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Residential Land Use, the Urban Heat Island, and Water Use in Phoenix: A Path Analysis

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Abstract

While previous studies have shown that urban heat islands (UHI) tend to increase residential water use, they have not yet analyzed the feedbacks among vegetation intensity, diurnal temperature variation, water use, and characteristics of the built environment. This study examines these feedback relationships with the help of a path model applied to spatially disaggregated data from Phoenix, Arizona. The empirical evidence from the observations in Phoenix suggests the following: (1) impervious surfaces contribute to increased residential water use by exacerbating UHI; (2) larger lots containing pools and mesic vegetation increase water demand by reducing diurnal temperature difference; and (3) smart design of urban environments needs to go beyond simplistic water body- and vegetation-based solutions for mitigating uncomfortably high temperatures and consider interactions between surface materials, land use, UHI, and water use.

Keywords

water use, heat islands, land use, land cover, path analysis

Introduction

Increasing concerns over the sustainability of fresh water resources in many parts of the world have led to renewed calls for water conservation and protection of the sources from contamination (Gleick 2006; United Nations Development Program 2006; Collins and Bolin 2007). In comparison to the global scenario, the North American continent is relatively free of persistent water supply problems, at least until now. The highly developed water storage and delivery infrastructure in the United States is being tested by rapidly increasing demands in some regions, overexploitation of the sources, and a changing climate. In 2003 the U.S. Government Accounting Office reported that water managers in thirty-six states anticipate local, regional, or statewide water shortages some time in the next ten years. Metropolitan Phoenix is among the regions that have experienced periodic drought conditions and occasional water supply shortfalls. In this article, we examine how the localized impact of urban heat islands (UHI) may lead to increased demand for water in Phoenix and the direct and indirect effects of land use and land cover on urban water use. Although this study focuses on local-area impacts of the urbanization process, it provides insight into the general climate and resource dynamics of cities in a warmer future.

UHI form when roads, buildings, and other urban construction materials with high heat absorption capacities absorb the sun's radiant energy during the day and then release heat to the atmosphere at night (Oke 1987). This localized nighttime emission of heat elevates diurnal low temperatures when compared to unbuilt areas in the urban periphery (Unger 2004). One clear indication of the intensification of UHI effects is the rapid rise in the minimum daily temperatures compared to the slower rise in maximum temperatures, which results in diminished diurnal temperature range (DTR) (Landsberg 1981; Zhou et al. 2004).

Phoenix's UHI formations have been the subject of numerous studies since the early 1980s (Cayan and Douglas 1984; Balling and Brazel 1986a, 1986b, 1987; Hawkins et al. 2004; Brazel et al. 2007). Temperature records from twelve Phoenix weather stations between 1949 and 1985 showed rapid increases in low temperatures in the central portions of the city and expansion of areas affected by UHI (Balling and Brazel 1987). More recent studies show that the location of new subdivisions and the pace of development determine the extent of elevated nighttime temperatures in Phoenix (Brazel et al. 2007). The low temperatures recorded by the weather stations that were included in the study rose by almost 2°F for every one thousand new homes built within a radius of 0.5 kilometers. As expected,

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urban core locations were, on average, 4°F warmer than the surrounding rural countryside on a typical June night. In addition to rapid urbanization, Phoenix's warm, dry climate and large number of clear, calm days create conditions that are conducive to UHI development (Brazel et al. 2000).

At least one previous study has already established the statistically significant relationship between UHI and increased water demand (Guhathakurta and Gober 2007). This 2007 study reported noticeable increase in water demand in single-family houses located in areas affected by heat islands, after controlling for other factors determining water use. The study, however, did not examine feedbacks among vegetation intensity, nighttime temperatures, water use, and single-family residential design characteristics at a neighborhood scale. For example, while higher vegetation intensity is expected to increase water demand in Phoenix, it may also reduce nighttime temperatures, thereby moderating water demand. Similarly, the presence of pools, which undoubtedly increases water demand, could lower local nighttime temperatures, reduce evaporation, and lower water demand. We use a path model to show the direct and indirect effects of design features of the single-family residential neighborhoods on local DTR and water use. Finally, we provide some guidelines for the design of neighborhoods that mitigate excess heat and avoid unnecessary water demand.

Scenarios of Future Water Availability

Rapid growth, rising affluence, and global warming are placing increased pressure on many urban water supplies. Although the problem of inadequate water supplies occurs primarily in developing countries, climate change is expected to exacerbate periodic and chronic shortfalls across the world, particularly in arid and semiarid regions (Intergovernmental Panel on Climate Change 2007). There is now a broad consensus among climate models that arid portions of southwestern North America will warm and dry significantly, with likely reductions in the amount of water available to the region's major cities. Seager et al. (2007) argue that the transition to a warmer, drier climate future is already under way. At the same time, rapid population growth has increased water demand across the western USA. A recent National Research Council report on Colorado River Basin water management warns that "steadily rising population and increasing urban water demands in the Colorado River region will inevitably result in increasingly costly, controversial, and unavoidable trade-off choices to be made by water managers, politicians, and their constituents" (National Research Council 2007, 2-3).

Water, Climate, and Urban Design

The dual challenges of climate change and rapid growth have caused many land and water managers in the West to look for novel ways to reduce urban water consumption. In the past, the typical conversation about water demand management has focused on pricing schemes, rate structures, voluntary and mandatory conservation programs such as outdoor water restrictions and rebates, and public education. More recently, attention has shifted to deeper, more structural considerations that involve the form of urban development, patterns of land uses, types of land cover in the city, and the water-consumptive lifestyles that are the norm in many new master-planned communities. The practice of sustainable urban development involves consideration of street patterns, block size and form, lot configuration, layout of parks and public spaces, and the use of impervious surfaces, although there is still considerable disagreement about the specific impacts of such attributes in the overall context of sustainability (Jabareen 2006). Yannas (1998) has outlined design principles that include the density and type of buildings, the configuration of street canyons, building design, urban materials, and vegetation to influence evaporative cooling processes and traffic flows. Preventing sprawl and promoting a more compact city with greater diversity of land uses generally are thought to reduce the use of environmental resources such as water and energy.

In a review of water supply and demand conditions in Barcelona, Saurí (2003) notes that domestic water consumption rose between 1975 and 2000, despite a relatively stable population. He pointedly questioned whether gains from water conservation and technical efficiency could compensate for increases in water demand stemming from growing affluence, smaller households, and the proliferation of low-density residential development. Another study also established that lot size, a surrogate for density; the presence of pools; and type of landscape treatment significantly impact household water demand in Phoenix (Wentz and Gober 2007). Studies elsewhere found similar relationships between the nature of the built environment, size of garden, landscape treatment, and residential water consumption (Renwick and Green 2000; Mukhopadhyay, Akber, and Al-Awadi 2001; Syme et al. 2004; Domene, Saurí, and Pares 2005). These studies offer insights into the ways urban design and prevailing lifestyles affect water consumption and future sustainability.

Relationships between urban design and the UHI have also emerged as an important topical theme in the fields of urban climatology and urban planning (Sailor 2006; Stone 2004, 2005; Stone and Norman 2006). As climatologists have achieved a clearer understanding of the physical properties and causal mechanisms for the UHI, they have begun to address UHI-mitigation strategies and to characterize and quantify the effects of land use patterns on surface warming. There is, however, no definitive answer about how the density and nature of development affects surface temperatures. In a recent study of Atlanta, Georgia, Stone and Norman (2006) found that the amount of impervious surface and lawn area on land parcels were positively associated with the net black body flux, an indicator of surface warming. Significantly, this study noted that lawns were among the biggest contributors to net black body flux in Atlanta, whereas a tree canopy cover had the opposite effect. Surface warming was negatively related to tree canopy cover percentage, confirming the value of tree-planting programs in mitigating surface warming. A 25 percent reduction in impervious surfaces and residential lawn space combined with an increase in tree canopy from 45 to 60 percent would reduce the net black body flux by approximately 40 percent.

Previous Studies Linking Water to Heat Islands

There is much confusion about the effects of vegetation and pools in regulating temperatures at nighttime, although their use for moderating daytime temperatures is quite common. Recent research seems to indicate that while surface evapotranspiration can reduce the rise in temperature during the day through evaporative cooling of the surface, it has little, if any, effect on nighttime temperatures (Cao, Mitchell, and Lavery 1992; Verdecchia et al. 1994; Mearns et al. 1995; Dai, Trenberth, and Karl 1999). Furthermore, both empirical and theoretical research has indicated that evapotranspiration rates are higher and the DTR lower over vegetated surfaces than over bare soil (Saltzman and Pollack 1977; Oliver et al. 1987; Radersma and de Reider 1996; Xue, Fennessy, and Sellers 1996). More recently, studies examining a peculiar phenomenon in the Eastern United States, where the DTR has two comparable maxima between autumn and spring separated by a broad summer minimum, have concluded that the most salient explanation involves the growing season and the vegetative cover that offers (Durre and Wallace 2001). While the seasonal warming during the day reaches a peak just before the onset of the growing season, it slows down after "first leaf" due to daytime evaporative cooling through transpiration, thereby reducing the DTR (Schwartz 1996). These studies together suggest that higher intensity of vegetative cover may actually reduce DTR by moderating temperatures during the daytime but not at night.

The studies in Atlanta and Phoenix reported earlier also point to the markedly different contribution of different types of vegetative covers to surface heating. While lawns and small shrubs might increase net black body flux, trees with large leafy canopies may have the opposite effect. Hence, the combination of different types of plants and natural land cover may lead to complex feedback dynamics as they relate to black body flux. Modeling and predicting the resultant effect on diurnal temperature difference is not trivial and requires further research.

The availability of water in residential areas and the ease with which it evaporates depends on the characteristics of the lot, the presence of pools, and the type and intensity of vegetation (Guhathakurta and Gober 2007; Wentz and Gober 2007). Larger lot sizes enable more areas of vegetative cover and larger pools, thereby having an indirect positive effect on water demand. According to the most frequently cited report by the Soil Conservation Service (1975), the percentage of impervious areas decreases with increasing lot sizes (Arnold and Gibbons 1996). In contrast, a more recent study of forty thousand single-family homes in Madison, Wisconsin, found that increasing lot sizes was associated with more impervious areas (Stone 2004). Regardless, gross pervious to impervious ratios at the neighborhood level are widely accepted to be in accordance with Soil Conservation Service guidelines. Pervious surfaces retain more moisture that is then subject to evaporation under specific temperature and climatic conditions. Hence, lot sizes have both direct and indirect effects on water demand in residential neighborhoods.

As in the case of vegetative cover, the evaporation rate of water at different times of the day is the subject of some debate. The literature provides a profusion of equations and no consensus on their use in predicting evaporation from free water surfaces. A survey by Sartori (2000) compared twenty models for calculating evaporation and demonstrated that the results from these models were significantly different. A widely used formula for deriving evaporation rates from pools is provided in the handbook published by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE; 2005). Although this evaporation equation has also been questioned (see Smith, Löf, and Jones et al. 1994), the fundamental drivers of evaporation rate are widely accepted to be (1) the evaporation coefficient (which depends upon wind velocity), (2) the difference between the humidity ratio in saturated air and the same ratio as measured in air at the time, and (3) the latent heat of water at pool temperature (Smith, Löf, and Jones 2004; ASHRAE 2005). Based on these drivers, it is easy to demonstrate that evaporation rates would be much greater when the difference between the air temperature and water temperature is high, or when the humidity level in the air is at a minimum (under *ceteris paribus* assumptions). In Phoenix wind speeds are lower at night than during the day, and pool and air temperatures are closer, suggesting lower levels of evaporation at night than during the day.

Pools and large water bodies are routinely used as amenities as well as cooling devices in hot urban regions. The specific trade-offs between elevated water demand due to evaporation from water bodies and the relief from uncomfortably high temperatures they offer remains unexamined in the literature. The effect of pools on water consumption is both direct and indirect (induced). While evaporation from pool surfaces requires direct replenishment of water either through automatic water control or manual filling, the moderating influence on temperature and increasing humidity among other factors, will indirectly influence this rate of evaporation. Our path models are able to compare these two effects and provide a better understanding of the trade-offs between the extent of water use and the degree of temperature offsets.

Data and Measurement Issues

Temperature and Water Use in Phoenix

This study required temperature data at a fairly detailed spatial scale to capture the potential effects of variations in development patterns and densities. No empirical record of temperature variation existed at a sufficiently detailed spatial scale, so we used modeled data representing air temperatures from the work of Grossman-Clarke et al. (2005), whose simulation was performed for a typical day in June 1998. Grossman-Clarke et al. made several modifications to the National Center for Atmospheric Research Mesoscale Model (MM5), including a refined urban land cover classification and improved energy balance accounting. Their modeled temperatures agreed well (within 4 percent variation from actual temperatures in degrees Fahrenheit). Actual temperatures were measured at Sky Harbor Airport near the city center and a network of fifteen weather stations located across a range of land uses. While these data are not perfect representations of real-world conditions, they provide good estimates of intraurban variations in temperature resulting from land use and land cover conditions. We operationally defined daily low temperature and daily high temperature as the simulated temperatures derived by Grossman-Clarke et al. at 5 a.m. and 5 p.m., respectively, on June 8, 1998. Geographic information systems (GIS) software (ESRI ArcGIS 9.2) was used to spatially interpolate the output of simulation available as a two-kilometer raster data to the census tract level for the purpose of our analysis.

The variation in summer low temperatures in Phoenix clearly shows higher low temperatures over the central areas of Phoenix, including the Sky Harbor Airport, and low temperatures that decline steadily towards both the north and the south. The mean low temperature for June 8, 1998, was 70°F, with the highest low temperature (72.8°F) recorded at the Sky Harbor site. Our data show the lowest low temperatures that day at the northern and northeastern edge of the city. The difference between the daytime high and nighttime low temperatures followed a slightly different pattern, with areas just northwest of the city center registering the least difference between highs and lows (approximately 17°F). However, we found the maximum difference occurred in the same areas that had the lowest low temperatures in the city (see Figure 1).

We obtained detailed breakdowns of water use from the City of Phoenix Water Services Department for June 1998. Although the original data set included many different categories of water users (single-family, several forms of multifamily units, various office types, industrial, public, and others), we extracted information on water use for single-family units only, which we then aggregated to census tracts.

According to the data provided by the Water Services Department, the consumption of water in June 1998 by single-family residences in Phoenix averaged approximately 17,000 gallons per unit, with significant variation throughout the city. The top 10 percent of residential water consumers used at least 21,578 gallons that month, while the bottom 10 percent used 11,515 gallons or fewer. Single-family residences showed a clear pattern of high demand just north and northeast of the city center, near the oldest areas of the city. Average water usage by residents of single-family homes tended to decline

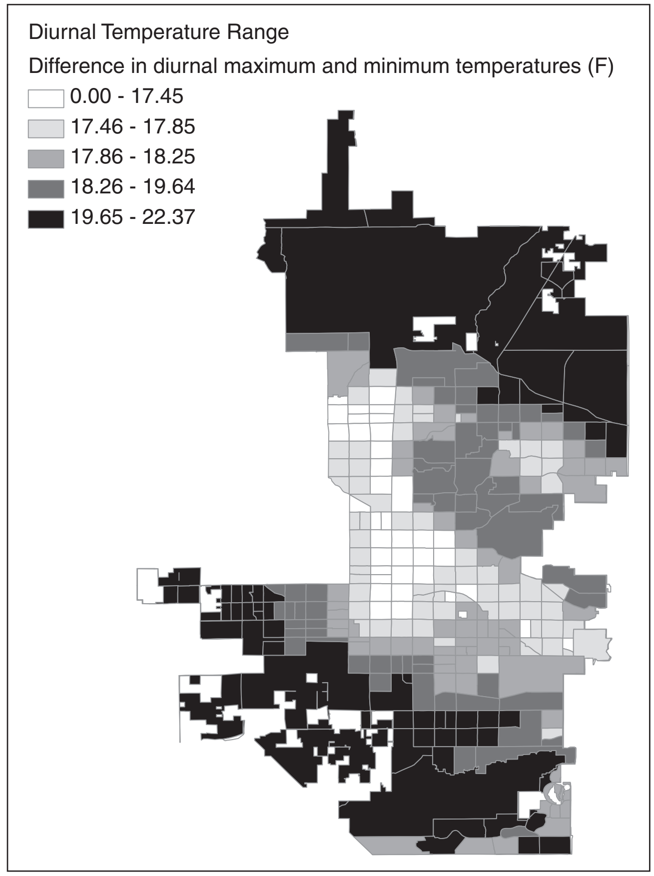

Figure 1. Spatial variation in diurnal temperature range (DTR) in Phoenix (June 1998)
Source: Authors' calculations based on simulations conducted by Grossman-Clarke et al. (2005).

further to the north, in the parts of the city developed more recently. Single-family units in the southern areas surrounding a large mountain preserve also used less water than the city average. Although water use corresponded roughly to age of development, with the oldest areas showing the highest average single-family water use, age of development also correlates with vegetation cover and land use type, other factors that contribute to water use.

Although the water meter data do not distinguish between indoor and outdoor uses, almost two-thirds of residential use is for outdoor purposes, mainly landscaping. In a study of water use in ten cities, including Phoenix, Mayer and DeOreo (1999) found far less variability in indoor use than outdoor use. The typical household in their study used 4,560 gallons per month. While indoor use goes up with family size, there is not a one-to-one correspondence. They estimate that each additional person adds 37 gallons per day, with a threshold water use of about 69 gallons per day. Thus, the large variations that we see across the city are due in large part to the patterns of outdoor use. Mayer and DeOreo also reported that more water is allocated to residential landscaping than to any other uses, including

Table 1. Descriptive Statistics of the Variables Affecting Water Demand and Heat Island Effects in Phoenix

Variables	Description	Minimum	Maximum	Mean	Standard deviation
NIGHTTEMP	Mean low temp (5 a.m.) °F	64.57	72.77	70.11	1.88
DAYTEMP	Mean high temperature (5 p.m.) °F	85.26	90.35	88.69	1.01
TEMPDIFF	Difference in high and low temperature °F	17.08	22.37	18.57	1.21
GPHU	Gallons of water per single-family unit	7,846.62	38,468.55	16,474.14	4,339.28
PCTPOOL	Percentage pools	0.00	86.38	24.63	20.47
MESICPCT	Percentage mesic vegetation	0.49	86.48	19.47	15.83
PCTIMPERV	Percentage impervious surface	1.19	56.42	30.27	10.17
LOTSIZE	Mean lot size (square feet)	5,257.82	30,272.61	9,682.95	4,047.69
Valid *N* (listwise) = 276					

pools, golf courses, and indoor uses. Demand for outdoor uses of water is especially sensitive to climatic conditions, hence ideally suited for examining the impact of heat island on water use.

Attributes of the Built Environment Impacting Water Use

Previous studies have shown that the factors influencing the outdoor uses of water in single-family residential units are (1) the presence of pools, (2) the size of the residential lot, (3) the amount and type of vegetation, and (4) the amount of impervious surface (Guhathakurta and Gober 2007; Wentz and Gober 2007). The significance of each of these variables and their measurement issues are discussed below. Table 1 provides descriptive statistics on all the variables used in this analysis.

Mean lot size. Upwards of two-thirds of water consumption in single-family units is for outdoor uses. A significant part of this water is used to maintain lawns, plants, and other vegetation. A larger lot would likely include more vegetative cover and, hence, is expected to have a positive correlation with water use and with the amount of mesic vegetation.

Percentage of single-family units with pools. Outdoor pools are common in Phoenix and require significant amounts of water to compensate for water lost through evaporation. It is reasonable to expect a positive relationship between water demand and the percentage of single-family units with pools in a census tract.

Percentage mesic. The amount of vegetation as reflected in lawn surfaces and density of plants and trees directly affects water demand in single-family units. We expected a higher intensity of mesic vegetation to be correlated with higher levels of water use, since leafy plants require more water than xeriscaping. This variable is calculated from a land cover database, which was developed with the help of a classified 1998 Landsat TM image. The classification algorithm utilized an expert system methodology developed by Stefanov, Ramsey, and Christensen (2001). The mesic residential areas were further adjusted to account for flood irrigation provided to some central city neighborhoods supplied by Salt River Project (SRP), another water provider in Phoenix. This step ensured that the percentage of mesic vegetation was mostly influenced by water provided by the city of Phoenix (the variable in our model) (Wentz and Gober 2007).

Percentage impervious surface. The amount and type of impervious surface within an urban neighborhood has significant impact on its microclimate and the formation of heat islands. However, estimating the amount of impervious surface for the entire city by individual census tracts is not straightforward since no such database exists. Our approach has been to first determine the various residential land use categories from the classified 1998 Landstat TM image mentioned earlier and then apply RTIMP (impervious surfaces) values from Table 4.2 of the Drainage Design Manual for Maricopa County: Hydrology (Flood Control District of Maricopa County 2003). The RTIMP values are provided by land use type and residential density. Although not perfect, this method offers the best estimate of the percentage of impervious surface and has been adopted by the Flood Control District of Maricopa County.

Constructing a Path Model

Path models are frequently used to study patterns of causality among a set of variables (Dillon and Goldstein 1984). They capture direct and indirect effects in a complex system. A key condition of causality is that the observed covariation between *X* and *Y* should not disappear when logically prior variables are added to the system. The method is not designed to deduce causal relationships from the values of correlation coefficients but to provide a quantitative assessment of relationships that are known to hold and to separate direct from indirect effects. Path analysis is appropriate for this study of the UHI and water use because we want to show how surface features such as pools, irrigated vegetation, and lot sizes affect water use both directly by adding to household water use and indirectly by exacerbating the UHI.

The path model developed for this article is designed to examine the complex causal pathways among some of the drivers of heat island effects and their direct and indirect impact on water demand. Mesic vegetation requires the artificial

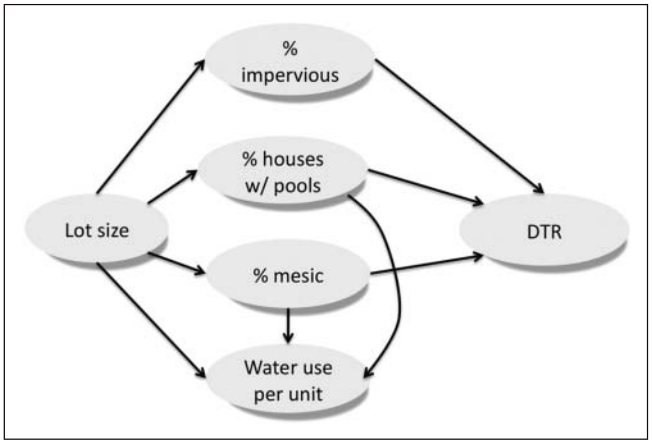

Figure 2. Hypothesized causal paths examining the relationship between water use and diurnal temperature range (DTR)

application of water and thus increases water use directly. It also reduces the diurnal range in temperature, thereby increasing water use indirectly via UHI effects. Similarly, pools affect water use directly, and we ask whether there is an indirect effect as well through diurnal temperature differences. The path model provided in Figure 2 can offer some answers regarding the effects of vegetation and pools on water demand through their direct as well as induced effect.

The model is based on the hypothesized relationships noted in previous studies discussed earlier. For example, increasing size of lots would most likely entail a reduction in the percentage of a tract's impervious surfaces and a higher probability of including pools. Previous research also indicates that there is a positive relationship between amount of impervious surface and surface warming (Stone and Norman 2006). Most importantly, the model includes the effects of pools and mesic vegetation on both the DTR and water demand. Pools and vegetation are the design elements often used to lower uncomfortably high temperatures, although they have a positive impact on water demand. This model would assess whether their use actually increases the DTR and thereby mitigates the heat island effect. If, on the other hand, the use of pools and mesic vegetation increases UHI effects (by reducing DTR), it would trigger a positive feedback loop and further increase water use.

An assessment of the correlation matrix for the variables under study offers some important insights (Table 2). First, the difference in diurnal temperature is negatively associated with both the nighttime low and the daytime high temperatures. However, the correlation with the nighttime low temperatures is about twice the size of the correlation with daytime high temperatures. That is, the nighttime low temperatures significantly determine the diurnal difference in temperatures. This is expected since the heat island effect is mostly a nighttime phenomenon as described earlier. Additionally, the relationship between diurnal temperature difference and percentage impervious surface is strong and negative as expected. Higher percentage of impervious surface tends to decrease diurnal temperature difference by contributing to the heat island effect. As noted earlier, impervious surfaces absorb the sun's radiant energy during the day and radiate that energy in the form of heat at night, thereby moderating diurnal temperature difference.

The correlations of gallons of water used per household with nighttime temperature, as well as with the diurnal difference in temperature, are significant at the 99 percent confidence level. However, the same correlation between water used per household and daytime high temperatures is insignificant even at the 95 percent confidence level. This finding is important given that, without accounting for other factors that may also explain water use, nighttime temperatures play a more significant role in driving the pattern of water demand than daytime temperatures. The other significant correlations between water demand and percentage of houses with pools, average lot size, and percentage of mesic vegetation are also strong and in the expected positive direction. That is, more pools, larger lots, and more mesic vegetation tend to increase water demand in single-family residences when examined individually in isolation from other factors.

Path coefficients are the standardized regression coefficients (betas) derived from maximum likelihood or ordinary least squares (OLS) estimates. The model can be estimated as a series of regression analyses with each variable defined in terms of logically prior variations. Endogenous variables are those with prior relationships. We have specified lot size as an exogenous variable that is not determined by other variables in the system. The other five are endogenous, and they capture the outdoor aspects of water demand in single-family homes and their relationship to heat island formation. The following equations are estimated with the help of the SAS® statistical package and its PROC CALIS command scripts:

$$\text{Tempdiff}_i = \beta_{pti}\text{Pool} + \beta_{mti}\text{Mesic} + \beta_{vti}\text{Impervious} + \varepsilon_{it}$$
$$\text{Pool}_i = \beta_{lpi}\text{Lotsize} + \varepsilon_{ip}$$
$$\text{GPHU}_i = \beta_{twi}\text{Tempdiff} + \beta_{pwi}\text{Pool} + \beta_{mwi}\text{Mesic} + \beta_{lwi}\text{Lotsize} + \varepsilon_{iw}$$
$$\text{Mesic}_i = \beta_{mli}\text{Lotsize} + \varepsilon_{im}$$
$$\text{Impervious}_i = \beta_{vli}\text{Lotsize} + \varepsilon_{iv},$$

where

Tempdiff = diurnal temperature difference;
Pool = percentage of single-family units with pools in census tract;
Mesic = percentage of mesic vegetation;
Impervious = percentage of impervious surface of total tract area;
Lotsize = average size of single-family residential lot in census tract;
GPHU = average gallons of water demanded by single-family units in tract in June 1998;
ε = estimates of error coefficients; and
β = maximum likelihood estimates of independent variables.

Table 2. Pearson Correlations between the Variables Used

	NIGHTTEMP	TEMPDIFF	PCTIMPERV	PCTPOOL	LOTSIZE	GPHU	MESICPCT	DAYTEMP
NIGHTTEMP	1	−0.875**	0.596**	−0.249**	−0.089	0.158**	0.220**	0.813**
TEMPDIFF	−0.875**	1	−0.496**	−0.011	−0.020	−0.157**	−0.262**	−0.430**
PCTIMPERV	0.596**	−0.496**	1	−0.347**	−0.400**	−0.215**	−0.106*	0.516**
PCTPOOL	−0.249**	−0.011	−0.347**	1	0.475**	0.527**	0.246**	−0.479**
LOTSIZE	−0.089	−0.020	−0.400**	0.475**	1	0.585**	0.515**	−0.191**
GPHU	0.158**	−0.157**	−0.215**	0.527**	0.585**	1	0.442**	0.105*
MESICPCT	0.220**	−0.262**	−0.106*	0.246**	0.515**	0.442**	1	0.095
DAYTEMP	0.813**	−0.430**	0.516**	−0.479**	−0.191**	0.105*	0.095	1

See Table 1 for definitions of variables.
$*p < .1$. $**p < .01$.

Table 3. The Maximum Likelihood Unstandardized and Standardized Coefficient Estimates

	Exogenous					
Endogenous	TEMPDIFF	PCTPOOL	GPHU	MESICPCT	LOTSIZE	PCTIMPERV
TEMPDIFF						
β		−0.008		−0.022		−0.068
St. β		−0.139		−0.285		−0.568
t		−2.787		−5.802		−11.715
PCTPOOL						
β					0.002	
St. β					0.475	
t					8.941	
MESICPCT						
β					0.002	0.188
St. β					0.563	0.120
t					10.073	2.141
GPHU						
β	−379.600	68.098		41.916	0.376	
St. β	−0.107	0.321		0.154	0.350	
t	−943.700	6.380		2.991	6.160	
PCTIMPERV						
β					−0.001	
St. β					−0.400	
t					−7.240	

See Table 1 for definitions of variables. β = unstandardized coefficient; St. β = standardized coefficient; *t* = *t*-score.

The unstandardized and standardized estimates of the coefficients (β) are provided in Table 3. These estimates suggest that the heat island effect, as measured by changes in diurnal difference in temperature, is influenced significantly by percentage of pools, percentage of mesic vegetation, and percentage impervious surfaces in the tract. More importantly, increasing proportionally the amount of any of the three variables reduces the diurnal temperature difference, thus increasing heat island effects. Impervious surfaces absorb daytime heat and release it at night, reducing the diurnal differential. Increasing the proportion of mesic vegetation increases grass cover and seems to retard nighttime cooling, a finding similar to what Stone and Norman (2006) found in their Atlanta study. The presence of pools also appears to reduce diurnal differences. This can be anticipated from the fact that the bivariate correlation coefficient between percentage pools and daytime high temperatures is negative and almost twice as strong as with nighttime low temperatures. The net effect of significantly lowered daytime high temperatures and marginally lowered nighttime low temperatures with increasing percentage of houses with pools is the reduction in DTR.

Another important finding of this study is the significant impact of heat island effect on water demand. As expected, average lot size, percentage of mesic vegetation, and percentage of pools in tract all contribute to increased water demand in single-family units. However, even after accounting for the three variables mentioned above, lowering the difference in diurnal temperature seems to have a positive effect on water demand. A one-degree reduction in diurnal temperature difference leads to an increase of 379 gallons in average water demand in single-family units for the month of June. This result confirms earlier studies showing similar positive impact of

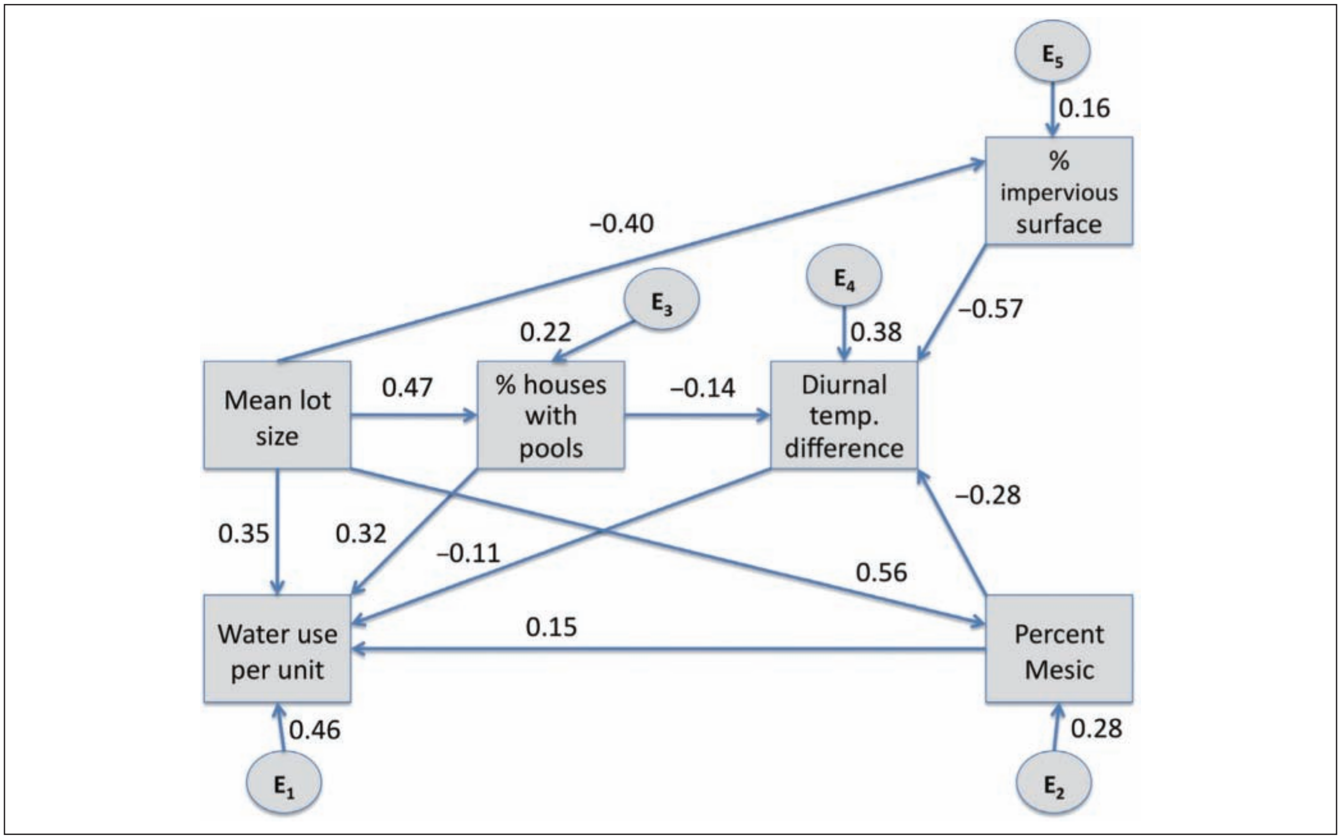

Figure 3. The estimated weights for the path model
Note: E1 through E5 are the estimated error coefficients.

heat islands on residential water demand (Guhathakurta and Gober 2007).

The path model with the beta weights and residuals is provided in Figure 3. The goodness-of-fit measures for this model are mostly appropriate and confirm the validity of the results. The goodness-of-fit index (GFI) is high (.99), the root mean square error of approximations (RMSEA) is low (.08), and the Bentler-Bonnet normed fit index (NFI) is high (.98). Several alternative specifications of the path model in Figure 3 were examined and were found to have poor goodness-of-fit measures compared to the one presented in this article.

The direct, indirect, and total impact of the path variables on the diurnal difference in temperature and average water use is provided in Table 4. As expected, the largest standardized coefficient impacting the diurnal difference in temperature is percentage impervious surface (–.57). The two variables of special concern in this study, percentage mesic vegetation and percentage of houses with pools, also impart a significant negative impact on diurnal temperature difference. That is, more pools and vegetation and larger percentage of impervious surface individually and uniquely reduce diurnal temperature differences in the Phoenix urban environment. In comparison, the influence of lot size on diurnal temperature difference is small, indirect, and positive. The endogenous variables not included in Table 4, percentage mesic, percentage impervious, and percentage pools, are directly impacted by just one variable, lot size, which is the only exogenous variable in the model.

In summary, average water consumption in single-family units in Phoenix is driven largely by lot size. Larger lots have both a direct and indirect impact on increasing water demand, with the direct impact being slightly larger than the indirect impact. Lot size indirectly affects changes in water demand through its correlation with pools, percentage mesic vegetation, and, importantly, its influence on heat island formation. Not surprisingly, percentage of units with pools is the second most important driver of water demand, followed by percentage of mesic vegetation and diurnal temperature difference, which is negatively associated with water demand. Amount of impervious surface has a small and indirect impact on average water demand through its strong association with diurnal temperature difference. The estimated coefficients confirm that the relationship between pools, vegetation, UHI, and household water demand tend to form a positive feedback loop that increases water use and intensifies heat islands.

Analysis

The empirical evidence from the observations in Phoenix suggests that (1) increasing heat island effects that reduce diurnal temperature difference have a significant positive impact on

Table 4. The Direct, Indirect, and Total Effect of Drivers of Diurnal Temperature Range and Average Water Demand

	Diurnal temperature difference			Average water demand in June		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
Mean lot size		0.01	0.01	0.35	0.24	0.59
Percentage of houses with pools	−0.14		−0.14	0.32	0.02	0.33
Diurnal temperature difference				−0.11		−0.11
Percentage impervious surface	−0.57		−0.57		0.08	0.08
Percentage mesic vegetation	−0.28		−0.28	0.15	0.03	0.18

single-family water demand; and (2) the presence of pools and green vegetation also tend to reduce diurnal temperature difference and, thereby, add indirectly to water demand. The first conclusion confirms a limited number of studies that have already shown heat island effects to increase water usage. The second finding is novel and perhaps more controversial. Regardless, there are several possible explanations about why evaporative cooling can work differently during the day than at night. Additionally, if indeed water bodies and vegetation moderate daytime temperatures and not the nighttime temperatures, the diurnal difference in temperature would be reduced. In this case, the diurnal difference in temperature is not necessarily measuring the heat island effect but the mitigation of daytime high temperatures due to the presence of pools and vegetation.

Our data do not support the conclusion that diurnal temperature difference is driven mostly by lowering daytime high temperatures rather than by increasing the nighttime lows. As noted earlier, the correlation between diurnal difference in temperature and the nighttime low temperature is twice that between diurnal temperature difference and daytime highs. Hence the alternative explanation that suggests an opposite role for pools and vegetation during the night in keeping the lows to be higher than surrounding areas seems to be more plausible. This empirical finding from Phoenix needs to be confirmed both by tests conducted in other areas and by studies in atmospheric physics.

As noted earlier, the finding that higher intensity of vegetation can lead to higher nighttime temperatures than surroundings conforms to some of the theoretical and empirical research in atmospheric physics and climatology. Additionally, the moderating impact of pools on the DTR is not unexpected given higher rates of evaporative cooling during the day than at nighttime and the radiation of latent heat at night. The implication of this finding is also significant, in that the potential solution to lowering heat island effects would not necessarily involve pools and vegetation. Especially, the specific forms of vegetative cover and landscaping elements seem to matter considerably, as shown in prior studies in Atlanta and Phoenix (Stone and Norman 2006).

More detailed research is necessary to explain the unique contributions of vegetation of various intensities, canopies, and heights. The study presented here is limited to the geographic context of one county in a unique (Sonoran Desert) ecosystem and simulates temperatures for just one day in June 1998. The validity of the results in other regions needs to be verified through additional studies. What is clear is that vegetation, by itself, if not carefully designed, may in fact be contributing to heat island effects as shown in this research. The use of pools and vegetation for moderating temperatures during the day may actually keep temperatures higher than normal during the night. In addition, the use of pools and vegetation has a significant adverse impact on water demand. Thus, new design and engineering solutions are required to solve the twin problems of excessive heat and minimizing water use.

Conclusion

This study investigated the causal pathways through which household swimming pools and vegetation contribute to changes in the DTR and the effect of such temperature changes on water demand. The data used are from the city of Phoenix and based on temperature simulations performed for a typical day in June 1998. The results confirm the findings of previous studies showing that single-family residential water demand is uniquely and significantly impacted by heat island effects even after accounting for the usual sources of water demand such as pools and lawns. The results of this study also indicate that the presence of pools and lush vegetation may not help in mitigating high nighttime temperature, although their use in reducing uncomfortably high daytime temperatures is widely accepted. In fact, under particular climatological circumstances, pools and vegetation may have the opposite effect on nighttime temperatures than they have during daytime. Therefore, this study offers a cautionary note about the use of large water bodies and vegetation as a strategy for relieving heat island effects.

The findings of this research need to be confirmed by more studies in other regions with different climates and ecological settings. Research examining the contribution of different types of vegetative covers to net black body flux and, consequently, to temperature variations is urgently needed. Recent studies noted earlier in this article have suggested that the use of water bodies and certain types of vegetative covers in mitigating high temperatures especially at nighttime needs to be reexamined. Although such scientific results provide confidence in the validity of the findings in this study, the science of microclimates is continuing to discover the complex interactions between various aspects of temperature, humidity, wind speed, albedo, solar radiation, and land cover. Therefore more work is needed in both empirical analysis of the actual climate-environment interactions and in the theoretical understanding of such processes.

The results of this study have important implications for planning and urban design strategies. An important finding that has implications for planning concerns design criteria and regulations affecting lot sizes. Large lots in urban areas tend to boost water demand without necessarily reducing heat island effects. In fact, under particular meteorological conditions, higher intensity of vegetation and pools that are often present in large lots tend to constrict DTR. Simplistic solutions that only incorporate large water bodies and lush vegetation may not serve the purpose of mitigating uncomfortable nighttime temperatures. Future research in climate-sensitive design needs to engage climatological aspects together with material properties and appropriate alignment of interior and outdoor spaces. A better understanding of the complex relationships between the built environment and climate will provide more comfortable living without compromising energy efficiency and elevating water use.

Results also have implications for water planning in the face of climate change. Traditional approaches to water conservation in urban areas stress indoor water savings by replacing high-water-use fixtures such as showers, faucets, and toilets with water-efficient ones; fixing leaks; and taking shorter showers. Increasingly, interest has shifted to outdoor conservation such as replacing irrigated turf grass with native desert plants, running sprinklers at night, and resetting timers to match seasonal water needs. Only recently has the conversation shifted to the critical linkage between land and water. When we build low-density, sprawling cities, we make de facto water decisions in the process. This is especially true in Phoenix, where two-thirds of residential water use is outdoors. Water plans in Denver and San Diego now recognize the link between the pattern of urban development and subsequent water use (Bush 2007) and can achieve substantial water savings from more compact development. The path analysis presented in this article represents an attempt to look at urban resource use as a system and to consider the obvious as well as the more subtle relationships within that system.

Authors' Note

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