Integrated Water Resources Management Incorporating Water Quality, Energy Consumption and Ecological Requirement

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Abstract
Water demand is increasing with the population growth and economic development, which result in the conflicts between different water users with limited water resources. This calls for an integrated water resources management, which considers water quantity and quality along with the socio-economic factors. This study developed a system dynamics model for water resources management in Hillsborough County. The model considers multiple water users including ecological system, different water supply options, water quality, and energy consumption associated with water supply. The result shows that current water management mainly focuses on water quantity, especially for municipal water withdrawal. The incorporation of water quality and associated energy consumption in decision making will change the supply options. Surface water will be preferred for water supply and the simulated groundwater level will increase by 0.6-0.8% with minor decrease in the surface water level.

Keywords: System Dynamics; Water Level; Water Quality; Energy Consumption; Water Withdrawals

1. Introduction

Available water supplies in the U.S. have been declined due to deterioration of surface water quality and depletion of groundwater resource. Approximately 60 percent of water bodies in the U.S. are impaired due to urbanization and agricultural practices (Jelks et al., 2008). At the meanwhile, water demand is increasing with the population growth and associated socioeconomic development. It is challenging to manage the limited and impaired water resources to meet the human water needs as well as ecological functions. This calls for an integrated water resources management that considers water and its related resources along with economic and social welfare. There are a number of system dynamics models were developed to support for integrated water resources management (Fernandez and Selma, 2004; Ford, 1996; Ho et al., 2005; Simonovic and Rajasekaram, 2004; Zarghami and Akbariyeh, 2012). However, these models focused only on the water quantity. Water quality and energy consumption associated with water supply options are not considered in these studies. The absence of water quality and its related issues result in some issues. For example, the lack of water quality and energy consumption leads to the inappropriate representation of water reuse. Besides, the over surface water withdrawals decrease water level, which threatens the natural habitat.

Therefore, this study developed a system dynamics model for water resources management in Hillsborough County, FL incorporating water quality, energy consumption, and water demand for natural systems. The rest of the study is organized as follows: research approach is specified in Section 2 followed by model validation in Section 3; results and discussions are provided in Section 4 followed by conclusions in Section 5.

2. Research Approach

2.1. System Dynamics

System Dynamics (SD) is a thinking model and simulation methodology that is developed to support the study of the dynamic behavior in a complex system (Ford, 1996; Hjorth and Bagheri, 2006). It is often used for scientific research, testing policy, and as a tool for learning (Homer, 1996; Lane, 2008). SD is well suited for interdisciplinary study because of the capability to link the physical system to human system and to capture the interactions of the components within the system. Taking into account the large number of factors and feedback loops in integrated water resource management, SD is applied in this study.

2.2. System Boundary

Hillsborough County is chosen as the study area. This county is located in the southwest coast of Florida and also within the boundary of the Southwest Florida Water Management District (SWFWMD), which manages both surface- and ground-water supply (Error! Reference source not found.). Hillsborough County has a population of 1,229,226 in 2010 (U.S. Department of Commerce, 2013). Approximately 50 percent of the land is urbanized, and 22 percent is used for agriculture (SWFWMD, 2013). Hillsborough River and Floridan Aquifer are the major surface water and groundwater sources within boundary. The annual precipitation is around 51 inches, about 60 percent of which is received from June to September. Due to the seasonal variation, the model is developed in monthly step and then aggregated to annual output.

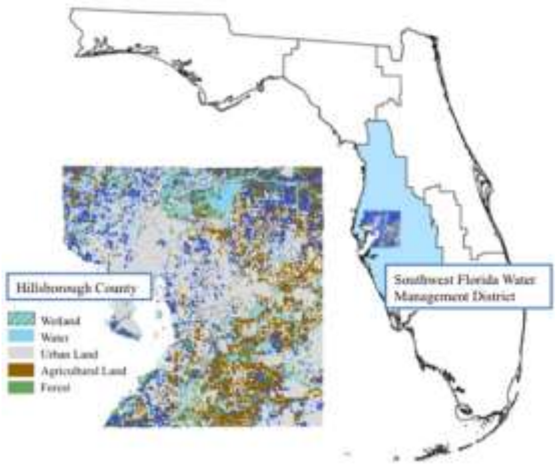

Figure 1. Geographic Location and Land Use of Hillsborough County

2.3. Water Demand

Water demand consists of the demand in municipality, agriculture, industry, and power generation.

Water Demand in Municipality. Water demand in municipality refers to the residential water use through public supply systems and self-domestic supply. It is divided into indoor and outdoor water demand (**Figure 2**). The indoor water demand is determined by the indoor water demand per capita and population. Indoor water demand per capita can be reduced by demand options, including budget on municipal water conservation education, indoor water appliance rebate program, and water rate. Outdoor water demand mainly refers to the lawn irrigation, which is determined by weather, lawn area, and municipal irrigation efficiency. The efficiency can be reduced by rebate program for outdoor water efficient appliances and water conservation awareness. Water rate and municipal irrigation efficiency can also affect on the outdoor water demand.

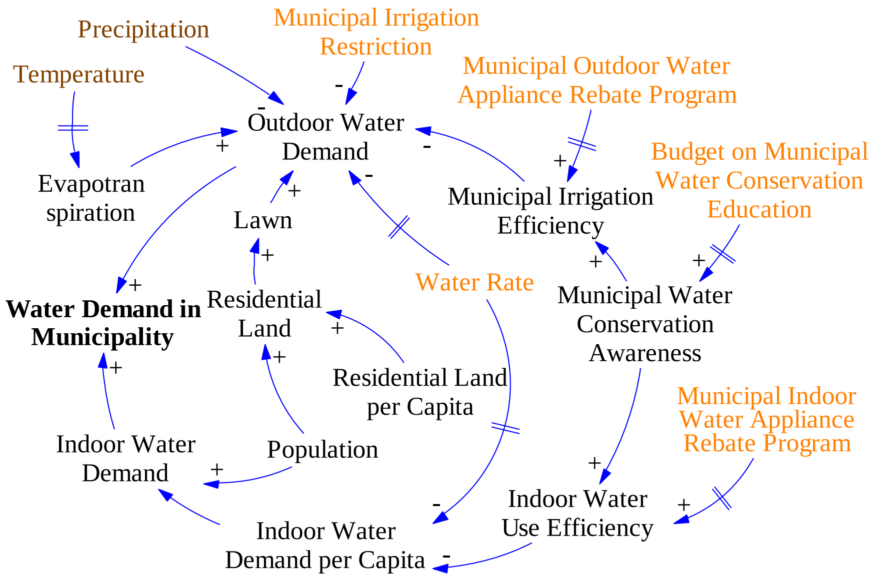

Figure 1. Causal-Loop Diagram of Water Demand in Municipality. *The positive sign represents the reinforcing causal relationship, and the negative sign represents balancing causal relationship. The two-line bar in the middle of the link represents time delay. The orange variables represent the demand options, and brown variables represent the weather condition, which is simulated in the climate change scenario.*

Water Demand in Agriculture. Water demand in agriculture is determined by irrigated land, irrigation efficiency, precipitation, and crop evapotranspiration (**Figure 2**). Irrigated land decreases due to the conversion to residential land, which is driven by population growth. Agricultural irrigation efficiency can be changed by the management options including agricultural water conservation education, agricultural best management practice (BMP) program, and water permit cost. The weather condition includes precipitation and evapotranspiration, but the change of crop pattern (e.g. types of crops, growth period, etc.) will affect the crop evapotranspiration.

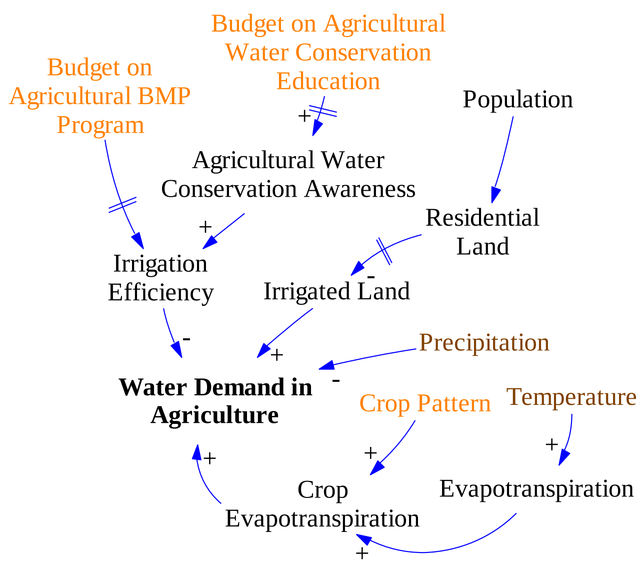

Figure 2. Water Demand in Agriculture. *The positive sign represents the reinforcing causal relationship, and the negative sign represents balancing causal relationship. The two-line bar in the middle of the link represents time delay. The orange variables represent the*

demand options, and brown variables represent weather condition, which is simulated in the climate change scenario.

Water Demand in Industry. Water demand in industry is divided into water demand in food processing and product manufacturing that is determined by the water intensity (water demand for food processing/product manufacturing per employee) and the number of employees.

Water Demand in Energy Production. Due to the lack of fossil fuel mining within the boundary, water demand in energy mainly refers to the water demand in power generation. Power generation in the system is determined by the energy requirement per capita, population, and imported energy. The direct discharge of cooling water will increase the water temperature in the Tampa Bay, which in turn increases the water intensity for power generation.

2.4. Water Supply

Freshwater. Freshwater includes surface- and ground-water, which interact through soil water storage (Figure 3). Surface water increases with surface water inflow, precipitation, return flows after water uses, and runoff; it decreases with evaporation, infiltration (to soil), and surface water withdrawals. The surface water withdrawal is determined by surface water level, water quality, and energy consumption, which is discussed in **Section 2.6**. Similarly, groundwater storage increases with groundwater inflow, infiltration (from soil), seawater intrusion, and groundwater recharge; it decreases with groundwater outflow and groundwater withdrawal.

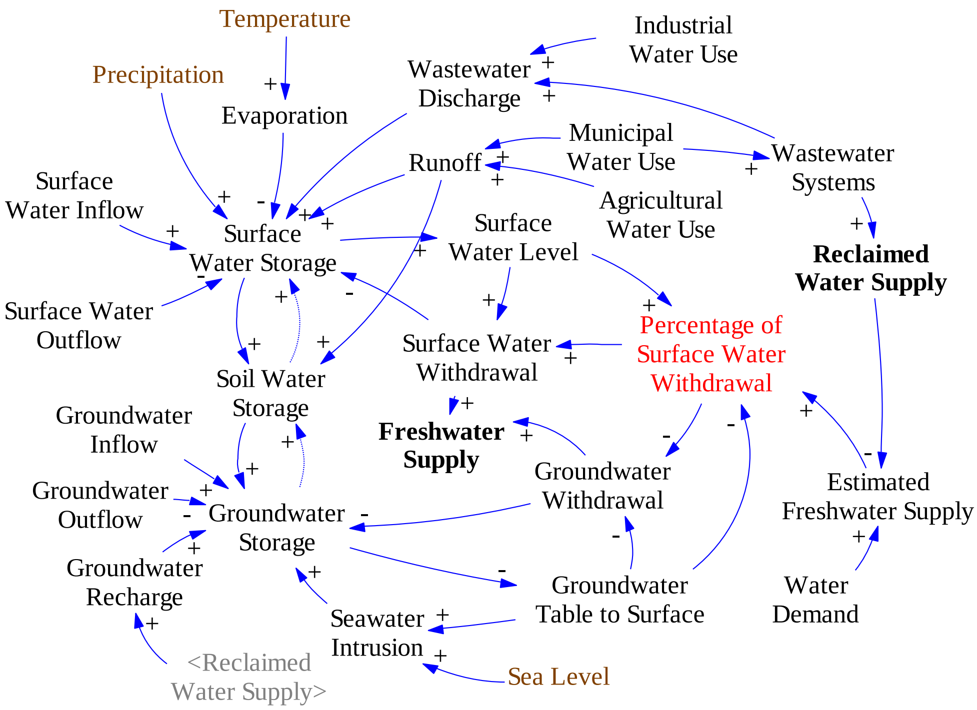

Figure 3. Freshwater Supply. *The positive sign represents the reinforcing causal relationship, and the negative sign represents balancing causal relationship. The brown variables are the weather condition, which is simulated in the climate change scenario.*

Reclaimed Water. Reclaimed water is used for residential irrigation and cooling; however, due to the relatively low use in cooling, this study focuses on the reclaimed water to offset the potable water use in municipal irrigation (Figure 4). Reclaimed water supply increases with the demand and infrastructure capacity. The demand for reclaimed water increases with the public acceptance, which is influenced by peer endorsement, the price of reclaimed water, and municipal water conservation awareness. Reclaimed water capacity refers to the existing infrastructure, especially the purple pipelines. Increase in budget can increase the capacity, and it also affects on the unit reclaimed water cost and price.

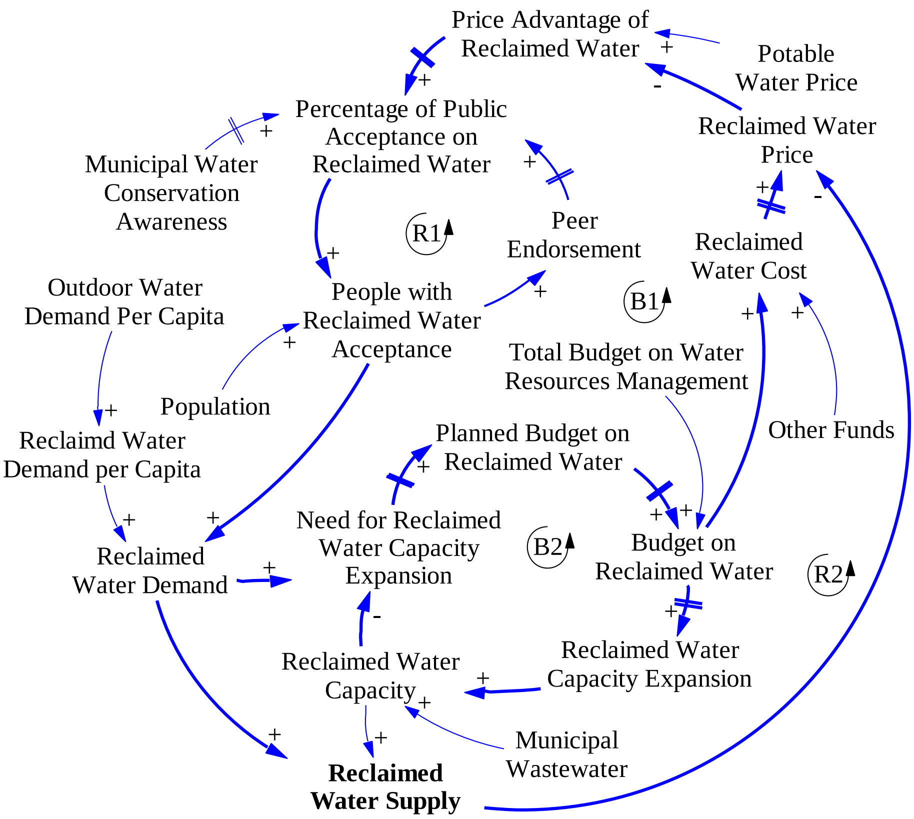

Figure 4. Reclaimed Water Supply. *The positive sign represents the reinforcing causal relationship, and the negative sign represents balancing causal relationship. The two-line bar in the middle of the link represents time delay. R and B represent reinforcing and balancing loops, respectively.*

Bay Water. Bay water is the major source for power generation cooling. It is also a supplementary water supply source through reverse osmosis under water shortage.

2.5. Water Quality

Water quality is considered in every inflow and outflow in surface- and ground-water withdrawals, which is represented as a water quality index,

$$\mathrm{I_Q} = \frac{\Sigma(\mathrm{I_Q^{high}})_i}{\mathrm{N_{high}}} + \frac{\Sigma(\mathrm{I_Q^{low}})_j}{\mathrm{N_{low}}} \qquad (1)$$

$$(\mathrm{I_Q^{high}})_i = \begin{cases} 100 - \frac{(c_{high}^{upper} - c_{high})_i}{(c_{high}^{upper} - c_{high}^{lower})_i} \times 100, (c_{high}^{lower})_i < (c_{high})_i < (c_{high}^{upper})_i \\ 100, (c_{high})_i \geq (c_{high}^{upper})_i \\ 0, otherwise \end{cases} \qquad (2)$$

$$(\mathrm{I_Q^{low}})_j = \begin{cases} 100 - \frac{(c_{low}^{lower} - c_{low})_j}{(c_{low}^{lower} - c_{low}^{upper})_j} \times 100, (c_{low}^{lower})_j < (c_{low})_j < (c_{low}^{upper})_j \\ 100, (c_{low})_j \leq (c_{low}^{lower})_j \\ 0, otherwise \end{cases} \qquad (3)$$

Where, I_Q is the water quality index, which is dimensionless and with the scale between 0 to 100; I_Q^{high} is the water quality index for the high concentration preferred indicator, and I_Q^{low} is water quality index for the low concentration preferred indicator; N is the number of indicators. c is the concentration; c^{lower} and c^{upper} are lower and upper range of the concentration; i represents the high concentration preferred indicator, and j represents the low concentration preferred indicator. Four water quality monitoring indicators, dissolved oxygen, total nitrogen, total dissolved solids, and total organic carbon, are considered in this study. Except for dissolved oxygen, the rest three indicators are low concentration preferred indicators.

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

Water quality and energy consumption associated with water supply is considered in the percentages of surface- and ground-water withdrawals.

$$f_m^n = \mathrm{w}_1 I_{A,m}^n + \mathrm{w}_2 I_{E,m}^n \quad (4)$$

$$I_{A,m}^n = \frac{w_3\left({}^{l}/_{l_{Minimum}}\right)_m + w_4\left({}^{I_Q}/_{I_Q^{n,ideal}}\right)_m}{\sum_{m=1}^{2}[w_3\left({}^{l}/_{l_{Minimum}}\right)_m + w_4\left({}^{I_Q}/_{I_Q^{n,ideal}}\right)_m]} \quad (5)$$

$$I_{E,m}^n = 1 - \frac{E_t \times (I_{Q,m}^n - I_Q) + (E_{c1} \times d_m^n + E_{c2})}{\sum_{m=1}^{n}[E_t \times (I_{Q,m}^n - I_Q) + (E_{c1} \times d_m^n + E_{c2})]} \quad (6)$$

Where, f is the percentage of freshwater withdrawals; m is the type of water sources, 1 represents surface water, and 2 represents groundwater; n is the type of end user, 1 to 3 represent municipal, agricultural, and industrial user, respectively; I_A is the index for water availability determined by water quantity and quality (**Eq. 5**); I_E is the index for energy consumption associated with water supply; *l* is the depth of water body; E_t is energy intensity for water treatment expressed in the unit of KWh/Gallon; E_{c1} is the energy intensity for raw water conveyance and E_{c2} is the energy intensity for end use water conveyance, which are expressed in the unit of KWh/Gallon; d is the average distance for water source to end user; w_1 to w_4 are the weighting factors for water availability, energy consumption, water quantity, and water quality, respectively.

2.7. Considering Environmental Water Demand

Environmental water demand (or water demand for natural system) is considered through minimum or ideal water level for withdrawals (**Eq. 5**). For example, the increase of ideal surface water level will decrease its percentage of withdrawal, which eventually increases the surface water level.

3. Model Validation

A three-step model validation process is established in this study (Barlas, 1996): a) direct structure test, b) structure-oriented behavior test, and c) behavior test.

Direct Structure Test. The direct structure test was conducted by examining the causal and mathematical relationship between variables by comparing available knowledge about water systems, such as governmental reports, peer-reviewed publications.

Structure-oriented Behavior Test. The structure-oriented behavior test included extreme condition test and sensitivity test. **Figure 5** shows that the model behaves as expected under extreme condition such as surface water gradually decreases to zero with the absence of precipitation, and water demand quickly drops to zero with no population in the study area. **Figure 6** shows the sensitivity of precipitation. Surface water quality is most sensitive to precipitation, largely because of the stormwater runoff.

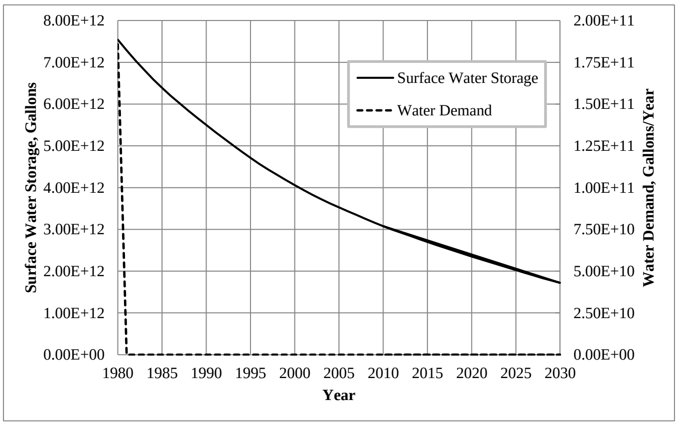

Figure 5. Extreme Condition Tests: Surface Water Storage with No Precipitation and Water Demand with No Population

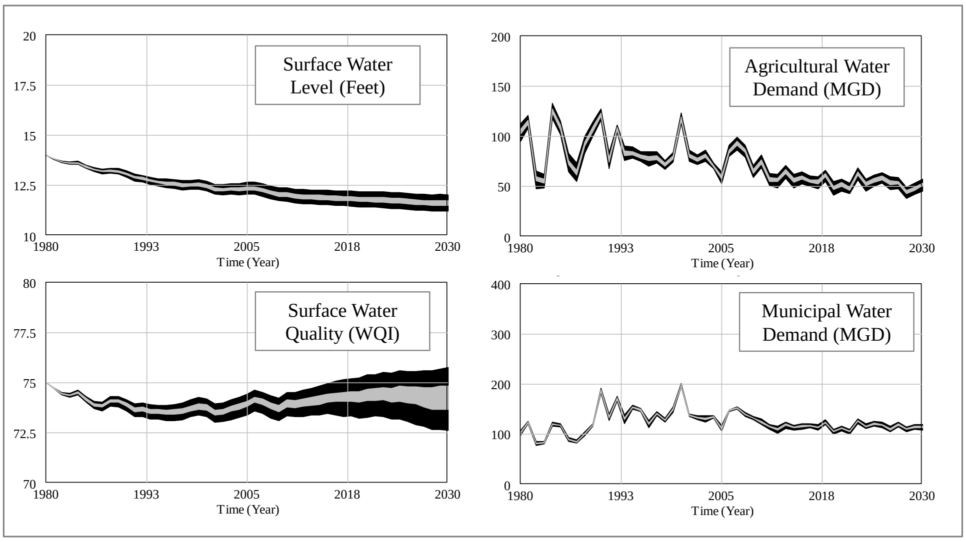

Figure 6. Sensitivity Analysis of Precipitation

Behavior Test. **Figure 7** shows the behavior test of agricultural and municipal water withdrawals. The major oscillations were captured, and the simulated results are cross correlated to real data but with white noise.

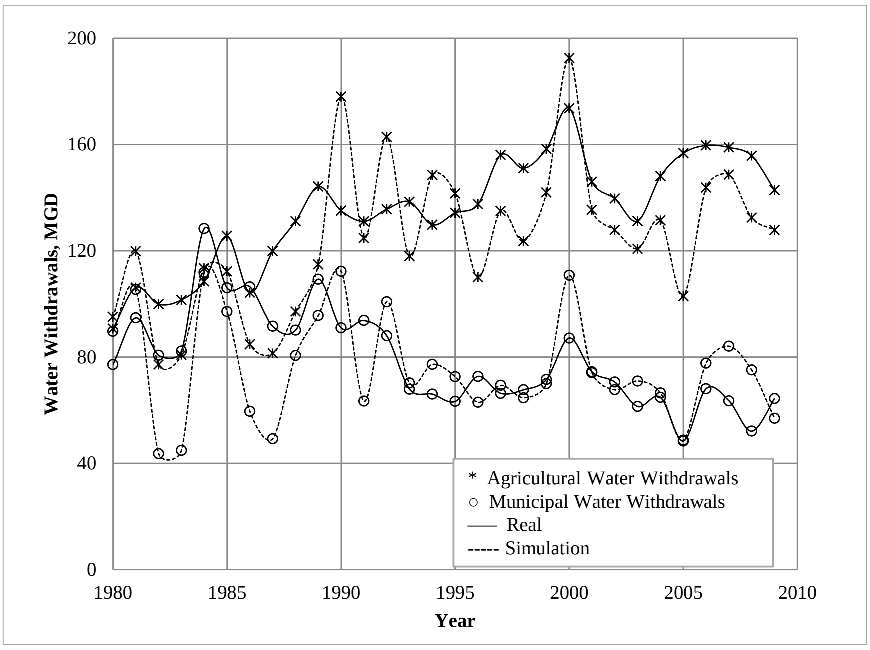

Figure 7. Behavior Test of Agricultural and Municipal Water Withdrawals from 1980 to 2009

4. Results and Discussions

4.1. Reference Behavior

The reference behavior was simulated under current weather condition (e.g. precipitation, evaporation) and the population projection from the Florida Housing Data Clearing Housing. The results show that municipal water withdrawals increase with the population growth and agricultural water withdrawals decrease with the diminished irrigated land (shown in **Figure 8**).

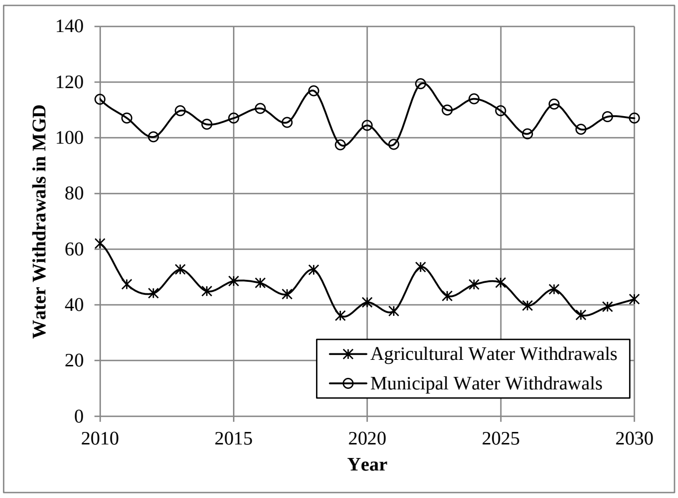

Figure 8. Reference Behavior of Agricultural and Municipal Water Withdrawals from 2010 to 2030

4.2. Considering Water Quality and Energy Consumption

Water quality and associated energy consumption are considered in the determination of the percentage of surface- and ground-water withdrawals as shown in **Eq. 4-6** (**Section 2.6**). The validity of these equations has to be tested. As shown in **Table 1**, the simulated percentage of municipal surface water withdrawal (56%) aligns well with the real data (55%). The percentage for agricultural water withdrawal from surface water sources is also in line with the real data (4% for simulation and 5% for real data). The simulated percentage of industrial water withdrawal is higher than reported. It is mainly because the industrial water use in this study includes not only self-supplied water (usually groundwater), but also the water used through public supply (usually surface water); however, the industrial water use through public supply is not reported separately. Accordingly, **Eq. 4-6** can be applied to represent the percentages of surface- and ground-water withdrawals.

According to **Table 1**, current municipal water withdrawal focuses only on the water quantity (w_1=w_3=1, w_2=w_4=0). Agricultural water withdrawal is also quantity-oriented scheme (w_1=1, w_2=0), but energy consumption (or cost) plays a more important role, which accounts for 95 percent (w_3=0.05, w_4=0.95). It is because surface water bodies in Hillsborough County are not close to the irrigated lands and a large amount of energy is needed for water conveyance. As a result, groundwater is the major source due to relatively low energy consumption for pumping compared with surface water. It is similar for industrial water withdrawals. **Table 1** also shows the percentages of surface water withdrawals for different water users under different weighting schemes. With the consideration of water quantity only, the percentages of surface water withdrawals increase. It indicates that the aquifer is much lower than minimum level, which results in a preference in surface water withdrawals. If water quality is also equally considered (w_1=w_2=0.5, w_3=1, w_4=0), the percentage of surface water withdrawal for municipal water decreases by 18.3%, but it increases for agriculture and industry. It is because the water requirement for agricultural and industrial uses is lower. Although groundwater quality is higher, surface water is also accepted. Besides, surface water quantity is higher, so it is still more preferred than groundwater. If the energy consumption associated with water supply is also equally considered in the decision-making (w_1=w_2=w_3 =w_4=0.5), the percentages of surface water withdrawals for both agriculture and industry decrease by 41%. One major reason is the long distance from the surface water sources to the agricultural and industrial end users, which result in a high energy consumption. On the other hand, municipal water treatment facilities in Hillsborough County are close to surface water bodies, so the energy consumption for extracting surface water is much lower than pumping groundwater. In addition, the groundwater quality is not significantly better than surface water, which results in similar energy consumption for water treatment. **Table 1** also indicates that groundwater level will increase with the consideration of water quality and energy consumption in the management options. Although the surface water levels decrease, the percentages of changes are lower than the groundwater level.

Table 1. Change of Surface- and Ground- Water Level with Water Quality and Energy Consumption Consideration

Management Option	Percentage of Surface Water Withdrawal			Surface Water Level Change	Groundwater Level Change
	Municipality	Agriculture	Industry		
Current Condition	0.56	0.03	0.18	NA	NA
With Water Quantity Consideration	0.60	0.53	0.53	-0.2%	+0.8%
With Water Quantity and Quality Consideration	0.49	0.56	0.56	-0.1%	+0.6%
With Water Quantity, Water Quality, and Energy Consumption Consideration	0.64	0.33	0.33	-0.1%	+0.7%

4.3. Considering Environmental Demand

The environmental water demand or minimum water level for natural systems also affects the supply decisions options. **Table 2** shows the change of surface- and ground-water level under different weighting schemes and minimum water levels. The result shows that the improvement in surface water level leads to the decrease in groundwater level (vice versa) because the total freshwater withdrawals are not reduced. With considering energy consumption, the strategy to increase minimum surface water level by 50% decreases the surface water level. It is mainly because of municipal uses. Surface water consumes less energy (especially for delivery), so even with the goal to decrease surface water withdrawal, it is still preferred. It is also because the minimum water level is not mandatory in this study (i.e. not included in the feedback loops). Take the municipal water withdrawal for example, **Figure 9** shows the feedback loops associated with percentage of surface water withdrawal for municipal use. The minimum water level is considered as exogenous factor. When the surface water level is lower than the minimum level, it only indicates that surface water is not a preferred source, but still available for withdrawals. As a result, minimum water level has to be considered with water demand or water supply options. When the water level is lower than the minimum level, new water supply source, such as reclaimed water, should be developed, or water demand needs to be reduced.

Table 2. Water Level Change under Different Weighting Schemes and Ideal Water Levels. *SW and GW represent surface- and ground-water respectively.*

Management Option	Water Level Considerations	SW Level Change	GW Level Change
Current Condition	Increase Minimum Surface Water Level by 50%	1.6%	-0.5%
	Increase Minimum Groundwater Level by 50%	-0.8%	+0.7%
	Increase Both Levels by 50%	1.5%	-0.3%
With Water Quality Consideration	Increase Minimum Surface Water Level by 50%	-0.2%	0.8%
	Increase Minimum Groundwater Level by 50%	-0.2%	0.8%
	Increase Both Levels by 50%	-0.2%	1.0%
With Water Quality and Energy Consumption Consideration	Increase Minimum Surface Water Level by 50%	-1%	1.2%
	Increase Minimum Groundwater Level by 50%	-2%	1.0%
	Increase Both Levels by 50%	-2%	1.3%

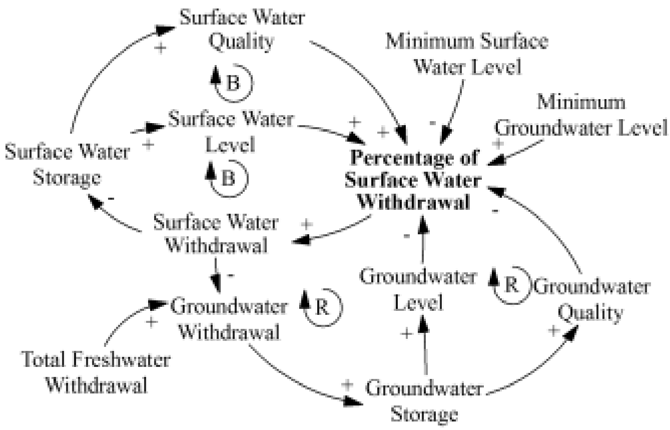

Figure 9. Feedback Loops Associated with Percentage of Surface Water Withdrawal for Municipal Use.

5. Conclusion

This study developed a system dynamics model for water resources management in Hillsborough County. The model consists of multiple water users and different types of water users. Water quality, energy consumption associated with water supply, and environmental water demand are incorporated in the water supply options. The result shows that current water management, especially municipal water withdrawal, focuses only on water quantity. Decisions for freshwater withdrawals for agricultural and industrial uses are made mainly based on energy consumption for water delivery (the distance of nearest water source). The incorporation of water quality and energy consumption to choose water supply sources results in an increase in the groundwater level but minor decrease in surface water level. The result also shows that the minimum water level for ecological functions has to be strictly enforced; otherwise the increase of minimum water level for one water source usually results in the decrease of water level for the other water source unless the total freshwater withdrawals is decreased. Although this study includes reclaimed water, the interactions of reclaimed water and tradition water supply sources should be further investigated.

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