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Drivers of urban water use

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ABSTRACT

In this paper we develop water demand models for four common urban land use types based on climate, demographics, and built environmental variables. The water demand models estimate annual water use at the parcel level for each land use type: single family residential, semi attached residential, apartments, and commercial. We hypothesize that water use is a function of climate, demographic, and built environmental variables and assessed whether the relative importance of these demographic, built environment, and climate variables on urban water use varies by land use type. We used analysis of variance to determine differences in mean annual use between urban land use types and ordinary least squares regression to measure the effect of independent variables on annual water use. Our paper identifies the driving factors of water use by urban land use type and suggests planning strategies; specifically form-based zoning codes, to promote water conservation in new developments.

1. Introduction

In many parts of the world, water sustainability may well be the defining issue in the future (Rudd & Fleishman, 2014). Rapid population growth and urbanization have tripled global water withdrawals over the last 50 years and predictions forecast that almost half of humanity will face water scarcity by 2030 (OECD 2008). In the United States, people use more than 400 billion gallons of water each day (USGS 2012). While the primary uses of water in the U.S. are irrigation and agriculture, urban water consumption constitutes a significant share of overall water consumption at 44.2 billion gallons per day (USGS 2012). Understanding how water is used in cities, and what drives use, is needed to design policies aimed at sustaining global water resources.

The way in which water is used in cities is a widely researched topic. Some researchers have assessed urban water use to plan for drought (Moncur, 1987), offered guidance to decide how to invest in water infrastructure (Niemczynowicz, 1999), assessed the implications of population growth on water demand (Seckler, Amarasinghe, Molden, de Silva, & Barker, 1998), addressed environmental concerns (Liverman, Varady, Chavez, & Sanchez, 1999), and estimated water use under climate uncertainty (Boland, 1997). In a review of the published urban water demand literature, House-Peters and Chang (2011) illustrated the extent to which researchers are attracted to this topic: where once fewer than ten published urban water demand papers came out a year, now, over thirty papers annually is not uncommon. The key contribution of our paper is to demonstrate that water demand research must incorporate measures of the built environment, climate, and demographics in order to understand urban water use. How these variables drive water use is sometimes unclear, and urban water demand modelers have faced numerous challenges in this regard.

In this paper, we develop water demand models for four urban land use types that relate the built environment, climate, and demographics to annual water use. Following a review of the published literature on urban water use, we employ cross-sectional empirical models and a detailed disaggregated database to identify major drivers of urban water consumption. These models are developed based on a case study of Salt Lake City, Utah, in the United States. We believe that our results will help inform the practice of city planning and the design of the built environment with respect to water demand in the U.S. if not beyond. Our methodology may also be replicable in other regions.

A key limitation of current water demand analysis is that most research is based on consumption patterns aggregated across cities, counties, or larger units of analysis (House-Peters, Pratt, & Chang, 2010; Michelsen, Thomas McGuckin, & Stumpf, 1999), therefore important subtleties of water use are lost. Our research is unique in three ways. First, it is based on disaggregated water demand analysis using a very large sample size. Our database includes 77,256 parcels in Salt Lake City, Utah, with water use, location, and urban land use type specified for each. Secondly, our research identifies water demand differences between types of urban land uses in a

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city, such as industrial, residential and commercial. Knowing these differences allows for more accurate predictions of future water demand and offers insight into how the built environment can be designed to minimize water use. Third, where data availability constrains much of the past research on water demand (Gaudin, 2006), we have compiled a rich database that includes climatic, built environment, and demographic data for the parcels in our database.

We ask:

1) What is the relative importance of demographic, built environment, and climate variables on water use?
2) How does water use vary by urban land use type?
3) Does the relative importance of demographic, built environment, and climate variables change for common urban land use types?

1.1. Conceptual framework

We hypothesize that water use is a function of climate, demographic, and built environmental variables. These hypotheses are based on findings from existing studies. We hypothesize the relationships as follows:

Climate: We hypothesize climate variables such as seasonality, precipitation, and temperature affect water use. It follows that water use will be higher in the summer and that warmer drier weather is associated with more water use (Abrams, 2011; Kenney, Goemans, Klein, Lowery, & Reidy, 2008; Maidment & Miaou, 1986; Polebitski & Palmer, 2010; Worthington & Hoffman, 2008). We test whether intra-seasonal variations in an urban area affect water use.

Built environment: We hypothesize that built environment variables influence water use. We hypothesize that the year built, the lot size, the number of stories, the total number of rooms, the number of bathrooms and kitchens all influence water use. Lot size is correlated to lawn size and larger households, and has been found to have a large impact on water use (Abrams, 2011; Guhathakurta, 2007). Larger lots have larger lawns, more vegetative cover, more bathrooms and appliances, and therefore lot size has a positive correlation with water use (Balling, 2007; Blokker, Vreeburg, & van Dijk, 2010; Guhathakurta, 2007; Polebitski & Palmer, 2010; Renwick, Green, & McCorkle, 2000). The year a building was built likely affects water use, where older buildings tend to use more water (Guhathakurta, 2007; Rockaway, Coomes, Rivard, & Kornstein, 2011). We anticipate that additional rooms, kitchens, and bathrooms will increase water use.

Demographics: We hypothesize that demographics such as income, household size, and whether a resident rents or owns a property influences water use. We anticipate that residents who own will have higher income, and therefore have a larger household size and use more water (Domene & Sauri, 2005; Ferrara, 2008).

Later in this paper, we test these hypotheses using empirical data for Salt Lake City, Utah.

1.2. Previous research

In this section, we describe some of the previous research that has been conducted on urban water use. We review the key variables used in water demand modeling, previous methods of modeling water demand, and limitations of previous research. From this previous research, we identify key variables that have been found to influence water use.

Residential water consumption has been studied in hundreds of scholarly articles with particular interest in "investigating demand and/or price elasticity's effect on reducing water use" (Arbués, Garcıa-Valinas, & Martınez-Espineira, 2003; Rockaway et al., 2011). The general motivation for these researchers is to identify strategies to reduce water consumption through a feasible market strategy. Most studies indicate that water is an inelastic good, which means that an increase in water price does not proportionally decrease water use (Abrams, 2011; Barkatullah, 1996; Carver & Boland, 1980; Renwick & Archibald, 1998; Thomas & Syme, 1988; Worthington & Hoffman 2008). For example, Renwick, Green, and McCorkle (1998) found that a 10 percent increase in price reduces water demand only by 1.6–2.0 percent. It is thought that water is inelastic because it is a basic good that everyone needs; there is no substitute for water; and water bills constitute a small portion of household expenditures; and price information is delayed or imperfect (Arbués, 2004; Balling, 2007; Cavanagh, Hanemann, & Stavins, 2002; Gaudin, 2006).

Demographic variables have been found to influence urban water use. Income has been found to be a significant determinant of urban water use: as with nearly all goods and services, water use increases with a corresponding rise in as income (Ferrara, 2008; Guhathakurta, 2007). Household size significantly influences water consumption (Gaudin, 2006; Wentz & Gober, 2007) because households with more people use more appliances than smaller households. Other demographic variables such as education, attitudes, values, or perceptions likely have an influence on water use (Jorgensen, Graymore, & O'Toole, 2009), but are difficult measures to obtain.

Built environmental variables have also been found to influence urban water use. The age of a dwelling can have an effect on water demand, as older homes are more likely to have appliances and fixtures that are less water efficient than newer homes. With older appliances and fixtures there is likely to be water leakage because of wear and tear (Guhathakurta, 2007; Rockaway et al., 2011). Households on large lots, on average, have higher levels of water use (Abrams, 2011). Larger lots usually mean larger lawns, more vegetative cover, and larger houses. The type of building, or urban land use type, may have an effect on water use. Troy, Holloway, and Randolph (2005) explored the water consumption profiles of households living in different forms of residential development in a range of locations across Sydney, Australia. An overall finding of the research was that the per capita consumption of water is, for all practical purposes, the same for people living in traditional houses as it is for those in high density dwellings.

Climatological variables can be key drivers of urban water use. For example, in the summer months as temperatures rise, gardens dry out and households increase outdoor water use (Abrams, 2011). Studies of water use during the summer months have seen increases in water use of 30–40 percent (Cavanagh et al., 2002; Guhathakurta, 2007; Kenney et al., 2008). Rainfall plays a role in water usage, too. The most important consideration for residential water use is when it occurs and its intensity (Maidment & Miaou, 1986). Polebitski and Palmer (2010) found that a 10 percent increase in rain in May and June led to a 2.5 percent decrease in total water usage.

Based upon a selection of these key variables, many researchers have developed models that relate water consumption to a variety of independent variables. Ordinary least squares regression, generalized least squares, two and three stage least squares, logit and instrumental variables have all been used to model water use, but ordinary least squares regression "dominates the literature" (Worthington and Hoffman, 2008). This method was found to be useful for short-term forecasting, identifying the elasticity of price, and assessing the important determinants of demand (House-Peters & Chang, 2011).

The models developed based upon these predictors fit water consumption data reasonably well; r^2 values range between 0.40 and 0.80 and provide useful insights into water demand (Hewitt