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Residential Water Consumption Modeling in the Integrated Urban Metabolism Analysis Tool (IUMAT)

Nariman Mostafavi[a], Hamid Reza Shojaei[b], Arash Beheshtian[c], Simi Hoque[a,*]

[a] Department of Civil, Architectural and Environmental Engineering, Drexel University, 3141 Chestnut Street, Curtis 251, Philadelphia PA 19104, United States
[b] Department of Physics, University of Massachusetts, Amherst 1126 Lederle Graduate Research Tower (LGRT), 01003, United States
[c] Department of City and Regional Planning, Cornell University, 129 Sibley Dome, Ithaca NY, 14853, United States

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ABSTRACT

This paper details a method for residential water consumption modeling within the Integrated Urban Metabolism Analysis Tool (IUMAT), a computational modeling platform for evaluating environmental performance of urban communities under alternative growth scenarios. A bottom-up approach is introduced to generate end-use indoor and outdoor water profiles by applying GLM and Ridge regression methods to Residential End Uses of Water, Version 2 (REU II-2016) dataset and investigating the influence of demographic and climate factors, as well as utility rate structures on patterns of consumption. The data is collected from 2010 through 2013 by nine utilities that operate in North America on 771 and 838 single family units for indoor and outdoor water use respectively. Potential advances to surveying methods as well as the need for tools that allow simultaneous, isolated assessment of educational and technological conservation measures are explained.

1. Introduction

Today as a result of growing migration from rural to urban areas (United Nations, 2014), larger energy and water supply systems are needed to keep up with the rising urban household and industrial resources demand. Cities are facing greater pressures to address the stresses on energy, water and land resources while maintaining robust population growth, expanded local economies and higher standards of living. Within a wide range of essential resources, water is universally regarded as the most vital to human survival (Vörösmarty et al., 2010). Failing to address future water issues and unsustainable management of available reservoirs will result in serious negative social, economic and environmental fallouts (The United Nations World Water Development Report, 2016). For cities, in addition to resource scarcity (Jury and Vaux, 2005), the capacity to predict demand in response to climate change uncertainties is an unfolding water management issue (Herrera et al., 2010).

The design and operation of regional and municipal water supply systems requires long-term understanding of industrial and residential demand origins as well as natural stream flows and aquifers' anatomy (Runfola et al., 2013). As well, rapidly growing population numbers make it more crucial to secure water supply at desired quality and pressure (Pingale et al., 2014). Consequently, decentralized supply systems and water re-use innovations are becoming increasingly favorable practical solutions, although budget issues, regulatory barriers and behavioral resistance have slowed the adaptation of these practices (Krozer et al., 2010; Giurco et al., 2011).

The United States used about 355 billion gallons (1,344 billion liters) of water per day (bgd) in 2010 (saline and freshwater) (Maupin et al., 2014). United States Geological Survey (USGS) roports that despite economic growth and population rise, national water use has been declining in the past thirty years with a steeper drop since 2005 (440 and 400 bgd for 1980 and 2005 respectively) (USGS, 2016). Per capita water use peaked at 1900 gallons (7,192 L) per day in 1980, and shrunk by 13% between 2005 and 2010, dropping to 1,100 gallons per capita day (gpcd). In 2010, water consumption by municipal/industrial, agriculture and thermoelectric sectors were 268, 480 and 640 gpcd (1014, 1817 and 2422 lpcd) respectively (Barber, 2014). According to the EPA, 70% of the 300 gallons (1,136 L) of water that an average American family uses every day occurs indoors (EPA, 2016). Of course, this varies substantially in different climate zones across the country based on irrigation and landscaping water requirements. The residential sector was responsible for 88 gallons per capita day (gpcd) in 2010 (333 lpcd), ranging from 50 to 170 gpcd (189–644 lpcd) from Wisconsin to Idaho (Donnelly and Cooley, 2015).

The water sector is also a major consumer of energy. United States had 18.7, 23.4 and 5.6 billion kWh of energy use attributed to water source/conveyance, treatment and distribution as well as 11.0 and 1.5

* Corresponding author.
E-mail addresses: sm3892@drexel.edu (N. Mostafavi), hshojaei@physics.umass.edu (H.R. Shojaei), ab2348@cornell.edu (A. Beheshtian), sth55@drexel.edu (S. Hoque).

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billion kWh for collection/treatment and discharge of wastewater respectively (60.2 billion kWh total) in 2005 (ACEEE, 2014). Conserving end-use water demand could ease the pressure on natural water sources and reduce the life-cycle cost of city water provision and the carbon footprint by lowering the energy consumption associated with it. Higher efficiency measures by utilities and improved plumbing codes have had a major role in reducing the per capita water consumption in the recent twenty years (Polebitski and Palmer, 2009). Yet, domestic water consumption grew by 11% between 1985 and 2010 (USGS, 2010), which is the category with the highest contribution to GHG emissions. As an example, a report by the Environment Agency notes that in the United Kingdom, 89% of the water related carbon emissions are associated with residential use (including hot water) compared to 11% due to public water treatment and supply (Reffold et al., 2008). The fact that the correlation between population growth and water use has been getting smaller over the last decades is encouraging, but it makes water consumption modeling and planning for the future more challenging since further demographic/technological information and process details are required for the accuracy of simulations. It is increasingly complicated for utility companies to accurately predict residential water use patterns (Rockaway et al., 2011), and national average estimated figures such as 98 gallons (371 L) per person per day (Kenny et al., 2009) do not demonstrate the complexities of changing consumption patterns any longer.

Residential water management difficulties have been attributed to unstable climate, changing demographics and evolving fixtures and equipment, but the influence of these elements on water consumption within specific communities is heterogeneous. Drivers of the global water crisis including climate change and globalization surge, impact different communities differently depending on socio-economic factors and local economic and hydrologic characteristics. Top-down simulation of water consumption has the disadvantage of overlooking the human dimension of water use by focusing attention on geospatial parameters such as land use, population dynamics, runoff and climate variables. Community traditions and cultural values play a role in human water management practices (Srinivasan et al., 2012) and therefore, location-specific research is needed to capture local pricing structures, consumption behaviors, government regulations, efficiency profiles of water appliance stock, public environmental literacy and other factors that can impact the validity of water saving strategies.

Domestic water demand prediction models have been developed in household (Cahill et al., 2013), city (Kontokosta and Jain, 2015) and census tract (Polebitski and Palmer, 2009) levels. The focus of most of the existing studies has been mainly to examine price elasticity of demand (Espey et al., 1997; Klaiber et al., 2014), despite income/market elasticity of domestic water use being disputable (Worthington and Hoffman, 2008; Dalhuisen et al., 2003) due to the nature of water as a fundamental resource. However, responsiveness of demand does increase with higher consumption rates beyond basic levels of need (Ferrara, 2008). Major determinants of water use are assumed to be household size and total housing area for indoor (Mayer et al., 1999; Wentz and Gober, 2007) and existence of swimming pools, precipitation rates, degree days and density (as a surrogate for yard size and urban form) for outdoor water use (Gaudin, 2006; Haley et al., 2007).

Many different techniques including ordinary least squares regression (e.g., Rietveldt et al., 2000; Timmins, 2002; Hoffman et al., 2006), two and three stage least squares (e.g., Renwick and Archibald, 1998; Chicoine et al., 1986; Hoglund, 1999; García-Valiñas et al., 2010), generalized least squares (e.g., Gaudin et al., 2001), maximum likelihood (e.g., Hadjispirou et al., 2002; Guhathakurta and Gober, 2010), instrumental variables (e.g., Martínez-Espiñeira, 2002; Nieswiadomy and Molina, 1989; Higgs and Worthington, 2001), co-integration and error correction models (e.g., Martínez-Espiñeira, 2003), system equations (e.g., Agthe et al., 1986) and generalized method of moments (e.g., Nauges and Thomas, 2003; Garcia and Reynaud, 2003; Binet et al., 2014) have been used so far for residential water use modeling (see Worthington and Hoffman, 2008). The focus of most of these studies is price elasticity and economic assessments of demand, and many climate and built environment variables are left out or not adequately included. This gap in knowledge about the non-budgetary elements of water consumption as well as the lack of expanded, detailed surveys have limited the integration of environmental conservation with the interests of consumers, regulators and utility managers in water modeling approaches. Over the last decade, there has been an increasing number of studies that capture demographic, economic, climate and built environment variables in water use patterns and the models have started to include more behavioral (e.g., Russell and Fielding, 2010; Talebpour et al., 2014; Romano et al., 2014; Matos et al., 2014; Fox et al., 2009) and geo-spatial (e.g., Gato et al., 2007; Praskievicz and Chang, 2009; Corbella and i Pujol, 2009; Lee et al., 2011) factors. Stoker and Rothfeder (2014) highlight the importance of incorporating demographic, environmental and climate, and morphological parameters in urban water demand research methods. The emergence of smart water metering technologies and the advent of surveys with high spatial and temporal resolutions (e.g., Makki et al., 2015; Cominola et al., 2015) simultaneous with growing concerns for the environment have promoted the development of models that are hybrids of economic, behavioral and geo-spatial models.

A major challenge to linking sub-categories of water consumption to physical and socio-economic variables is accurate water end-use metering. Mayer et al. (1999) provided end-use figures for 1,190 surveyed single family homes in 14 US and Canada cities. Since then, a handful of end-use studies have focused on the US residential sector (e.g., DeOreo et al., 2011; Aquacraft Inc., 2011a; Mayer and Feinglas, 2012). Similar surveying efforts are more popular in water stressed regions such as California (e.g., Aquacraft Inc., 2011b), New Zealand (e.g., Heinrich, 2007) and Australia (e.g., Loh and Coghlan, 2003; Athuraliya et al., 2008). For instance, Willis et al. (2013) recruited 151 homes in Gold Coast City in Australia with distinct socio-economic makeups to examine the impacts of family size, age of infrastructure and ownership status on differing end-use categories. They used data loggers to collect pulse counts at 10-s intervals as part of a smart metering network and used surveys to investigate water behavior as well as the appliance stock. The researchers found strong correlations between household makeup, income and appliance efficiency with residential end-use water. Altogether, promoting state of the art water consumption measurement devices and methods has not been as attractive as cutting edge energy metering techniques, due to higher prices of energy compared to water. Residential water use is typically reported annually and may have up to four seasonal data points (Britton et al., 2008).

The common quarterly approach to water data collection limits analyzing weekly and monthly patterns of consumption and precludes disaggregating integral consumption figures into separate end-use divisions (such as toilets, showers, garden irrigation, dish washers and laundry). Disaggregating and allocating water use from the whole-dwelling data to specific fixtures and appliances is complicated. Intrusive metering (Rowlands et al., 2015) where on-device sensors capture water end-use separately for different appliances are costly and sometimes difficult for occupants to manage and track. However, in contrast to non-intrusive flow measurement at household level, smart metering techniques contribute to an inclusive understanding of water use patterns and the impact of climatic and psychographic variables on different categories of consumption. In addition, effective water use reduction policy assessments are controlled by the availability of high resolution data produced via automated sub-metering technologies and smart end-use analyses methods. Reliable data sets and nation-wide surveys are required for identifying the categories of water consumption and evaluating the influence of water saving measures within different socio-economic clusters.

This paper presents a residential water model that operates within the Integrated Urban Metabolism Analysis Tool (IUMAT), a system-based holistic framework for quantifying collective environmental