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Determinants of single family residential water use across scales in four western US cities

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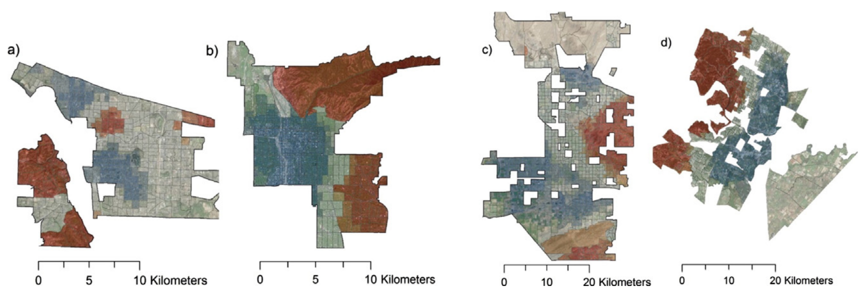
HIGHLIGHTS

- Common and different variables explain SFR water use variations by season and city.
- Tax assessed value and building age are common determinants of SFR water use.
- Impervious surface area is a significant predictor for summer SFR water use.
- Spatial variations of SFR water use are smoothed at a coarser spatial scale.
- SFR water use shows strong spatial dependence and neighboring effects.

GRAPHICAL ABSTRACT

Hotspots (red) and cold spots (blue) of summer (June–September) household water use at the Census Block Group scale based on the Getis-Ord Gi* statistic - a) Portland, Oregon; b) Salt Lake City, Utah; c) Phoenix, Arizona; and d) Austin, Texas.



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ABSTRACT

A growing body of literature examines urban water sustainability with increasing evidence that locally-based physical and social spatial interactions contribute to water use. These studies however are based on single-city analysis and often fail to consider whether these interactions occur more generally. We examine a multi-city comparison using a common set of spatially-explicit water, socioeconomic, and biophysical data. We investigate the relative importance of variables for explaining the variations of single family residential (SFR) water uses at Census Block Group (CBG) and Census Tract (CT) scales in four representative western US cities – Austin, Phoenix, Portland, and Salt Lake City, - which cover a wide range of climate and development density. We used both ordinary least squares regression and spatial error regression models to identify the influence of spatial dependence on water use patterns. Our results show that older downtown areas show lower water use than newer suburban areas in all four cities. Tax assessed value and building age are the main determinants of SFR water use across the four cities regardless of the scale. Impervious surface area becomes an important variable for summer water use in all cities, and it is important in all seasons for arid environments such as Phoenix. CT level analysis shows better model predictability than CBG analysis. In all cities, seasons, and spatial scales, spatial error regression models better explain the variations of SFR water use. Such a spatially-varying relationship of urban water consumption provides additional evidence for the need to integrate urban land use planning and municipal water planning.

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1. Introduction

The cities of the 21st century are subject to increasing pressure to develop a sustainable water supply in the global south and north due to water stresses associated with growing populations (Grafton et al., 2011), inadequate and aging water infrastructure (Clark et al., 1999; Grigg, 2005), poor regulation (Massarutto and Ermano, 2013), and climate variability (Hunt and Watkiss, 2011). While per capita water use has declined in recent years in the global north (Chang et al., 2014; Ashoori et al., 2016), the absolute growth in population could negate the effect of water conservation in many places. Furthermore, as urban areas grow, new infrastructure is needed requiring new investment as well as investment in updating, maintaining, and replacing old infrastructure. Similarly, the effectiveness and financing of water infrastructure depends on public and private regulatory agreements to deliver reliable and safe water. Finally, climate variability and change will likely reduce water supplies in many areas around the world, particularly in semi-arid and arid climates, compounding the challenges faced by water providers (IPCC, 2014).

To address these ranging concerns of water security, many urban water providers have designed and implemented water conservation programs (Mini et al., 2014). These programs typically involve incentives, such as rebates on water saving bathroom fixtures, conversion programs for high water use landscaping, and seasonally based pricing structures. These water conservation programs have been typically applied at the water provider scale, neglecting the spatial and temporal heterogeneity of single family residential (SFR) water use patterns in complex urban water systems, and thus lowering the effectiveness of such programs in terms of reducing SFR water use. For these conservation programs to be successful, we first need to know what factors affect SFR water use, where the hotspots of SFR water use are, and how the water use patterns vary over space and time.

Prior research investigating the factors influencing SFR water use show that structural (lot and property characteristics), environmental, spatial, social, and behavioral factors influence water use (Guhathakurta and Gober, 2007; Wentz and Gober, 2007; Balling and Cubaque, 2009; Chang et al., 2010a; House-Peters and Chang, 2011a, 2011b; March and Saurí, 2010; Polebitski et al., 2011; Breyer et al., 2012; Aggarwal et al., 2012; Fielding et al., 2012; Halper et al., 2012; Giner et al., 2013; Saurí, 2013). Table 1 summarizes these factors with examples of the impact on water use. A dominant theme in the literature is the impact of climate variables on household water use. Many studies positively correlate higher water consumption with warmer temperatures associated with seasonal variations (Rockaway et al., 2011; Chang et al., 2014; Prandvash and Chang, 2016) with some studies specifically identifying the concentration of the urban heat island effect as a determining factor (Guhathakurta and Gober, 2007; Gober et al., 2012). Many cities throughout the eastern, central, and northwestern portions of the United States are also facing water shortages and drought, influencing water use (Hornberger et al., 2015; Chang and Bonnette, 2016). The combination of projected rises in air temperature with decreases in precipitation will further diminish water supply for increasing municipal water demand into the future.

In addition to climate variation in different cities, local variations, such as those found at the household and tract level are likely due to other factors, such as the use of pools, the size and style of lawns, micro-climate variations, and other external factors (Guhathakurta and Gober, 2007; Balling and Cubaque, 2009). Research on single-family housing water use is shifting from aggregated generalities of water use at the city scale to specific, parcel level analysis (Ferrara; 2008, Fox et al., 2009; Arbue's et al., 2010; Gage and Cooper, 2015; Ojeda et al., 2017). Studies at the parcel level report higher water use is aligned with larger irrigation areas, higher incomes, warmer climates, larger house sizes, and a larger household size (Wilson and Boehland, 2005; Harlan et al., 2009; Gato-Trinidad et al., 2011; Romero and Dukes, 2013). These studies, however, tend to be limited to a small sample within a community, focus on water use associated with rate-changes, or focus on weekly water consumption rather than seasonal. It is challenging therefore to examine the impact of neighborhood influences that, at the aggregate scale, have shown to be influential (Ouyang et al., 2014). This limits the usefulness of the results for water policy implementations because it is difficult to influence either individual behavior or the residents of an entire city using a single water policy. The ability to analyze and understand scalar dynamics within cities at Census Track (CT) and parcel is important for making decision-relevant water policy.

While there have been a number of studies investigating various factors affecting SFR water use at different scales of analysis, few studies have compared multiple cities in a spatially explicit way using a common data set with the same study design. As such, it has been difficult to directly compare the locally varying SFR water use patterns across different cities. A small number of exceptional case studies were conducted as part of a collaborative research effort between Portland and Phoenix (Breyer et al., 2012; Gober et al., 2012; Lee et al., 2015), showing some common and contrasting predictors of urban water use in both places. However, there exist no studies comparing SFR water use in

Table 1
Generalized factors that explain increases and decreases to single family residential water use.

Factor type	Examples	Impact on water	Notes	References
Structural	⇧Lot size	+		Chang et al., 2010a, 2010b; Polebitski et al., 2011; Halper et al., 2015
	⇧Turf	+		Giner et al., 2013; Mini et al., 2014; Gage and Cooper, 2015
	⇧Swimming pools	+		Domene and SaurÍ, 2006; Wentz and Gober, 2007; Larson et al., 2009
	>Building age	±	1	Chang et al., 2010a, 2010b; Reynaud, 2013; Ouyang et al., 2014; Halper et al., 2015
Environmental	⇧Urban heat island	+		Guhathakurta and Gober, 2007; Balling and Cubaque, 2009; Gober et al., 2012
	Summer	+		Chang et al., 2014; Prandvash and Chang, 2016
	⇧Drought	±	2	Polebitski and Palmer, 2013; Breyer and Chang, 2014
Spatial	⇧Building density	−		Wilson and Boehland, 2005; House-Peters et al., 2010; Breyer et al., 2012
	Neighborhood		3	Wentz et al., 2016; Gage and Cooper, 2015
	Park or common pool	−		Halper et al., 2012
Socioeconomic	⇧Income	+		Harlan et al., 2009; March and Saurí, 2010; Fielding et al., 2012
	⇧Education	+	4	House-Peters et al., 2010; Baerenklau et al., 2014
	⇧Incentives	−		Lee, 2016
	Price structure	±	5	Grafton et al., 2011; Yoo et al., 2014
Behavioral	⇧Graywater reuse	-		Straus et al., 2016
	⇧Short shower times			Jorgensen et al., 2013; Liu et al., 2016
	⇧Turning off faucet when teeth brushing			Suero et al., 2012

Notes: 1 = depends on study; 2 = depends on water restriction regulations; 3 = neighbors having similar water use habits; 4 = correlation with income; 5 = depends on the policy.