



EFFECTS OF URBAN SPATIAL STRUCTURE, SOCIODEMOGRAPHICS, AND CLIMATE ON RESIDENTIAL WATER CONSUMPTION IN HILLSBORO, OREGON¹

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ABSTRACT: In the Portland metropolitan area, suburban growth in cities such as Hillsboro is projected to increase as people seek affordable housing near a burgeoning metropolis. The most significant determinants for increases in water demand are population growth, climate change, and the type of urban development that occurs. This study analyzes the spatial patterns of single family residential (SFR) water consumption in Hillsboro, Oregon, at the census block scale. The following research questions are addressed: (1) What are the significant determinants of SFR water consumption in Hillsboro, Oregon? (2) Is SFR water demand sensitive to drought conditions and interannual climate variation? (3) To what magnitude do particular census blocks react to drought conditions and interannual climate variation? Using ordinary least squares multiple regression and spatial regression methods, we found that base use, representing indoor water use, is dependent on household size and that seasonal use, representing external water use is dependent on both education level and the size of the property's outdoor space. Spatial analysis techniques determined that although the water demand of the study area as a whole is not sensitive to drought conditions, certain individual census blocks do respond with a higher magnitude of water use. The most climate-sensitive census blocks tend to contain newer and larger homes, and have higher property values and more affluent and well-educated residents.

(KEY TERMS: geospatial analysis; planning; sustainability; water demand; statistics; urban areas.)

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INTRODUCTION

Historically, water managers have focused on supply-side management, such as altering hydrologic budgets through dams and reservoirs. However, a new shift points to managing the demand side of human water consumption as knowledge of environmental damage and prohibitive expense has made large hydrologic projects less feasible. Cooley and Gleick (2009) introduced the idea of a transition to a

“soft path” to water use, which involves a wide range of changes in water management policies and approaches. These changes include deconstructing demand to identify sectors of water use within which efficiency can be improved in order to reduce pressure on the water supply (Gleick, 1998). During the last decade, demand-side management methods have increased in significance as balances between freshwater resources and human demand have shifted toward negative, especially during peak use (Fox *et al.*, 2009).

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Increased uncertainty in future climate forecasts are causing local water planners to shift away from short-term fixes designed to deal with drought conditions. Instead, the focus is on long-term strategies that respond to climate change, environmental regulations, and increasing competition for supplies (Balling *et al.*, 2008). These concerns echo a warning from the Intergovernmental Panel on Climate Change (IPCC) which states, “reduced water supplies coupled with increases in demand are likely to exacerbate competition for over-allocated water resources” (Bates *et al.*, 2008, p. 130).

Overall streamflow in the Pacific Northwest (PNW) of the United States has been found to be decreasing due to a shift in climate that occurred during the mid-20th Century (Hamlet *et al.*, 2005; Luce and Holden, 2009). Because the climate of the PNW is dominated by high winter precipitation, a decreasing trend in Oregon levels of April 1, Snow Water Equivalent, will likely change summer streamflow patterns (Kalra *et al.*, 2008). Research in the Upper Clackamas River Basin, located in the snow-dominated Cascade mountains, found that water supply projections based on 21st Century climate change scenarios forecast moderate reductions in spring and summer flows by the 2020s and significant reductions by the 2080s (Graves and Chang, 2007). Another study in the Rock Creek Basin, a rainfed urbanizing basin located in the western Portland metropolitan area, showed that summer water availability will further decline with rising temperature and diminished summer rainfall (Franczyk and Chang, 2009a). These climate change impact studies indicate that there will be increased stress on water management systems as difficult tradeoffs have to be balanced between maintaining ecologically sufficient instream flows and serving the water needs of a growing residential, commercial, and agricultural population. The coupling of a growing population with the threat of a warmer, drier future climate has led to a call for water managers and urban planners to help communities to think critically about their current and future water needs and how best to meet them (Page and Susskind, 2007).

This paper focuses on single-family residential (SFR) water consumption in Hillsboro, Oregon, a large suburb of Portland. We use census block level water consumption data to determine whether the variation in household water consumption in two distinct years, 2004 (an average climate summer) and 2006 (a drought summer), can be explained by socioeconomic variables and physical property characteristics. Also, we analyze the relation between the determinants of SFR water consumption and sensitivity to variations in climate, including drought and interannual seasonal variation. The following research

questions are addressed. (1) What are the significant determinants of SFR water consumption in Hillsboro? (2) Is SFR water demand sensitive to drought conditions and interannual climate variation? (3) Can socioeconomic variables and physical property characteristics explain the spatial pattern exhibited by climate sensitivity?

Determinants of Residential Water Demand

Over the last decade, the literature analyzing demand-side residential water management has grown in both depth and breadth. However, due to the influence of numerous economic, social, climatic, policy, and psychological factors, comprehensive models for estimating and forecasting municipal water demand remain complex. Previous research has found that the most significant determinants for increases in water demand are population growth, climate change, and the type of urban development that occurs (Domene and Saurí, 2007; Wentz and Gober, 2007; Cooley and Gleick, 2009). It is also true that water use patterns are not distributed evenly over space and time, and thus are affected not only by socioeconomic, climatic, and physical property variables, but also by the geographical location of a region and its interactions with other adjacent regions. The result of this spatial bias is that households tend to use water at a level comparable to their neighbors irrespective of their demographic and economic characteristics (Wentz and Gober, 2007; Franczyk and Chang, 2009b).

A number of studies have analyzed the significance of socioeconomic variables in an attempt to predict residential water demand. Research has shown that high volume water users tend to be wealthier (Syme *et al.*, 2004; Guhathakurta and Gober, 2007; Kenney *et al.*, 2008; Schleich and Hillenbrand, 2009) and older (Kenney *et al.*, 2008; Fox *et al.*, 2009; Schleich and Hillenbrand, 2009). The significance of occupant age is found on the principle that retired people use more water at home rather than at their workplace and that children tend to use less water (Fox *et al.*, 2009; Schleich and Hillenbrand, 2009). The ability of the variable household size to explain variation in residential water use has been substantiated in many studies (Zhang and Brown, 2005; Domene and Saurí, 2007; Guhathakurta and Gober, 2007; Wentz and Gober, 2007; Schleich and Hillenbrand, 2009). At the household scale, as occupancy increases, overall total water demand increases, due to more water being used for bathing, laundry, toilet flushing and dishwashing, but per capita use decreases (Wentz and Gober, 2007; Fox *et al.*, 2009; Schleich and Hillenbrand, 2009).

Recent literature stresses the importance of recognizing relations between physical housing characteristics, such as lot size, building size, and outdoor space, and likely levels of household water use (Tinker *et al.*, 2005; Fox *et al.*, 2009). Research has shown that higher-density urban development reduces demand and lessens the costs of augmenting existing water infrastructure and supply (Balling *et al.*, 2008). The relations between the explanatory variables mean lot size, mean age of housing, and household water demand are well demonstrated in arid climates (Syme *et al.*, 2004; Guhathakurta and Gober, 2007; Kenney *et al.*, 2008). In Phoenix, Arizona, Guhathakurta and Gober (2007) found that for each 1,000 square foot increase in average lot size, water use increased by 1.8%. Pertaining to the variable building size, a study in the United Kingdom found significant differences between the water demanded during the peak summer months by properties with one bedroom *vs.* those with more (Fox *et al.*, 2009).

External water use has been shown to comprise a significant amount of household water use. In Australia, Askew and McGuirk (2004) reported that as much as 50% of household water is used externally and Head and Muir (2007) found that in the greater Sydney area, garden maintenance accounted for 25% of total household water use. In Austin, Texas, 45% of summertime water use was attributed to external uses (Tinker *et al.*, 2005), while in Arizona, landscapes were found to consume between 30 and 60% of summertime water supplies (McPherson, 1990). Due to the relation between outdoor space and increased water use, the greatest water consumption has been found to occur in detached properties with garden space (Zhang and Brown, 2005; Fox *et al.*, 2009). Although thoroughly examined in arid climates, the effect of outdoor space on water consumption is not well known for other climates, including the maritime temperate climate of the PNW of the United States.

The Influence of Climate on Water Demand

Total water use is composed of base use and seasonal use, where base use is assumed to represent indoor water use that is independent of the effects of climate, and seasonal use represents external water use, which is influenced by weather conditions, including air temperature, evaporation, and rainfall (Maidment *et al.*, 1985; Zhou *et al.*, 2000; Syme *et al.*, 2004; Gato *et al.*, 2007). Base use is generally defined as average winter water use and seasonal use is equal to total water use minus base use. Gato *et al.* (2007) warns that, in certain climates, base use may be weather dependent, taking into account wintertime garden watering; however, the climate

experiences a very wet season in the winter, thus this warning probably does not apply to our study area.

Studies of climate variability and residential water consumption in Phoenix found that per capita water use significantly increases during periods of high temperatures and droughts and decreases with higher precipitation (Balling and Gober, 2006; Guhathakurta and Gober, 2007). Balling *et al.* (2008) similarly reported finding that the strongest correlate is the drought variable. In a study of Albuquerque, New Mexico, Gutzler and Nims (2005) found that over 60% of the variation in year to year changes in summer residential water demand was accounted for by interannual temperature and precipitation changes when using a linear regression model, with precipitation being the primary correlate. Maidment and Miaou (1986) report that seasonal water use during rainless periods is closely related to air temperature, once air temperature rises above the threshold value of 21.1°C (70°F). Similarly, one degree increase in maximum temperature can increase daily per capita water consumption in July by 4 liters in Seoul, Korea (Praskievicz and Chang, 2009).

An important trend in the literature that is also analyzed in our paper is the progress toward determining the exact nature of spatial variations in climatic sensitivity. In a study of Phoenix, Balling *et al.* (2008) found that one-third of census tracts had little to no sensitivity to climate, whereas one tract had over 70% of its monthly variance in water use explained by climatic conditions. Further evidence of a geographic pattern in climate sensitivity is the ratio of summer *vs.* winter water use. Across the city of Phoenix as a whole, SFR water use averages about twice the levels in the peak use summer months as in the low use winter months. Balling *et al.* (2008) reported that the greatest sensitivity to climate was found in census tracts with large lots, high occurrence of pools, a large proportion of non-native vegetation, and a high percentage of wealthy residents.

This review of the literature illustrates that while water consumption patterns have been comprehensively studied in arid and semiarid climates, research of the determinants of demand and the effects of drought on water use in other climates is lacking. Additionally, most previous studies were not comprehensive, only examining either structural or socioeconomic or climatic variables that affect water consumption (Chang *et al.*, 2010). This paper contributes to filling this gap in the literature by elucidating the relationship among climate, socioeconomic variables and water use in the PNW, the United States, a maritime temperate climate. Our findings will be especially useful to water resource managers and urban planners, as this paper aims to identify specific target areas where conservation efforts can be used

most efficiently to manage water demand, especially during peak summer demand.

STUDY AREA

Hillsboro is the fifth largest city in the state of Oregon with an estimated 2009 population of 88,300 people (Figure 1). The city is located in the Tualatin River Valley, 27 km west of the city of Portland and is considered part of the greater Portland metropolitan area (City of Hillsboro, 2009). Hillsboro is one of the main suburbs of Portland and is experiencing rapid population growth estimated at 25.8% between April 1, 2000 and April 1, 2008, far exceeding the 8.2% growth rate of the state of Oregon (Oregon Blue Book, 2009; U.S. Census Bureau, 2009). Located in marine west coast climate, approximately more than 70% of Hillsboro's annual precipitation falls during the wet season from November to April. Accordingly, municipal water supply depends on winter rainfall kept in both Hagg Lake in the Upper Tualatin River and Barney Reservoir in the Coastal Range mountains to meet peak demand in the summer months, which corresponds with the low flow season for the Tualatin River. Predicting a high rate of continued growth in the future, the city of Hillsboro has created a 50-year water demand projection based on urban development forecasts and expected population

growth. The current projected demand for water outpaces the current available supply from the sources of the river and the reservoirs (City of Hillsboro, 2009).

Hillsboro is an appropriate location for this type of research, a city balancing the dual uncertainties of future population growth and the potential for the summer water flow in the Tualatin River to be negatively affected due to climate change over the next 50 years. Furthermore, Kenney *et al.* (2008) warn that suburbs often face the strongest growth pressures coupled with the least robust supply systems and Domene and Saurí (2007) observed a pattern of rising water consumption in the suburbs as compared with the denser city core, which they attribute to a higher percentage of suburban housing being single family residences with garden space.

DATA AND METHOD

Data

We obtained SFR water records for the period 2004-2007 from the City of Hillsboro's Water Department. The dataset contained over 21,800 records at the spatially fine household level scale with a bi-monthly temporal scale, based on the billing period. The household level data were aggregated to the

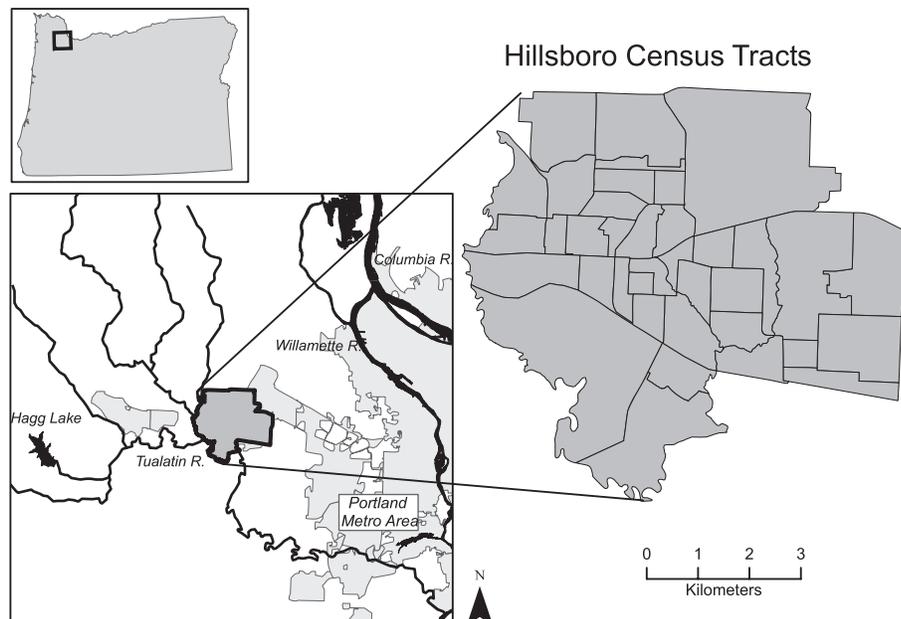


FIGURE 1. Map of Hillsboro, Oregon, the Study Area, in Relation to Portland, Oregon. Inset map depicts the 37 census blocks that comprise the city of Hillsboro water district.

census block scale using the geo-coding tool in Environmental Systems Research Institute's (ESRI) ArcGIS (ESRI, Redlands, California). The geo-coding process produced 19,753 address matches; however, due to address errors in the dataset, approximately 300 individual records were unable to be geo-coded and were eliminated.

During the aggregation process, the individual water consumption records were checked for errors. Each bi-monthly billing cycle was examined, and 64 outliers were removed. Outliers most commonly occurred because within the single-family dwelling dataset, multi-family homes or homeowner's association irrigation districts erroneously appeared. Records were considered outliers and excluded if a bi-monthly usage record exceeded the sum of the previous six bi-monthly billing records. The retention of these very high consumption outliers would have inaccurately skewed the results of our analysis. The very low consumption outliers, including properties with at least one time period of a zero reading, were retained because the property may have been vacant at the time of the reading, which is representative of the area. After cleaning the data, we were left with 18,163 SFR water consumption records, which we then finished aggregating to the census block scale. The study area is comprised of 37 total census blocks (Figure 1). Next, the water consumption records were converted from hundred cubic feet to 1,000 l and then standardized to 1,000 l/household/month, by dividing the total liters per census block by the number of SFR properties in the census block. The final step was to divide total water consumption into base use and seasonal use, defining base use as equal to winter consumption, and seasonal use as equal to total use minus base use.

We obtained climate data from the Oregon Climate Service database from the Hillsboro meteorological station in order to determine a 30-year average (1974-2003) for summer (defined as July, August, September, and October) precipitation and temperature for the study area. The average summertime precipitation and temperature values were then compared with the climate data for the four summers in our dataset. Climate data for the years 2004 to 2007 were obtained for the Hillsboro area from the National Climatic Data Center database (Station 353908) (National Climatic Data Center, 2009). Summer 2004 had average maximum temperatures and precipitation levels very similar to the 30-year average. Summer 2006, however, recorded half as much precipitation as the 30-year mean and had exceeded the 30-year mean's average maximum temperature by approximately 1°C (Table 1). Thus, in our analysis, 2004 represents the normal summer and 2006 represents the drought summer. Although summer

TABLE 1. Description of Climate for the Years, 2004 and 2006.

	Year	Winter (January, February)	Summer (July, August, September, October)
Average monthly maximum temperature (celsius)	2004	7.11	24.22
	2006	9.50	25.33
Average monthly precipitation (mm)	2004	143.76	44.45
	2006	176.28	10.41

2006 was hot and dry, Hillsboro did not experience water supply shortage because winter precipitation had filled storage reservoirs to maximum capacity. We chose to define the summer season as July, August, September, and October for two reasons. First, our water consumption data has a bi-monthly temporal scale, starting with January/February, thus we could not separate September and October. Second, we wanted the summer season to represent the dry season in the Northwest climate, which generally begins in late June and continues until the middle of October.

Variables

The following seven dependent variables were derived from the SFR water consumption dataset and used in our analysis:

1. 2004 Base use (1,000 l/household/month) = (January + February 2004 water use)/2.
2. 2004 Seasonal use (1,000 l/household/month) = [Total use (July + August + September + October)/4] - 2004 base use.
3. 2006 Base use (1,000 l/household/month) = (January + February 2006 water use)/2.
4. 2006 Seasonal use (1,000 l/household/month) = [2006 Total use (July + August + September + October)/4] - 2006 base use.
5. Drought sensitivity = (2006 seasonal use)/(2004 seasonal use).
6. 2004 Interannual climate sensitivity = (2004 seasonal use)/(2004 base use).
7. 2006 Interannual climate sensitivity = (2006 seasonal use)/(2006 base use).

Based on our review of the literature and the available data, we chose to investigate the role of socioeconomic and physical property characteristics in explaining the variation in water use in Hillsboro. We are aware that a major limitation of our study is that we do not directly analyze the influence of vegetation, climate, or behavior variables on the observed water use. The four socioeconomic explanatory variables

are: median household income (\$), average education level (%), average household size, and median population age. These socioeconomic data were acquired from the U.S. Census Bureau. The five explanatory physical property variables are: outdoor size (m²), average year built, lot size (m²), building size (m²), and total property value (\$) (Table 2). The physical property data were provided by Washington County's Department of Long-Range Planning in the form of a tax lot dataset. We hypothesize that a combination of the socioeconomic and the physical property variables will be statistically significant in explaining the variation in water consumption throughout the study area.

Statistical Analysis

Our statistical analysis took several forms. First, we explored the dependent and independent variables using descriptive statistics (Table 2). We used ArcGIS to map each of the dependent variables to visually assess the existence of a spatial pattern of low and high water consumption (Figures 2 and 3). To quantify the degree of spatial dependence in water consumption, we calculated the Moran's I sta-

tistical value for each of the water consumption variables using the GeoDa statistical software (Anselin *et al.*, 2006). Moran's I is a global measure of spatial autocorrelation with possible values ranging from 1 (clustered pattern) to -1 (dispersed pattern), where a value of 0 indicates a perfect random spatial pattern (O'Sullivan and Unwin, 2003).

To determine the independent variables that are statistically significant in explaining the variation in base use and seasonal use across the study area, we created an ordinary least squares (OLS) multiple regression model for the following four dependent variables: (1) 2004 base use; (2) 2004 seasonal use; (3) 2006 base use; and (4) 2006 seasonal use. After reviewing the results of the Moran's I statistic and the OLS regressions, we decided to generate spatial lag regression models to correct for the influence of spatially correlated residuals and for patterns of spatial autocorrelation within the study area.

To ascertain a significant expression of sensitivity of SFR water consumption to drought conditions, we employed a two-sample *t*-test to compare the mean 2004 seasonal use and the mean 2006 seasonal use for the entire study area. A statistically significant *p*-value would confirm that the amount of water used during the drought summer was substantially larger

TABLE 2. Descriptive Statistics on Dependent and Independent Variables to Analyze Single Family Residential Water Consumption in Hillsboro, Oregon, Per Census Block.

Variable	Description	Mean	Standard Deviation	Minimum	Maximum
Dependent variables					
2004 Base water use (1,000 l)	Winter use 2004	18.79	4.00	5.96	25.40
2004 Seasonal water use (1,000 l)	Total summer use 2004 – Base use 2004	23.09	6.21	6.93	39.33
2006 Base water use (1,000 l)	Winter use 2006	18.24	3.04	10.51	27.06
2006 Seasonal water use (1,000 l)	Total summer use 2006 – Base use 2006	24.55	6.36	12.83	42.90
Drought sensitivity	Ratio of 2006 Seasonal use to 2004 Seasonal use	1.08	0.17	0.88	1.85
2004 Interannual climate sensitivity	Ratio of 2004 Seasonal use to 2004 Base use	1.24	0.28	0.80	1.96
2006 Interannual climate sensitivity	Ratio of 2006 Seasonal use to 2006 Base use	1.36	0.34	0.81	2.22
Socioeconomic variables					
Income (\$)	Median household income	60,834	17,549	29,151	95,014
Education (%)	Percentage of adult population with a college diploma	16.47	8.43	2.23	37.9
Average household size (persons)	Average number of persons per property	2.95	0.52	2	4
Population age (years)	Median age of the population	31.62	4.91	23	47
Physical property variables					
Outdoor size (m ²)	Property lot size (m ²) - Building size (m ²)	483.27	346.99	-121.73	1,311.04
Year built (year)	Average year built	1,972	15.15	1,924	1,993
Property lot size (m ²)	Size of the property lot, land only	633.28	367.85	41.03	1,510.66
Building size (m ²)	Size of the building	158.05	20.80	121.21	199.62
Total value (\$)	Land value (\$) + Building value (\$)	264,123	37,347.00	175,825	340,011

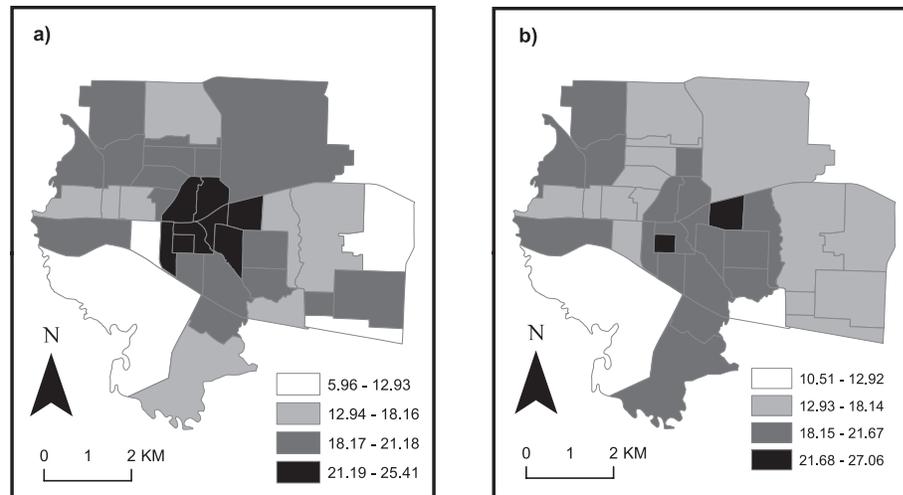


FIGURE 2. Average Base Water Consumption in (a) 2004 and (b) 2006 (1,000 l/household/month).

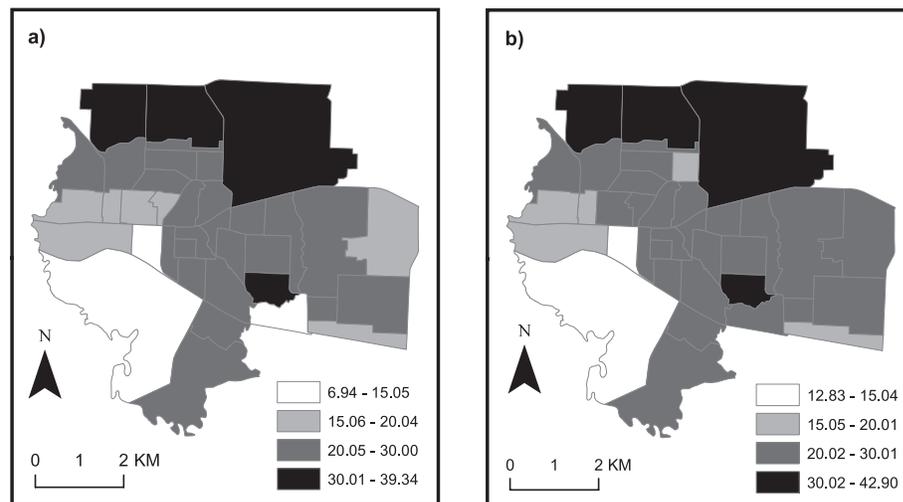


FIGURE 3. Average Seasonal Water Consumption in (a) 2004 and (b) 2006 (1,000 l/household/month).

than the amount used during a normal summer, thus verifying drought sensitivity. We used the same method to determine interannual climate sensitivity, comparing the mean seasonal use and the mean base use for each year. The *t*-test statistic measures significant difference between means across the entire study area, however, certain census blocks may display greater sensitivity than others. In order to capture a more individualized climate sensitivity, we produced maps of three ratios: (1) the ratio of 2006 seasonal use to 2004 seasonal use to detect drought sensitivity (Figure 4), (2) the ratio of 2004 seasonal use to 2004 base use to identify interannual climate sensitivity during a normal climate year (Figure 5a), and (3) the ratio of 2006 seasonal use to 2006 base use to identify interannual climate sensitivity during a drought year (Figure 5b).

Once a spatial pattern of climate sensitivity had been verified, we explained the variation in this pattern using the same socioeconomic and physical property variables introduced earlier. In this analysis, we utilized three dependent variables: (1) the ratio of 2006 seasonal use to 2004 seasonal use; (2) the ratio of 2004 seasonal use to 2004 base use; and (3) the ratio of 2006 seasonal use to 2006 base use. All data values for the independent and dependent variables were converted to their standardized *z*-score, based on the mean and standard deviation of the dataset, in order to compare the variables at the same scale. Using a paired sample *t*-test, we compared the socioeconomic and structural characteristics of the five most climate-sensitive and the five least climate-sensitive census blocks. These statistical analyses were conducted in SPSS 13.0 (SPSS Inc., Chicago, Illinois).

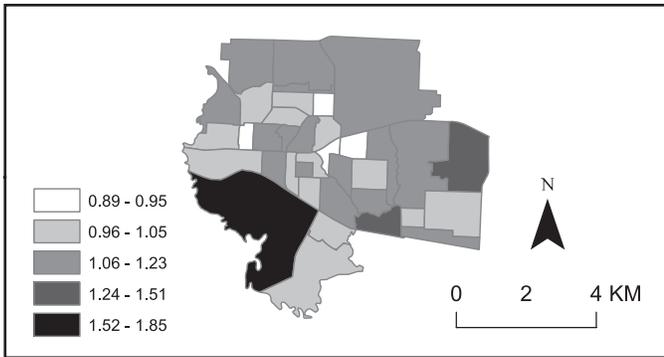


FIGURE 4. Map of Drought Sensitivity: Ratio of 2006 to 2004 Seasonal Water Use.

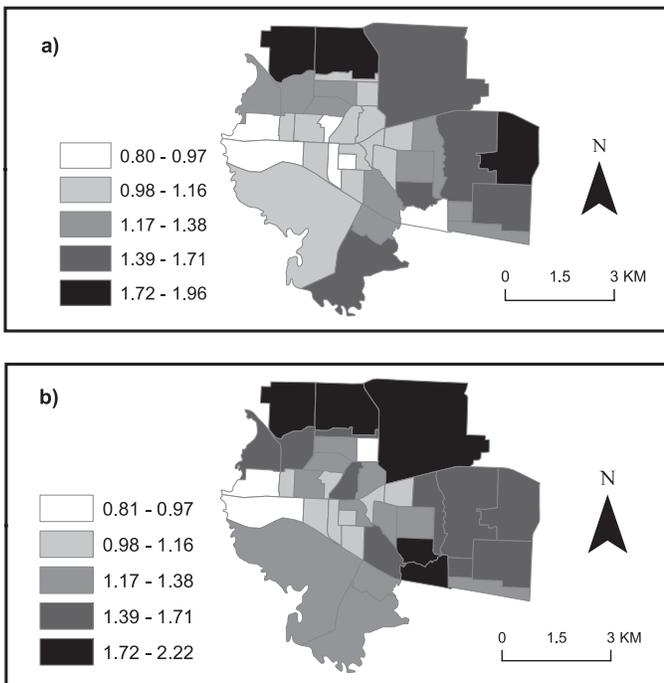


FIGURE 5. Interannual Climate Sensitivity for (a) 2004 and (b) 2006. Ratio of seasonal water use to base water use in each year.

RESULTS

The water consumption maps revealed a visually explicit pattern of high and low water using census blocks (Figures 2 and 3). Interestingly, the high use clusters for both 2004 and 2006 base use are concentrated in the middle of the study area and the low use clustering exists in the northern periphery. The pattern for high water use clustering is reversed for both 2004 and 2006 seasonal use, with the high water use clusters existing at the periphery of the study area. The Moran's I values of spatial autocorrelation

verify this visual pattern. For the four dependent variables, 2004 base use, 2004 seasonal use, 2006 base use, and 2006 seasonal use, the Moran's I values range from 0.2895 to 0.3461, indicating a spatial pattern of moderate clustering throughout the study area. The Moran's I values calculated for the sensitivity of water use to interannual climate variation indicated a more significant clustering pattern, with values ranging from 0.4004 to 0.4178. However, the Moran's I value associated with the variable drought sensitivity (-0.0920) suggests a highly random pattern of drought sensitivity across the study area.

The OLS and spatial regression models reveal that the independent variables that explain the variation in SFR water consumption vary for the two categories of dependent variables, base use and seasonal use, but do not vary for the two years, 2004 and 2006 (Table 3). The only significant independent variable in determining 2004 and 2006 base use water consumption is the average household size. The OLS regression model coefficient of determination, R^2 , values for both 2004 base use and 2006 base use are weak, 0.16 and 0.36 respectively, but are improved by the spatial lag model, $R^2 = 0.28$ for 2004 base use and 0.42 for 2006 base use, thus further indicating the existence of spatial autocorrelation within the study area. For the dependent variables, 2004 seasonal use and 2006 seasonal use, there were two significant explanatory variables, percent of adult residents with a college education and size of outdoor space (the difference between lot size and building size). The R^2 values for the OLS regression model for 2004 and 2006 seasonal use are stronger, 0.57 and 0.65, respectively, and increased slightly using the spatial lag model to 0.58 and 0.68, respectively.

The overall sensitivity of water use in the study area to drought was tested using a two-sample t -test, comparing 2006 seasonal use and 2004 seasonal use. The t -test produced a p -value of 0.16, which is not statistically significant and thus indicates that water use for the city as a whole is not sensitive to drought conditions. However, the ratio of 2006 seasonal use to 2004 seasonal use illustrates that particular individual census blocks are highly sensitive to drought, consuming up to 1.85 times more water for external purposes during a drought summer than an average summer (Figure 4). In 2004 and 2006, the water consumption of the entire study area exhibited significant sensitivity to interannual climate variation; both t -tests produced p -values equal to 0.00. There are individual census blocks where the ratio of seasonal use to base use is less than one, indicating a lack of external water use; however, the ratio value for many of the census blocks is above 1.5, suggesting that during the summer, a large proportion of total household water is used externally (Figure 5).

We found the spatial variation in climate sensitivity across the study area interesting and potentially important for future land use planning and conservation efforts, and thus sought to discover the socioeconomic and physical property characteristics that defined the most and least climate sensitive census blocks. For the variable drought sensitivity, when all five of the physical property variables were considered, the difference between the mean values of the variables for the most and least drought sensitive areas was significant ($p = 0.03$); however, the difference between the mean values of the socioeconomic variables was not at all significant ($p = 0.90$). This finding suggests that sensitivity of SFR water consumption to drought in the study area is a function of physical property not socioeconomic characteristics.

For the dependent variable, 2004 interannual climate sensitivity, there are scarcely statistically significant differences between the means of the five physical property variables ($p = 0.05$) but very significant differences between the four socioeconomic variables ($p = 0.01$). The individual variables whose means vary the most between the census blocks that use the most external summertime water and the least are: average year built ($p = 0.00$), average building value ($p = 0.02$), average total property value ($p = 0.01$), median household income ($p = 0.01$), and college education ($p = 0.00$). During the drought summer, 2006, the differences between the means of the five physical property variables ($p = 0.00$) are the most significant in explaining variations between census blocks that use the most water externally and those that use the least. The differences between the means of the four socioeconomic variables are only moderately significant ($p = 0.05$). The individual variables whose means vary the most are: average year built ($p = 0.00$), average building value ($p = 0.01$), average total value ($p = 0.00$), and college education ($p = 0.02$). These results indicate that during a summer with less precipitation and higher maximum daily temperatures, 2006, external water use is more dependent on physical property characteristics and less dependent on socioeconomic characteristics than during an average summer, such as 2004 (Table 4).

DISCUSSION

The results of the regression analysis demonstrate that certain socioeconomic and structural variables do influence residential water demand. Base use, which is representative of indoor use, is dependent on the variable household size exhibiting a strong positive relation to base use in both years, 2004 and

TABLE 3. Regression Coefficients and Model Results Using Ordinary Least Squares (OLS) and Spatial Methods.

	2004 Base Use (OLS model)	2004 Base Use (spatial model)	2004 Seasonal Use (OLS model)	2004 Seasonal Use (spatial model)	2006 Base Use (OLS model)	2006 Base Use (spatial model)	2006 Seasonal Use (OLS model)	2006 Seasonal Use (spatial model)
Constant	9.75 (0.01)	3.79 (0.39)	11.37 (0.00)	12.08 (0.00)	8.00 (0.00)	3.30 (0.35)	11.57 (0.00)	13.09 (0.00)
Spatial lag coefficient (ρ)	-	0.41 (0.03)	-	0.02 (0.93)	-	0.34 (0.07)	-	-0.02
Mean household size (persons)	3.07 (0.01)	2.50 (0.02)	-	-	3.48 (0.00)	3.02 (0.00)	-	-
College education (%)	-	-	0.54 (0.00)	0.50 (0.00)	-	-	0.59 (0.00)	0.56 (0.00)
Outdoor space (m ²)	-	-	0.01 (0.02)	0.01 (0.02)	-	-	0.01 (0.04)	0.01 (0.00)
R ²	0.16	0.28	0.57	0.58	0.36	0.42	0.65	0.68
Standard error	3.72	3.35	4.46	3.95	2.47	2.28	4.18	3.56
Significance of F-statistic	0.01	-	0.00	-	0.00	-	0.00	-

Note: The parentheses contain the p -value for each variable in the model.

2006. This finding is similar to results from a study in Perth, Australia, which reports that variations in water consumption inside the home are relatively stable across socioeconomic groups and housing types, but instead are based on increases in household size (Syme *et al.*, 2004). Our results indicate that for each additional person in a household, the monthly base water use increases by over 3,000 l. Seasonal use, which is indicative of external water use, was found to be dependent on and increase as the percentage of adults with a college education increased and as the size of the outdoor space increased. Interestingly, and contrary to our initial hypothesis, the variables year built, building size, total property value, household income, and population age were not significant determinants of overall water consumption patterns in our study area.

The correlation between an increase in household water demand and outdoor space has been substantiated in similar research that has been undertaken in arid climates (Syme *et al.*, 2004; Guhathakurta and Gober, 2007; Kenney *et al.*, 2008). This finding is a significant contribution to the literature because typically the northwest climate is assumed to be water rich and thus not at great risk for water demand outpacing water supply. However, these findings demonstrate that similar to cities in arid climates, overall water consumption in Hillsboro, a city located in the maritime temperate climate of the PNW of the United States, is significantly influenced by external water use. This finding implies that properties with large outdoor spaces are sensitive to variations in climate, especially an increase in summertime temperature, which is widely projected to be an outcome of anthropogenic climate change.

Significantly, we did not find water use in the entire study area to be sensitive to drought conditions, a finding that contradicts previous research performed in arid climates of the Southwest United States (Balling *et al.*, 2008) and Australia (Syme *et al.*, 2004). However, we did find individual census blocks that respond with a significantly greater amount of seasonal water usage during a drought

period. The most sensitive census blocks contained newer houses than the least sensitive census blocks. In our analysis of the ratio of seasonal water use to base use, results imply that external water use during a normal summer is influenced by both socioeconomic and physical property characteristics. The census blocks that used the most external water during the summer 2004 had newer and larger homes, higher property values, and more affluent and well-educated residents. During the drought summer, 2006, the highest magnitude of external water use, similarly occurred in census blocks with newer and larger homes, higher property values, and a high percentage of well-educated residents. Importantly, our results suggest that during periods of low precipitation and higher than average maximum temperatures, seasonal water use tends to be more dependent on physical property variables rather than socioeconomic variables. The identification of the most sensitive census blocks and their physical and socioeconomic characteristics is important to local planning and conservation policy, as it determines effective targets for conservation efforts and highlights design strategies for new housing developments that may reduce stress to the water supply system, especially during peak summer demand.

The relation between the increase in the physical property variable, outdoor space, and the resultant increase in household water use has important implications for residential and landscape planning. In Arizona, research found that landscapes can consumer between 30 and 60% of municipal, summertime water supplies, which can exacerbate water supply shortages, as peak landscape demand normally coincides with peak municipal water demand (McPherson, 1990). Based on the results of this study, one planning suggestion is to decrease the number of detached homes with their own gardens and instead increase the number of townhouse style homes. The recommended design should maximize the ratio of building size to lot size and include communal outdoor garden space that is shared by a number of homes.

TABLE 4. Results of the Paired Samples *t*-Test for the Climate Sensitivity Variables.

	All Physical Property Variables	All Socioeconomic Variables	Year Built	Building Size	Total Property Value	Median Income	College Education
Drought sensitivity	0.03 ¹	0.90	0.08	0.23	0.38	0.66	0.55
2004 Interannual climate sensitivity	0.05 ¹	0.01 ²	0.00 ²	0.02 ¹	0.01 ²	0.01 ²	0.00 ²
2006 Interannual climate sensitivity	0.00 ²	0.05 ¹	0.00 ²	0.01 ²	0.00 ²	0.08	0.02 ¹

¹Denotes significance at 0.05 level.

²Denotes significance at 0.01 level.

CONCLUSIONS

This research is important to advancing goals set by the IPCC, which call for future research focusing on the impacts of climate change to real-world water systems and on specific aspects of demand-side approaches that will allow water managers to enhance their effectiveness (Bates *et al.*, 2008). This paper also contributes to the literature by establishing spatially explicit knowledge of various determinants of residential water use in a climate that has not been extensively studied. Given the large population increase the city of Hillsboro has witnessed within the past 10 years it is critical that residential water demand be evaluated in order to adequately plan for future growth. In addition to the pressures of population growth, climate variability has been shown to have significant effects on water demand. With climate change projections indicating increased air temperatures (IPCC, 2007) causing intensification of the hydrological cycle at global and regional scales (Huntington, 2006), the pressures on Hillsboro's residential water supply are likely to increase dramatically, but not consistently over space. Given this likely increase in demand it was the goal of this study to consider the determinants of SFR water use. Our analysis indicates that both physical property and socioeconomic variables have an impact on water demand, though the significance of the relation tends to vary depending on the season and the average precipitation.

Recommendations for future research include analyzing water demand at the neighborhood scale to establish relations between micro-scale determinants and drivers of water use in a more homogenous setting. Potentially significant explanatory variables, such as vegetation characteristics, including the percentage of drought-tolerant native vegetation per property lot, should be analyzed and may prove a more accurate variable than the proxy variable, outdoor space.

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LITERATURE CITED

Anselin, L., I. Syabri, and Y. Kho, 2006. GeoDa: An Introduction to Spatial Data Analysis. *Geographical Analysis* 38(1):5-22.

- Askew, L.E. and P.M. McGuirk, 2004. Watering the Suburbs: Distinction, Conformity and the Suburban Garden. *Australian Geographer* 35(1):17-37.
- Balling, R.C., Jr. and P. Gober, 2006. Climate Variability and Residential Water Use in the City of Phoenix, Arizona. *Journal of Applied Meteorology and Climatology* 46:1130-1137.
- Balling, R.C., Jr., P. Gober, and N. Jones, 2008. Sensitivity of Residential Water Consumption to Variations in Climate: An Intra-urban Analysis of Phoenix, Arizona. *Water Resources Research* 44, W10401, doi: 10.1029/2007WR006722.
- Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (Editors), 2008. *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.
- Chang, H., H. Parandvash, and V. Shandas, 2010. Spatial Variations of Single Family Residential Water Use in Portland, Oregon. *Urban Geography* (in press).
- City of Hillsboro, 2009. *City of Hillsboro Master Plan*. <http://www.ci.hillsboro.or.us/>, accessed May 2009.
- Cooley, H. and P.H. Gleick, 2009. Urban Water-Use Efficiencies: Lessons From United States Cities. *In: The World's Water 2008-2009: The Biennial Report on Freshwater Resources*, P.H. Gleick (Editor). Island Press, Washington, D.C., pp. 101-126.
- Domene, E. and D. Saurí, 2007. Urbanization and Water Consumption: Influencing Factors in the Metropolitan Region of Barcelona. *Urban Studies* 43(9):1605-1623.
- Environmental Systems Research Institute (ESRI), 2009. ArcGIS 9.3.1. Redlands, California.
- Fox, C., B.S. McIntosh, and P. Jeffrey, 2009. Classifying Households for Water Demand Forecasting Using Physical Property Characteristics. *Land Use Policy* 26:558-568.
- Franczyk, J. and H. Chang, 2009a. The Effects of Climate Change and Urbanization on the Runoff of the Rock Creek in the Portland Metropolitan Area, OR, USA. *Hydrological Processes* 23(6): 805-815.
- Franczyk, J. and H. Chang, 2009b. Spatial Analysis of Water Use in Oregon, USA, 1985-2005. *Water Resource Management* 23:755-774.
- Gato, S., N. Jayasuriya, and P. Roberts, 2007. Temperature and Rainfall Thresholds for Base Use Urban Water Demand Modeling. *Journal of Hydrology* 337:364-376.
- Gleick, P.H., 1998. Water in Crisis: Paths to Sustainable Water Use. *Ecological Applications* 8(3):571-579.
- Graves, D. and H. Chang, 2007. Hydrologic Impacts of Climate Change in the Upper Clackamas River Basin, Oregon, USA. *Climate Research* 33:143-157.
- Guhathakurta, S. and P. Gober, 2007. The Impact of the Phoenix Urban Heat Island on Residential Water Use. *Journal of the American Planning Association* 73(3):317-329.
- Gutzler, D.S. and J.S. Nims, 2005. Interannual Variability of Water Demand and Summer Climate in Albuquerque, New Mexico. *Journal of Applied Meteorology* 44:1777-1787.
- Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier, 2005. Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States. *Journal of Climate* 18(21):4545-4561.
- Head, L. and P. Muir, 2007. Changing Cultures of Water in Eastern Australian Backyard Gardens. *Social and Cultural Geography* 8(6):889-905.
- Huntington, T.G., 2006. Evidence for Intensification of the Global Water Cycle: Review and Synthesis. *Journal of Hydrology* 319:83-95.
- IPCC (Intergovernmental Panel on Climate Change), 2007. *Summary for Policymakers*. *In: Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate

- Change. Cambridge University Press: Cambridge, United Kingdom, and New York.
- Kalra, A., T.C. Piechota, R. Davies, and G.A. Tootle, 2008. Changes in U.S. Streamflow and Western U.S. Snowpack. *Journal of Hydrologic Engineering* 13(3):156-163.
- Kenney, S.D., C. Goemans, R. Klein, J. Lowery, and K. Reidy, 2008. Residential Water Demand Management: Lessons From Aurora, Colorado. *Journal of the American Water Resources Association (JAWRA)* 44(1):192-207.
- Luce, C.H. and Z.A. Holden, 2009. Declining Annual Streamflow Distributions in the Pacific Northwest United States, 1948-2006. *Geophysical Research Letters* 36:6.
- Maidment, D.R. and S. Miaou, 1986. Daily Water Use in Nine Cities. *Water Resources Research* 22(6):845-851.
- Maidment, D.R., S. Miaou, and M.M. Crawford, 1985. Transfer Function Models of Daily Urban Water Use. *Water Resources Research* 21(4):425-432.
- McPherson, E.G., 1990. Modeling Residential Landscape Water and Energy Use to Evaluate Water Conservation Practices. *Landscape Journal* 9(2):122-134.
- National Climate Data Center, 2009. NOAA Satellite and Information Service. National Environmental Satellite, Data, and Information Service (NESDIS). <http://www.ncdc.noaa.gov/oa/ncdc.html>, accessed August 2009.
- Oregon Blue Book, 2009. Oregon State Archives. <http://bluebook.state.or.us/local/index.htm>, accessed January 2010.
- O'Sullivan, D. and D.J. Unwin, 2003. *Geographic Information Analysis*. Wiley, Hoboken.
- Page, G.W. and L. Susskind, 2007. Five Important Themes in the Special Issue on Planning for Water. *Journal of the American Planning Association* 73(2):141-145.
- Praskievicz, S. and H. Chang, 2009. Identifying the Relationships Between Urban Water Consumption and Weather Variables in Seoul, Korea. *Physical Geography* 30(4):308-323.
- Schleich, J. and T. Hillenbrand, 2009. Determinants of Residential Water Demand in Germany. *Ecological Economics* 68:1756-1769.
- SPSS Inc., an IBM Company, 2010. SPSS 13.0. Chicago, Illinois.
- Syme, G., Q. Shoa, M. Po, and E. Campbell, 2004. Predicting and Understanding Home Garden Water Use. *Landscape and Urban Planning* 68:121-128.
- Tinker, A., S. Bame, R. Burt, and M. Speed, 2005. Impact of "Non-Behavioral Fixed Effects" on Water Use: Weather and Economic Construction Differences on Residential Water Use in Austin, Texas. *Electronic Green Journal* 1(22). <http://www.escholarship.org/uc/item/7rh33286>, accessed January 2010.
- U.S. Census Bureau, 2009. State and County Quickfacts. <http://quickfacts.census.gov/qfd/states/41/4134100.html>, accessed January 2010.
- Wentz, E.A. and P. Gober, 2007. Determinants of Small-Area Water Consumption for the City of Phoenix, Arizona. *Water Resources Management* 21:1849-1863.
- Zhang, H.H. and D.F. Brown, 2005. Understanding Urban Residential Water Use in Beijing and Tianjin, China. *Habitat International* 3:469-491.
- Zhou, S.L., T.A. McMahon, A. Walton, and J. Lewis, 2000. Forecasting Daily Urban Water Demand: A Case Study of Melbourne. *Journal of Hydrology* 236:153-164.