Geographic Variability in Public Water Withdrawals and Efficiencies: Community Responses to Urbanization, Climate Change, and Policies in the USA

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Introduction

Rising water demands are a primary concern in growing cities, where the majority of residents live worldwide. The 2015 Sustainable Development Goals recognize this challenge by emphasizing increasing water-use efficiency, along with sustainable cities and consumption patterns. These goals are the focus of this paper, with additional focus on managing water during times of drought or in the face of a drier, warmer future. Understanding spatial and temporal variation in water demands is critical for "soft path" approaches that emphasize enhancing water-use efficiencies and reducing rates of consumption through a variety of behavioral and technological strategies (Gleick 2002). Demand management also offers mechanisms for adapting to climate change by reducing the stress placed on scarce water resources.

Based on research in the United States, we summarize central insights regarding four focal points. First, we discuss regional patterns in public supply withdrawals overall as well as per-capita efficiencies for the entire U.S.[1] Second, we report on the complex ways in which income and education levels differentially affect the efficiency of water withdrawals across distinct regions of the U.S. Third, we demonstrate differential responses to drought in terms of how per-capita water withdrawals change in the context of drought for various cities of the U.S.[2] Fourth, we zoom in more closely to select cities to examine the effects of drought—coupled with water management strategies and policies—on per-capita water withdrawals.[2]

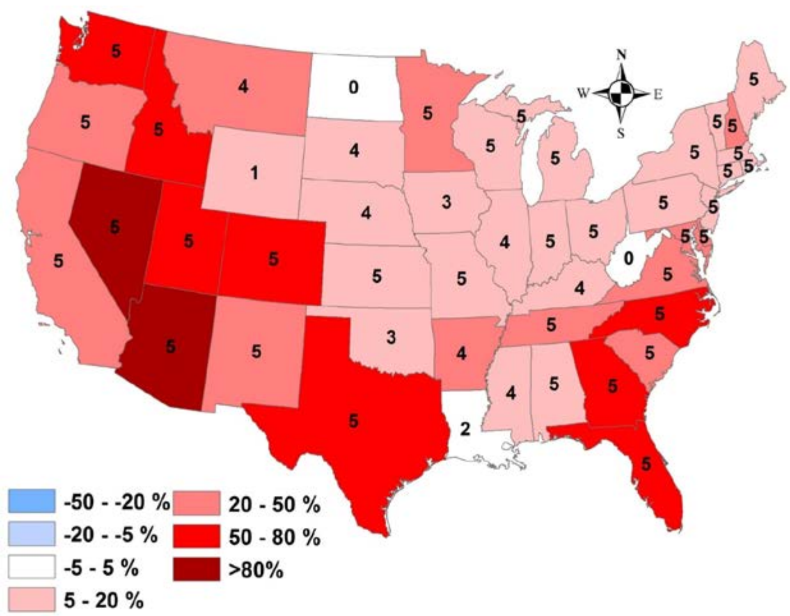
Although the findings were derived from the U.S., a few lessons emerge for water management as a whole. One key point is that the societal dynamics surrounding water use and management vary geographically and, thus, are context specific. Another highlight is that there are no single or simple solutions to complex water system dynamics.

[1] This analysis and the results are based on county-level data from the contiguous U.S. for five-year intervals covering the time period 1985-2010.
[2] This analysis is based on monthly billing data from water utilities in select cities of the U.S.

Regional Trends in Public Water Withdrawals across the U.S.

As the maps below indicate, withdrawals of water for public (municipal) purposes have risen in several states of the U.S. This is particularly the case in the southerly "SunBelt" region, which has experienced significant in-migration and population growth in recent decades (Fig. 1). In spite of growth and the rise of water withdrawals overall (Fig. 2), several states—especially in the relatively arid Western U.S.—have experienced significant declines in per-capita rates of public withdrawals (Fig. 3). This suggests gains in water-use efficiency in many regions, though our associated findings reveal that urban counties have become more efficient relative to rural ones (at least in seven of the nine climate regions analyzed; see Table 1).

Fig. 1: Percentage change in population 2005 and 1985. The numbers on each state indicate the number of years (1990, 1995, 2000, 2005, and 2010) over which population increased.



A number of possible reasons explain enhanced efficiencies in cities over time. First, as urban development occurs, the new infrastructure and buildings have built-in efficiencies in terms of low-flow appliances and fixtures, in addition to new pipes that are less prone to leaks and losses. Second, modern forms of urbanization offer more compact designs that result in reduced water demands, especially due to lower outdoor water uses from smaller yards. In some areas—specifically in southwestern states such as Arizona, Nevada, and California, changing landscape preferences and choices—away from grass yards and toward drought-tolerant plants and alternative types of groundcover (e.g., gravel or mulch)—are also leading to reduced water consumption. In many places, this shift in the water requirements of residential landscapes has been supported or required through rebate and incentive programs, or through local and regional ordinances that restrict lawns for water conservation purposes. Lastly, greater capacities for planning and managing water in cities may facilitate policies and other actions aimed at reducing water demands.

Figure 2: Percentage change in *total* public supply withdrawals between 2010 and 1985, where % increase = (2010-1985)*100/1985. Numbers on each state indicate the number of periods (1990, 1995, 2000, 2005, and 2010) over which public supply withdrawals increased.

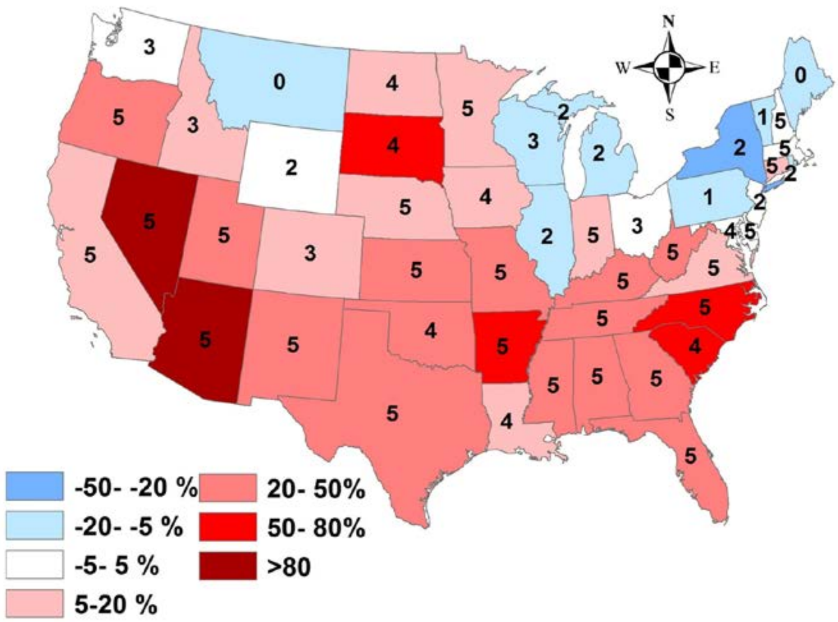
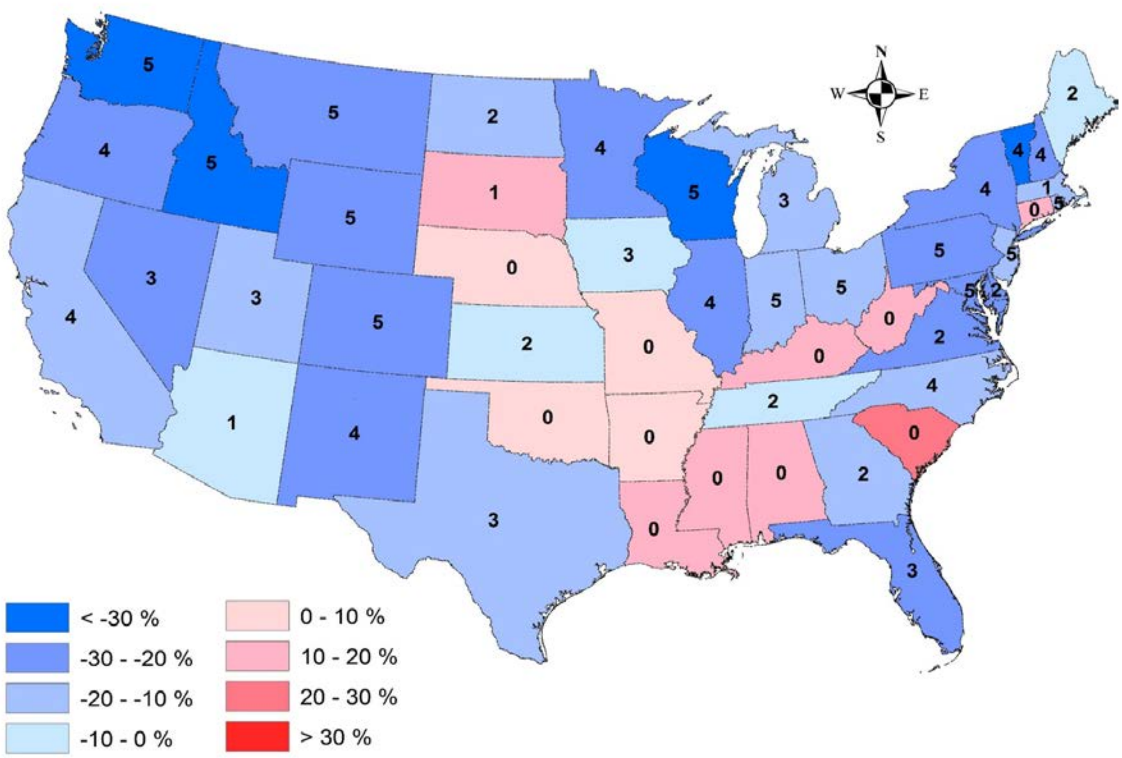


Figure 3: Percent change in public supply withdrawal *per capita between 2010–1985*, where - % changes on per-capita use = (2010-1985)*100/1985. Numbers on states indicate the number of periods (1990, 1995, 2000, 2005, 2010) for demand decreases.



Socioeconomic Controls on Per-Capita Withdrawals

Next, we present results concerning the effect of per-capita income and education on per-capita withdrawals. This analysis is of interest since there are different rationales for how those factors might affect water withdrawals; on the one hand, higher socioeconomic status may lead to greater capacity in conserving water and thereby enhancing water-use efficiency; on the other hand, lower socioeconomic status—especially in terms of household income—may lead to higher rates of water consumption, as shown in other studies (Harlan et al. 2007).

Per-capita household income levels were associated with gains in water-use efficiency in four of the nine climate regions analyzed (see Table 1). In contrast, two other regions saw increases in per-capita withdrawals with higher income levels. Together, these findings indicate that the relationship between income and water-use efficiency may depend on context, since in some regions affluence increases consumption while in other regions wealth is linked to water conservation.

Table 1: Summary of Relationships between Change in Per-Capita Withdrawals and Socio-economic Factors by Region. Based on Negative (Positive) correlations ($p<0.05$), the table indicates Conservation (Consumption) at relatively Moderate and more Significant levels.

Climate Region (States)	Income	Education
Northwest (WA, OR, ID)	Moderate Conservation	Moderate Conservation
West North Central (MT, WY, ND, SD, NB)	None	None
East North Central (MN, WI, MI, IA)	Moderate Consumption	Moderate Conservation
Northeast (ME, NH, VT, NY, CT, RI, MA, NY, PA, MD)	Significant Consumption	Significant Consumption
West (CA, NV)	None	None
Southwest (NV, CO, AZ, NM)	None	Significant Conservation
South (OK, TX, AR, LA, MS)	Significant Conservation	Significant Conservation
Central (MO, IL, IN, OH, WV, KY, TN)	Significant Conservation	Significant Conservation
Southeast (VA, NC, SC, GA, AL, FL)	Significant Conservation	Significant Conservation

The influence of educational levels is stronger and consistent relative to income, likely because education contributes to greater awareness of water scarcity. Moreover, education likely leads to greater intellectual (and perhaps financial) capacity to reduce water demands (e.g., through adoption of water-efficient technologies or drought-tolerant landscaping). Across the nine climate regions examined, two-thirds (six) demonstrated this link between education levels and water conservation (Table 1). Only one region—the Northeast U.S.—has experienced higher consumption in relation to higher education levels.

Our findings underscore the complex and context-specific nature of interactions between people and water resources. However, additional research and field work is needed to understand the exact nature of these dynamics across regions of developed and developing nations.

Fluctuations in Water Demands in the Context of Drought

Given our observation that efficiency gains have been made in urban areas of the American Sunbelt, we focus the remainder of our discussion on this relatively warm and fast-growing region of the U.S. Of particular interest are the dynamics of per-capita water use in the context of recurring drought. To understand how water demands fluctuate during drogth conditins, we analyzed time-series data for 20 water utilities in the Southern U.S. These data were compared with monthly drought conditions, as measured by the Palmer Drought Severity Index (PDSI).

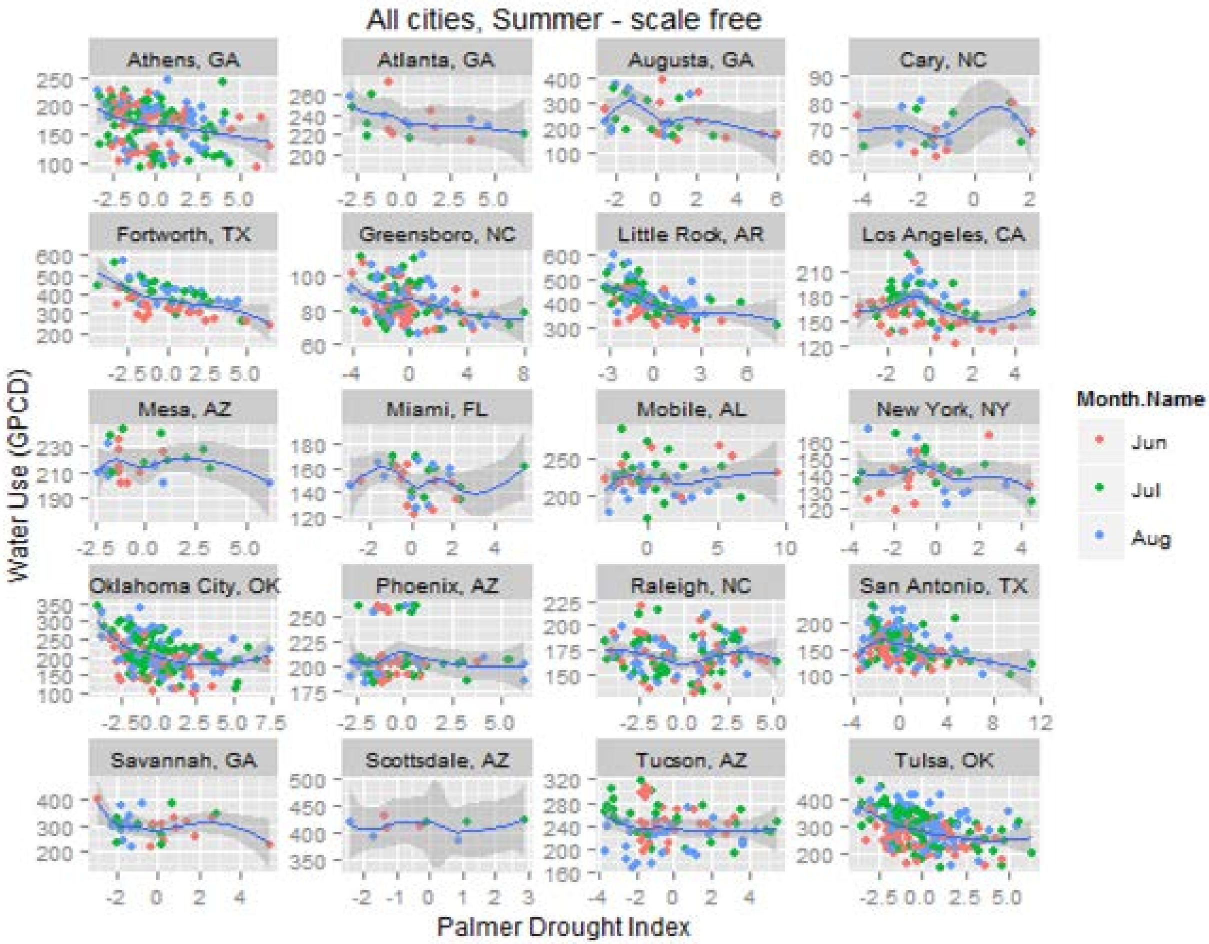
Not suprisingly, drought and water use were tightly coupled during summer months. However, contrary to the popular notion that drought inspires conservation, nearly every city increased per-capita consumption at the onset of drought (Fig. 4). This is likely the result of amenity-preserving behaviors; for instance, people use more water to maintain their lawns, swimming pools, and other water features (e.g., fountains) as conditions get drier, especially during warm summer months. Interestingly, the relationship does not persist with continued drought conditions. Rather, an adaptation signal is observed over time wherein response to drought is delayed, and water efficiencies can be gained in the context of prolonged drought.[3]

The Impact of Management Regimes on Changes in Urban Demands

Above, we introduced and described some of the context-specific features exhibited in the interactions between people and water. Here, we unravel some of these place-based dynamics by investigating urban water use in two Sunbelt states, Arizona and North Carolina. For each state, we describe the water demand trends in four cities—both in emerging megapolitan regions, where multiple cities are converging through urban expansion.

[3] Additional statistical findings on these relationships are presented elsewhere in a paper by A. Sankarasubramanian et al. (see acknowledgements.)

Figure 4: Pairwise correlations between per-capita water use and concurrent drought conditions for 20 municipalities during summer months in the United States.

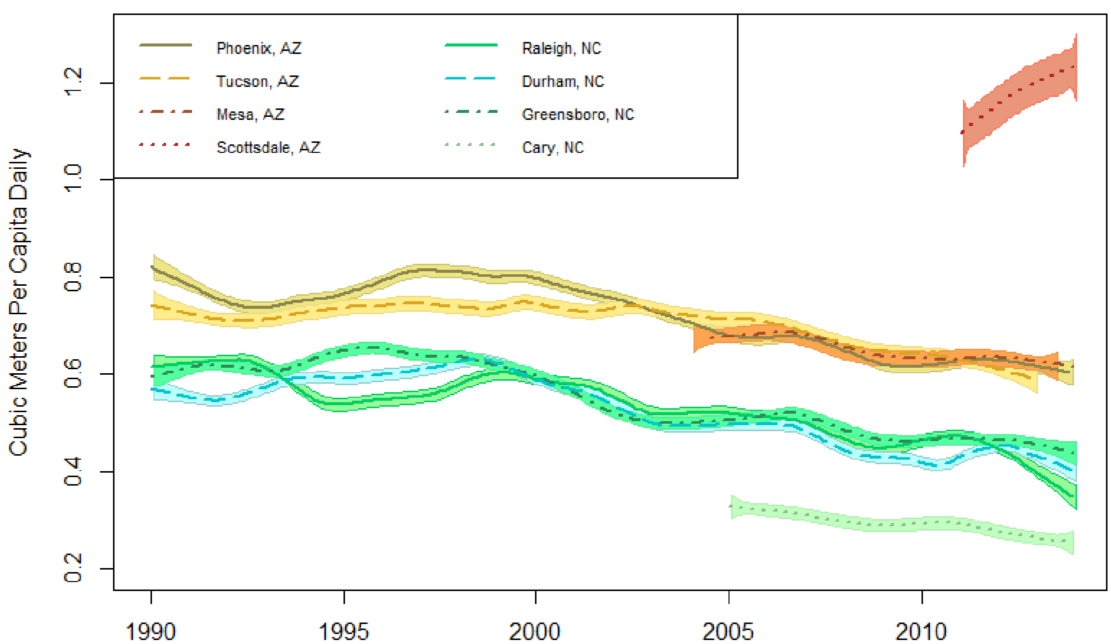


Arizona is located in the arid southwest, where the study cities of Phoenix, Tucson, Mesa, and Scottsdale operate with limited yet highly centralized and engineered water supplies. For much of its history, the State has focused on expensive reservoir and canal systems to expand water storage capacity. In the early 1900s, a series of reservoirs were built to store water in the Phoenix-area Salt and Verde Rivers. More recently, the Central Arizona-Phoenix (CAP) Canal was such a project, transporting water from the Colorado River over 300 miles to the Phoenix metropolitan area. By augmenting supplies, cities in the Phoenix region (e.g., Scottsdale) have maintained irrigated lawns, swimming pools, and water features (e.g., fountains) in spite of the desert climate. Further, the Phoenix region has taken a somewhat *laissez faire* to water conservation and demand management, with little reliance of the regulatory power of the government (Larson et al. 2009). Altogether, these conditions have led to relatively high water-consumption rates throughout the Phoenix region, especially in affluent cities such as Scottsdale (Fig. 5).

Historically and up until the early 2000s, the Phoenix region exhibited substantially higher water consumption rates than nearby Tucson. Unlike Phoenix, the Tucson region has been largely dependent on groundwater and did not receive Colorado River water through the CAP canal until the late 1990's. Since surface water is lacking in Tucson, moreover, the City has implemented conservation pricing (i.e., increasing block rates), staged water restrictions, staffed enforcement programs, and xeriscaping initiatives over time and earlier than the Phoenix region. These conditions have historically fostered low levels of per-capita water use in Tucson compared to the Phoenix region. More recently, however, per-capita rates of consumption have converged among several Arizona cities; as seen in Fig. 5, the demand rates for Phoenix and Mesa dropped to Tucson's relatively low levels around 2005.

What is particularly interesting about the gains in efficiency among Arizona cities is that they have been achieved through diverse mechanisms. In Phoenix, for example, reductions in per-capita water use have come about in the absence of restrictions on irrigation or consumption. Further, and unlike other municipalities in the region, the City of Phoenix has not employed landscaping rebates for converting grass to drought-tolerant yards. Yet landscape designs have become more drought-tolerant and efficient over time, likely due to the availability of native and low water-use plant materials coupled with a shift in consumer preferences toward more desert-style yards. Gains in efficiency have also been achieved through more compact urban development and the installation of low-flow water-using devices.

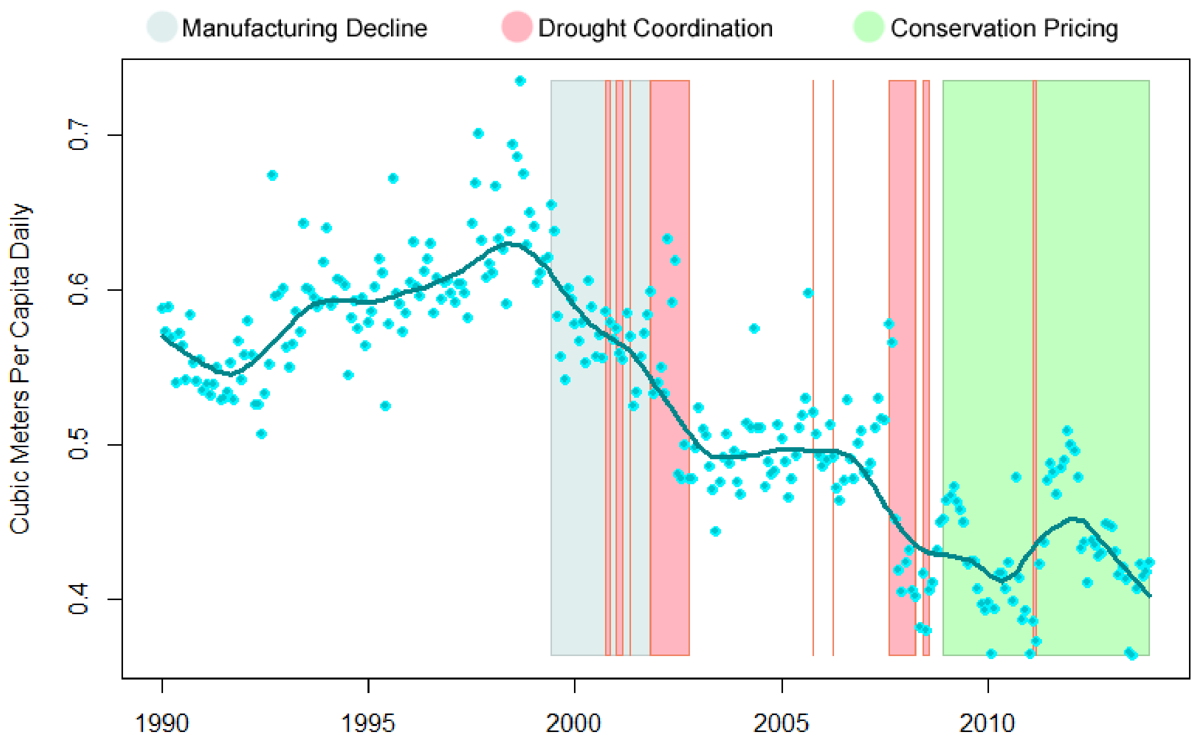
Figure 5: Per-capita water-use trends for four municipalities in Arizona and four in North Carolina (calculated by local regression).



Compared to Arizona, water-use rates in cities of North Carolina have been consistently lower (Fig. 5). This is partly because the relatively humid climate of North Carolina requires less water to maintain lawns and other water-intensive activities, especially those pertaining to outdoor water use. Similar to Arizona cities, the cities in North Carolina we studied (Raleigh, Durham, Cary, and Greensboro) have also conserved water through a combination of factors—some more intentional than others.

The City of Durham is emblematic of how a variety of factors affect urban water demand trends (Fig. 6). Between 1990 and 2010, initial reductions came about from economic declines in water-intensive manufacturing (e.g., electronics). However, water conservation has become more intentional over time, with coordinated drought warnings spurring reductions in water demands under the auspices of North Carolina's Drought Management Advisory Council (http://www.ncdrought.org/) beginning in 2003. This state-level initiative facilitated the timely recognition of regional drought conditions and encouraged a consistent response across local municipalities. As seen for two periods from 2000-20110, these efforts led to reductions in per-capita water demands for all four cities we examined in North Carolina (Fig. 5). Locally for Durham (Fig. 6), such drought responses began with staged restrictions around 2003 and 2008, but later implemented conservation pricing and other permanent measures (e.g., smart irrigation, drought tolerant landscaping).

Figure 6: Per-capita water use trend for Durham, North Carolina. Dots denote monthly water use removed of seasonal oscillations. Vertical bands mark pivotal transformations in water demand rates.



The City of Cary, North Carolina is also noteworthy given its water management accomplishments—that is, in terms of consistently low rates of consumption (Fig. 5). In the early 1990s, the State of North Carolina required Cary to commit to water conservation efforts before it would permit an inter-basin transfer of water to the City. In contrast with high consumption rates in wealthy Scottsdale, Arizona, the affluent City of Cary has significantly lowered its water demands by investing in "soft path" approaches to management. In particular, Cary implemented water pricing for conservation, recruited neighborhood leaders to encourage conservation, passed landscaping ordinances to reduce irrigation, and began routinely enforcing water-use restrictions. As a result, Cary can serve as an example of effective water conservation programming for cities in developed regions.

Highlights and Conclusions

Our U.S.-based research has highlighted a number of key insights that we will summarize here. First, although total water demands may rise with population growth, gains in efficiency (i.e., reductions in per-capita consumption) can help offset water scarcity risks. This is especially true in the context of urbanization. The mechanisms of change are variable, however, and context specific. How and why water demands change is a function of several factors including historic and current water supply conditions, the occurrence and persistence of drought, as well as the particular demand management regimes in place. Although the local context matters, regional coordination and state-level water management initiatives can help spur change more broadly (as seen in North Carolina cities).

Second, caution must be used when generalizing findings from one area to another, since the dynamics in one place may not play out in another. Given our findings about complex and conflicting relationships between socioeconomics and water demand, additional research is needed to more fully understand how income, education, and related dynamics affect water demands and resource management in particular regions. For now, we cannot assume that wealth, or even education, will lead to reductions in water demands since although some affluent cities are progressive in water conservation (e.g., Cary, NC), others are excessive in their rates of consumption (e.g., Scottsdale, AZ). Having said this, a general trend seems to suggest that higher education levels tend to encourage conservation, whereas the relationships between water demands and wealth are more complicated and varied.

Third, community response to drought can be varied over time and space. Although some cities may be quicker to respond than others, the general trend we found in urban regions of the U.S. indicates that water use increases with the onset of drought. However, over time, gains in efficiency can be made as drought persists, particularly when drought conditions are coupled with warnings and other initiatives such as temporary restrictions on irrigation.

Fourth, and lastly, "soft path" approaches to water management can substantially reduce demands and thereby help in mitigating water scarcity. Yet, importantly, there is no one path to demand reductions. Conservation can come about from a variety of strategies, including regulatory (e.g., in NC and Tucson) and non-regulatory (e.g., in Phoenix, AZ) means. Broadly, though, a combination of approaches—which could encompass conservation campaigns, pricing structures, and a variety of restrictions or incentives—appear to be most effective in reducing water demands.

To conclude, we hope this paper has provided interesting and pertinent insights to readers and participants in this PERN CyberSeminar on Water. We realize some findings apply mostly to developed cities. However, some lessons stretch more broadly—specifically those concerning the gains in water-use efficiencies that can accompany urbanization, development, and perhaps education. Additionally, as the global climate changes and water scarcity rises into the future, "soft path" approaches focused on reducing demands and enhancing efficiencies—will most certainly be central to water resource sustainability. They are not a panacea, especially if (or when) total water demands exceed supplies, but they are an important part of the water management toolkit.

Works Cited

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