Climate Variability and Residential Water Use in the City of Phoenix, Arizona

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ABSTRACT

In this investigation, how annual water use in the city of Phoenix, Arizona, was influenced by climatic variables between 1980 and 2004 is examined. Simple correlation coefficients between water use and annual mean temperature, total annual precipitation, and annual mean Palmer hydrological drought index values are $+0.55$, -0.69, -0.52, respectively, over the study period (annual water use increases with higher temperature, lower precipitation, and drought). Multivariate analyses using monthly climatic data indicate that annual water use is controlled most by the overall state of drought, autumn temperatures, and summer-monsoon precipitation. Model coefficients indicate that temperature, precipitation, and/or drought conditions certainly impact water use, although the magnitude of the annual water-use response to changes in climate was relatively low for an urban environment in which a sizable majority of residential water use is for outdoor purposes. People's perception of the landscape's water needs and their willingness and ability to respond to their perceptions by changing landscaping practices are probably more important than the landscape's need for water in assessing residential water demand and the variation therein.

1. Introduction

In 1980, the state of Arizona passed landmark legislation to reduce drastically the mining of its underground aquifers. The Groundwater Management Act was brokered by then Governor Bruce Babbitt in response to a threat from the federal government to withdraw support for the Central Arizona Project, a 530-km-long aqueduct designed to deliver Colorado River water to the rapidly growing desert cities of Phoenix and Tucson of central and southern Arizona. The successful legislation resulted from a delicate and complicated set of agreements from the state's water stakeholders: farmers, utilities, industry, Native American communities, and municipalities (Connall 1982; Jacobs and Holway 2004). To win concessions from farmers and other users, municipalities agreed to reduce gradually their per capita water consumption. Most communities, including the city of Phoenix, implemented water conservation policies, such as distributing water-saving

devices, requiring low-flow devices for new and replacement fixtures, establishing educational programs, and creating pricing structures (Campbell 2004). Although annual water consumption has declined in a general way, sizable annual variation, presumably related in some part to climate variability, confounds efforts to evaluate systematically the effects of water conservation and behavior changes in use (Fig. 1). Climatic variability is particularly relevant in Phoenix because it is estimated that 74% of residential water use is for outdoor purposes, which are sensitive to variations in temperature and rainfall (Mayer and DeOreo 1999).

We use a time series of water use measured in terms of annual liters per capita per day that was developed by Phoenix city government to meet its reporting requirements under the Groundwater Management Act of 1980, per-household monthly water consumption for single-family homes based on the authors' calculations from Phoenix city-government metered water records, and climate records from the U.S. Historical Climatology Network (USHCN) to evaluate the effect of climate variability on water use. Results yield estimates of potential water consumption under different drought conditions and suggest the relative importance of climate versus nonclimate determinants of water demand.

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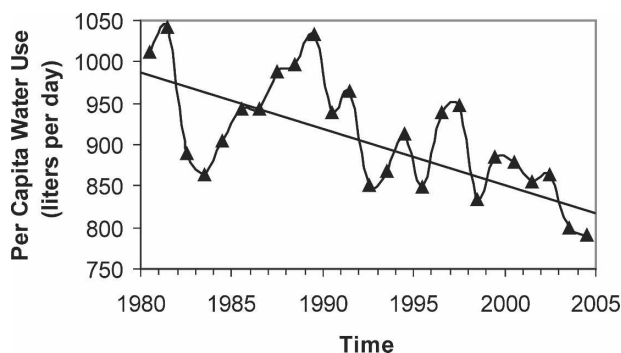E-mail: robert.balling@asu.edu

FIG. 1. Phoenix per capita annual water use (liters per capita per day) from 1980 through 2004.

Economists have examined the determinants of residential water demand, with emphasis on price. Results demonstrate that water demand is, in most cases, relatively inelastic because water has no substitutes for basic uses and because expenditure on water represents a small share of total household income. It would take large increases in price to influence water use substantially, and the nature of this relationship can be estimated using econometric functions (Arbués et al. 2003). While recognizing the value and importance of this work from a policy perspective we choose to focus instead on the sensitivity of water use to variation in climatic conditions—how responsive, in other words, is water-use behavior to changes in rainfall and other climatic processes? Do humans adapt to change in environmental conditions by altering their landscaping practices?

2. Literature review

Studies in other cities have produced mixed results about the effects of climatic variables as predictors of water demand, in part because of their differing environmental circumstances and attitudes about water use, but also because they use different indicators of climate and water demand, some including only residential users and others considering municipal demand from all uses. Using a standardized measure of outdoor water use across 12 cities in North America, Mayer and DeOreo (1999) found that net evapotranspiration explained 59% of the spatial variation in average water use. Their study focused on the spatial variability in outdoor water use. Many others have examined temporal variability in water use as related to variations in climate.

The link between climate and water consumption would seem obvious, especially for cities in the semiarid to arid regions of the American Southwest. However,

as noted recently by Gutzler and Nims (2005, p. 1778), studies "in the southwestern United States have reached surprisingly diverse and apparently contradictory conclusions about the impact of climatic variability on water demand." For example, Berry and Bonem (1974) found only a trivial relationship between climate and water use in towns and cities in New Mexico, including Albuquerque, and Cochran and Cotton (1985) came to the same basic conclusion in cities in Oklahoma. Gegax et al. (1998) and Michelsen et al. (1999) found no relationship between rainfall and water use in the western cities studied and only a slight link with temperature.

Other investigators have found a linkage between the temporal variations in climate and water use, although their studies are set in different cities, use different databases, and employ different time frames. Maidment and Parzen (1984) and Wilson (1989) showed that increased rainfall in Fort Worth and semiarid regions in Texas was related to decreased water demand. Rhoades and Walski (1991) and Billings and Agthe (1998) found that elevated temperature and decreased precipitation increased water demand in Austin, Texas. Gutzler and Nims (2005) showed that annual relationships between climate and water use may mask seasonal patterns, particularly during the summer season.

Several studies have indicated that climate variations and water use are significantly related in the cities of Arizona. Woodard and Horn (1988) found that the thunderstorms associated with the southwestern monsoon (typically in July and August) reduced water demand in Arizona. They found that not only was total precipitation important to reducing water demand, but the number of events of a certain magnitude and even just the forecasting of rainfall reduced water demand. Water use in Tucson has been found to be significantly related to precipitation (Young 1973), temperature and precipitation (Billings and Day 1989; Agthe and Billings 1997), and evapotranspiration minus rainfall (Billings and Agthe 1980). In a meta-analysis of Tucson water demand studies, Martin and Kulakowski (1991) found positive correlations between temperature or evapotranspiration and water use.

The focus of these studies is on price, with climatic variables as controls, because economists are interested fundamentally in the way tariff structures can be implemented to reduce demand. Although climate is insensitive to human manipulation, it is not irrelevant to use. Outdoor landscaping requires less water for irrigation during cool, wet spells, but it is unclear how adaptable consumers are to these conditions because their water use is complementary with durable water-using equipment, and few are equipped with automatic sensing de-

vices. This study is focused on how adaptable human behavior is to naturally varying climatic conditions.

3. Water use in Phoenix

Approximately two-thirds of the water used in Phoenix is for residential purposes, 51% by the residents of single-family homes. In a spatially weighted regression analysis of single-family residential water demand at the census tract level, Wentz and Gober (2007) found that four variables—average household size, the percent of homes with a swimming pool, average lot size, and average percent of lots covered with mesic (turf) vegetation—explained more than 80% of the spatial variation in metered water use. Larger household size increases indoor water use for such purposes as toilet flushing, showers, laundry, and dishwashing, although Arbués et al. (2003) note the tendency for less-than-proportional increases in use because of economies of scale in water use. Swimming pools, lot size, and vegetation type account for outdoor use from pool evaporation and garden irrigation. We anticipate that residential water use is climate sensitive because of the heavy reliance on outdoor uses in Phoenix's water portfolio.

In a study of the effect of the urban heat island on water use in Phoenix, Guhathakurta et al. (2005) examined the spatial effects of June nighttime temperature on residential water use, controlling for the presence of pools, vegetation type, size of house and lot, number of residents, and other socioeconomic, demographic, and housing variables. The effect of temperature was statistically significant, and the regression coefficient indicated that an increase of 1°C resulted in an increase in household water use of 4.61 kL annually. In an environment in which the typical residence uses more than 600 kL of water, this constitutes 0.77% of annual use for every 1°C of urban heating. With the heat-island effect exceeding 6°C, residential water use can be affected by over 4.5%.

In a study of the end-use demand for residential water in 12 North American cities (Cambridge, Ontario, Canada; Waterloo, Ontario, Canada; Seattle, Washington; Tampa, Florida; Lompoc, California; Eugene, Oregon; Boulder, Colorado; San Diego, California; Tempe, Arizona; Denver, Colorado; Walnut Valley, California; Scottsdale, Arizona; Las Virgenes, California; and Phoenix), indoor water use varied only moderately from 204.8 kL per home in Seattle to 288.8 kL in Walnut Valley, with Phoenix somewhat above average at 268.4 kL per household. Outdoor use varied by a factor of 30, with a low of 29.5 kL in the two Canadian cities to 807.0 kL in the metropolitan water district of
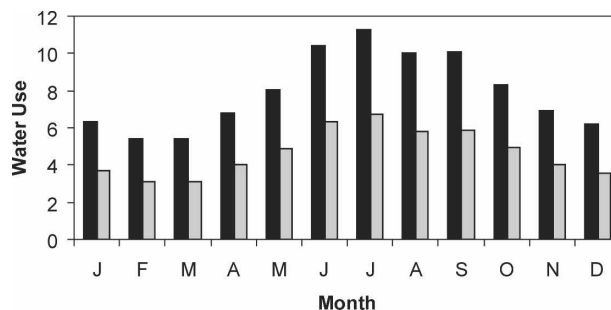

FIG. 2. Total (black) and single-family (gray) monthly water use (10^6 L) over 1995–2004.

Las Virgenes in southern California; Phoenix reports outdoor use to be 612.8 kL per home, which is artificially low because it is based only on municipal water sources (Mayer and DeOreo 1999). Supplemental water is provided for outdoor uses in the form of flood irrigation, delivered directly by the Salt River Project, which is the region's water utility. The city's water records that we use actually underestimate the water used for outdoor purposes and the proportion that is theoretically climate sensitive.

Consistent with the importance of outdoor use in Phoenix are substantial differences in seasonal use. Total and residential water consumption both peak during the summer and early autumn months, with more than 40% of annual use occurring in June, July, August, and September (Fig. 2).

In response to conservation mandates in the Groundwater Management Act, the Phoenix city government instituted a number of conservation policies after 1980. These policies included a pricing system that charged for use on a unit basis over 6 units (16.99 kL month^{-1} from October through May) and 10 units (28.31 kL month^{-1} from June through September), distribution of low-flow fixtures and institution of a devices ordinance, distribution of seeds for water-conserving plants, distribution of brochures about water conservation, and hardware retrofit assistance programs for the low-income elderly population. Campbell (2004) systematically studied the effects of these programs, holding other variables, including evapotranspiration and precipitation, constant. Important for our study is the finding that both evapotranspiration and precipitation were statistically significant. Their coefficients are interpreted as elasticities because the variables were transformed logarithmically. The coefficient of 0.464 for evapotranspiration means that a 1% increase in evapotranspiration resulted in a 0.464% increase in residential water use. The effect of precipitation was statistically significant and in the expected negative direction, but smaller in magnitude; a 1% rise in precipitation

resulted in a 0.001% drop in water use. Climatic variables accounted for a significant portion of the variation in monthly water use, but their effects were surprisingly small and were dwarfed by the effects of housing age and value, household size and wealth, and a range of policy-oriented variables.

4. Databases

We used two time series of water use in Phoenix that were calculated in different ways. The annual average of the liters per capita per day (LPCD) is the total amount of water delivered by the city's water services department to the city's customers on a per capita basis between 1980 and 2004. Excluded are deliveries to neighboring jurisdictions, people in Phoenix who have their own wells, and industries or developments that have their own reclaimed systems. Like most such data, the city's per capita water estimates are based on imprecise estimates of population and imperfect billing records. They are nonetheless the best indicators of variations in water use. The second dataset consists of monthly records for single-family residential properties between 1995 and 2004. Included are metered records summed for all single-family residential users and then divided by the number of users. It represents the amount of water used by the typical single-family household as opposed to overall consumption included in the LPCD figure.

We used the USHCN (Karl et al. 1990) monthly and annual time series to represent temperature, precipitation, and drought in the Phoenix area. The USHCN data are derived from many weather stations within relatively homogeneous climate divisions. The records in this dataset had been adjusted for time-of-observation biasing (Karl et al. 1986), instrument adjustments (Karl and Williams 1987; Quayle et al. 1991), and missing data from stations within a division. We assembled the annual temperature, precipitation, and drought data for the "south-central" climate division of Arizona that contains our study area. This division covers 12.8% of Arizona; it includes the Phoenix metropolitan area, and it extends over 100 km west of the city. There were no missing data over the 1980–2004 time period.

The temperature record shows a mean annual temperature of 21.41°C, with mean monthly temperatures ranging from 11.26°C in December to 32.21°C in July. Temperatures in Phoenix approach 0°C on cool winter nights to over 45°C in summer season. Total annual precipitation in our study area averaged 281 mm over the 1980–2004 period, with approximately one-half of the rain falling from cyclonic storms occurring between December and March and approximately one-quarter of the rainfall coming from convective storms in July and August. Annual potential evapotranspiration (PE) is approximately 1780 mm, representing a PE-to-rainfall ratio of over 6:1.

We selected the Palmer hydrological drought index (PHDI) to represent drought conditions in our study area. Palmer (1965) developed the PHDI, along with other drought measures, and these indices have been used in many research studies as well as in operational drought monitoring during the past 40 yr. The PHDI accounts not only for precipitation totals, but also for temperature, evapotranspiration, soil runoff, and soil recharge. The index varies generally between −6.0 and +6.0, although there are a few values in the magnitude of +7 or −7. Values near zero indicate normal conditions for a region, values less than −2 indicate moderate drought, values less than −3 indicate severe drought, and values less than −4 indicate extreme drought. On the opposite end, values greater than +2 indicate moderately wet conditions, those above +3 represent very wet conditions, and PHDI values above +4 are for extremely wet conditions. Alley (1984) identified three positive characteristics of the index that contribute to its popularity: 1) it provides decision makers with a measurement of the abnormality of recent weather for a region, 2) it provides an opportunity to place current conditions in a historical perspective, and 3) it provides spatial and temporal representations of historical droughts. There are certainly limitations when using the PHDI (or any other index), and these are described in detail by Alley (1984), Karl and Knight (1985), and Guttman (1991).

5. Analyses and results

We assembled the climate and per capita annual water-use data into a matrix with 25 rows, one for each year from 1980 through 2004, and 41 columns, including year of record, annual water use per capita per day, and monthly and annual temperature, precipitation totals, and PHDI values. Because several of the statistical techniques used in our study assumed that the data are normally distributed (a Gaussian distribution), we tested all variables for this property using the standardized coefficients of skewness z_1 and kurtosis z_2, calculated as

$$z_1 = \frac{\left[\sum_{i=1}^{N}(x_i - \overline{X})^3/N\right]\left[\sum_{i=1}^{N}(x_i - \overline{X})^2/N\right]^{-3/2}}{(6/N)^{1/2}}$$

and

$$z_2 = \frac{\left\{\left[\sum_{i=1}^{N}(x_i - \overline{X})^4/N\right]\left[\sum_{i=1}^{N}(x_i - \overline{X})^2/N\right]^{-2}\right\} - 3}{(24/N)^{1/2}},$$

where the resulting z values are compared with a t value that is deemed to be appropriate for a selected level of confidence (e.g., for $N = 25$, $t = 2.80$ for the 0.01 level). If the absolute value of z_1 or z_2 exceeds the selected value of t, a significant deviation from the normal distribution is confirmed. Otherwise, no statistically significant deviation from a normal distribution is determined (the null hypothesis that the samples came from a normal distribution cannot be rejected). We also used the Kolmogorov–Smirnov one-sample test to evaluate further the normality of each variable.

The results of the tests indicated no significant ($\rho = 0.01$) deviations from normality in the water-use, temperature, and PHDI time series. However, significant skewness and kurtosis deviations were identified for January, May, June, and October precipitation. A square root transformation was required to eliminate the significant deviations from normality in these four time series. We conducted all analyses with and without the transformations and found that our results were robust against these deviations from normality. We also determined the level of autocorrelation for each variable and found no case in which the autocorrelation was significant at the $\rho = 0.05$ level of significance.

The annual per capita water use averaged 911.3 L day^{-1} over the 1980–2004 time period and had a standard deviation of 69.2 L day^{-1}; the coefficient of variation was 0.07, indicating relatively low variation around the mean value. We used simple linear regression with water use (LPCD) as the dependent variable and year of record as the independent variable to detrend the data. The equation took the form LPCD = 13 237 − 6.19 × Year; the r (Pearson product–moment correlation coefficient) value of the linear fit was −0.65 ($\rho = 0.00$) and the adjusted R^2 (coefficient of determination) was 0.41; the residuals from the trend line had a standard deviation of 52.12 liters per capita per day (Figs. 1 and 3). The residual time series was tested for normality, and no significant deviation from the Gaussian distribution was identified. Among other findings, this result suggests that in the absence of some change in climate, or some other intervening variable, the conservation plan introduced in Phoenix has reduced per capita water consumption by 15%, from near 984 liters per capita per day in 1980 to near 835 liters per capita per day in 2004.

With respect to any change in climate, we found an upward trend in temperature of 0.03°C yr^{-1} ($\rho = 0.02$) that reflects regional warming that has occurred over
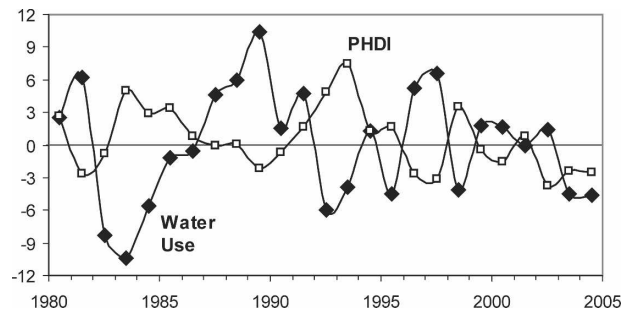

FIG. 3. Plot of PHDI values (dimensionless; open squares) and the water-use residuals (dekaliters per capita per day; filled diamonds).

the past few decades, as well as the urban heat island effects that have developed with the urbanization of the Phoenix area. Total annual precipitation decreased at a rate of 3.81 mm yr^{-1} ($\rho = 0.12$), although the trend is not statistically significant. The PHDI values have a downward, but not significant, trend over the 1980–2004 time period of 0.13 yr^{-1} ($\rho = 0.10$), indicating that the increases in temperature and slight decrease in precipitation have led to a trend toward increased drought (Fig. 3). In all three cases, the Durbin–Watson statistic was greater than 1.40, indicating no significant autocorrelation in any of the residual time series.

We calculated the Pearson product-moment correlation coefficient between the per capita water-use residuals and each of the annual climate variables. The strongest relationship was between the water use and annual precipitation ($r = -0.69$), followed by annual temperature ($r = 0.55$) and annual PHDI ($r = -0.52$). Not surprising is that per capita water use significantly increases with higher temperatures, decreases with higher precipitation, and increases in times of drought. Figure 3 clearly shows the propensity for water use to increase when PHDI is low (drought) and that water use is relatively low when PHDI is high (moist periods). Even at this relatively simple level of analysis, there is clear evidence that water use in Phoenix is significantly related to variations in weather and climate. The 1980–2004 study period is relatively short and does not allow a rigorous evaluation of the stationarity of these correlation coefficients.

Simple regression analysis provides an estimate of the influence of temperature and precipitation variations on per capita water use in Phoenix. For mean annual temperature, the regression equation is LPCD$_{res}$ = −1300.9 + 60.76T_{ann}, showing that for every 1°C increase (decrease) in temperature, the detrended per capita water-use residual value increases (decreases) by 60.76 liters per capita per day, representing a 6.66% change based on the 1980–2004 average water-use data
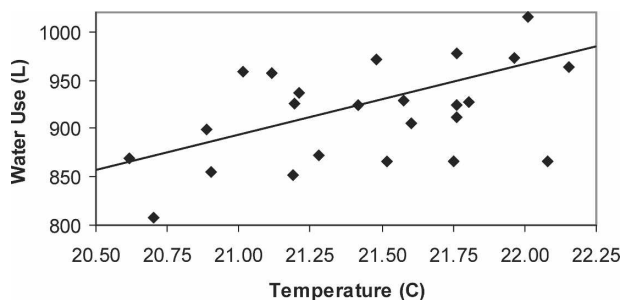
FIG. 4. Detrended per capita annual water-use data (mean of 911.35 liters per capita per day) vs mean annual temperature; the *r* value for the regression line is 0.55.
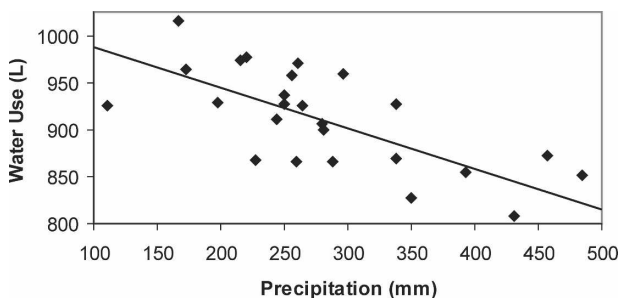

FIG. 5. Detrended per capita annual water-use data (liters per capita per day) vs total annual precipitation (mm); the *r* value for the regression line is −0.69.

(the mean during that period is 911.3 liters per capita per day). As seen in Fig. 4, mean annual temperatures have varied over the study period by over 1.5°C and appear to account for variations of over 100 liters per capita per day, or 11.6% of normal water use.

The simple regression equation for total annual precipitation is $LPCD_{res} = 111.3 - 0.40P_{ann}$, showing that a reduction (increase) in precipitation of 10 mm would increase (decrease) water use by only 4 liters per capita per day. Given that annual precipitation averaged 281 mm over the 1980–2004 study period, the simple regression suggests that for every 10% decrease (increase) in total annual precipitation, water use would increase (decrease) by 3.9%. However, as seen in Fig. 5, total annual precipitation over the period of 1980–2004 has varied from near 100 to near 500 mm, and these observed variations in total annual precipitation have been associated with changes in per capita water use of over 160 liters per capita per day, or 17.5% of normal water use. Mean annual temperature and total annual precipitation share a significant ($\rho = 0.00$) correlation of −0.68, and, therefore, a multiple regression with both as predictors is inappropriate.

To identify better the relative importance of climate variables on per capita water use, a principal components analysis was conducted on the time series matrix of monthly and annual temperature, precipitation, and PHDI values. Seven orthogonal components had an eigenvalue above 1.00; they explained over 86% of the variance in the matrix, and the component scores were used as independent variables with per capita water use as the dependent variable. A stepwise multiple regression analysis selected only three of these components as being significant in explaining variance in the water-use time series. The three components explained nearly one-half (49.8%) of the variance in the detrended water-use data, and the three contributed nearly equally in explaining the variance.

The first component selected in the multiple regres-

sion analysis was also the first and most important component in the principal components analysis and had high loadings (>0.80) on the annual and all monthly PHDI time series. This inclusion in the model simply reinforces the obvious link between drought and water use. The next component selected in the stepwise process was the fourth vector calculated in the components analysis—its highest loadings were on late-autumn-season temperatures. Even with the drought level controlled for statistically in step 1, late-autumn temperatures are relatively important in determining the annual per capita water use. The late-autumn period is a dry time in Phoenix prior to the relatively wet winter season. During the autumn, many residents choose to "overseed" their lawns, switching from grasses that can survive the summer heat to grasses that can grow during the winter. Overseeding requires substantial watering and may account for the importance of autumn temperatures in controlling variations in annual residential water use. The third and final component selected in the stepwise process was the second vector calculated in the components analysis, and its highest loadings were on July–September precipitation. This inclusion clearly shows the importance of the monsoon-season precipitation in affecting water use in the Phoenix area (with the effect of drought controlled for statistically in step 1).

The combination of principal components analysis and stepwise multiple regressions allows a further isolation of the temperature impact on water use in Phoenix. The final stepwise equation is

$$LPCD_{res} = -23.22\mathbf{V}_1 + 22.05\mathbf{V}_4 + 18.14\mathbf{V}_2,$$

where $LPCD_{res}$ is the residual series from the detrended per capita water use (liters per capita per day), $\mathbf{V}_1$ is the drought eigenvector, $\mathbf{V}_4$ is the late-autumn temperature component, and $\mathbf{V}_2$ is the summer rainfall vector. The analysis suggests that for every increase of

one standard deviation in autumn temperatures, per capita water use increases by 22.05 liters per capita per day. Given that monthly mean temperatures in late autumn have a standard deviation near 1.5°C, a 1°C increase would cause per capita water use to increase by just over 14.70 liters per capita per day, or about 1.5% of the average per capita water use over the 1980–2004 period. The higher sensitivity (60.76 liters per capita per day per 1°C) determined in simple regression did not control for interaction among temperature, precipitation, and drought and represented the impact of annual temperature changes, not just those of the autumn season.

6. Discussion and conclusions

Results show that there are statistically significant relationships between climatic conditions and water use in Phoenix. Model coefficients indicate that changes in temperature, precipitation, and/or drought conditions certainly affect water use, although the magnitude of the water-use response to changes in climate is relatively low in an urban environment in which a sizable majority of residential water use is for outdoor purposes. We believe there are both climatic and social and behavioral explanations for this finding. In climatic terms, Phoenix is an arid city in which annual potential evapotranspiration is more than 6 times the normal annual precipitation. It is possible to sustain an urban region of almost 4 million residents in this desert setting because Phoenix is reliant for water, not on local supplies, but on a vast water frontier, including the Colorado River Basin and the upstream watersheds of the Salt and Verde Rivers. Phoenix is so chronically short of precipitation that even sizable variation in local climatic conditions has a small effect on local water demand patterns because local demand is met by hydroclimate conditions in faraway places (e.g., the upper reaches of the Colorado River Basin).

Also relevant are effects of water policy and human behavior. The city had a water conservation program in effect during the study period, and we estimate that it reduced per capita water use by 15%. In addition, there are behavioral barriers that limit the responsiveness of water use to climatic conditions. To reduce outdoor water use during cooler, wetter periods, residents would need to adjust their mechanical irrigation systems or change their watering habits. In a study of the differences in water use between mesic and xeric applications in Phoenix, Martin (2001) found surprisingly little difference because residents with xeric designs do not adjust their water applications to account for seasonal changes in evapotranspiration. Water use is in-

herently a human-dominated activity, and the critical issue is their perception of the landscape's needs and their ability to respond to that perception by changing their watering practices. Climate and water use are linked by a complicated set of behavioral processes, about which we know relatively little, but which are crucial for the design of programs for the more efficient use of urban water in a desert city.

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