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A geospatially-enabled web tool for urban water demand forecasting and assessment of alternative urban water management strategies

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A R T I C L E I N F O

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A B S T R A C T

This study develops and demonstrates the Integrated Urban Water Model (IUWM) for forecasting urban water demand with options to assess effects of water conservation and reuse. While water and energy balance drive hydrologic, storage and recycling simulations on a daily timestep, social and infrastructural processes are resolved by spatially distributed parameters. IUWM is deployed as an online tool with geographical information system (GIS) interfaces, enhancing its ease of use and applicability at building to municipal scales. The performance of the model at varying spatial scales was evaluated with extensive water metering data for the City of Fort Collins, Colorado. The calibrated model provided very good estimates of demands at individual block group as well as the municipal service area. The capacity of IUWM for the assessment of the spatiotemporal variability of water consumption and effects of water demand management strategies under climate and urban growth scenarios is discussed.

Software availability

Web tool URL: https://erams.com/iuwm
Documentation URL: https://erams.com/documentation/iuwm/
Source Code Repository (permission by authors is required):
https://alm.engr.colostate.edu/cb/hg/csip-iuwm_v2https://bitbucket.org/iuwm/iuwm

1. Introduction

Water supply systems in the United States and throughout the world are increasingly vulnerable to chronic and episodic shortages due to population growth and changes in climate (Yigzaw and Hossain, 2016). Water supply and demand assessment under alternative climate, land use and population scenarios is an area of growing interest amongst urban planners and water managers. Intensifying competition for water from urban, agricultural, industrial and environmental users has increased consideration of urban water conservation and use of non-traditional water sources (Brent et al., 2015). Savings from water conservation and reuse are increasingly relied upon to alleviate projected supply shortfalls (NAP, 2016). Conservation strategies also have long-term implications for controlling inflation of water rates and tap fees, particularly in areas where changing climate and population growth are likely to increase the demand for water (Craley and Noyes, 2013). However, decisions are often made regarding choice of practices to promote in a city based on perceived benefits from studies in other regions, primarily due to lack of understanding of the coupled social, ecological and infrastructural processes that govern urban water use (House-Peters and Chang, 2011). Urban water models are useful tools to understand coupled natural-human factors that drive consumption, conservation and use of alternative water sources (Bach et al., 2014).

Various methods have been developed for urban water demand modeling. These methods can be broadly categorized to long-term methods for planning and design of water supply infrastructure systems; and short-term forecasting approaches for operation and management (House-Peters and Chang, 2011). The economic literature is replete with methodologies for exploring the long-term trends in the correlation between water consumption with price, income and tariffs and other economic factors (Arbués et al., 2003). However, these methods are often developed using spatial data at municipal or household scales. The use of aggregated city-level data inherently neglects the spatial variability of natural and social processes that influence water use, which could influence the reliability of water demand forecasts (Wentz and Gober, 2007). These models incorporate average annual climatic conditions and stationarity to estimate outdoor demand and corresponding

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behavioral responses.

Seasonal and temporal variability of climate is an important consideration in the characterization of urban water demand. Water consumption tends to be higher during warmer and drier periods, when outdoor evapotranspiration demands from landscape irrigation or water features are higher. Studies on water use conducted in the late 1990s (Mayer et al., 1999) and in (DeOreo et al., 2016) both showed that indoor demand remains relatively constant within the year. However, outdoor demands are influenced by temporal factors including air temperature, evaporation and precipitation (DeOreo et al., 2016). Time series analysis using autoregressive (AR), autoregressive moving average (ARMA), autoregressive integrated moving average (ARIMA) and Dynamic Panel Data models are among approaches that are used to enhance urban water demand forecasts incorporating seasonal and temporal variability of climate (Zhou et al., 2000; Nauges and Thomas, 2003; Arbués et al., 2010; Polebitski and Palmer, 2010).

Short-term demand forecasting models are important for day to day operations and management of urban water supply systems. The use of multiple regression and time-series analysis for short-term, e.g., 24 h or smaller time steps, has been growing over the past decade (Bougadis et al., 2005; Bakker et al., 2013; Hutton and Kapelan, 2015). Particularly, the availability of water data from smart metering systems has improved the applicability of short-term projections (Romano and Kapelan, 2014; Cominola et al., 2015; Creaco et al., 2016). However, highly nonlinear interactions between natural and social factors that influence water consumption inhibit broad applicability of the traditional regression-based or time-series analysis methodologies. Hence, artificial neural networks (ANN), fuzzy neural networks (FNN) and fuzzy inference systems (FIS) have been used to improve short-term forecasts in complex urban water systems (Ghiassi et al., 2008; Bárdossy et al., 2009; Ghiassi and Nangoy, 2009).

Short-term forecasting statistical methods typically assume static water demand functions. This assumption is not suitable for evaluating dynamic system components, including climate, behavioral factors and alternative water conservation and reuse strategies. Dynamic models, such as Agent-Based Models (ABM) and System Dynamics Models (SDM), provide great value to enable forecasting water demand as a function of changing climate, urban form, housing, pricing and conservation policies (Athanasiadis et al., 2005; Qi and Chang, 2011; Koutiva and Makropoulos, 2016). ABM and SDM are useful to understand drivers of adoption of water conservation strategies (Stave, 2003; Ahmad and Prasha, 2010) and also to assess scenarios for demand projection (Galan et al., 2009; Qi and Chang, 2011). However, because they are developed based on empirical observations, their application for simulating system behavior in response to changes in system forcings, boundary and initial conditions outside of observations (e.g. unanticipated changes in system drivers) remain limited. Similarly, identification of effective strategies for demand reduction and comparisons amongst various water conservation and reuse strategies that are not yet widely adopted (e.g. beneficial use of graywater and stormwater) requires process-based representation of system components and responses. Comparing and contrasting water demand reduction strategies should incorporate physical principles including water balance that govern the whole urban water cycle, commonly referred to as integrated urban water management (Mukheibir et al., 2015).

While data-driven statistical models are versatile tools for exploring water consumption patterns, their focus is solely on water demand and thus they fail to fully integrate all components of the water cycle, i.e. water supply, wastewater and stormwater. Integrated urban water management tools are needed to evaluate emerging water management practices such as use of graywater, stormwater and wastewater effluent to meet non-potable and potable demands (Bach et al., 2014; Cominola et al., 2015). Integrated urban water models present the opportunity to enhance urban water demand forecasting (Cominola et al., 2015). Some existing integrated models include the Aquacycle (Mitchell et al., 2001), City Water Balance (CWB) (Mackay and Last, 2010) and Urban Water Optioneering Tool (UWOT) (Makropoulos et al., 2008; Rozos and Makropoulos, 2013), and WaterMet^2 (Behzadian et al., 2014) models. Other efforts at development of integrated urban water models have involved modification of legacy models such as the WaterCress model, which was originally developed for simulation of stormwater capture, but has evolved to consider water recycling (Paton et al., 2014).

These models have substantially contributed to decision making to advance integrated and sustainable water systems. However, there are limitations in application of the models across varying spatial and temporal scales and inclusion of all source water end use combinations. For example, while WaterCress can be applied across spatial scales including household systems for collection of roof runoff to larger, centralized supply sources, but does not include an explicit option for use of graywater (Paton et al., 2014). On the contrary, UWOT includes household graywater and roof runoff collection, but works by building unit blocks at the site level to form clusters (i.e. uniform unit blocks) and a catchment area (Rozos and Makropoulos, 2013), based on the approach developed for Aquacycle (Mitchell et al., 2001) and City Water Balance (Mackay and Last, 2010). This approach requires extensive input to build a municipal scale model, limiting the model for use preliminary screening tool for municipal scale decision making. Integrated urban water management tools are needed that include flexibility to work from the building to municipal scale with options for multiple source water end use combinations, including non-potable and potable uses.

In addition to overcoming limitations in applicability of integrated urban water models, several challenges in development and application of integrated models must be addressed for widespread use of those models (Bach et al., 2014). First, these models must be enhanced to resolve coupled social/behavioral, natural and infrastructural processes using distributed-parameter physically-based approaches. This approach will ensure the applicability of the models at varying spatial and temporal scales, while facilitating calibration of model parameters at distributed computational units. Second, with the increasing complexity of the structures of integrated models, streamlined data collection and assimilation along with integration with geographic information systems (GIS) can substantially improve the accessibility of integrated models (Bach et al., 2014). Although graphical user interfaces have improved the applicability of these models (e.g., Rozos and Makropoulos, 2013), the existing tools remain platform-dependent, which results in low accessibility by end users.

The overall goal of this study is to develop a process based, mass balance urban water model with explicit options for projections of water demand under varying scenarios of water conservation and reuse strategies, as well as changes in population, land use and climate from building-level to municipal scales. The model, called the Integrated Urban Water Model (IUWM), is deployed as an accessible, platform independent online tool with GIS capabilities for spatial mapping and visualization. IUWM is developed to be readily applied across spatial and temporal scales, enabling specification of model parameters either at distributed computational units or at a single subunit, depending on user goals (e.g., preliminary screening versus detailed assessment of alternatives). Specific objectives of this study are to: (i) investigate the versatility of IUWM for simulating indoor residential and commercial, industrial and institutional demands as well as outdoor water