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Exploring Policy Options for Management of Water Resources: A Simulation Modeling Approach

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ABSTRACT: With enormous growth in population, changes in land use, substantial agriculture activity, and need to protect vital environmental resources such as Everglades, south Florida presents a very challenging case for water resources planning. To meet challenges of water resources planning in south Florida, we explore: (i) What are some major changes in terms of population growth, land use, water demand, and water availability that can be expected in south Florida in the short and long term?; and (ii) What are the most promising policies for south Florida's water management in response to growth?

We present a simulation approach, based on system dynamics principles, to model and evaluate different short and long term (up to 50 years) water management policies. The policies considered include improving irrigation efficiency, rotating crops, pricing, and conservation through low flow appliances.

Model, developed using Stella, tracks the water balance considering inflows, rainfall, evaporation, and water releases and also considers population growth and land use changes. Model is calibrated and shows a good match. The intervention to reduce agricultural demand involves reduction in sugarcane cultivation and increase in micro irrigation, and results in a reduction in water demand by 20.6%. Similarly, intervention to reduce municipal demand involves water saving fittings for homes and commercial establishments and pricing, and results in a 25.5% reduction in municipal water demand.

Keywords: System Dynamics, Water Demand, Urban Water Use, Agricultural Water Use, South Florida, Stella.

INTRODUCTION

We develop an adaptive and dynamic simulation model, based on system dynamics modeling principles, for analysis of short and long term policies for sustainable management of water resources. System dynamics is a technique to model complex systems by capturing feedback among different components of the system.

We use the south Florida region as a case study to develop and test this simulation model. With enormous growth in population, changes in land use, substantial agricultural activity, and need to protect vital environmental resources such as Everglades, south Florida presents a very challenging case for water management. Between 1950 and 2000 the population of south Florida has grown about 800 percent (from 0.8 million to about 6.5 million). The region also has a significant influx of seasonal and tourist population. The permanent resident population of the region is projected to reach 8.2 million by 2020 (SFWMD, 1998). Between 1950 and 2000 the urban land use increased from 2.2 percent to 13.3 percent, and agricultural land increased from 9.5 percent to 27.8 percent of total land during the same period. These changes in population and land use have had significant impacts resulting in increased demands for water; increased needs for flood protection; and a reduction in lands in their natural state.

We use the simulation model to explore questions: (i) What are some major changes in terms of population growth, water demand, and water availability that can be expected in south Florida in the short and long term?; and (ii) What are the most promising policies for south Florida's water management in response to growth and climate change? The policies considered include improving irrigation efficiency, rotating crops, pricing, and conservation (low flow appliances, xeriscaping).

THEORETICAL BACKGROUND

Water Resources Planning and Management

Sustainable water resources planning and management is a complex task; numerous factors influence the task. We divide important influencing factors that impact water demand and availability into four major groups. The four groups are: population; land use; environment; and economy.

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Total available water is in the form of ground and surface water. Water availability is through natural means such as inflows, net rainfall (rain fall—evaporation) or through human intervention such as desalination, and water transfers. Water demand mainly consists of agriculture, urban, and environmental demands. Population changes through births, deaths, and net migration. Increasing population generates demand for water, urban land, consumer goods, and agriculture products. The increased demand for water reduces water available for other uses; increases pressure to make water available though desalination or water transfers, and impacts environment by producing pollution in the form of waste water and agriculture return flow with nutrients. Similarly, increased demand for urban land reduces available land for other uses such as agriculture and natural use.

Economy is another major driver. Economic growth makes region more attractive for job seekers, thus increasing migration that results in generating more demand for water, housing, and urban infrastructure. Moreover, higher standard of living is also associated with higher consumption of water.

Urban development competes for land that is in agricultural or natural use. Increased urban development increases water demand, and impacts environment by increasing pollution. Urban development has other hydrologic impacts; it increases impermeable surface area causing flooding.

The interactions among different components of the system over time, presence of feedbacks, and time delays result in a dynamic system capable of producing counter intuitive results. The ability to understand and capture these dynamic interactions in a simulation model is an important first step towards exploring different water management policy options. System dynamics modeling approach provides one such tool.

System Dynamics (SD) Modeling

A system dynamics model is developed to evaluate both short and long-term (up to 50 years) water management policies with a goal to balance available supply with growing demands. SD provides a unique framework for integrating the disparate physical and social systems important to water resource management, while providing an interactive environment for engaging the stakeholders. SD is formulated on the premise that the structure of a system—the network of cause and effect relations between system elements—governs system behavior (Sterman, 2000). "The systems approach is a discipline for seeing wholes, a discipline for seeing the structures that underlie complex domains. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots, and for seeing processes rather than objects" (Simonovic and Fahmy, 1999). In SD approach systems are modeled as a network of stocks and flows. For example, the change in volume of water stored in a reservoir is a function of the inflows less the outflows. Key to this framework is the feedback between the various stocks and flows comprising the system. In our reservoir example, feedback occurs between evaporative losses and reservoir storage through the volume/surface area relation for the reservoir. Feedback is not always realized immediately but may be delayed in time, representing another critical feature of dynamic systems. The model construction proceeds in a graphical environment, using objects as building blocks. These objects are defined with specific attributes that represent physical or social processes. These objects are linked together so as to mimic the general structure of the system. In this way, the SD approach provides a transparent, structured and intuitive environment for model development.

System dynamics has a long history as a modeling paradigm with its origin in the work of Forrester (Forrester, 1961), who developed the subject to provide an understanding of strategic problems in complex systems. SD is grounded in control theory and the theory of nonlinear dynamics (Sterman, 2000). System dynamics is becoming increasingly popular for modeling water resource systems, e.g., river basin planning (Palmer, 1998); sea-level rise (Matthias and Frederick, 1994), water planning (Tidwell *et al.*, 2004), environmental management (Ford, 1999), and stakeholder participation (Stave, 2003). Simonovic *et al.* (1997) and Simonovic and Fahmy (1999) have used the SD approach for long-term water resources planning for the Nile River Basin in Egypt. Simonovic and Li (2003) have developed a SD model to evaluate the impact of climate change on the performance of flood protection system. Other SD models include reservoir operation (Ahmad and Simonovic, 2000a), flood damages studies (Ahmad and Simonovic, 2000b, 2000c), economic analysis of flood management policies (Ahmad and Simonovic, 2001), and water resources management (Ahmad and Simonovic, 2004).

Study Area: South Florida

South Florida is home to about 6.5 million people (45 percent of the State population) living in an area of approximately 43520 km^2 (31 percent of State area). The region includes critical environmental resources such as Everglades National Park and Lake Okeechobee (Figure 1). South Florida has a sub-tropical climate, warm temperatures, and an average annual rainfall of 135 cm. Seventy-three percent, or 98 cm, of the region's spatially averaged annual rainfall occurs in the six month period from May through October (Ali and Abtew, 1999). Rain may vary between 112 and 168 cm during one-in-ten-year dry and wet conditions. Although rainfall is relatively abundant in Florida, a major portion of it is never available for use due to evaporation. Measured runoff averages from zero to 25.4 cm per year in much of south Florida.

The Lake Okeechobee, located in south Florida, covers an area of about 1813 km^2 with an average depth of about 3 meters and maximum depth of less than 6 meters. Recharge of the lake comes from rainfall and from the Kissimmee River in the north. Lake has two outlets: the Caloosahatchee River to the west, and the St. Lucie river to the east, discharging to the Gulf of Mexico and the Atlantic Ocean, respectively. Four major canals (West Palm Beach, Hillsboro, North New River and Miami) from the Lake provide releases to meet water demands. The Lake has a surface water storage capacity of over 3.78 million m^3. The lake provides irrigation water for the 1792 km^2 Agriculture Area and represents a critical supplemental water supply for the Everglades during dry periods (SFWMD, 2002). Lake Okeechobee has multiple functions and is operated to protect against flooding, to prevent saltwater intrusion, and to provide water for agricultural irrigation and drinking water supplies to large urban areas in South Florida. Operation of the Lake impacts a wide range of environmental and economic issues. The ability to simulate the Lake conditions is very important for water management.

Commercial agriculture is a major industry and the main water user in south Florida; generating 62 percent of total water demand. Major agriculture activity in the region include: sugarcane; vegetable crops; citrus; and cattle and dairy farms. Ground water accounts for 32 percent of the water used for agriculture. Overall, ground water supplies 53 percent of the total fresh-water demands in south Florida (USGS, 1999). Surface water plays an important role in maintaining the availability of ground water, which is recharged through rainfall and the regional canal system.

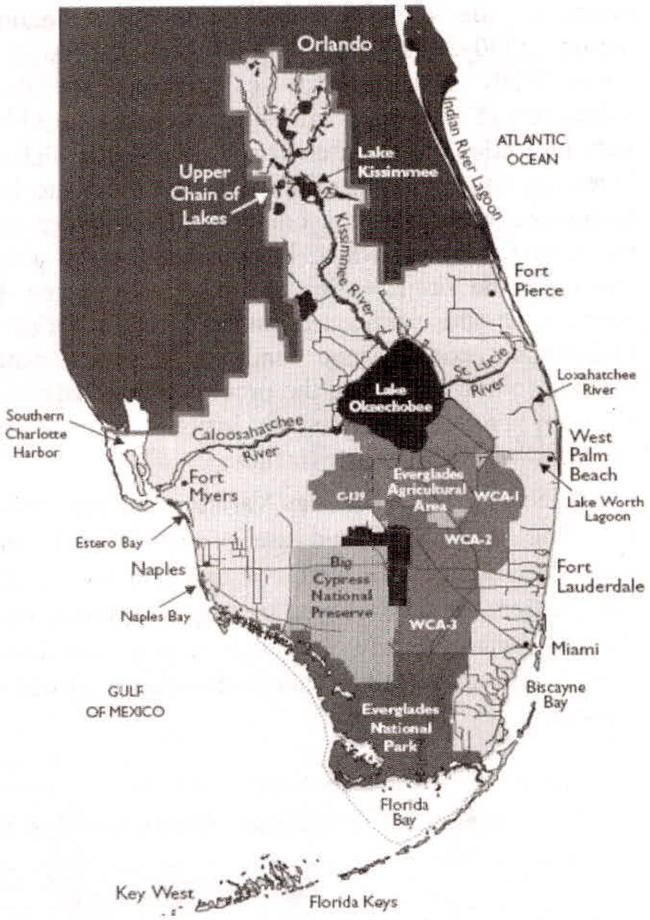


Fig. 1: Map of South Florida (study area)

METHODS

Modeling Process

Following steps are involved in the modeling process:

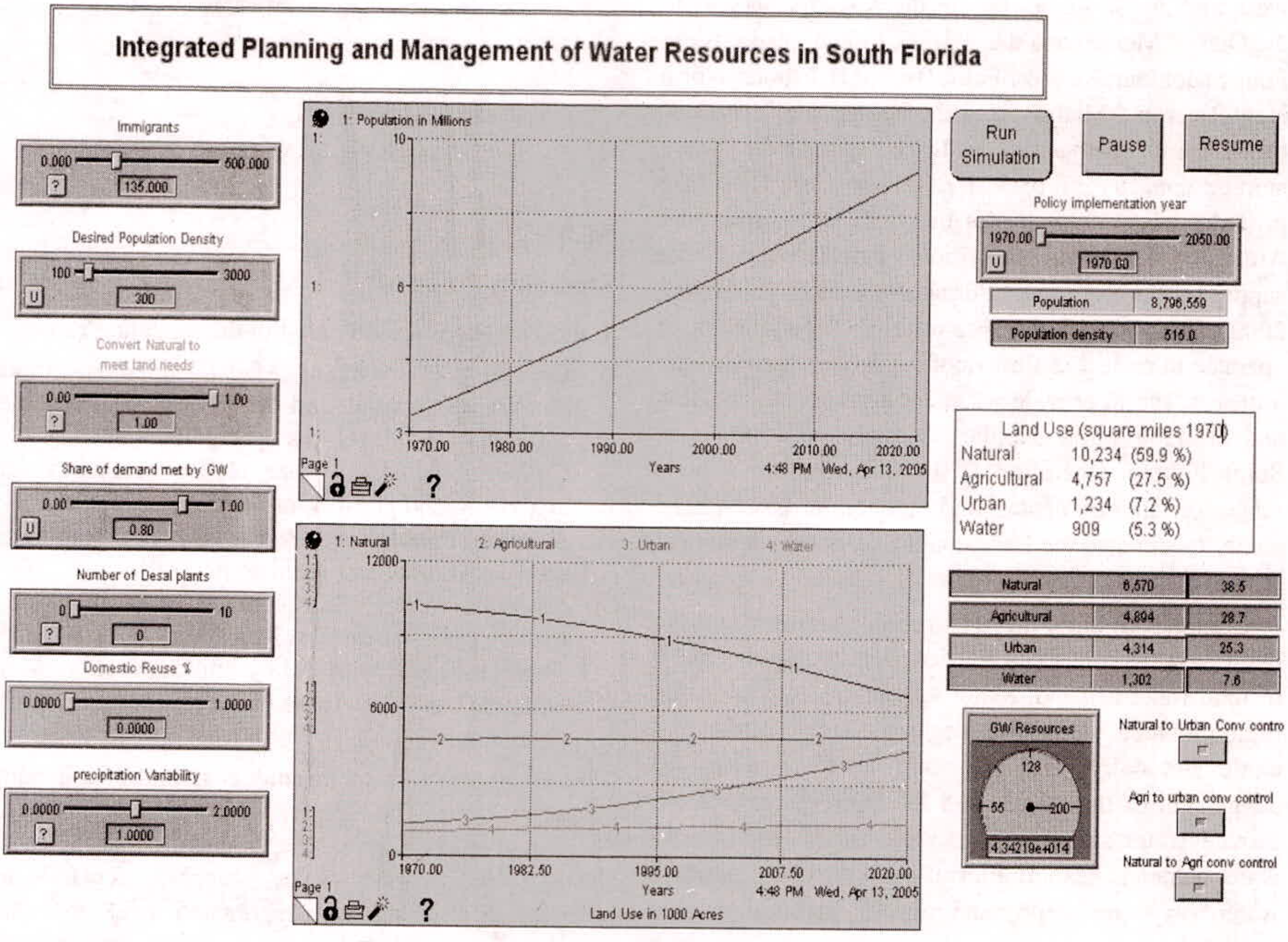
1. *Develop Conceptual Model:* identify model boundaries (spatial and temporal), key variables, and outcomes; develop a conceptual model.
2. *Collect and Process Data:* Collect secondary data, analyze it, and produce projections.
3. *Develop Simulation Model:* Develop simulation model, calibrate and validate it.
4. *Simulate Policy Scenarios:* Use simulation to explore policy scenarios. Run scenarios both without (base case) and with policy implementation. Major outcome will be water savings for each policy simulated.

The basic structure of the model is that of a dynamic water budget. The spatial extent of the model is delimited according to the boundaries of SFWMD. Thus, the various water supply, demand and conservation terms are aggregated over four sub-regions. Temporally, the model operates on a monthly time step encompassing the period 1970–2050. This period includes a 31 year calibration and validation period (1970–2000) and 50 year planning horizon (2001–2050). The monthly calculations are then aggregated to get annual values to match key variables with projections form external sources. At the highest level, the model is organized into two separate but interacting water budgets, one for surface water and the other for ground water. In both budgets the water stored in the basin varies monthly in response to changes in the associated inflows and outflows. Population, economy and land use generate water demand (outflows) and in the process impact environment by producing pollution. Inflows and rainfall provides water availability (inflows).

We collected data on key variables in the model including population, land use, water demand, and water availability. We analyzed the data to identify historic trends and developed scenarios capturing how these key parameters will change in short and long-term. We used secondary data from publicly available sources.

The simulation model is used to analyze various water management policies. Indoor water use can be reduced by way of low flow appliances and fixtures. The user have the option of requiring all new homes (built after any selected year) to be constructed with low flow appliances, including sinks, showers, toilets and washing machines. Additionally, the user can choose what percentage of existing homes will be retrofitted with low flow appliances. The user have the option of requiring xeriscaping around all new home construction, and the option to retrofit a user-specified percentage of existing homes. Because of the broad variation in what is termed xeriscaping, the user is allowed to define the degree of water savings to be achieved.

Policy maker can also achieve water savings by increasing the price of water. Here, the change in demand for all residential/non-residential sectors resulting from a price change is captured by the price elasticity of demand (Sheila *et al.*, 2007). Reduction in agriculture water use can be achieved by crop rotation and by increasing irrigation efficiency.



Immigrants: 0.000 – 600.000; 135.000

Desired Population Density: 100 – 3000; 300

Convert Natural to meet land needs: 0.00 – 1.00; 1.00

Share of demand met by GW: 0.00 – 1.00; 0.80

Number of Desal plants: 0 – 10; 0

Domestic Reuse %: 0.0000 – 1.0000; 0.0000

precipitation Variability: 0.0000 – 2.0000; 1.0000

Policy implementation year: 1970.00 – 2050.00; 1970.00

Population	8,796,559
Population density	515.0

Land Use (square miles 1970)

Natural	10,234	(59.9 %)
Agricultural	4,757	(27.5 %)
Urban	1,234	(7.2 %)
Water	909	(5.3 %)

Natural	6,570	38.5
Agricultural	4,894	28.7
Urban	4,314	25.3
Water	1,302	7.6

GW Resources: 4.34219e+014

Fig. 2: Graphical user interface of simulation model

RESULTS AND DISCUSSION

Selected results from calibration of model, sensitivity analysis, and different policy runs aimed at reducing agricultural and urban water demand are shown in Figures 3–7. Comparison of population estimates by the model with US census data are shown in Figure 3. Model estimates of area under sugarcane cultivation and comparison with actual historic data are shown in Figure 4.

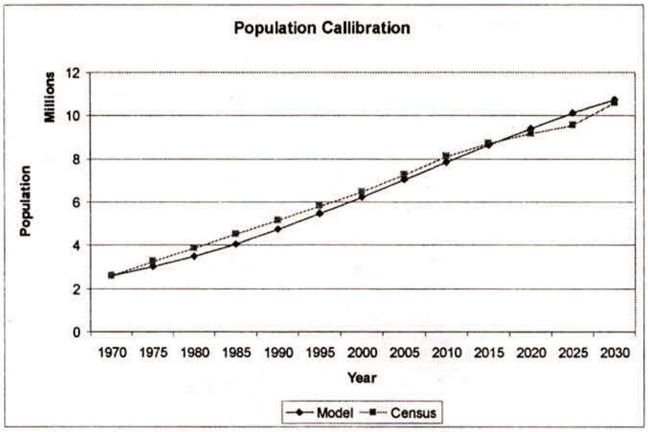


Fig. 3: Comparison of population estimates by the model with US census data

The intervention to reduce agricultural demand consists of (i) area under sugarcane cultivation reduced by 20% and replaced with other crops; and (ii) area under micro irrigation increased by 25%. This results in a reduction in water demand for irrigation by 20.6% (Figure 5). Approximately 58% of savings are due to crop substitution, and remaining 42% are due to increase in micro irrigation (Figure 7b).

The intervention to reduce municipal demand consists of (i) water saving fittings for homes constructed after 2010; (ii) price increase of 30% for municipal water users; (iii) restrictions on outdoor use; and (iv) water saving fittings in public and commercial establishments. This results in a reduction in municipal water demand by 25.5% (Figure 6). About 61.6% of reduction is due to water saving appliances, 19.2% due to outdoor use restriction, and remaining 19.2% are due to price increase (Figure 7a).

Figure 8 shows changes in Lake Okeechobee water levels in response to changes in municipal and agricultural water use.

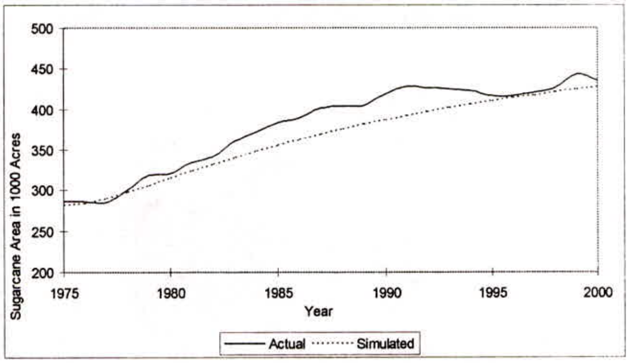


Fig. 4: Comparison of actual and model estimated area under sugarcane cultivation

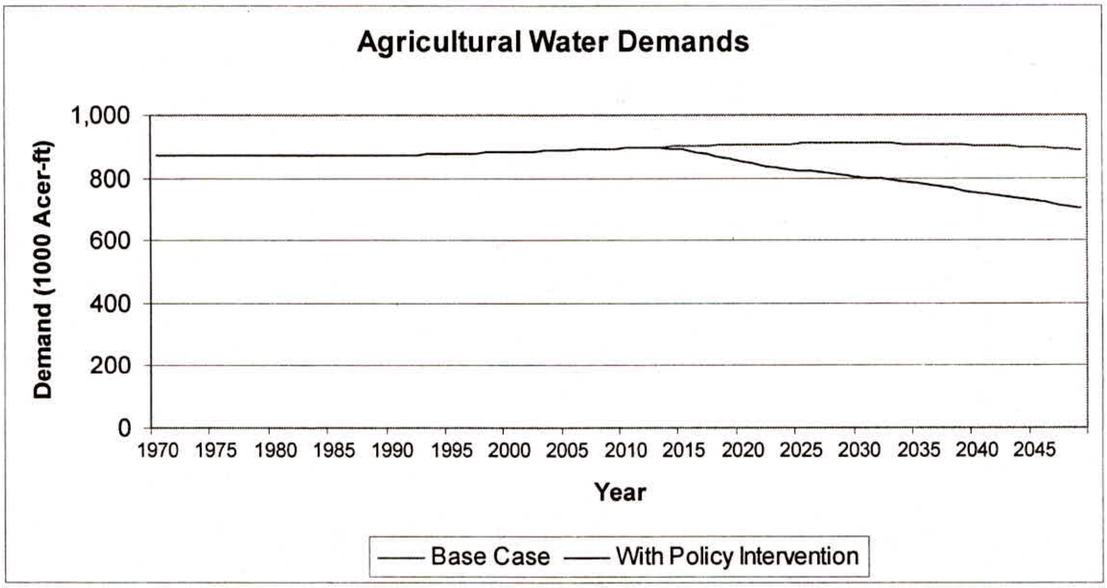


Fig. 5: Change in agricultural water demand with and without policy intervention

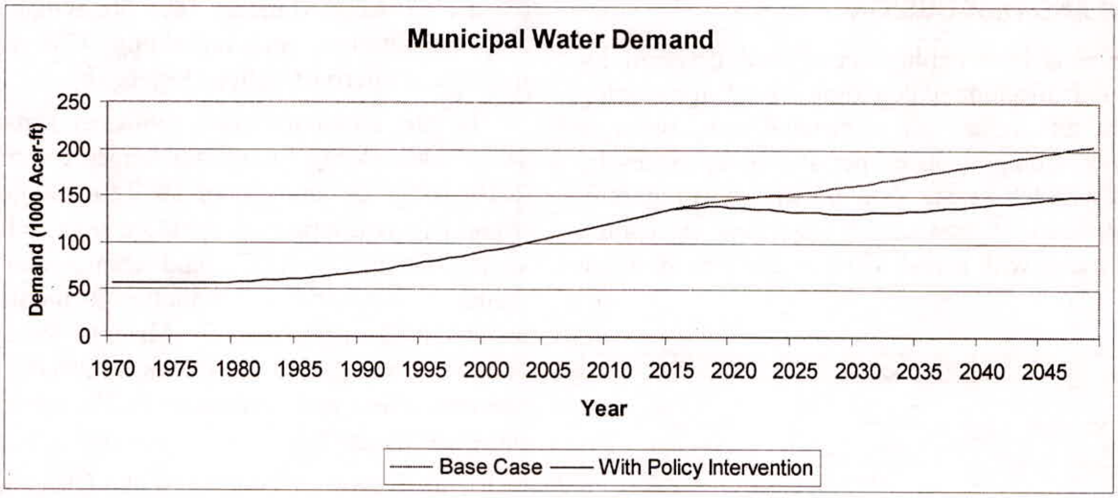


Fig. 6: Change in municipal water demand with and without policy intervention

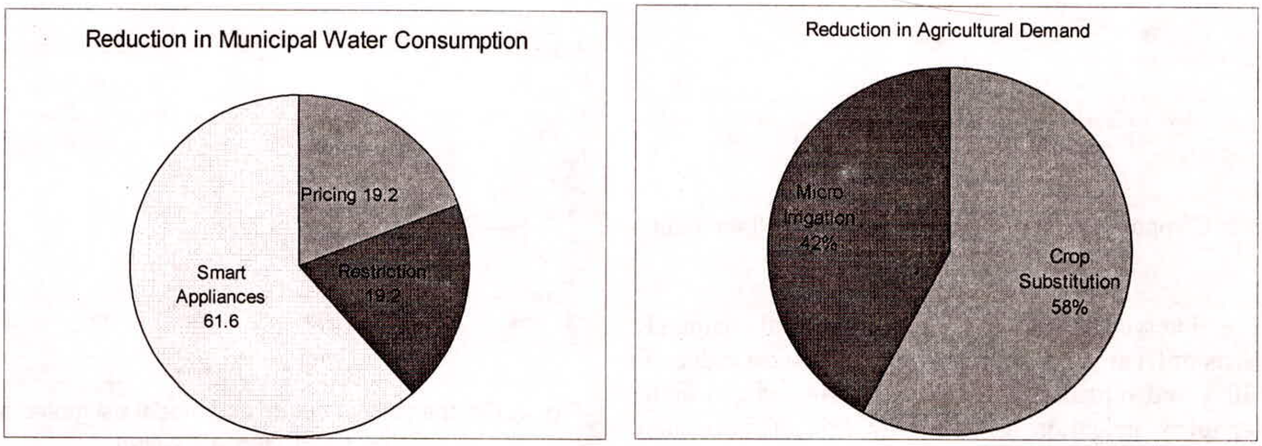


Fig. 7: Relative contributions of different interventions to reduce (a) municipal water consumption (b) agricultural water consumption

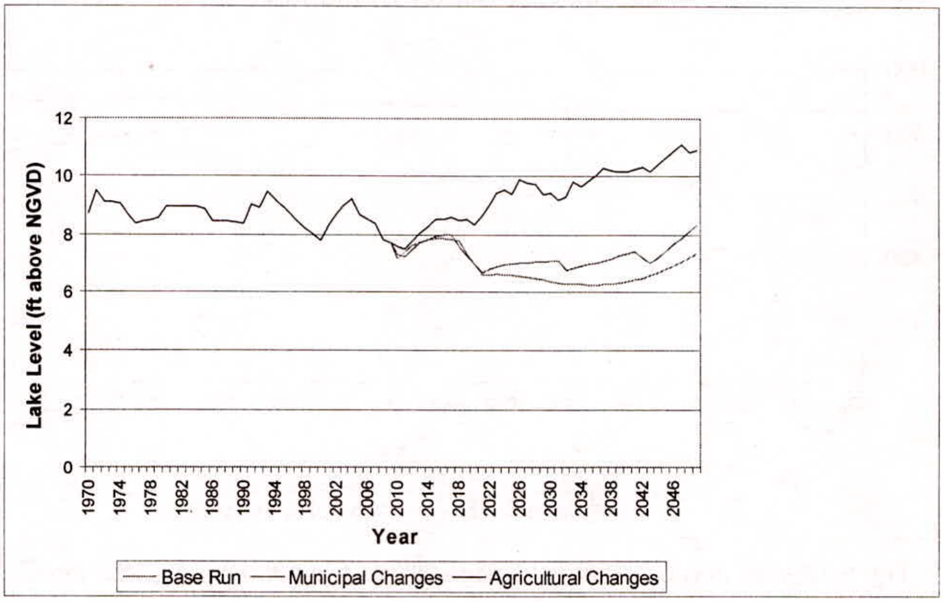


Fig. 8: Water levels in Lake Okeechobee in response to changes in municipal and agricultural water use

We see the value of simulation model through three important contributions: (i) stakeholder engagement; (ii) explaining the complex system; and (iii) providing a quantitative framework. There are uncertainties involved in long term forecasting of population growth, land use changes, agriculture practices, technological innovations, and economic growth. The input data used to characterize surface and groundwater supplies, water demands, and land use changes in the model are limited by the availability and quality of existing data sets, as well as by our own project time and resource constraints. The calibration, with its own limitations, is used to rectify and resolve inconsistencies in data sets to achieve an integrated model for south Florida. For those model parameters that lack good data, values are estimated and then varied in sensitivity analysis to determine the sensitivity of overall conclusions to variation in the uncertain parameter.

It is important to mention that model is not intended to be a predictive tool; rather it is a tool for enhancing the understanding of the system, and evaluating water management policies. The model allows planners/decision makers to understand both the problem and potential solutions to that problem.

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