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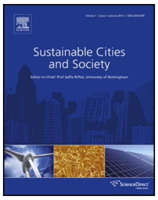

Agent-based modeling to simulate the dynamics of urban water supply: Climate, population growth, and water shortages

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ABSTRACT

The sustainability of water resources depends on the dynamic interactions among the environmental, technological, and social characteristics of the water system and local population. These interactions can cause supply-demand imbalances at diverse temporal scales, and the response of consumers to water use regulations impacts future water availability. This research develops a dynamic modeling approach to simulate supply-demand dynamics using an agent-based modeling framework that couple models of consumers and utility managers with water system models. Households are represented as agents, and their water use behaviors are represented as rules. A water utility manager agent enacts water use restrictions, based on fluctuations in the reservoir water storage. Water balance in a reservoir is simulated, and multiple climate scenarios are used to test the sensitivity of water availability to changes in streamflow, precipitation, and temperature. The framework is applied to the water supply system in Raleigh, North Carolina to assess sustainability of drought management plans. Model accuracy is assessed using statistical metrics, and sustainability is calculated for a projected period as the satisfaction or deficit of meeting municipal demands. Multiple climate change scenarios are created by perturbing average monthly values of historical inflow, precipitation, and evapotranspiration data. Results demonstrate the use of the agent-based modeling approach to project the effectiveness of management policies and recommend drought policies for improving the sustainability of urban water resources.

1. 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 through 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 may lead to the depletion of freshwater reserves and the construction of large infrastructure systems comprised of pipe networks and pumping stations. Continuing to use a supply management approach is not feasible for many utilities due to the limitations of local resources and the need to satisfy additional goals, such as reducing greenhouse gas emissions, minimizing energy consumption, and averting water shortages. As a result, demand management has emerged as a promising paradigm for sustainable management of water resources. Demand management focuses on reducing demands through water pricing, educational campaigns, incentives and rebates for water-saving technologies, regulations, and metering.

Both supply and demand management strategies are typically developed using linear projections of demands based on population growth and evaluations of 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, including per capita, regression, and extrapolation models for forecasting demands and water balance models based on the

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assumption of a static climate. This research develops a sociotechnical modeling approach to capture 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 (ABM) approach is developed to couple models of consumers and utility managers with a reservoir model. Households are represented as agents, and water use behaviors are represented as rules. An 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 water utility manager agent enacts water use restrictions, based on fluctuations in the reservoir water storage. Water balance in a reservoir is simulated, and stochasticity in climate variables is applied 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 ABM framework is applied to simulate water demand and supply for Raleigh, NC. The model is applied to simulate a historic scenario from 1983 to 2014 and compared to observed values for water supply delivered, reservoir storage, and reservoir release. The ABM is also applied to simulate demand and supply for a projected 19-year period. Results are generated for stochastic simulation of climate variables to provide insights about the behavior of the system for alternative decision-making strategies. Drought management strategies are evaluated using performance metrics, including vulnerability, resilience, maximum deficits, and reliability, as they contribute to sustainability. The methods that are developed, coupled, and demonstrated here provide a comprehensive evaluation of a water supply system.

2. Agent-based modeling for water resources systems simulation

An ABM framework is developed to simulate urban water resources as a complex adaptive system (Holland, 1995). A complex adaptive system is a system composed of a large network of decentralized actors without a centralized controller and with the capability to adapt to a changing environment. The collective actions of individual components give rise to complex, hard-to-predict, and changing behaviors of the system (Mitchell, 2009). The complex behavior of the system at the macroscopic level, as it emerges from the collective actions of many interacting components, can be simulated and described using an ABM approach. ABM provides the modeling capabilities to directly represent individual actors as agents and avoids the use of simplifying hypotheses about aggregated variables of the system. ABMs describe individuals or agents as unique entities, which vary in characteristics, such as size, location, and history. Agents are autonomous, and they can act independently to pursue individual objectives. Agents also adapt their behaviors or decisions based on their current state, messages from agents, and the environment.

Recently, broad review papers have argued for a transformation of hydrologic science to include human activities and argue for a coupled approach to better study the hydrologic cycle (Sivapalan, Savenije, & Bloschl, 2012; Vogel et al., 2015; Wagener et al., 2010). They cite several studies demonstrating that land-surface and global circulation models can be useful tools for examining coupling among human and natural hydrologic systems and emphasize that the human system needs to be coupled to understand the impact of landscape changes on hydrology by developing understanding of interactions across multiple scales. The concept of integrated water resources management is not new (Cohen & Davidson, 2011) and has generated new understanding across natural and engineered systems; however, there is a need to more fully integrate social sciences with natural sciences and engineering, so that human activities are modeled as endogenous within the water resources systems, rather than remaining exogeneous as forcing conditions (Wheater & Gober, 2015). Feedback loops are important processes among consumers, resources, and utility managers in managing urban water resources: the scarcity of water and land affect how consumers decide to use natural resources; subsequently, consumers' decisions affect the availability of resources; and, finally, utility operators rely on consumers altering their water use behaviors to maintain the supply-demand balance (Liu et al., 2007; Pahl-Wostl, 2007).

ABM provides a dynamic modeling approach for studying a number of coupled human and natural systems (An, 2012) and specifically to capture the coupled processes across social, infrastructure, and water resources systems. ABM frameworks have been developed to yield new insight about the water availability and satisfaction of water demands based on the interactions of a small number of stakeholders, such as farmers (Ng, Eheart, Cai, & Braden, 2011), municipalities (Yang, Cai, & Stipanovic, 2009), hydropower plants, and agencies protecting environmental ecosystems (Van Oel, Krol, Hoekstra, & Taddei, 2010; Guiliani & Castelletti, 2013). Instead of a small set of actors, a large population of consumers can also be represented as agents that make decisions about water use, and consumer agents can be directly connected to infrastructure and water resources models to simulate feedbacks and adaptations in the context of surface water systems and land use change (Giacomoni, Kanta, & Zechman, 2013; Giacomoni & Berglund, 2015); water supply and adoption of low-flow devices (Kanta & Zechman, 2014); and groundwater resources and land use change (Zellner, 2007; Reeves & Zellner, 2010). To simulate human consumers as agents, ABM approaches have used simple rules to represent behaviors, social connections, and reactions of a population. Studies use ABM to simulate human behaviors in water end uses and the frequency of changing end uses (Chu, Wang, Chen, & Wang, 2009; Yuan, Wei, Pan, & Jin, 2014); the purchase of water efficient technologies (Klotz & Hiessl, 2005); and the volume of water consumed per day (Moss & Edmonds, 2005). Other studies use survey results about the personality characteristics of a specific population to parameterize agents in the adoption of water-efficient appliances (Schwarz & Ernst, 2009) or econometric and information diffusion models as rules of behavior in water use decisions (Athanasiadis, Mentes, Mitkas, & Mylopoulos, 2005; Galán, López-Paredes, & del Olmo, 2009).

This research develops a modeling framework that couples agent-based models with models of the reservoir release and storage and explores the accuracy of the modeling approach. The studies that apply ABM for urban water supply simulation (Athanasiadis et al., 2005; Galán et al., 2009; Klotz & Hiessl, 2005; Rixon, Moglia, & Burn, 2007; Schwarz & Ernst, 2009) explore what-if scenarios and generate insight about the effects of water conservation. ABM approaches are not typically validated as accurate, beyond testing varying degrees of social influence in a population (Moss & Edmonds, 2005). In general, ABM and system dynamic models are often criticized for relying on informal and subjective validation or no validation at all (Edmonds & Chattoe, 2005). Validating ABM approaches for simulating social systems is challenged by several difficulties: (1) path dependencies and the stochastic nature of human behavior models make point predictions impossible; (2) the domains in which these models are applied lack consolidated data sources; and (3) social system models are complex with huge feature spaces (Pahl-Wostl, 1995; Bharathy & Silverman, 2012). ABM is typically validated using internal consistency checks, which ensure that the microspecifications of behaviors are adequate representations of actors' activities (Gilbert,

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