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Modeling the determinants of large-scale building water use: Implications for data-driven urban sustainability policy

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ABSTRACT

As the world's population continues to urbanize, cities are struggling to meet the demand for key resources such as clean water. In urban areas, enhancing the sustainability and water efficiency of buildings is crucial to meeting the resource needs of a growing population. Nevertheless, the understanding of the determinants of urban water consumption – and specifically of multi-family residential buildings that constitute the bulk of the urban building stock – is limited. Using an extensive database of actual water use from New York City's Local Law 84, coupled with land use and demographic data from the NYC Primary Land Use Tax Lot Output (PLUTO) database and Census data, we apply weighted robust regression and geographically weighted regression (GWR) models to analyze the determinants and spatial patterns of water consumption in over 2300 multi-family buildings located in New York City. Our results indicate that occupancy, building size, building age, ownership structure, neighborhood demographic and socioeconomic characteristics, and the energy use intensity (EUI) of a building all have statistically significant effects on the water use intensity (WUI) of multi-family housing. Results of the GWR spatial analysis demonstrate large spatial variability across building characteristics, demographic variables and household income. The analysis and findings presented here give further support to the potential of targeted measures and incentives, segmented and classified by building characteristics and neighborhoods, to be effective tools for policymakers seeking to increase water efficiency in urban buildings and to accelerate reductions in resource use at the city scale.

1. Introduction

As the well-documented urbanization of the world's population continues, the influx of people to urban centers has intensified the strain on key resources such as clean water (UNDESA, 2011). Meeting this increased need will be a daunting challenge, with only 60% of global demand for potable water expected to be satisfied in 2030 (Boccaletti, Grobbel, & Stuchtey, 2010). Despite having substantial natural water resources, the United States is facing significant water shortages, especially in the western states, and current water conservation projects are not expected to meet goals set by the United States Environmental Protection Agency (EPA) (Christen, 2003; Lee, Tansel, & Balbin, 2011). Taking into account the impact of climate change effects over time, a large portion of the United States is projected to be at high risk of failing to meet water demand by 2050 (Roy et al., 2012).

Increasing water efficiency of the urban built environment offers significant opportunities to reduce overall water usage and meet the conservation targets necessary to enhance the long-term sustainability of our cities. Buildings are increasingly becoming major contributors of water consumption in the United States, with residential and commercial buildings accounting for over 95% of all consumption growth from 1985 to 2005 (U.S. DOE Building Energy Data Book). The growth in urban population has led to a commensurate increase in the population living in multi-family housing. According to data from the 2009 U.S. Residential Energy Consumption Survey, approximately 17% of the 119 million residential buildings in the U.S. consist of multi-family structures with five or more units, and 43% of households live in such structures. Of these, fully 97% are located in urban areas (U.S. Department of Energy Residential Energy Consumption Survey, 2009). Of particular importance, almost 88% of those that live in multi-family housing are renters, and are more likely to be poor, minority households. Nationally, according to data from the

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National Multi-Housing Council, 63% of households in multi-family rental housing earn less than $35,000, with a median income of just $25,768 compared to $45,964 for all U.S. households (National Multi-Housing Council, 2014). In New York City, which has the highest population density in the country, multi-family buildings account for over two-thirds of the total housing units and represent a large majority of potable water consumption.

Burdened by aging and strained infrastructure, many cities now face significant challenges in both providing an adequate supply of potable water to meet demand and processing wastewater outflows (American Society of Civil Engineers, 2013). In New York, for example, the Combined Sewer Overflow (CSO) system mixes stormwater and wastewater and, when flows exceed twice design capacity, this flow is diverted directly into the City's waterways. In this scenario, the wastewater is left untreated, creating significant impacts on water quality and public health (City of New York, 2010). In addition to potential health impacts, the cost of water continues to increase. Between 2007 and 2014, the average annual rate increase was 10.2% in New York, reflecting a growing cost burden for lower-income households and raising the annual water cost for an average multi-family housing unit to $666 per year.

Given the necessity to lower operating and capital costs of utility infrastructure and delivery, as well reduce carbon emissions to mitigate the effects of climate change, cities have been at the forefront of establishing policies to increase the efficiency and overall sustainability of buildings, either through the adoption of green building standards or the passage of disclosure and reporting requirements (Fuerst, Kontokosta, & McAllister, 2014; Kontokosta, 2011). While energy consumption has been the primary focus of building efficiency programs, water efficiency has become a more prominent component of green building standards and building codes (Hoecker & Bracciano, 2012). However, despite the identified cost and energy/water savings potential of installing more efficient systems and changing behavior, such efficiency and conservation measures have been relatively slow to proliferate throughout existing buildings. Commonly cited reasons for not adopting such measures include capital cost and return on investment, uncertainty over actual savings realized, and unfamiliarity with available measures (Kontokosta, 2013). Of course, these barriers vary by building sector and type; in the residential sector, differences in the motivations and constraints facing owners and renters in single-family homes and multi-family housing are substantial.

Using an extensive database of actual water use from New York City's Local Law 84, coupled with land use and demographic data from the NYC Primary Land Use Tax Lot Output (PLUTO) database and Census data, we apply weighted robust regression and geographically weighted regression models to analyze the determinants and spatial patterns of water consumption in over 2300 multi-family buildings located in New York City. We aim to provide insight into the drivers of water consumption in multi-family buildings to inform policy measures designed at reducing and managing water consumption in buildings as part of a broader sustainability agenda. Specifically, our research goals are to (1) understand the drivers of multi-family housing water consumption in order to develop building-level benchmarking and water performance measures, (2) analyze patterns of use both spatially and by building type to identify opportunities to segment the multi-family housing stock, and (3) examine differences in consumption patterns and intensity by socioeconomic status of households and by neighborhood income and demographics. The next section explores relevant research in urban planning, water consumption, and water resource management, followed by a description of our data, methodology, and results. The paper concludes with a discussion of the implications of the results for policy and planning, limitations of the work, and future steps.

2. Background

Urban water demand modeling has been extensively studied over the last several years as highlighted by House-Peters and Chang's (2011) comprehensive review paper. A substantial proportion of the literature has been focused on understanding the socioeconomic factors and physical building characteristics that impact single-family residential water use (Chang, Parandvash, & Shandas, 2010; House-Peters, Pratty, & Chang, 2010; Ouyang, Wentz, Ruddell, & Harlan, 2013; Polebitski & Palmer, 2009; Wentz & Gober, 2007). Yet, despite building typology being shown to impact water usage in several studies, there is a dearth of research examining the socioeconomic factors and physical building characteristics that impact water usage in multi-family residential buildings in dense urban areas like New York City (Domene & Saurí, 2006; Fox, McIntosh, & Jeffrey, 2009; Wentz et al., 2014; Zhang & Brown, 2005). Schleich and Hillenbrand (2009) conducted determinant analysis of water usage for several building types, but water consumption data was not available at the spatial granularities necessary to conduct building-by-building analysis. Similarly, Shandas and Parandvash (2010) examined water consumption across building types, although detailed data on multi-family buildings was not available to conduct analyses specific to this type. Therefore, a primary contribution of this paper will be to extend previous research to encompass multi-family buildings and analyze actual building-level water use data.

2.1. Determinants of water consumption

Previous work has found household income (Grafton, Ward, To, & Kompas, 2011; Guhathakurta & Gober, 2007; Kenney, Goemans, Klein, Lowrey, & Reidy, 2008; Schleich & Hillenbrand, 2009), household size (Arbués & Villanúa, 2006; Arbués, Villanúa, & Barberán, 2010; Campbell, Johnson, & Larson, 2004; Domene & Saurí, 2006; Grafton et al., 2011; House-Peters et al., 2010; Mazzanti & Montini, 2006; Schleich & Hillenbrand, 2009; Wentz & Gober, 2007), age of household members (Fox et al., 2009; Kenney et al., 2008; Schleich & Hillenbrand, 2009), education level of household members (Arbués & Villanúa, 2006; House-Peters et al., 2010; Shandas & Parandvash, 2010) and race distribution (percent Hispanic) (Balling, Gober, & Jones, 2008) to be key socioeconomic factors that impact residential water usage. Recent research has also found numerous physical building characteristics to impact water usage, including: building size (square footage) (Balling et al., 2008; Chang et al., 2010; Domene & Saurí, 2006; Harlan, Yabiku, Larsen, & Brazel, 2009; Tinker, Bame, Burt, & Speed, 2005; Wentz & Gober, 2007), housing typology (Domene & Saurí, 2006; Fox et al., 2009; Zhang & Brown, 2005) and the number of bedrooms per unit or per house (Fox et al., 2009; Kenney et al., 2008). The impact of socioeconomic and physical building variables has been shown to substantially differ from one geographic region to another. For example, Schleich and Hillenbrand (2009) found in their study of residential usage in Germany that as income increases, water consumption disproportionally increases, while House-Peters et al. (2010) did not find income to be a significant driver of water usage in Hillsboro, a suburban city of Portland, Oregon. Consequently, conducting determinant analysis using localized water use data is essential to assess the applicability of previous models and conclusions to the local conditions of New York City, and potentially other large cities with significant proportions of multi-family housing.

Previous research has also begun to highlight the impact local spatial proximity has on urban water usage. Differences in neighborhood characteristics have been shown to influence water consumption patterns, perhaps by capturing (unobserved) effects of localized climate conditions, neighborhood socioeconomic and cultural differences, and variations in the provision of water