simulations are used to generate the confidence limits. The annual average Lake Okeechobee levels with the upper and lower 95% confidence limits are shown in Figure 4.45. A graph showing 100 runs is given in Figure 4.44. Five year rolling averages of annual water levels in the lake were used to obtain the confidence limits to reduce the annual variations and see the overall trends more clearly.

Table 4.10 Performance measure of Lake Okeechobee for various scenarios.

Scenario	Resilience	Reliability	Vulnerability
Status Quo	0.66	0.91	0.43
Agricultural Intervention	0.90	0.97	0.23
Municipal Intervention	0.68	0.92	0.42
Normal Rainfall	0.66	0.91	0.43
10% above normal	0.90	0.97	0.23
10% below normal	0.34	0.65	2.00
Wetter than normal	0.82	0.95	0.27
Drier than normal	0.52	0.86	0.59
Prolonged Drought	0.66	0.80	2.80

Table 4.10 shows the performance evaluation criteria results for Lake Okeechobee for various policy and rainfall scenarios. For status quo scenario, the resilience has a value of 0.66, i.e., once the water level in the lake drops below 11 ft NGVD, it takes on average (1/0.66) or 1.5 months to recover. Reliability value 0.91 indicates that the lake levels stay above 11 ft NGVD for 91% of the entire time horizon from 1970 to 2050. Thus, it fulfills all its functions for 91% of the time. Vulnerability which represents the magnitude of failure has a value of 0.43 for status quo scenario. This implies that the lake levels on average drop below the 11 ft mark by 0.43 ft per failure event.

Table 4.11 and Table 4.12 summarize the results and findings from the agricultural and municipal intervention scenarios respectively. Column 2 gives the details of changes in demand as compared to the year 1970. Column 3 shows cumulative water savings achieved from 2010 to 2050 due to the corresponding policy option. Column 4 is the average percent change in the demands from 2010 to 2050. Column 5 displays the reduction or increase of demands in 2050 due to corresponding policy options as compared to status quo simulations.

Table 4.13 shows the variation in annual agricultural demand with changes in annual precipitation. Since a change in precipitation results in a change in soil moisture, therefore, the agricultural demand is also expected to change proportionally. However, for the prolonged drought scenario, the change in rainfall is assumed to be between 2020 and 2030. Therefore, the system is able to recover by 2050, thus the final agricultural demand is not affected for this scenario. Column 1 gives the description of the rainfall scenario and column 2 shows the corresponding annual agricultural demand in 2050. Column 3 shows the increase or decrease in annual agricultural demand as compared to normal rainfall scenario. Column 4 gives the annual maximum, minimum, and average lake levels in 2050. The variation in lake levels is due to the combined effect of changes in inflow as well as changes in agricultural demand. Column 5 gives the number of instances of exceedances which is defined in the FAC as "An "exceedance" is a decline below 11 feet NGVD for more than 80, non-consecutive or consecutive, days, during an eighteen month period. The eighteen month period shall be initiated following the first day Lake Okeechobee falls below 11 feet NGVD, and shall not include more than one wet season, defined as May 31st through October 31st of any given calendar year."

The exceedance criteria in the model, however, is modified in order to consider an exceedance to have occurred if the lake levels drop below 11 feet NGVD for three consecutive or non consecutive months over an eighteen month period. The eighteen month period being initiated following the first month the average lake levels drop below 11 feet NGVD and not including more than one wet season. This alteration was done because a monthly time step was used in the model simulations.

Table 4.11 Summary of the results for the agricultural intervention scenario.

Sr. No.	(Col 1) Scenario	(Col 2) Agricultural Demand (1000 Ac-ft)				(Col 3) Cumulative Change from 2010 to 2050 (1000 Ac-ft)	(Col 4) Average % Change from 2010 to 2050	(Col 5) % Change in Final Year	(Col 6) Scenario Description
		1970	2000	2030	2050				
1	Status Quo (1000 Ac-ft)	2,602	2,950	3,041	3,027				No changes in growth rate
	% of total water demand	84	71	60	55				
	Change from 1970 (1000 Ac-ft)		347	438	424				
	% Change from 1970		13.34	16.86	16.31				
2	Micro Irrigation (1000 Ac-ft)	2,602	2,950	2,681	2,667	-14,415	-8.44	-11.88	Sugarcane increased from- 0 to 20% Citrus from 80 to 90%
	% of total water demand	84	71	57	52				
	Change from 1970 (1000 Ac-ft)		347	78	64				
	% Change from 1970		13.34	3.03	2.49				
3	Acreage Reduction (1000 Ac-ft)	2,602	2,950	2,598	2,583	-19,893	-11.37	-14.65	Sugarcane acreage reduced by 20%
	% of total water demand	84	71	56	51				
	Change from 1970 (1000 Ac-ft)		347	-4,185	-19,137				
	% Change from 1970		13.34	-0.16	-0.74				
4	Substitution (1000 Ac-ft)	2,602	2,950	2,911	2,887	-8,270	-4.28	-4.64	20% sugarcane area shifted to row crops
	% of total water demand	84	71	59	54				
	Change from 1970 (1000 Ac-ft)		347	308	284				
	% Change from 1970		13.34	11.84	10.92				
5	Combined (1000 Ac-ft)	2,602	2,950	2,393	2,376	-23,639	-16.34	-21.48	Combination of scenarios 2 & 3
	% of total water demand	84	71	54	49				
	Change from 1970 (1000 Ac-ft)		347	-209	-225				
	% Change from 1970		13.34	-8.06	-8.68				

-ve values reflect a decrease in demand

Table 4.12 Summary of the results for the municipal intervention scenarios.

Sr. No.	Scenario	Municipal Demand (1000 Ac-ft) 1970	2000	2030	2050	Cumulative Change from 2010 to 2050 (1000 Ac-ft)	Average % Saving from 2010 to 2050	% Change in Final Year	Scenario Description
1	Status Quo (1000 Ac-ft)	505	1,180	2,051	2,445				No change in growth rates
	% of total water demand	16	29	40	45				
	Change from 1970 (1000 Ac-ft)		674	1,546	1,939				
	% Change from 1970		133.43	305.7	383.55				
2	Price Increase (1000 Ac-ft)	505	1,180	1,939	2,311	-4,473	-4.82	-5.49	Price increase of 30%
	% of total water demand	16	29	39	43				
	Change from 1970 (1000 Ac-ft)		674	1,433	1,805				
	% Change from 1970		133.43	283.4	357.00				
3	Low Flow Appliances (1000 Ac-ft)	505	1,180	1,914	2,244	-5,364	-6.58	-8.19	Mandatory after 2010, 20% old homes retrofitted
	% of total water demand	16	29	39	43				
	Change from 1970 (1000 Ac-ft)		674	1,409	1,739				
	% Change from 1970		133.43	278.6	343.92				
4	Outdoor Restrictions (1000 Ac-ft)	505	1,180	1,949	2,318	-4,053	-4.97	-5.17	Mandatory Xeriscaping
	% of total water demand	16	29	39	43				
	Change from 1970 (1000 Ac-ft)		674	1,443	1,813				
	% Change from 1970		133.43	285.4	358.53				
5	Combined (1000 Ac-ft)	505	1,180	1,729	2,026	-12,748	-15.64	-17.11	Combination of the scenario # 2, 3 and 4
	% of total water demand	16	29	36	40				
	Change from 1970 (1000 Ac-ft)		674	1,223	1,521				
	% Change from 1970		133.43	241.9	300.81				
6	Pop Growth Rate +10% (1000 Ac-ft)	505	1,180	2,176	2,637	4,743	5.82	7.85	Population growth rate 10% more than expected
	% of total water demand	16	29	42	47				
	Change from 1970 (1000 Ac-ft)		674	1,670	2,131				
	% Change from 1970		133.43	330.4	421.49				

7	Pop Growth Rate -10% (1000 Ac-ft)	505	1,180	1,928	2,230	-4,875	-5.98	-8.77	Population growth rate 10% less than expected
	% of total water demand	16	29	39	42				
	Change from 1970 (1000 Ac-ft)		674	1,422	1,725				
	% Change from 1970		133.43	281.3	341.16				

-ve values reflect a decrease in demand

Table 4.13 Agricultural demand and lake levels for the rainfall scenarios.

(Col 1)	(Col 2)	(Col 3)	(Col 4)			(Col 5)
	Agricultural Demand	Change in Ag Demand in 2050	Lake levels in 2050 (ft NGVD)			Number of Exceedances
Rainfall Scenario	(1000 Ac-ft)	(1000 Ac-ft)	Max	Min	Avg	
Normal	3,027		13.75	10.48	12.86	13
10% increase	2,805	-221	15.93	11.88	13.79	0
10% decrease	3,266	238	11.66	6.40	9.21	80
Wetter than normal	2,911	-116	15.40	11.61	13.52	4
Drier than normal	3,116	88	13.68	9.90	12.12	27
Prolonged drought	3,027	0	14.70	11.08	12.90	40

Violation condition adopted for the model: Average monthly Okeechobee levels falling under 11ft NGVD for three consecutive or non consecutive months in a span of 18 months.

4.8 Comparison of Policy Options

This section compares the policy options described in the previous sections based on their performance. The previous sections describe the overall effectiveness of these measures. But to compare policies, they must be tested for the maximum savings they can achieve as well as the extent of intervention required in order to achieve a fixed amount of saving.

Table 4.14 Comparison of agricultural intervention policies.

Policy	Change Required for 5% Reduction in Consumption	Maximum Reduction Achievable
Micro Irrigation (Sugarcane)	20.5%	24.20%
Micro Irrigation (Citrus)	80% to 95%	7.50%
Acreage Reduction (Sugarcane	10.5%	47.20%
Substitution (Sugarcane to Row Crops)	28.5%	17.54%

Table 4.14 shows the evaluation of the policy options in the agricultural sector. Column 1 gives the details of the policy. Column 2 shows the extent of intervention required to achieve a 5% reduction in water consumption which would be equal to 150,000 Ac-ft/yr. Introduction of micro irrigation to 20.5% of sugarcane acreage can reduce agricultural water consumption by 5% and a maximum conservation of 24.2% can be achieved by converting the entire sugarcane acreage into micro irrigation. For citrus, which already have 80% of acreage under micro irrigation 7.5% reduction in water can be achieved by converting it entirely into micro irrigation. The (--) represent either mandatory policy options for which give a fixed amount of conservation, or for policy options which are unable to yield a 5% saving even for maximum possible intervention.

Table 4.15 Comparison of municipal intervention policies.

Intervention	Requirement to reduce demand by 5%	Max Reduction Possible
Mandatory L F Appliances	--	5.70%
LF Appliances for old homes	55%	9.20%
Mandatory Xeriscaping	--	2.20%
Xeriscaping (old homes)	--	3.40%
Combined Xeriscaping	Mandatory + 73% old	5.60%

Table 4.15 similarly shows the relative success of the components of the municipal intervention scenario to reduce municipal demand by 5% or 125,000 ac-ft/yr of water. For the policy of mandatory use of low flow appliances in new homes, a maximum of 5.7% of conservation can be achieved. 55% old homes have to be retrofitted in order to reduce water consumption by 5% and retrofit can achieve a maximum of 9.2% of saving. Mandatory use of xeriscapes for new homes can save 2.2% of municipal water annually and a maximum of 3.4% reduction in consumption can be achieved by completely adopting xeriscapes for all old homes in South Florida.

Depending upon the targeted conservation, a single policy or a combination of policies in the agricultural and municipal intervention can be adopted. Although the absolute success rate of the policies can not be determined without undertaking a detailed economic analysis of all these measures. Nonetheless, this section helps in identifying the most efficient conservation measure in terms of water savings achieved.

4.9 Summary of Results

1. The model simulations reveal that the number and frequency of failure events for all major water bodies in the district increased considerably after the year 2010.

2. In status quo scenario Lake Okeechobee is unable to meet agricultural and municipal demands, while at the same time ensuring the designated MFLs for the rivers, wetlands and estuaries.

3. Municipal intervention scenario, which is introduced in the model to achieve water conservation in the domestic water consumption, is able to reduce consumption by up to 17% of the municipal water consumption or 7.5% of total water consumption in 2050.

4. Notwithstanding the success of the municipal intervention scenario in reducing the demand, it has a very little impact in reducing the number of failures of environmental flows. This counter-intuitive result can be attributed to the very heavy reliance of SFWMD on groundwater sources to fulfill its municipal demand.

5. The agricultural intervention scenario, implemented in the model to reduce the agricultural water demand, succeeded in reducing the water consumption by up to 21% of agricultural water consumption or 13% of total water consumption in 2050.

6. The agricultural interventions prove successful in reducing the number of environmental flow failures in Lake Okeechobee, as well as the ecosystems fed by the lake. These results signify the effect of agriculture on the surface water bodies of South Florida.

7. Model simulations run under agricultural and municipal intervention scenarios show that the agricultural sector reforms are more capable of relieving the stress from the district's water bodies.

8. Changing the population growth rates by ± 10% changed the municipal water consumption but it did not have a significant impact on the lake levels and it did not reduce the environmental flow failures by a great extent.

9. Significant variations are observed in case of simulation runs under variable rainfall rates. A 10% increase in annual average rainfall amount caused the violations to be eliminated and it gave comparable results to the agricultural intervention scenario. A 10% reduction in the rainfall however, revealed very disquieting results. The lake dropped to alarmingly low levels, which resulted in a cessation of the environmental flows.

10. The Monte Carlo simulations for Lake Okeechobee water levels show that average annual water levels will remain between 12.1 feet to 12.6 feet NGVD with a 95% confidence limit.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This study provides a detailed picture of the interactions between the various components of a natural watershed and their effect on water availability and demands. For a region that hosts a diversity of land use from natural wetlands to large urban areas, it is often a difficult task to balance all the needs of the population and meet the requirements of the environmental systems simultaneously. Nevertheless, with use of simulation modeling approach, it is possible to evaluate the current and future needs of the population, agriculture, and the environment.

An advantage of using SD for modeling systems on a large scale is that it can encompass all moving parts of the system within the boundary with a reasonable degree of accuracy. It can give the decision makers an insight into the total system behavior rather than the behavior of the individual components, thus facilitating more informed decisions. It also allows seeing the effect of the policies on the components that are removed from the subject of their immediate policies. Based on the experience of modeling the SFWMD watershed, it can be said that SD is a very useful tool to model systems containing disparate data, and integrating science and decision making. Although this model is developed specifically for the SFWMD watershed but with appropriate modifications it can be applicable to any other similar system.

5.1 Conclusions

The model simulations show that SFWMD, given its growth rate of water consumption, will suffer some setbacks with regards to its objective of avoiding a conflict between balancing the needs of the various competing uses. The water resources of the district will prove to be insufficient to satisfy the growing demands of the region if the present growth rate is continued without much effort to make the water resources management more efficient. Therefore, it is essential to use the existing sources of water more efficiently in order to prolong their productivity and useful life. Water conservation can go a long way in resolving this conflict of water use. The broad conclusions that can be derived from the study are as follows.

1. SD is successful in capturing the growth of a complex natural watershed.
2. The model is helpful in evaluating and comparing the available policy options.
3. the region will not be able to meet all its demands without significant changes in the way it allocates and uses water.
4. Municipal interventions have little impact in reducing failures of environmental flows.
5. Agricultural interventions result in a significant reduction in the number of environmental flow failures.
6. Water conservation to an extent is successful in reducing the MFL violations.

The study improves the understanding of the working of natural watersheds having a variety of land use, varying population densities, and fragile natural reserves. It can form a background for a more extensive study encompassing other components of the system which impact the overall behavior. The next section suggests some additions that can be made to the study to make it more accurate and to enable it to answer many more questions that the policy makers might be interested in asking.

5.2 Recommendations

Based upon the findings of this research, the following recommendations can be made to the SFWMD to reduce consumption and improve water availability in the district.

1. Status quo leads to deterioration of water supply to environmental sector therefore is not acceptable.
2. Agricultural interventions are more effective in reducing the environmental flow failures therefore should be given higher priority.
3. Acreage reduction can be used in conjunction with micro irrigation to reduce water consumption while maintaining the production.
4. Low flow appliances were comparatively more successful than Xeriscaping in reducing water consumption therefore should be prioritized.

5.3 Future Work

The presented research encompasses most of the directly quantifiable measures available to the policy makers to conserve water. The economy achieved by these measures is relatively easy to quantify as compared to other intangible and indirect methods of water conservation such as education and sensitization of the consumers towards the water shortage and their role in conservation. People who are aware of the importance of conserving water and the needs of environmental systems are more likely to use water more efficiently than those who are not. The outcome of these abstract conservation measures is not perceptible immediately and also is likely to have a delay of a few years. Education and awareness can play an important role in the water conservation efforts all around the world. Therefore, it is necessary to exert more efforts to study the relationship between environmental awareness and water conservation.

In this research the study area is aggregated into a single unit comprising of several physical features and land use types. Future studies may subdivide the study area into a number of units such as LEC, EAA, ENP, and Kissimmee River basin depending upon the nature of water use in these units. The disaggregation of the study area would be advantageous in identifying the water management problems faced by each subregion and developing a more region specific solution to those problems. The model assumes that the ratio of water withdrawals from ground and surface water sources will remain constant throughout the time horizon. The actual withdrawal trends may change with time because of a growth in demands.

A simplistic approach has been adopted in this research for modeling the impacts of climate and rainfall variability. For further research, a more rigorous and detailed approach should be adopted. Forecasts from Global Climate Change (GCM) models or Intergovernmental Panel for Climate Change (IPCC) climate scenarios can be used to estimate water availability in the future.

Though multiple policies in agricultural and municipal sectors were tested for their potential in conserving water, no economic analysis was performed to estimate the cost of implementing the policies. A detailed cost effectiveness analysis will help in identifying the most promising policies.

Policy options considered in this study included only those which can reduce the consumption thereby affording more water to the ecosystem. Alternate sources of water such as stormwater reuse, desalination etc. are not taken into consideration. It would be useful to study these options along with the conservation efforts to evaluate the effect on the overall balance of water availability and use. Although desalination is an expensive process, but it can be considered as a feasible alternative when a reliable, drought proof source of clean drinking water is required. The desalination plant at Tampa Bay in Florida is the largest desalination facility in the US and produces 25mgd of desalinated water with a maximum capacity of 35mgd. The plant was built in order to reduce Tampa Bay Water's groundwater dependency and withdrawal (swfwmd.state.fl.us). Desalination as an alternative source of fresh water for SFWMD can be explored in addition to water conservation to augment the freshwater supply in the district.

Another important source of freshwater for SFWMD, i.e., Biscayne aquifer is affected by saltwater intrusion all along the LEC. The intrusion occurs through three principal mechanisms namely, subsurface movement of seawater, seepage from tidal canals and streams, and upward movement of connate water (Sonenshein 1995). Irrespective of the mechanism involved, the effect of the saltwater intrusion into the groundwater leads to a deterioration of the water quality, often rendering it non potable. In addition to saltwater intrusion, Biscayne Aquifer is also susceptible to contaminations due to its shallow depths. Since Biscayne Aquifer is such an important contributor to the water availability in South Florida, it would be an added advantage to the policy makers to foresee the change in water availability due to saltwater intrusion and contamination from Biscayne Aquifer during the course of time. The following points summarize the future work that can be carried out to improve the model and increase its applicability.

1. Inclusion of soft conservation measures such as education and awareness.
2. Studying the effect of alternate water sources such as wastewater reuse, desalinated water, stormwater use etc. on water availability in the district.
3. Disaggregating the study area in order to address region specific water management issues.
4. Adoption of more exhaustive climate and rainfall variability scenarios in order to forecast water availability and demand under changing climate scenarios.
5. Study the correlation of groundwater and surfacewater in a greater detail and evaluating the effect of low flows in surface bodies on groundwater levels.
6. Evaluating the impacts growing municipal demands on groundwater withdrawals and its impact on saltwater intrusion into Biscayne Aquifer.

Complex problems, intrinsic to systems wherein nature and human development is closely correlated, necessitate the adoption of a comprehensive approach for appropriate representation. SD is able to integrate science and policy making and therefore representing the overall process in detail. The present study provides a generic description of long term changes in a watershed under the influence of growing population, sustaining agriculture, and maintaining the environment. The current model can be applied to other similar systems with appropriate modifications.

APPENDICES

Agricultural Demand

Agricultural_Demand_ = ((Area_Citrus*Citrus_Irr) + (Area_Fruit_Orchards*Fruit_Orchards_Irr) + (Area_Mixed_Crops*Mixed_Crops_Irr) + (Area_Other_Orchards*Other_Orchards_Irr) + (Area_Row_Crops*Row_Crops_Irr) + (Area_Sugarcane*Sugarcane_Irr))*1.15/12

Citrus_Area_Micro = if Agricultural_Intervention = 0 and time < 480 then 0.67
else if time > 480 and Agricultural_Intervention = 0 then 0.67
else Citrus_Area_Under_Micro

Citrus_Irr = if time < 480 then (Monthly_Citrus/0.67)-0.35*Monthly_Rainfall
else if time = 480 then (Monthly_Citrus/0.67)-0.35*Monthly_Rainfall
else if time > 480 and Agricultural_Intervention = 0 then (Monthly_Citrus/Irrigation_Efficiency)-0.35*Monthly_Rainfall
else (Monthly_Citrus *((Citrus_Area_Micro / Micro_Irrigation) + ((1-Citrus_Area_Micro) / Irrigation_Efficiency)) -0.35 * Monthly_Rainfall)

Fruit_Orchards_Irr = if time < 480 then (Monthly_Fruit_Orchards/0.67)-0.35*Monthly_Rainfall
else if time = 480 then (Monthly_Fruit_Orchards/0.67)-0.35*Monthly_Rainfall

else (Monthly_Fruit_Orchards/Irrigation_Efficiency)-0.35*Monthly_Rainfall

Mixed_Crops_Irr = if time < 480 then (Monthly_Mixed_Crops/0.67)-0.35*Monthly_Rainfall

else if time = 480 then (Monthly_Mixed_Crops/0.67)-0.35*Monthly_Rainfall

else (Monthly_Mixed_Crops/Irrigation_Efficiency)-0.35*Monthly_Rainfall

Other_Orchards_Irr = if time < 480 then (Monthly_Other_Orchards/0.67)-0.35*Monthly_Rainfall

else if time = 480 then (Monthly_Other_Orchards/0.67)-0.35*Monthly_Rainfall

else (Monthly_Other_Orchards/Irrigation_Efficiency)-0.35*Monthly_Rainfall

Row_Crops_Irr = if time < 480 then (Monthly_Row_Crops/0.67)-0.35*Monthly_Rainfall

else if time = 480 then (Monthly_Row_Crops/0.67)-0.35*Monthly_Rainfall

else (Monthly_Row_Crops/Irrigation_Efficiency)-0.35*Monthly_Rainfall

Sugarcane_Area_Micro = if Agricultural_Intervention = 0 and time < 480 then 0

else if time > 480 and Agricultural_Intervention = 0 then 0

else Sugarcane_Area_Under_Micro

Sugarcane_Irr = if time < 480 then (Monthly_Sugarcane / 0.67) - 0.35 * Monthly_Rainfall

else if time = 480 then (Monthly_Sugarcane / 0.67) - 0.35 * Monthly_Rainfall else if time > 480 and Agricultural_Intervention =0 then (Monthly_Sugarcane / Irrigation_Efficiency) - 0.35 * Monthly_Rainfall

else (Monthly_Sugarcane * ((Sugarcane_Area_Micro / Micro_Irrigation) + ((1-Sugarcane_Area_Micro) / Irrigation_Efficiency)))- 0.35 * Monthly_Rainfall

Monthly_Citrus = GRAPH(TIME)

(1.00, 3.22), (2.00, 2.01), (3.00, 0.401), (4.00, 0.624), (5.00, 0.974), (6.01, 2.11), (7.01, 1.85), (8.01, 1.61), (9.01, 1.12), (10.0, 1.87), (11.0, 2.18), (12.0, 2.94)

Monthly_Fruit_Orchards = GRAPH(TIME)

(1.00, 2.00), (2.00, 1.89), (3.00, 1.51), (4.00, 0.95), (5.00, 0.6), (6.00, 0.46), (7.00, 0.46), (8.00, 0.56), (9.00, 0.7), (10.0, 0.98), (11.0, 1.33), (12.0, 1.72)

Monthly_Other_Orchards = GRAPH(TIME)

(1.00, 2.00), (2.00, 1.89), (3.00, 1.51), (4.00, 0.95), (5.00, 0.6), (6.00, 0.46), (7.00, 0.46), (8.00, 0.56), (9.00, 0.7), (10.0, 0.98), (11.0, 1.33), (12.0, 1.72)

Monthly_Sugarcane = GRAPH(TIME)

(1.00, 2.58), (2.00, 3.73), (3.00, 4.46), (4.00, 3.82), (5.00, 3.05), (6.01, 1.45), (7.01, 1.21), (8.01, 1.42), (9.01, 2.40), (10.0, 2.81), (11.0, 2.44), (12.0, 1.69)

Environmental Demand

WCAs(t) = WCAs(t - dt) + (WCA_Inflow - WCA_Outflow) * dt

INIT WCAs = 1882000

INFLOWS:

WCA_Inflow =

Drainage_from__Surrounding_Areas+Okee_to_WCA+Monthly_Rainfall_Rate*1371*64
0/12

OUTFLOWS:

WCA_Outflow =

Flow_to_ENP+0.05*Monthly_Municipal_Demand_in_Ac_Ft+0.03*Agricultural_Deman
d_+Flood_Control+Seepage+WCA_Evapotranspiration

Drainage_from__Surrounding_Areas = 1530000/12

Flood_Control = if WCAs>1882000 then (WCAs-1882000)
Else 0

Flow_to_ENP = 358000/12

Seepage = 825000/12

WCA_Area = 1371*640

WCA_Evapotranspiration = ET_Rate*0.7*WCA_Area/(12*12)

WCA_Level = WCAs/WCA_Area

Groundwater

Groundwater_(t) = Groundwater_(t - dt) + (Recharge - Consumption_ - Wastages) * dt

INIT Groundwater_ = 25964800

INFLOWS:

Recharge =

Seepage+Infiltration_+Recharge_from_agri_demand+Recharge_from_outdoor_municipal_demand

OUTFLOWS:

Consumption_ = 0.96 * Monthly_Municipal_Demand_in_Ac_Ft + 0.62*Agricultural_Demand_

Wastages = Discharge_to_Biscayne_Bay+Evapotranspiration

Area_Biscayne = 2569145

Discharge_to_Biscayne_Bay = Max ((Groundwater_ - 27964800), 0.58 * Recharge)

Evapotranspiration = 0.34 * Recharge

Infiltration_ = Area_Biscayne * Monthly_Rainfall_Rate * 0.633

Recharge_from_agri_demand = Agricultural_Demand_*0.05

Recharge_from_outdoor_municipal_demand =

0.05*Monthly_Municipal_Demand_in_Ac_Ft

Biscayne_Levels = GRAPH(Groundwater_)

(1.4e+006, 10.0), (4.7e+006, 30.0), (8e+006, 50.0), (1.1e+007, 70.0), (1.5e+007, 90.0),

(1.8e+007, 110), (2.1e+007, 130), (2.5e+007, 150), (2.8e+007, 170)

Land Availability

Agricultural_Land(t) = Agricultural_Land(t - dt) + (Cultivation -

Agricultural_to_Urban_Land) * dt

INIT Agricultural_Land = 3108340.83

INFLOWS:

Cultivation = (Rate_of_Change_in_Agricultural_Land/100)*Agricultural_Land

OUTFLOWS:

Agricultural_to_Urban_Land =

Land_Use_Conversion_Factor*Annual_Population_Change*0.5

Citrus(t) = Citrus(t - dt) + (- Sugarcane_Acreage_Flow) * dt

INIT Citrus = 580000

OUTFLOWS:

Sugarcane_Acreage_Flow = 0.0018*(Citrus-Sugarcane)

Natural_Land(t) = Natural_Land(t - dt) + (- Cultivation - Natural_to_Urban_Land) * dt

INIT Natural_Land = 7031281.326

OUTFLOWS:

Cultivation = (Rate_of_Change_in_Agricultural_Land/100)*Agricultural_Land

Natural_to_Urban_Land =

Land_Use_Conversion_Factor*Annual_Population_Change*0.5

Sugarcane(t) = Sugarcane(t - dt) + (Citrus_Acreage_Flow) * dt

INIT Sugarcane = 281000

INFLOWS:

Citrus_Acreage_Flow = 0.0033*(Citrus-Sugarcane)

Urban_Land(t) = Urban_Land(t - dt) + (Agricultural_to_Urban_Land +

Natural_to_Urban_Land) * dt

INIT Urban_Land = 1414830.999

INFLOWS:

Agricultural_to_Urban_Land =

Land_Use_Conversion_Factor*Annual_Population_Change*0.5

Natural_to_Urban_Land =

Land_Use_Conversion_Factor*Annual_Population_Change*0.5

Area_Citrus = smthn((Citrus)+(Transfer_to_Citrus),24,1)

Area_Fruit_Orchards =

smthn((0.0105*Agricultural_Land)+(Transfer_to_Fruit_Orchards),450,5)

Area_Mixed_Crops =

smthn((0.002*Agricultural_Land)+(Transfer_to_Mixed_Orchards),450,5)

Area_Other_Orchards =

smthn((0.012*Agricultural_Land)+(Transfer_to_Other_Orchards),450,5)

Area_Row_Crops = smthn((0.126 *Agricultural_Land)+(Transfer_to_Row_Crops),450,5)

Area_Sugarcane = smthn(Sugarcane * (1 - Sugarcane_Area_Red_Factor),24,1)

Change_in_Sugarcane_Area = Area_Sugarcane * Sugarcane_Area_Red_Factor

Sugarcane_Area_Red_Factor = if TIME <480 then 0

else Sugarcane_Area_Reduction_Rate_Selector

Sum_of_Agri_Area_Transfer_Rates =

Citrus_Rate_Selector+Fruit_Crop_Rate_Selector+Mixed_Crop_Rate_Selector+Other_Orchards_Rate_Selector+Row_Crops_Rate_Selector

Transfer_to_Citrus = Citrus_Rate_Selector*Change_in_Sugarcane_Area

Transfer_to_Fruit_Orchards = Fruit_Crop_Rate_Selector*Change_in_Sugarcane_Area

Transfer_to_Mixed_Orchards =
Mixed_Crop_Rate_Selector*Change_in_Sugarcane_Area

Transfer_to_Other_Orchards =
Other_Orchards_Rate_Selector*Change_in_Sugarcane_Area

Transfer_to_Row_Crops = Row_Crops_Rate_Selector*Change_in_Sugarcane_Area

Land_Use_Conversion_Factor = GRAPH(Annual_Population_Change)
(0.00, 0.228), (30000, 0.228), (60000, 0.223), (90000, 0.223), (120000, 0.223), (150000, 0.22), (180000, 0.218), (210000, 0.213), (240000, 0.205), (270000, 0.195), (300000, 0.185)

Rate_of_Change_in_Agricultural_Land = GRAPH(TIME)
(1.00, 0.07), (96.9, 0.058), (193, 0.0513), (289, 0.0415), (385, 0.0348), (481, 0.0265), (576, 0.019), (672, 0.0123), (768, 0.00775), (864, 0.0025), (960, 0.00)

Municipal Demand

Change_Due_to_Pricing = 1 + (Pricing_Effect - 1) * Elasticity

Commercial = 0.19 * Per_Capita_Municipal

Conserv_Indoor_Use =

L_F_BathShower+L_F_Faucets+L_F_Housekeeping+L_F_Laundry+L_F_Leakages+

L_F_Toilets

Consumption_New_Residents = Conserv_Indoor_Use * Population_after_2010

Consumption_Old_Conserving_Residents = Conserv_Indoor_Use *

No_Old_Residents_Conserving

Consumption_Old_Residents = Non_Conserv_Indoor_Use * (Population_up_to_2010 *

(1 - Fraction_Old_Residents_Conserving))

Domestic = 0.61 * Per_Capita_Municipal

Domestic_Use = (Consumption_Old_Residents + Consumption_New_Residents +

Consumption_Old_Conserving_Residents + Outdoor_Consumption)

Elasticity = -0.3

Industrial = 0.05 * Per_Capita_Municipal

Monthly_Municipal_Demand_in_Ac_Ft = Municipal_Demand_*30*3.06888E-6

Municipal_Demand_ = Total_Demand * Monthly_Variations

Net_Per_Cap = Outdoor_Consumption/Total_Population

Non_Conserv_Indoor_Use = Bathshower + Faucet + Housekeeping + Laundrry + Leakages + Toilets

Non_Domestic_Use = (Commercial + Industrial + Public) * Total_Population

No_Old_Residents_Conserving = Population_up_to_2010 * Fraction_Old_Residents_Conserving

Outdoor_Consumption = Per_Cap_Outdoor_Use * Total_Population

Per_Capita_Daily__Indoor_Use = if time < 480 then (0.75 * Domestic)
else (0.75 * Domestic * Change_Due_to_Pricing)

Per_Capita_Municipal = 174

Per_Cap_Outdoor_Use = if time < 480 then 0.25 * Domestic
else (0.25 * Domestic * Low_Flow_Irrigation_Methods *

Restrictions_*Change_Due_to_Pricing)

Pricing_Effect = if time < 480 then 0

else Pricing_Selector

Public = 0.15 * Per_Capita_Municipal

Restrictions_ = if time < 480 then 1

else if time >480 and Intervention_Municipal = 0 then 1

else 0.7

Total_Demand = (Domestic_Use+Non_Domestic_Use)

Monthly_Variations = GRAPH(TIME)

(1.00, 0.922), (2.00, 0.986), (3.00, 1.03), (4.00, 1.04), (5.00, 1.15), (6.01, 1.06), (7.01, 0.982), (8.01, 0.978), (9.01, 0.916), (10.0, 0.984), (11.0, 1.01), (12.0, 0.941

Municipal Intervention

Low_Flow_Faucets = if Intervention_Municipal = 0 then 1

Else if Intervention_Municipal = 1 and TIME < 480 then 1 Else (0.4*(2 - Saving_Rate_Correction))

Low_Flow_Flush = if Intervention_Municipal = 0 then 1

Else if Intervention_Municipal = 1 and TIME < 480 then 1 Else (0.4*(2 - Saving_Rate_Correction))

Low_Flow_Showers = if Intervention_Municipal = 0 then 1

Else if Intervention_Municipal = 1 and TIME < 480 then 1 Else (0.4*(2 - Saving_Rate_Correction))

Low_Flow_Washers = if Intervention_Municipal = 0 then 1

Else if Intervention_Municipal = 1 and TIME < 480 then 1 Else (0.7* (2 - Saving_Rate_Correction))

L_F_BathShower = 0.19*Per_Capita_Daily__Indoor_Use*Low_Flow_Showers

L_F_Faucets = 0.16*Per_Capita_Daily__Indoor_Use*Low_Flow_Faucets

L_F_Housekeeping = 0.03*Per_Capita_Daily__Indoor_Use

L_F_Laundry = 0.22*Per_Capita_Daily__Indoor_Use*Low_Flow_Washers

L_F_Leakages = 0.14*Per_Capita_Daily__Indoor_Use

L_F_Toilets = 0.26*Per_Capita_Daily__Indoor_Use*Low_Flow_Flush

Non Intervention

Bathshower = 0.19*Per_Capita_Daily__Indoor_Use

Faucet = 0.16*Per_Capita_Daily__Indoor_Use

Housekeeping = 0.03 * Per_Capita_Daily__Indoor_Use

Laundrry = 0.22*Per_Capita_Daily__Indoor_Use

Leakages = 0.14*Per_Capita_Daily__Indoor_Use

Toilets = 0.26*Per_Capita_Daily__Indoor_Use

Performance

Failure_Severity(t) = Failure_Severity(t - dt) + (Failure_Severity_Addition) * dt

INIT Failure_Severity = 0

INFLOWS:

Failure_Severity_Addition = if Deficit > 0 then Deficit else 0

Low_Level_Count(t) = Low_Level_Count(t - dt) + (Low_Level_Counter) * dt

INIT Low_Level_Count = 0

INFLOWS:

Low_Level_Counter = if Okee_Level < 11 then 1

else 0

Resi_Failure_Numbers(t) = Resi_Failure_Numbers(t - dt) + (Resillience_Flow_1 -

Resillience_Flow_2) * dt

INIT Resi_Failure_Numbers = 0

INFLOWS:

Resillience_Flow_1 = if Okee_Failure_Condition = 1 and time > Resillience_Time_Scale

then 1

else 0

OUTFLOWS:

Resillience_Flow_2 = if Resi_Failure_Numbers = 0 and Resillience_Flow_1 > 0 then 0

else if Resi_Failure_Numbers > 0 and Resillience_Flow_1 = 0 then

Resi_Failure_Numbers

else 0

Resi_Stock(t) = Resi_Stock(t - dt) + (Resi_Flow_3) * dt

INIT Resi_Stock = 0

INFLOWS:

Resi_Flow_3 = Individual_Case_Resillience

Total_Failure_Months(t) = Total_Failure_Months(t - dt) + (Evaluation_Flow) * dt

INIT Total_Failure_Months = 0

INFLOWS:

Evaluation_Flow = if Okee_Failure_Condition = 1 then 1

else 0

Transition = Transition_Counter

INFLOW TO

Deficit = if Okee_Level < 11 then (11 - Okee_Level)

else 0

Individual_Case_Resillience = if Resillience_Flow_2> 0 then 1/Resillience_Flow_2 else 0

Reliability = (Reliability_Time_Scale - Total_Failure_Months)/Reliability_Time_Scale

Reliability_Time_Scale = if ReliabilityTime_Scale_Selector = 1 then 960

else 480

Resillience = if Transition_Count>0 then (Resi_Stock/Transition_Count)

else 0

Resillience_Time_Scale = if Resillience_Time__Scale_Selector = 0 then 480

else 0

Transition_Counter = if Resillience_Flow_2 > 0 then 1

else 0

Vulnerability = if Low_Level_Count > 0 then Failure_Severity/Low_Level_Count

else 0

Population

Population_after_2010(t) = Population_after_2010(t - dt) + (Pop_Growth_After_2010 - Pop_Decline_after_2010) * dt

INIT Population_after_2010 = 0

INFLOWS:

Pop_Growth_After_2010 = if time > 480 then (Pop_Inflow * (1+ Pop_growth_variability))

else 0

OUTFLOWS:

Pop_Decline_after_2010 = if time > 480 then Pop_Outflow

else 0

Population_up_to_2010(t) = Population_up_to_2010(t - dt) + (Population_Growth - Population_Decline) * dt

INIT Population_up_to_2010 = 2592893

INFLOWS:

Population_Growth = if time < 480 then (Pop_Inflow)

else 0

OUTFLOWS:

Population_Decline = if time < 480 then Pop_Outflow

else 0

Annual_Population_Change = Pop_Inflow - Pop_Outflow

Births = Total_Population * Birth_Rate / 12

Deaths = Death_Rate * Total_Population / 12

Pop_Inflow = Births + Immigration

Pop_Outflow = Deaths + Emigration

Total_Population = Population_after_2010 + Population_up_to_2010

Birth_Rate = GRAPH(Total_Population)

(1e+006, 0.018), (2.4e+006, 0.018), (3.8e+006, 0.018), (5.2e+006, 0.017), (6.6e+006, 0.018), (8e+006, 0.018), (9.4e+006, 0.017), (1.1e+007, 0.016), (1.2e+007, 0.016), (1.4e+007, 0.016), (1.5e+007, 0.016)

Death_Rate = GRAPH(Total_Population)

(0.00, 0.009), (1.5e+006, 0.009), (3e+006, 0.009), (4.5e+006, 0.009), (6e+006, 0.009), (7.5e+006, 0.0095), (9e+006, 0.01), (1.1e+007, 0.011), (1.2e+007, 0.011), (1.4e+007, 0.012), (1.5e+007, 0.012)

Emigration = GRAPH(Total_Population)

(3.1e+006, 7100), (4.3e+006, 7700), (5.5e+006, 8700), (6.7e+006, 11000), (7.9e+006, 12000), (9.1e+006, 12500), (1e+007, 13500), (1.1e+007, 13750), (1.3e+007, 14000), (1.4e+007, 14250), (1.5e+007, 14375)

Immigration = GRAPH(Total_Population)

(3.1e+006, 12000), (4.3e+006, 16000), (5.5e+006, 17500), (6.7e+006, 19500), (7.9e+006, 20000), (9.1e+006, 20100), (1e+007, 19600), (1.1e+007, 18200), (1.3e+007, 16100), (1.4e+007, 13500), (1.5e+007, 12300)

Surface Water

Exceedance(t) = Exceedance(t - dt) + (Exceedance_months) * dt

INIT Exceedance = 0

INFLOWS:

Exceedance_months = if int (mod (year, 2)) = 0 then 0

else if int (mod (year, 2)) > 0 and month = 5 and Low_Level_Months > 2 then 1

else 0

Low_Level_Months(t) = Low_Level_Months(t - dt) + (No_of_Failure_Months - Exceedance_months - Sink) * dt

INIT Low_Level_Months = 0

INFLOWS:

No_of_Failure_Months = if Okee_Failure_Condition = 1 then 1

else 0

OUTFLOWS:

Exceedance_months = if int (mod (year, 2)) = 0 then 0

else if int (mod (year, 2)) > 0 and month = 5 and Low_Level_Months > 2 then 1

else 0

Sink = if int (mod (year, 2)) = 1 and month = 5 then Low_Level_Months

else 0

Okeechobee(t) = Okeechobee(t - dt) + (Okee_Inflow_ - Okee_Outflow_ - Okee_Wastage)

* dt

INIT Okeechobee = 3335802

INFLOWS:

Okee_Inflow_ = Tributaries + Monthly_Rainfall * 444994/12

OUTFLOWS:

Okee_Outflow_ = Caloosahatchee+ Okee_Consumption + Okee_to_WCA

Okee_Wastage = Okee_Evaporation/12

INFLOWS:

Area_Kissimmee_Watershed = 2690560

Caloosahatchee = if Okee_Level > Okee_Zone_A then 190000

else if Okee_Level < Okee_Zone_A and Okee_Level > Okee_Zone_B then 170000

else if Okee_Level < Okee_Zone_B and Okee_Level > Okee_Zone_C then 130000

else if Okee_Level <Okee_Zone_C and Okee_Level > Okee_Zone_D then 110000

else 0

ET_Rate = 55

Monthly_Rainfall = Rainfall_Variability * Monthly_Rainfall_Rate *0 * 0.885 *0 + Prolonged_drought * Monthly_Rainfall_Rate * 0.885 *0 + Step_Increase * Monthly_Rainfall_Rate * 0.885 + Calibration * Monthly_Rainfall_Rate * 0

Okee_Consumption = (0.05 * Monthly_Municipal_Demand_in_Ac_Ft + 0.38 * Agricultural_Demand_) * 1.3

Okee_Evaporation = ET_Rate/12*Okee_Area

Okee_Failure_Condition = if Okee_Level < 11 then 1

else 0

Okee_to_WCA = if Okee_Level > Okee_Zone_A then 150000

else if Okee_Level < Okee_Zone_A and Okee_Level > Okee_Zone_B then 100000

else if Okee_Level < Okee_Zone_B and Okee_Level > Okee_Zone_C then 70000

else if Okee_Level <Okee_Zone_C and Okee_Level > Okee_Zone_D then 55000

else 0

Prolonged_drought = if time = 720 then 1

else if time > 720 and time < 840 then 0.83

else 1

Rainfall_Variability = if time < 480 then 1

else random(1,(Rainfall_Variation_Rate))

Step_Increase = if time > 480 then Step_Increase_Rate

else 1

St_Lucie = if Okee_Level > Okee_Zone_A then 25000

else if Okee_Level < Okee_Zone_A and Okee_Level > Okee_Zone_B then 20000

else if Okee_Level < Okee_Zone_B and Okee_Level > Okee_Zone_C then 18000

else if Okee_Level <Okee_Zone_C and Okee_Level > Okee_Zone_D then 11000

else 0

Tributaries = Area_Kissimmee_Watershed * Monthly_Rainfall * (0.003444717 * 0.15 +

0.924079356 * 0.28 + 0.072475927 * 0.07)*0.50 / 12

Calibration = GRAPH(time)

(60.0, 0.915), (72.0, 0.85), (84.0, 0.648), (96.0, 1.33), (108, 1.04), (120, 1.29), (132, 1.00), (144, 0.632), (156, 1.09), (168, 1.11), (180, 1.28), (192, 1.02), (204, 1.20), (216, 0.931), (228, 0.866), (240, 1.01), (252, 0.972), (264, 0.963), (276, 1.09), (288, 0.81), (300, 1.25), (312, 1.25), (324, 0.81), (336, 1.03), (348, 1.04), (360, 1.25), (372, 0.737), (384, 0.972), (396, 0.915), (408, 0.899), (420, 0.777)

Monthly_Rainfall_Rate = GRAPH(TIME)

(1.00, 2.01), (2.00, 2.08), (3.00, 2.39), (4.00, 2.85), (5.00, 6.21), (6.00, 9.33), (7.00, 5.70), (8.00, 7.58), (9.00, 7.63), (10.0, 5.64), (11.0, 2.66), (12.0, 1.83)

Okee_Area = GRAPH(Okeechobee)

(37844, 58725), (362431, 127961), (687018, 159163), (1e+006, 194605), (1.3e+006, 222795), (1.7e+006, 243870), (2e+006, 265220), (2.3e+006, 284435), (2.6e+006, 297888), (3e+006, 317055), (3.3e+006, 339142), (3.6e+006, 369489), (3.9e+006, 414669), (4.3e+006, 441092), (4.6e+006, 444994), (4.9e+006, 444994), (5.2e+006, 444994), (5.6e+006, 444994), (5.9e+006, 444994), (6.2e+006, 444994)

Okee_Level = GRAPH(Okeechobee)

(37844, 1.60), (362431, 2.30), (687018, 3.80), (1e+006, 5.10), (1.3e+006, 6.30), (1.7e+006, 7.90), (2e+006, 9.50), (2.3e+006, 10.8), (2.6e+006, 12.0), (3e+006, 12.7), (3.3e+006, 13.5), (3.6e+006, 14.7), (3.9e+006, 15.5), (4.3e+006, 16.3), (4.6e+006, 16.8), (4.9e+006, 17.1), (5.2e+006, 17.5), (5.6e+006, 18.0), (5.9e+006, 18.9), (6.2e+006, 19.7)

Okee Zones

Okee_Zone_A = GRAPH(COUNTER(1,12))

(1.00, 18.5), (2.00, 18.5), (3.00, 18.0), (4.00, 17.5), (5.00, 17.0), (6.00, 17.1), (7.00, 17.3), (8.00, 17.4), (9.00, 17.5), (10.0, 18.5), (11.0, 18.5), (12.0, 18.5)

Okee_Zone_B = GRAPH(COUNTER(1,12))

(1.00, 17.8), (2.00, 17.5), (3.00, 17.3), (4.00, 17.0), (5.00, 16.8), (6.00, 16.5), (7.00, 16.6), (8.00, 16.8), (9.00, 16.9), (10.0, 17.8), (11.0, 17.8), (12.0, 17.8)

Okee_Zone_C = GRAPH(COUNTER(1,12))

(1.00, 17.0), (2.00, 16.7), (3.00, 16.4), (4.00, 16.1), (5.00, 15.9), (6.00, 15.6), (7.00, 15.8), (8.00, 16.0), (9.00, 16.2), (10.0, 17.0), (11.0, 17.0), (12.0, 17.0)

Okee_Zone_D = GRAPH(Counter(1,12))

(1.00, 14.8), (2.00, 14.5), (3.00, 14.3), (4.00, 14.0), (5.00, 13.8), (6.00, 13.5), (7.00, 13.9), (8.00, 14.4), (9.00, 14.8), (10.0, 15.5), (11.0, 15.3), (12.0, 15.0)

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