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Integrating urban form and demographics in water-demand management: an empirical case study of Portland, Oregon

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Abstract. Theories of water-resource management suggest that water demand is mediated by three interacting factors: technological innovations, pricing structures, and individual behaviors and demographics. While these factors provide useful insights for ongoing water conservation strategies, such as outreach and education campaigns, pricing schemes, and incentives aimed at residential developments, few studies examine the relationship between land-use planning and water demand. This paper reports the results of a study on land-use zoning and development-induced water consumption in Portland, Oregon. We used a geographic information system to integrate land-use records, water-consumption data, sociodemographics, and property tax information for over 122 550 parcels of varying land uses, and employed multiregression analyses to measure the effect of urban form—as measured by both the type and the structure of land uses—on regional water demand. While our results corroborate previous studies that link demographic characteristics to water demand, we go further by identifying zoning and structural attributes of the households as explaining over 93% of water use in all parcels. The paper concludes with a discussion of the opportunities and challenges for coordinating water-resource management with land-use planning.

Introduction

Urban areas throughout the US face an impending crisis in water-resource management. Water-resource researchers and managers across the US anticipate that they will face local, regional, or statewide water shortages sometime during the next ten years (*Boston Globe* 2007; *New York Times* 2007; 2009; *Terra Daily* 2007). The National Academies have concluded that a combination of limited supplies, increasing demand, warmer temperatures, and the prospect of recurrent droughts in the US "point to a future in which the potential for conflict" over water resources will be ever present (GAO, 2003; NRC, 2004; 2007, page 137). While agriculture is responsible for upwards of 70% of water consumption in the US, over the last fifty years the highest growth in water demand has occurred in urban areas (Fitzhugh and Richter, 2004; Hutson et al, 2004). Although the sustained increase in urban populations holds significant implications for a wide array of environmental challenges, the provision of sufficient quantities of water for all forms of development while ensuring adequate supplies for agricultural and nonhuman use is arguably the most significant challenge faced by urban planning agencies.

In the western US the strained relationship between water-resource management and urban planning has become increasingly apparent. A case in point is the city of Tucson, Arizona, which attempted to manage urban growth by limiting the water supply from the mid-1970s to the mid-1990s. However, after two decades of conflict between natural resource conservationists and growth advocates, the Central Arizona Project, a federal reclamation project with the goal of building a 300-mile aqueduct to bring Colorado River water to Phoenix and Tucson, finally reached Tucson (Babbitt, 2005).

Several other municipalities are attempting to ensure adequate water supplies by restricting development unless developers can provide evidence that their projects provide for an adequate supply of water into the distant future. The most notable examples of such restrictions include those in the cities of the Colorado front range, some of which aim to limit homeowner use of water to specific times of the day (Smith, 2002; Snyder, 2002). Further evidence of the growing interest in linking land use and water management took the form of a February 2003 conference entitled *Wet Growth: Should Water Law Control Land Use?* Cosponsored by the Environmental Law Institute, the American Planning Association, and other organizations, the conference highlighted the immediate and serious threat of water scarcity in the Western United States (McKinney, 2003).

While municipal policies, conferences, and reports call for identifying the explicit links between water-resource management and urban planning, there is little literature available on this linkage. Despite the breadth and depth of research on water pricing and conservation schemes, investigation of the water-management process has largely excluded assessments of the impact of varying forms of urban development patterns on water demand. Development patterns are defined here as the individual and neighborhood structures of the built landscape which, in the US context, are often the direct and intentional outcome of land-use planning initiatives. While practitioners acknowledge that water demand is affected by increases in population and proxy development (manifest in aggregate measures of regional water demand) and allowances for the way in which land can be used (manifest by land-use planning measures), few researchers have attempted to link these two factors. Although many studies have documented the social, economic, and ecological impacts of urbanizing landscapes (Chenery, 1979; Falkenmark and Folke, 2003; Folke, 2003; Postel et al, 1996; York et al, 2003), few studies have addressed the relationship between urban planning approaches and water consumption (EPA, 2006), and even fewer have investigated the relationship between the physical attributes of a development and water use (for example, see Kallis and Coccossis, 1999). The literature in this area focuses on how land-use planning can protect water quality (Burby et al, 1983) or mitigate the effects of urban flooding (Burby et al, 1983; Platt, 1987). The consideration of land-use planning as a tool for mediating water demand has received much less attention (EPA, 2006; Otto et al, 2002).

In this study we seek to quantify the influence of specific zoning and structural characteristics of urban developments on water consumption in a metropolitan region. Since a focus on the purely physical dimensions of water demand discounts the behavioral side of water use, we also build on previous analyses by examining the extent to which demographic factors in combination with land-use patterns affect water consumption. Specifically, we use a geographic information system (GIS) to characterize 122 550 parcels of different land uses in Portland, Oregon, and statistically associate urban forms and sociodemographics of water users with empirical data on water consumption over a five-year period. While *urban form* has several meanings in the planning literature (see for example, Song and Knapp, 2004), we define it as the amount of built area in a given landscape. We assess urban form in terms of two dimensions: (1) individual developments, which consist of a description of the type and structural attributes of each parcel, and (2) neighborhoods, which consist of the developments within US census-defined block groups. It is important to note that we use the term *neighborhood* in a different manner than do planning agencies, which describe a neighborhood as geographic areas bounded by land uses that share similar characteristics. Owing to the availability of sociodemographic data from the US census at the block-group scale, we use the term *neighborhood* only to refer to the geographic region bounded by each block group.

We begin our paper with a review of the dominant policies guiding current water-resource management, followed by a description of our case study and methods. After focusing on the results of our analysis by expanding on the significant factors that we found help to explain water consumption, we conclude by offering guidance to land-use planning agencies interested in linking urban development to water-resource conservation.

The challenge of integrating land and water management

The dominant paradigm in water-demand management is to 'predict and provide' (Baumann et al, 1998; Butler and Memon, 2006) by applying economic analysis and technological solutions to increase water efficiency. Empirical research has identified several determinants of residential water demand, including policy variables, such as water price and water rate; household economic variables, such as income and available technology (eg water amenities, water metering, and/or water-saving plumbing fixtures); environmental variables, such as temperature and precipitation; and demographic variables, such as household size and attitudinal variables (Baumann et al, 1998; Clouster and Miller, 1980; Danielson, 1979; Garcia et al, 2001; Grima, 1972; Hanke and de Maré, 1982; Holtz and Sebastian, 1978; Howe and Linaweaver, 1967; Jones and Morris, 1984; Jones et al, 1984; Katzman, 1977; Lee, 1969; Vickers and Markus, 1992). One of the first studies to assess factors affecting water demand was that of Forster and Beattie (1979), who identified price, income, rainfall, and number of persons per household as the primary determinants of water demand. In a later study investigating the relationship between general sociodemographic attributes and domestic water demand, Kallis and Coccossis (1999) concluded that differences in water demand are associated with income or lifestyle. In a more recent study examining residential water-consumption patterns in Adelaide, Australia, Troy and Holloway (2004) not only concluded that water-consumption patterns vary among different types of residential units, but also that per capita consumption is not significantly different across dwelling types. Other studies have suggested that income, housing type, members per household, and the presence of gardens are factors in variations in water consumption (Domene and Suari, 2006; Renwick and Archibald, 1998). Recent studies have drawn an association between landscape features (eg swimming pools and impervious surfaces) and residential water consumption (Guhathakurta and Gober, 2007; Wentz and Gober, 2007).

These studies have led to the understanding that the coupling of environmental and social factors affects residential water consumption. What is less understood is the extent to which land-management policies—including those pertaining to zoning, regulations on housing size, and provisions for nonbuilt areas, as well as differences among land uses—affect water consumption. Such land-management policies, which affect the urban form of developments, are controlled by local governments in the US. Assessing the extent to which land-management policies affect water consumption can help to address several questions: What land-use strategies are most effective in reducing water demand? How does the density of a neighborhood impact water consumption? To what extent can alternative development patterns improve the conservation potential? Addressing these questions can help to frame an approach to understanding how land-use planning strategies can affect natural resources and how urban planning agencies can work in cooperation with water-management bureaus in implementing water-conservation strategies.

In this work we assess water consumption for single-family residential (SFR), multifamily residential (MFR), commercial, and industrial land use at the *parcel level*.

An explicit focus on water consumption at the individual parcel level is significant in two respects. First, as the land parcel is the most disaggregate unit at which development regulations are enforced, it serves as the optimal spatial unit for associating land-use policies with development-induced water consumption. Because spatial units at a higher level of aggregation, such as county or state, typically consist of numerous parcels subject to a diverse array of land-development regulations, any attempt to isolate the direct effect of a specific impact of land-use planning policies on water consumption while using them as units of analysis will lead to confounding results. By estimating water consumption at the parcel level, we can most accurately discriminate among the water-induced effects of land-use policies that may change from one form of development to the next.

Second, adopting the land parcel as the unit of analysis facilitates comparisons across multiple land uses. The current state-of-the-science in water-demand analysis relies on large-scale (eg regional, state-wide, or country-wide) consumption patterns to evaluate management options (Forster and Beattie, 1979; Garcia et al, 2001; Martin et al, 1994; Renwick and Green, 2000). Although such analysis describes the role of specific land-use categories and water-consumption patterns for different sectors, including the agricultural (Johnson and Wooten, 1958; Kulshreshtha and Tewari, 1991; Raup, 1962), residential (Billings and Agthe, 1998; Garcia et al, 2001; Gutzler and Nims, 2005; Maidment and Miaou, 1986; Rhoades and Walski, 1991), and industrial sectors (Faux and Perry, 1999; Giannias and Lekakis, 1997), to our knowledge, few studies have evaluated the relative parcel-level influence of different land uses on water demand. In fact, public and private water-management agencies that assess water demand using aggregate models of demographic factors (including per capita consumption), weather, pricing, technology, and land-use mix are unable to capture the role of individual land-use influences on regional water demand (Baumann et al, 1998; Regional Water Providers Consortium, 2004). As a result, simple forecasts of water consumption (those of residential, nonresidential, and nonrevenue water consumption), although easy to prepare, are less accurate because they do not consider variations in parcel conditions that may affect water-consumption conditions.

Case study

This study focuses on the Portland, Oregon region. We approach our analysis as a *case study*, which we define as an exemplar for conducting a systematic examination and evaluation of the factors that affect water use in a single geographic region. The goal of our case study, as it is of most studies, is to inform future practice, policy, theory, and education (Yin, 2003). By examining one geographic region in detail, we aim to retain the holistic and meaningful characteristics that impact water use, while using metrics for evaluation commonly used in urban planning and water-resource management practices. By describing the region in detail we strive to provide readers with an understanding of how this region is similar to and different from other parts of the globe.

Details of the case study

With its rain-fed landscape, it might be assumed that the northwestern city of Portland has little concern that it can maintain adequate water supplies for its population. With the exception of a few municipalities in the United States, Portland's planning policies are similar to those of many urban areas in that they do not require new developments to ensure an adequate water supply into the future. However, goal 2, one of the twelve comprehensive goals in Portland's land-use plan (July 2006), which includes the Public Facilities Plan, identifies 'water' as an infrastructure subsystem (City of Portland, 2004).

Although the plan identifies mechanisms for mitigating stormwater and watershed impacts, the current plan does not require developers of new structures or those making changes to existing structures to provide evidence of the long-term availability of water resources. While new policies are beginning to emerge in some states (eg Maryland, Colorado, California, and Arizona) that explicitly require large new developments to provide evidence of the availability of long-term water supplies, these policies are vague because they rely on regional-scale demand estimates of per capita consumption with little regard to the type (or form) of urban development (McKinney, 2003).

The Portland region is largely supplied by water from reservoirs in the Bull Run Watershed, which, east of downtown and covering 102 square miles, receives snowmelt from the Cascade mountain range. The water from the Bull Run Watershed that first flowed into Portland water taps on 2 January 1985 consisted of water from Bull Run Lake (a natural lake) and Bull Run River, with in-town storage reservoirs at Washington Park and Mt Tabor Park. The Portland metropolitan region currently has twenty-two water providers overseen by the Portland Water Bureau. Being responsible for the administration and technical aspects of providing water resources to approximately 802 000 Oregonians in nineteen of the region's water districts, the bureau is the largest provider in the state. In 2006–07 the Bureau directly served 146 000 residential households (both single-family and multifamily residences) and approximately 20 000 commercial and industrial customers.

Similar to other growing regions in the western US, the Portland metropolitan area is expected to accommodate 100 000 new residents by 2020 (Office of Economic Analysis, 2007). During the same period, climate change models predict that the Pacific Northwest will experience a 2 °C increase in temperature and a 1.3 billion gallon decrease in annual water supply (Palmer and Hahn, 2002). Concerns regarding the availability of water in Oregon and the possibility of 'climate refugees' fleeing into the Pacific Northwest are beginning to make front-page news in state newspapers (see *The Oregonian* 8 October and 30 December, 2008, http://www.oregonlive.com). Such pressures on water supply from population growth and climate change necessitate that we gain a strong understanding of how urban planning policies affect the availability and distribution of regional water resources and the consequences of development-induced water consumption (Vorosmarty et al, 2000). Doing so is particularly important, not only because new developments are at various stages of completion throughout Oregon, but also because existing urban growth boundaries are being expanded (Metro, 2002a; 2002b).

The Regional Water Providers Consortium (RWPC), a volunteer organization comprising twenty-two water providers in the Portland metropolitan area, is the only regional entity that promotes collaboration and coordination among its members to improve the planning and management of municipal water supplies. The RWPC developed a strategic plan (Regional Water Providers Consortium, 2004), in response to the Oregon Water Resources Department's 2002 requirement to develop water-supply plans with a "reasonable and appropriate schedule with 5-year benchmarks for implementation of conservation activities" (Oregon Administrative Rule 690-086-0130). While its approach is significant in terms of coordinating land-use planning and water-resource management, the RWPC does not have regulatory authority, and thus serves only as an advisory council. As a result, water-management and land-use planning occurs in the region, but with only limited coordination among the parties involved.

Research design

Our research approach consisted of a four-step process for assessing the influence of urban form and sociodemographics on water demand. In the first step we developed our *unit of analysis* using data from the regional land information system (RLIS), which provides data regarding individual parcels for the entire study region for tax assessment purposes. RLIS data, which are available as quarterly updates from the regional planning authority, known as Metro, from 1999 to the present, contain addresses, structural attributes (building area and lot size), and land-use information (zoning type and tax code). To ensure consistency across multiple years, we included structural and land-use data for the month of December for the year 1999 and the years 2002–05. Because water consumption data were not available for the years 2000 and 2001, we excluded data from those years from our analysis.

In the second step we incorporated metered, parcel-level consumption data provided by the Portland Water Bureau into our analysis. These water consumption data contained retail sale information regarding the total amount of water consumed in each parcel categorized by billing period for the years 1999 and 2002–05. Metered billing records are an invaluable resource for determining and allocating demands, because they are actual water-use measurements. However, because metered data rarely include information on spatial attributes, we used a GIS (ArcMap 9.1— ESRI, Redlands, CA) to georeference water consumption to specific parcels available throughout the RLIS region. Once a georeference was obtained, we summed the total amount of water consumed for each parcel over the entire year. We overlaid each georeference parcel on a zoning map for the same year and recorded the total area of each land use (in acres) and the total number of parcels for each land use (count). In accordance with earlier research conducted in other parts of the US, we included two regional sociodemographic factors for each block group: (1) median annual income; and (2) level of education in terms of the number of college-educated people.

In the third step of our analysis we focused exclusively on the relationship between SFR land use and water consumption. We did so for two reasons: first, consistent with most large metropolitan regions, over 80% of the developed land in the Portland metropolitan region is occupied by SFR units; thus, SFR units represent the largest cumulative zoned area in the metropolitan region. Second, SFR developments in North American cities typically consume the greatest proportion of water resources of any land-use type—upwards of 70% of total urban water use—and thus modifications in their design and landscape patterns may have tremendous potential for improving water conservation efforts. After gathering specific structural data regarding SFR developments from the RLIS (building area and number of units), and sociodemographic data for SFR neighborhoods (income and college education), we hypothesized that the urban form of individual parcels and neighborhoods affects water consumption.

Our final step consisted of statistical analysis of the data using the Pearson's correlation and multiregression models (SPSS 12.0 Inc—SPSS Inc., Chicago, IL). We performed a Pearson's correlation to determine the statistical associations between individual land uses across all years and all land uses for each year. We then used an additive combination of independent variables to create three ordinary least squares multiregression models. Our first model examined the total area zoned under each land-use category and the total water consumption per year. Since we were able to capture the zoned area of each land use within the study region, we were able to attribute total water consumption to individual land uses. Whereas all three regression models had the same dependent variable, namely the total amount of water consumed, each had a different independent variable (see table 1). The water-consumption unit

Table 1. Description of variables employed in the regression models.

Model	Variable	Description	Measurement unit	Source of data
1	X_{1i}	area zoned as SFR	acre	Regional Land Inventory System
	X_{2i}	area zoned as MFR	acre	Regional Land Inventory System
	X_{3i}	area zoned as commercial – industrial	acre	Regional Land Inventory System
	X_{4i}	area zoned as vacant	acre	Regional Land Inventory System
2	X_{1j}	total building area	square feet divided by 100	Regional Land Inventory System
	X_{2j}	SFR developments per acre zoned as SFR	number per acre	Regional Land Inventory System
	X_{3j}	median income	US dollars divided by 1000 per block group	US Census (2000)
	X_{4j}	total number of college-educated persons	number per block group	US Census (2000)

that we used in all three models as the *acre-foot*, a volume metric that consists of approximately 326 000 gallons (or 1.24 million liters).

The independent variable in the second regression model, which assessed the role of total building area of individual land uses in total water consumption per year, was the amount of building area per parcel. Because we were examining the same independent and dependent variables across multiple years, we developed a pooled cross-section model of both zoned and building area models across all years, which Gujurati (1995) described as the appropriate means of examining data across multiple years. To account for differences in the units we transformed several of the independent variables in model 2, either by multiplying or dividing by a factor of 10.

Our final regression model, which examined the total water consumption of 116 552 SFR developments in 2005, investigated only SFR developments and the impact of their attributes on water consumption. We used a GIS to summarize all parcel attributes according to census block group to directly account for sociodemographic factors while assessing the role of structural attributes on water consumption (model 2).

Results

We describe our results in two steps. First, because the individual years that we examined had varying number of cases, we provide general descriptive statistics, including the means and sums of all land uses in the models. Second, we describe the results we obtained from all the models by examining the relationship between the independent variables and water consumption in each year and across all years.

Descriptive statistical analysis

The total number and area of all land uses varied only slightly throughout all the years examined. Our average counts for all the land uses indicate that the largest proportion of developments was for SFR use and the smallest proportion was for industrial land use (see table 2). Because the results of the Pearson's analysis indicated that the

Table 2. Amounts of each land use and total water consumed, averaged for all years.

Land-use type	Unit	Mean	Sum
Commercial	count	9.69	4 156
	acres	7.06	3 027
Industrial	count	0.09	38
	acres	36.00	155
Multifamily residential	count	2.63	1 127
	acres	1.01	434
Rural	count	0.14	62
	acres	1.43	612
Single-family residential	count	271.68	116 552
	acres	41.74	17 905
Vacant	count	1.83	787
	acres	0.46	196
Water use	acre-foot	47.56	20 402

number of industrial land uses was too small to include separately in the statistical models, we combined industrial with commercial uses for our analysis. While combining industrial and commercial land uses is disadvantageous in that it confounds the results, it is advantageous in that it facilitates assessment of how the zoning and structural attributes of both these land uses affect water consumption. We also excluded rural, forest, and public land use from our analysis so that our statistical analyses included only the four land uses of commercial – industrial, MFR, and SFR, in addition to areas zoned as *vacant*, defined as open spaces that have been cleared for future development or land that has been abandoned. We included areas zoned as vacant in our analysis because they represent open spaces, spaces cleared for development, and abandoned lots, all of which are an integral part of every urban landscape.

The total amount of water use across all land uses averaged for all years was 20 402 acre-feet, which is approximately 6.4 billion gallons (25 billion liters). When interpreting the results for MFR units, it is important to note that our analysis considered one MFR unit to be one SFR unit, even if an individual MFR unit consisted of multiple households. Unfortunately, data on the number of units in each MFR were not available at the time of our analysis, which made it impossible for us to assess the role of individual MFR units on water use. However, we were able to account for MFR units separately, as will be shown in the discussion section.

Pearson's correlation matrices provide information regarding the extent to which individual land uses are correlated. The results of our calculation of the matrices indicate insignificant colinearity among most land uses and small correlation coefficients (Pearson's $r < 0.2$, $P = 0.001$) among the few cases of colinearity. In addition, we found the variance inflation factor values to be low ($V < 10$), which suggests minimal levels of multicollinearity among our regression variables.

Inferential statistical analysis

The first multiregression model examined the explanatory power of land-use zoning categories in predicting total water consumed for all land uses. Our results revealed several trends between 1999 and 2005 (see table 3). For 1999 we found a strong and significant correlation between the acres zoned for each land use and the water consumed ($R^2 = 0.74$, $P < 0.0001$). Beta coefficients for 1999 indicate that two land uses, namely SFR and commercial – industrial use, explain almost three quarters of the total water consumed. For 2002 – 05, SFR, commercial – industrial, and MFR use are significant, helping to explain 55% to 64% of the total water consumption. Vacant land

Table 3. Unstandardized beta coefficients for total land-use zoning areas and adjusted R^2 for yearly models.

Land-use type	1999	2002	2003	2004	2005
Commercial – industrial	0.28**	0.07*	0.24**	0.37**	0.36**
Multifamily residential	−0.16	3.27**	4.78**	3.72**	2.30**
Single-family residential	1.10**	0.51**	0.59*	0.74**	0.53**
Vacant	0.01	0.08	0.02	−3.38**	−3.11**
Model adjusted R^2	0.74**	0.66**	0.54**	0.63**	0.58**

* Significance < 0.05; ** significance < 0.01.

was significant only for 2004 and 2005, the years during which an increase of one acre of vacant land resulted in an approximately 3-acre-foot decrease in water consumption.

The second regression model examined the total building area of all land uses and total water consumed. The results suggest that the *amount of building area* for each land use explains a greater proportion of total water use than do the total areas *zoned* a specific land use (see table 4). The adjusted R^2 for the five years examined suggest that between 78% and 92% of total water use can be predicted by the total building area of SFR, MFR, and commercial – industrial developments. Vacant land units are not significant for any year, possibly owing to the fact that vacant lots, by definition, do not contain structures and building areas. The modest differences among the SFR, MFR, and commercial – industrial land-use coefficients across all years suggest predictable water-consumption patterns for these land uses.

We included both total zoned land use and building areas for all four land uses across all years in the pooled cross-section regression model (see table 5). Because we found the building area of vacant lots to be insignificant (see table 4), we replaced

Table 4. Unstandardized beta coefficients for total land-use building areas and adjusted R^2 for yearly models.

Land-use type	1999	2002	2003	2004	2005
Commercial – industrial	8.30**	0.24**	2.62**	2.44**	2.36**
Multifamily residential	5.45**	4.26**	4.79**	6.00**	5.20**
Single-family residential	5.70**	3.14**	3.87**	4.02**	3.50**
Vacant	0.77	1.14	0.47	7.24	1.15
Model adjusted R^2	0.92*	0.84**	0.78**	0.85**	0.83**

** Significance < 0.01.

Table 5. Unstandardized beta coefficients for total land-use zoned and building areas and adjusted R^2 for pooled cross-section regression model.

Land-use type	Coefficients	
	zoned	building area
Commercial – industrial	0.24*	1.66*
Multifamily residential	1.69*	3.88*
Single-family residential	0.72*	3.76*
Vacant	0.72	−0.10* [a]
Model adjusted R^2	0.84*	0.93*

* Significance < 0.05.

[a] Zoned, not building area.

building area with zoned area. Using areas which were zoned vacant allowed us to compare areas with and without structures in the same model. Our results suggest that MFR use has the greatest impact on water consumption and SFR and commercial–industrial use incrementally less so. MFR building areas have the highest level of consumption for all years, which indicates that for every one acre of additional MFR development built, an additional 3.9 acre-feet of water is required. In terms of building area, SFR use is similar to MFR use, requiring 3.8 acre-feet for every acre of development. On a per unit basis, MFR use includes more than one household; therefore, our results suggest that SFR development has the greatest demand on water consumption in the study region. Commercial–industrial use requires about half the amount of water as does MFR and SFR use, which suggests that every acre increase in commercial or industrial zoned land results in an additional 1.65 acre-feet in water consumption.

The last regression model examined the impact of SFR household and neighborhood characteristics on water consumption for 2005, the most recent year in our analysis. The results indicate that both urban form and sociodemographic factors contribute to and are significant in explaining water consumption (see table 6). Of note is the fact that an increase of 100 ft^2 (9.3 m^2) of SFR development resulted in an increase of almost 3 acre-feet (approximately 978 000 gallons or 3.7 million liters) of water consumed per year. In terms of neighborhood characteristics, an increase in one household per acre resulted in a decrease of water use by 1.26 acre-feet (411 000 gallons or 1.6 million liters), when accounting for sociodemographic factors.

Table 6. Results of third regression model examining the effect of household and neighborhood characteristics on water consumption. SFR denotes single-family residential.

SFR characteristic	Coefficient	Standard error	*t*-statistic
Building area (divided by 100)	2.90**	0.34	8.64
Households per acre	−1.26**	0.26	−4.84
Median income (divided by 1000)	0.14**	0.05	2.60
Total number of college-educated adults (multiplied by 100)	−0.20**	0.05	−4.14
Constant	22.95**	4.77	4.82
Adjusted R^2	0.71**		

** Significance < 0.001.

Consistent with the findings of other studies (Domene and Suari, 2006; Gutzler and Nims, 2005; Wentz and Gober, 2007), both income and the number of college-educated residents help to explain water consumption. Our results suggest that a $1000 increase in median income per block group resulted in a 0.14 acre-foot increase in water consumption, whereas an increase of 100 college-educated residents per block group resulted in a 0.2 acre-foot reduction in water consumption. These sociodemographic findings are consistent with normative theories of environmental behavior that suggest that education is one of several factors affecting environmental conservation (Clayton, 2007).

Discussion

This study explored the relationship between urban form and water use in an urban area of the US. The results suggest that examining the impact of the physical conditions of urban areas can be advantageous in increasing water conservation in urban and urbanizing regions. The role of the built environment in social processes has been well documented in early works, such as Whyte's *The Social Life of Small Urban Spaces* (1980), and in later studies highlighting the relationship between urban forms and stormwater (Schueler, 1994; 1995; Shandas, 2007), travel behavior (Buliung and Kanaroglou, 2006), human health (Handy et al, 2002), and air pollution (Stone, 2008). The results of some of these studies have been applied to the development of urban policies, including policies limiting the amount of impervious surfaces in urbanizing areas (Schueler, 1997) and requiring improvement in ventilation systems in developments located near highways (Bhatia, 2007). Similarly, this study suggests that modifying the physical pattern of development is one approach to consider for increasing water conservation.

Approaching water consumption through the lens of urban form has several advantages, including (1) providing a comprehensive perspective that encompasses several land uses directly linked to water-resource planning; (2) aiding in the development of land-use planning policies sensitive to types and forms that enable effective approaches to water conservation; and (3) identifying specific coefficients relevant to planners when evaluating future scenarios of urban growth. Below we discuss our results and offer three specific planning strategies that would likely reduce water consumption in new and existing developments in urban and urbanizing regions.

Design-oriented approaches to water conservation

When considered all together, our results provide a basis for examining the role of design-oriented approaches to water conservation. The results of our analysis indicate that, in terms of land use, SFR development leads to the greatest consumption of water in our study region. Additionally, they suggest that an effective design-based strategy for reducing development-induced water consumption among *new* SFR developments entails decreasing the size of residential developments and increasing residential density. The benefits of smaller development size and greater lot density are twofold. First, a decrease in building size reduces the amount of area that contributes directly to water consumption. Though our data precluded a description of the type of rooms (eg bathroom, kitchen, or laundry room) that are most water intensive, we were able to identify the extent to which changes in the size of an SFR development contribute to water demand. For example, a 25% reduction in the average building size—a reduction from 2800 ft^2 to 2100 ft^2 in the study region—is associated with a 20.3 acre-feet or 6.6 million gallon (25 million liter) reduction in water consumption per year. For a new residential development of 100 SFR units, such a reduction would reduce water consumption by almost 2000 acre-feet per year.

Second, we found an increase in residential density to be significantly negatively related to water consumption. Without any change in the size of buildings, an increase in the residential density by one household per acre would reduce the amount of water consumed by 1.26 acre-feet or 410 000 gallons (1.6 million liters) per year. Therefore, for a new subdivision of 100 homes, a 25% increase in the number of households per acre—an increase from 4 to 5 households per acre—would reduce cumulative water consumption by approximately 126 acre-feet. In addition, this modest increase in density would increase the land available for other uses. These results are significant given the fact that water conservation measures in rapidly growing areas of the western US are inextricably linked to the concern of reduced stream flows and other ecosystem impacts (Grimm et al, 2008; Patrinos and Bamzai, 2005).

Managing water consumption in existing developments

Although strategies such as delineating urban growth boundaries provide mechanisms for slowing the expansion of new developments, it is important to note that changes to a city's land-development regulations have little, if any, impact on existing developments.

As the vast majority of the Portland region's future development plans (eg its 2020 and 2040 land-use plans) are already in place, changes in peripheral development will have only a limited impact on regional water consumption. Accordingly, effective strategies for reducing water consumption must also address *existing developments*.

Our results suggest that targeting both SFR and MFR developments may be the most effective means of reducing overall water demand. Since MFR developments contain multiple households within each unit, it is not surprising that the MFR coefficient for water use is greatest in both zoned and built areas. However, on a per-unit basis, SFR developments consume the greatest amount in the study region. Of all the literature based on extensive empirical research that provides recommendations for increasing water conservation within SFR developments, Sharpe's (2006) framework provides the most suitable theoretical basis for involving urban planning agencies in the water management of SFR developments. Specifically, Sharpe (2006, page 112) explains:

> "Regulatory agencies could engage in more extended dialogue about whether and what constraints on water use are appropriate. Discussion of local reservoir levels could be a useful way of helping water users localize and visualize water issues during periods of scarcity. Water efficiency promotion—currently constrained by the dominant discussion about water as a commodity—could provide the means for households to participate in a wider process of managing regional water resources."

Because planning agencies are mandated to engage in public outreach campaigns, they are likely to have greater access to the urban citizenry than do water-management bureaus. By stressing the explicit charge of planning agencies to engage in a public participation process, water-management bureaus can develop outreach campaigns aimed at addressing behavioral aspects of water use, thereby further improving the effectiveness of conservation activities in existing SFR developments.

Engaging residents in existing MFR developments may also be an immediate and effective means of improving regional water-conservation efforts. While SFR units vary according to building specifics, builder expectations, and consumer preferences, MFR units often contain similar building codes within each unit. Requiring water-conservation technologies, such as low-flow devices and water-reuse systems, and providing incentives to owners can be part of an immediate approach by both water-management bureaus and planning agencies. However, while some planning bureaus in the US have established water-conservation policies during extreme drought events (see Redwood City, CA; Creedor, NC; the state of New Mexico), few municipalities have promulgated ordinances requiring water conservation for the construction of any type of development, whether MFR, SFR, commercial, or industrial.

As we did for SFR and MFR developments, we found that commercial and industrial land uses contained statistically significant results for both zoned and building areas for all the years examined. Because the growth of commercial and industrial land use has implications for regional economic development, water-management agencies may be reluctant to reduce building sizes or land-use density for those land uses. In the short term, however, planners can refer to the models described in the current literature for improving the efficiency of water use in commercial and industrial processes, which may provide benefits in addition to that of improving efficiency, including short-term and long-term financial savings to owners (Steiner and Thompson, 1997; USGCRP, 2001). Research in the field of industrial ecology has identified mechanisms for improving water efficiency in commercial and industrial establishments in the longer term (Prior and Potgieter, 1981; Robe, 1977; Steiner and Thompson, 1997). Specifically, researchers have identified specific means of increasing the efficiency of water resources for a variety of land uses, from restaurants to laundries to food processing plants, by designing processes that minimize water intake and maximize wastewater reuse at minimal cost (Carowin and Waynick, 1991; Girardet, 2005). While few such approaches have been applied to urban development plans (Waterman, 2004), impending water shortages in many parts of the western US will require the application of short-term and long-term approaches to improving the efficiency of water use by commercial and industrial processes.

Implications for urban water planning

Gaining an understanding of how changes in urban form affect water consumption can be instrumental in managing metropolitan growth. While Arizona and California are pioneers in requiring developers to provide evidence of a long-term water supply in order to obtain approval for development projects, most regions in the US, including Portland, have no explicit requirements based on the link between urban development and water-supply standards. Our analysis suggests that two characteristics of land-use plans, namely zoning and development regulations, are instrumental in predicting water demand. Zoning can be used to link types of future urban development (eg for 2030 and 2040) to include a combination of infill, expansion, and connection of urban clusters, with explicit identification of commercial, industrial, MFR, or SFR areas. The trends in the data suggest that some land-use policies aimed at zoning, rezoning, and infill may already be affecting the amount of water consumed in the Portland region. For example, the number of MFR units increased from 188 in 1999 to over 1100 in 2005, reflecting one objective of the Portland region's urban planning policy, and resulting in an increase of density within the urban center. Portland's development regulations, however, currently do not address water requirements when proposing land-use change.

While the explanatory power (adjusted R^2) of the building area suggests that it is a better predictor of total water consumption than is zoned area ($R^2 \sim 0.6$ versus $R^2 \sim 0.8$), the two models may provide different types of useful information for planners considering future development. Since the planning process is iterative and cumulative (Berke et al, 2006) and follows a rational model that proceeds in a systematically timed manner, a comparison of zoned area and built area can provide valuable information to planning agencies at different phases in the planning process. For example, the first step in creating an urban land-use plan is identifying the amount of area that will be zoned for SFR, MFR, and commercial – industrial development and classifying the areas not to be developed as vacant lots. The second step is determining the amount of built area for each of these land uses. Thus, the chronology of the land-use planning process allows for the consideration of expected water use at two periods in time—the first when general zoning occurs and the second when the amount of built area for each of the zoned areas is being appropriated. While estimates can be useful for determining the timing of new development, these estimates can also be used for predicting water demand when areas are being rezoned and slated to undergo infill development.

Conclusions

Over thirty years ago Dunne and Leopold (1978, page 53) described the relationship between water and planning in the following manner:

> "Water is central to many planning problems concerned with natural and altered environments. The awareness of mutual concerns and the value of shared experience are growing. The central position of water in planning the avoidance or the rectification of environmental problems is leading specialists to discover new and interesting problems to which their talents can be applied."

Unfortunately, water-management and land-use planning since Dunne and Leopold's seminal publications have become increasingly disparate in its administration, evaluation, and management. This study aims to improve coordination between land-use planning and water-demand management by providing information regarding the physical determinants of water use. Our specific aim is to improve the decision-making efforts of urban planning agencies by providing empirical evidence that allows them to gain understanding of how urban form can affect water use in urban areas.

With population growth and urban development affecting land use in profound and uncertain ways, approaching water use through the lens of urban planning can improve the effectiveness of water-conservation activities in a metropolitan region. Because the physical attributes of development can be readily manipulated through urban planning policies during the development or redevelopment process, land-use planning can play a direct role in water-resource management. In addition, because planning agencies have discretionary authority on the types, location, and intensity of land use, they are positioned to have considerable impact on water consumption by varying land-use patterns. This study offers specific mechanisms through which planning and water-resource managers can work together to improve conservation efforts. According to our results, planners have the ability to develop predictive models for assessing the demand on water resources when given alternative scenarios of urban development. By developing predictive models, water-resource managers can safeguard supplies in the event of uncertain climatic events, such as droughts or unanticipated reductions in snowfall, or in areas dependent on snowpack.

While our models provide insight into the linkage between land use and water planning, they represent only initial information on this significant relationship. A fully integrated approach should draw both on theoretical and empirical understandings of water demand in multiple regions to develop frameworks for defining the legal responsibilities of urban-planning and water-resource-management agencies. These frameworks may develop as formalized agreements, comprehensive plans with explicit water-management sections, and/or long-term urban management plans that mandate the integration of land-use planning with water-management policies. Because water-resource availability affects the economic, ecological, and human health of a region, such integrative approaches will become increasingly necessary as pressures from urban development and climate variability place greater stress on the natural resources upon which we depend.

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