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A COMPLEX ADAPTIVE SYSTEMS APPROACH TO SIMULATE INTERACTIONS AMONG WATER RESOURCES, DECISION-MAKERS, AND CONSUMERS AND ASSESS URBAN WATER SUSTAINABILITY

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The balance between water supply and demand for urban water resources is threatened by population growth, land use changes, and climate change. Interactions among environmental resources, infrastructure, societal norms, and management decisions create complexity and increase the unpredictability of the dynamics of water availability. This research develops a socio-technical framework to simulate interactions among technical and social systems and assesses urban water sustainability. An agent-based model (ABM) is implemented to simulate a community of heterogeneous households as agents. The ABM is coupled with a hydrological watershed model, a water reservoir model, and climate change projections. The increase in the number of household agents, dynamics of consumer demands for landscaping, and enactments of drought restrictions are simulated to assess the depletion of water in the reservoir. Population change projections are used to simulate the increase of households over a long-term planning horizon. Household water demands are simulated using residential end use models to calculate withdraws from a surface water reservoir. Utility manager agents respond to reservoir depletion to enact drought response plans and water use restrictions. Household agents respond to water use restrictions by limiting outdoor water use and to water rebate programs to retrofit water appliances. The ABM framework is applied to Raleigh, NC, which is a rapidly urbanizing area. Falls Lake Reservoir is the major water source for Raleigh, and the ABM framework is validated using historic data describing reservoir levels, withdraws, and releases. Future scenarios are explored to assess the effects of climate change and the effectiveness of policies. Results of the study facilitate insight about the influence of the dynamics of water supply and demands on urban water sustainability.

INTRODUCTION

Urban water resources should be managed sustainably to achieve an appropriate balance between water demand and supply. This balance is increasingly difficult to sustain as urban areas increase in size, and precipitation decreases due to climate change. Traditionally, water shortages are managed by supply management, which is based on the assumption that economic growth generates new demands. Supply management does not control demand, but increases the supply to meet demands. This approach leads to the depletion of freshwater reserves and the construction of large infrastructure systems comprised of pipe networks and pumping stations [1, 2]. Continuing to use a supply management approach is not feasible for many utilities due to greenhouse gas emissions, energy requirements, decaying infrastructure, and water shortages [3]. Subsequently, a demand management paradigm has emerged as a promising approach. Demand management focuses on reducing demands through water pricing, educational campaigns, incentives and rebates for water-saving technologies, regulations, and metering. Demand-side strategies have the potential to significantly reduce demands, but they rely on changes in human behavior, and their performance is impacted by social factors. Management strategies are typically developed using linear projections of population growth, demands, and system capacity under a stationary climate and a homogeneous population of consumers. The sustainability of water resources, however, may be affected by the dynamic interactions among the environmental, technological, and social characteristics of the water system and local population. The response of water consumers to demand management strategies can affect the performance of management, and the dynamic adoption of water-efficient appliances can impact the evolution of water availability. These interactions can cause supply-demand imbalances that may not be predictable using traditional engineering models and assumptions of a stationary climate.

This research develops a sociotechnical modeling approach to describe interactions among the public, environmental resources, and engineering infrastructure and to simulate emerging system-level properties of a water supply system. An agent-based modeling approach is developed to couple models of consumers and utility managers with watershed and reservoir models. Households are represented as agents, and their water use behaviors are represented as rules. A deterministic end use model is used to simulate indoor demands, and landscaping demands are calculated based on irrigation requirements of crops and behaviors of end users. A population growth model is used to simulate an increasing number of household agents. A water utility manager agent enacts water use restrictions, based on fluctuations in the reservoir water storage. A watershed model simulates inflows to a reservoir, and climate projections are used to test the sensitivity of water availability to changes in precipitation and temperature. The integrated framework provides insight for water utility operators and stakeholders about the interactions of management strategies, climate change, population growth, and consumer behaviors, and the impact that these behaviors have on long-term water supply sustainability.

The goal of this research is to develop long-term understanding of the emergence of water sustainability, rather than providing short-term predictions. Therefore, results are generated using scenario analysis to provide insights about the behavior of the system, which are used to evaluate decision-making strategies [4]. Several performance measures are used to evaluate and compare alternative water resources management strategies and scenarios [5]. The agent-based modeling framework is applied to simulate the water supply system of Raleigh, North

Carolina, and water resource sustainability indices are used to evaluate and compare alternative water shortage response plans and management policies for the water supply system.

AGENT-BASED MODELING FRAMEWORK

An agent-based modeling framework is developed to simulate urban water resources as a complex adaptive system [6]. Agent-based modeling is an approach for simulating networks comprised of autonomous, interacting agents [7]. The dynamic interactions among agents and a shared environment are modeled to simulate the emergence of system-level properties. The framework includes several subcomponents to represent social and technical subsystems of water resources in an urban area. The model includes household agents and a water utility manager agent (Figure 1). Household agents withdraw water from the reservoir, and a hydrologic model is used to simulate runoff from the contributing watershed based on climatological data. Household agents receive alerts from the water utility manger agent about the level of water use restrictions, which are enacted when storage in the reservoir drops below pre-defined stages. This model is based on a framework that was developed to simulate population growth, land use change, and water conservation for the City of Arlington, Texas [8, 9].

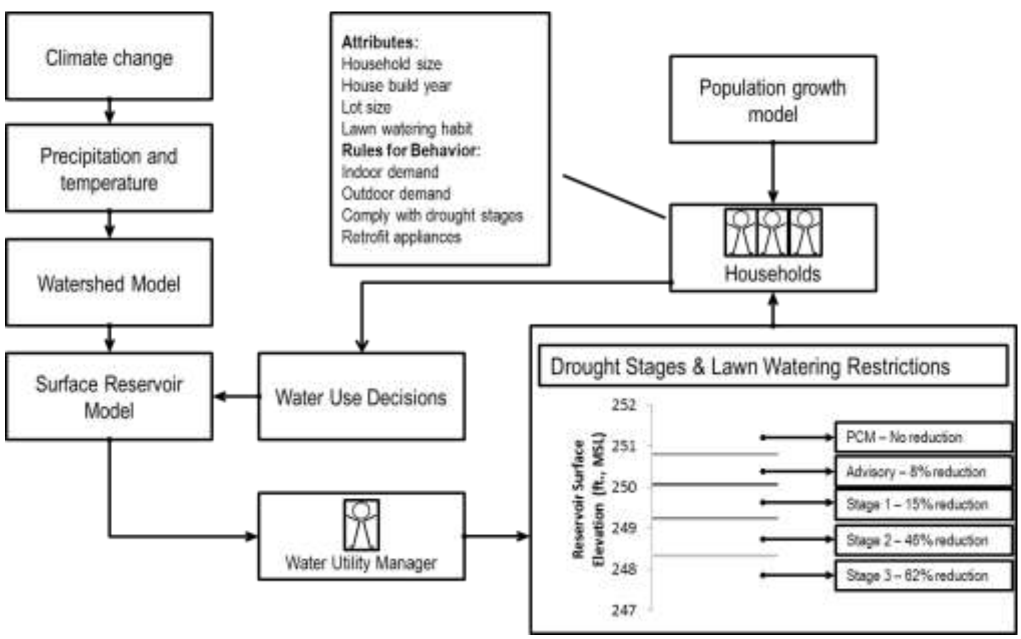

Figure 1. ABM framework. PCM is Permanent Conservation Measures.

Household agents

Households are simulated as agents, with properties and behavioral rules to simulate household-level demands. Household size, house built year, and lot size are properties, and rules are encoded to calculate indoor water use, adaptive outdoor water use, retrofitting water appliances, and lawn watering habits. Attributes are initialized using historic information and projections. For example, household agents are assigned a number of residents based on demographic information and distribution of household size. The total demand for a household agent is the sum of indoor end uses and the outdoor end use, described as follows.

An indoor end-use model, which describes the uses of water by a household at the appliance level, is developed to calculate indoor water demands based on the number of residents in a household [10]. Indoor water consumption in each household is disaggregated to eight end uses including showerhead, faucets, cloth washers, toilets, dishwashers, bathtub, leakage, and others. Household agents replace toilets, showerheads, and washing machines with more efficient appliances after the appliance life span has expired, and this changes the indoor water demand volume.

Outdoor demand is calculated as a function of climatic data and water demands for landscaping. A significant portion of residential outdoor demand is used for garden watering, and other outdoor demands, such as swimming pools and washing vehicles and driveways, are neglected. The water demands for landscape irrigation are calculated through a theoretical irrigation model based on a soil-water budget approach:

$$TIR = K_{crop} \times A \times ET_0 \tag{1}$$

where *TIR* is the monthly irrigation requirement; ET_0 is net evapotranspiration for a month (evapotranspiration minus excess rainfall); K_{crop} is the crop coefficient; and *A* is the area of land, in square feet, that is irrigated. An agent is assigned a behavioral factor to represent if it regularly waters the lawn.

Household agents receive information from a water utility manager agent about the level of outdoor water use restrictions. Households reduce outdoor demands based on utility restrictions. Indoor end uses are not affected by restrictions.

Population growth model

Population growth is simulated as an increasing number of household agents at each time step, or month. Data for the population growth is available through the U.S. Census.

Water utility manager agent

The water utility manager is simulated as an agent that receives information about the surface water elevation from the reservoir model at each monthly time step. Based on the reservoir storage, the water utility manager agent defines the level of water restrictions: Permanent Conservation Measures, Advisory Stage, and Drought Stages 1, 2, and 3. Restrictions are enacted in response to decreasing reservoir storage.

Water reservoir model

A reservoir system is implemented within the framework to determine storage and water levels. Reservoir storage is calculated on a monthly time-step using the continuity equation:

$$S_t = S_{t-1} + I_t - R_t - WS_t - SP_t \tag{2}$$

where S_t is the volume of water stored in the reservoir at time step *t*; I_t is the monthly net inflow to the reservoir (inflow plus precipitation over the lake surface minus evaporation from the lake surface). R_t is the reservoir outflow (water quality releases) at time step *t*. WS_t is the total water supply, which is the sum of the indoor and outdoor demands withdrawn from reservoir at time step *t*, and SP_t is reservoir spill, which occurs when the water level within the reservoir exceeds a pre-defined control elevation. Water quality and flood control releases are simulated as the operational rules that control the release based on water level fluctuations in the reservoir on a daily basis and inflow projections for subsequent days.

At the beginning of each month, the reservoir model receives stream flow values as input from the hydrologic model, the volume of water to be released based on operational rules, and the volume of withdrawals from consumer agents. The final storage at the end of the month is computed and used as input for the water utility manager agent, which selects water use restrictions in the subsequent month.

Hydrologic model

A hydrological model is integrated within the framework to simulate the runoff process for the contributing watershed. The reservoir model receives the information from the hydrologic model to calculate the water storage at each time step. Climate change is simulated using projections of precipitation and temperature as input for the hydrologic model.

SUSTAINABILITY INDEX

A sustainability index is used to summarize the performance of alternative management policies, based on resilience, vulnerability, and maximum deficit. For each time period t, the deficit D_t is defined as:

$$D_t = \begin{cases} Demand_t - Supply_t & \text{if Demand}_t > \text{Supply}_t \\ 0 & \text{if Demand}_t = \text{Supply}_t \end{cases} \quad (3)$$

Failure is defined as a deficit greater than zero. Resilience (*Res*) is the probability that a period of no failure follows a failure period and is evaluated for all failure periods. This statistic assesses the recovery of the system once it has failed:

$$\text{Res} = \frac{\text{No. of times } \text{D}_t = 0 \text{ follows } \text{D}_t > 0}{\text{No. of times } \text{D}_t > 0 \text{ occurred}} \quad (4)$$

Vulnerability represents the average value of deficits to express the severity of failures. Vulnerability is calculated as the sum of deficits divided by the number of time steps where the supply system failed. The average deficit is divided by the annual water demand so that vulnerability is dimensionless:

$$\text{Vul} = \frac{\left(\sum_{t=0}^{t=n} D_t\right)}{\text{No. of times } \text{D}_t > 0 \text{ occurred}} \Big/ \text{Water demand} \quad (5)$$

where n is the number of time intervals where the deficit is greater than zero. If deficits occur, the worst-case annual deficit is the maximum deficit (*Max def*):

$$\text{Max def} = \frac{\max\left(D_{Annual}\right)}{\text{Water demand}} \quad (6)$$

Finally, the Sustainability Index (*SI*) measures the combination of the performance criteria. *SI* is defined a geometric average of these performance criteria (Sandoval-Solis et al. 2010).

$$SI = \left[\text{Res} * \left(1 - \text{Vul}\right) * (1 - \text{Max def}) \right]^{1/3} \tag{7}$$

ILLUSTRATIVE CASE STUDY

The agent-based modeling framework is applied to simulate the water supply system of Raleigh, North Carolina. The city of Raleigh has a population of approximately 486,000 inhabitants over an area of 142.8 square miles, and the population of Raleigh is projected to increase to 848,000 inhabitants by the year 2032, as reported by the U.S. Census. The primary source of water supply for the city is Falls Lake, which is a man-made reservoir located on the upper Neuse River and managed by U.S. Army Corps of Engineers. Due to the population growth in the city of Raleigh and surrounding communities served by Falls Lake over the last decade, water storage in Falls Lake has been increasingly stressed. Droughts were recorded in the years 2002, 2005, and 2007 [11].

The model is implemented in Java using MASON agent-based simulation libraries. The agent-based model was initialized with 170,400 household agents. Household agents are assigned a household size, based on data available through U.S. Census data, and lot size, based on the total residential area of the city and total number of households. Household agents are assigned behavioral factors to describe their lawn watering habits [12]. Household agents use one of three rules for outdoor water use: agents water the lawn based on the irrigation demand calculated using Eqn. 1, water the lawn based on 50% of the demand calculated using Eqn. 1, or do not water the lawn. Population growth data for the city of Raleigh is obtained from U.S. Census for the period of 1983 to 2013, and projection data are used for simulation of future scenarios.

The water utility manager agent uses triggers for enacting conservation stages and reverse triggers to release conservation stages, as conditions return to normal. Reservoir storages of less than 70%, less than 50%, less than 30%, and less than 10% correspond to Advisory Stage, Stage 1, Stage 2, and Stage 3, respectively. The reverse triggers for Stage 1, Stage 2, and Stage 3 are 90%, 70%, and 50% of the reservoir storage, respectively. Drought stages limit the number of days during which household agents exert outdoor demand. The drought stage triggers are shown in Table 1.

Table 1. Drought stages

Conservation Stage	Trigger (% Storage)	Reverse Trigger (% WSSP)	Consumption Goal (gallon per capita per day)
Permanent Conservation Measures (PCM)	N/A	N/A	65
Advisory Stage	< 70%	N/A	60
Stage 1	< 50%	>= 100%	55
Stage 2	< 30%	>= 70%	35
Stage 3	< 10%	>= 50%	25

SCENARIOS

Six scenarios are created to explore the performance of the water supply system. Scenario 1 represents a base case that provides a benchmark. Household agents do not retrofit water appliances, and all household agents water lawns using the demand calculated by Eqn. 1, without reductions due to lawn watering habits. The water utility manager agent does not enact drought stages. In Scenario 2, household agents retrofit appliances, but the utility manager agent does not enact drought stages, and there is no reduction in outdoor water use. In Scenarios 3-6, household agents retrofit appliances, and the utility manager agent enacts drought stages. The scenarios with corresponding drought stage triggers are shown in Table 2.

Table 2. Scenarios with corresponding drought stage triggers

Scenarios	Settings		Triggers
1	NO Retrofitting	NO Drought Restriction	-
2	Retrofitting	NO Drought Restriction	-
3	Retrofitting	Drought Restriction	60%-40%-20%-0%
4	Retrofitting	Drought Restriction	70%-50%-30%-10%
5	Retrofitting	Drought Restriction	80%-60%-40%-20%
6	Retrofitting	Drought Restriction	90%-70%-50%-30%

RESULTS & CONCLUSIONS

The agent-based model simulates monthly values for total demands in the population, reservoir storage, and reservoir release. These values are compared to historical data for 1983-2013. Future scenarios are simulated for 2013-2032 to explore the performance of policies.

Fig. 2 shows preliminary results for the six scenarios. As additional demand management measures are implemented, the maximum deficit decreases; vulnerability decreases; resilience increases; and the overall *SI* increases.

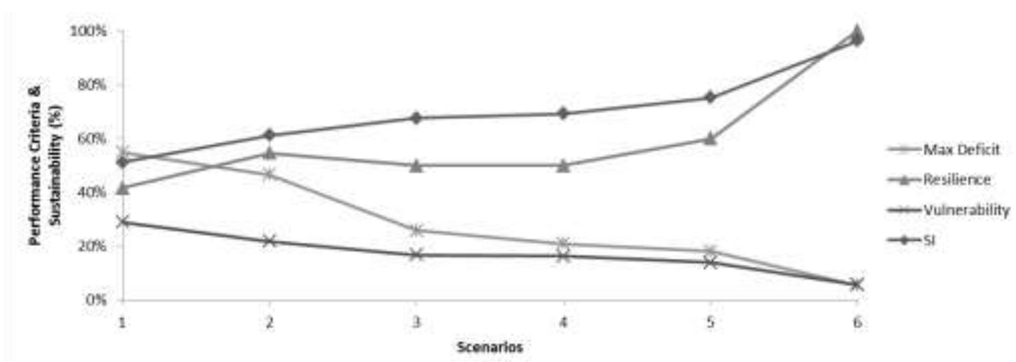

Figure 2. Performance criteria and sustainability index values for the scenarios.

Scenario 2 demonstrates that retrofitting water appliances have made a good impact on sustainability and all performance measures. Scenarios 3, 4, and 5 show only a small improvement in sustainability. Scenario 6, however, has high trigger percentages for enacting conservation stages, and improves the *SI* from around 60% to 80%.

This research develops an agent-based modeling framework to explore the dynamics of water supply and water demand in a water resources system. Dynamic interactions between consumers and the water utility manager are simulated to evaluate conservation programs and drought restrictions. An illustrative case study based on city of Raleigh, North Carolina, is used to test the methodology. The results demonstrate the influence of climate change, population growth, and water use behaviors of consumers on system-level performance of the reservoir storage. Drought management strategies are simulated to explore the performance of alternative strategies, based on the sustainability index. The results demonstrate that although a conservation program, such as retrofitting appliances, may not improve sustainability significantly, enacting aggressive drought stages may improve sustainability of meeting demands. Due to complexity and the stress in water resources systems, it can be difficult to identify policies that improve water management. The *SI* calculation is a comprehensive tool integrating multiple performance measures that helps to evaluate different management policies.

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