Decision Making Under Uncertainty: Ranking of Multiple Stressors on Central Arizona Water Resources

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Introduction

Decision making about water resource management are beset with uncertainty due to partial understanding of factors converging to stress its supply and demand. This is no where true than in the arid region of southwestern United States. Some of the factors that are converging to prompt concern about the adequacy of water resources are a) growing urban centers in the region seeking a range of services associated with water including recreational requirements and the need to preserve and enhance aquatic ecosystems; b) dwindling water storage due to multiyear drought condition of more than a decade, and c) human induced changes in climate and its consequences in the hydrologic system of the region. The situation is further complicated by water quality concerns due to urban runoff, agricultural waste, pesticide, and fertilizer leaching. Surprisingly, no water authority at the State level has ever made a comprehensive effort to investigate the real potential for water conservation and efficiency improvement in Central Arizona. This information is vital for meeting the ever growing urban need, restoring the health of the ecosystem, reducing the dependency on Colorado River, and attaining "safe-yield" goal set by the state of Arizona, and above all for addressing the uncertainty of decision-making about water resources management in this region.

This paper provides a sensitivity analysis of multiple factors (hereafter referred to as stressors) that influence water resources in the Phoenix Active Management Area (AMA), which includes the city of Phoenix, one of the fastest growing metropolitan areas in the country. Based on extensive literature review and the analysis of secondary data, this paper investigate the effects of multiple factors that are a stress on the water resources at present, and, using available data, attempts to extend this analysis up to 2025. Specifically, our goals in this paper are to: a) explore the value of multiple stressor analysis as a support for decision making under uncertainty; b) assess the significance of each stressor in its relation with the vulnerability of water systems of the Phoenix AMA; and c) generate a ranking of the stressors through a weight-of-evidence approach. It is important to note that while the focus of this paper is on the water resources management of Phoenix AMA, the findings may also have implications for other parts of the country facing similar conditions.

2. Phoenix AMA: biophysical context

Located primarily in the subtropical desert, the climate of the Phoenix AMA is semiarid and is characterized by low precipitation, hot summers, and mild winters. The average daytime temperatures during the hottest month of July consistently hover between 100^0F and 110^0F, with little relief during the night when temperatures rarely fall below 80^0F. In the winter, daytime temperatures for January, the coolest month, are between 60^0F and 70^0F, and nighttime lows can sometimes fall below freezing (TMP-ADWR, 1999). Since the 1930s there has been an overall increase in the average temperature. While in the urban areas this trend may be attributed to the urban heat island (UHI) effect, this rise in temperature has also been observed in rural areas (Brazel et al., 2000). These higher temperatures result in greater water demands, increased evaporation from exposed water bodies, and increased evapotranspiration from plants.

Annual precipitation averages 7-8 inches across the Phoenix AMA, with higher elevations receiving more rainfall (TMP-ADWR, 1999). The rainfall is bimodal, with summer monsoon rains from July to mid-September, and winter rainfall from November through mid-April. From a hydrological point of view, winter rainfall is more important because of its longer duration, lower intensity, and wider coverage, and therefore reduced surface run-off, greater percolation, and higher groundwater recharge.

Rainfall is characterized by a high degree of year-to-year variation. One of the key factors, especially during winter, is the El Niño-Southern Oscillation – ENSO, a multi year variation in equatorial Pacific Ocean temperatures and associated atmospheric circulation (Andrade and Sellers, 1988; Kiladis and Diaz, 1989; Allen and Ingram, 2002; Hidalgo and Dracup, 2002; McPhee et al., 2004). In recent years several La Niña phases of ENSO has occurred with widespread droughts in the region. Multidecadal fluctuations in ocean temperatures (e.g. AMO - Atlantic Multidecadal Oscillation and PDO - Pacific Decadal Oscillation) are also associated with persistent dry or wet conditions in this region (NRC, 2001). While the causes of PDO are not clear, it shows a remarkable temporal persistence lasting for 20-30 years (Zhang et al., 1997). Studies show evidence for two full PDO cycles in the past century with cool PDO (associated with persistent drought) regimes lasted for 1890-1924 and again from 1947-1976 while warm PDO regimes (associated with extended period of wet condition) from 1925-1946 and 1977-1996 (Mantua et al., 1997; Minobe, 1997). In recent year the PDO may have switched to a cool phase that can bring extended periods of drought to the southwestern U. S. (McCabe et al., 2004). Tree-ring records of Colorado River stream flow show periods of extended drought years in the 1580s, the early 1620s to 1630s, the 1710s, the 1770s, and the 1870s (Hirschboeck and Meko, 2005). Drought years mean less snow pack in the watershed of the rivers and therefore reduced supply of surface water, leading in turn to compensatory increases in groundwater pumping. These large scale patterns of climate variability associated with projected warming in the region will inevitably strain the precarious balance of water supply and demand in Arizona.

3. Overview of water demand and supply

Approximately 2.3 million acre-feet[1] (af) of water is used annually in the Phoenix AMA, primarily from four major sources: 1) local rivers; 2) Colorado River water; 3) groundwater; and 4) effluent. The Gila River along with four principle tributaries (the Salt, Verde, Agua Fria, and Hassayampa Rivers) forms the primary sources of surface water[2] for the AMA. Based on historic data, average surface water availability from these rivers is a little over one million acre-feet (maf) annually. Of the 2.8 maf of Colorado River water to which Arizona is entitled, the Phoenix AMA receives less than 0.5 maf through the Central Arizona Project (CAP) Groundwater withdrawal varies over time and is governed by the amount and timing of precipitation. Although the availability of effluent water is increasing overtime, it represent a small fraction of total water supply. In 1995 it was reported to be 286,000 af in 1995 (TMP-ADWR, 1999).

It is noteworthy that over the most recent 30 years, the lower Colorado River basin has witnessed a significant increase in temperature of 0.61^0C per decade with no visible trend in rainfall (Ellis et al., 2008). Rapid population growth and economic development, along with changing social demands on freshwater resources have imposed new challenges on water management in the AMA. Recently, southwestern U.S. has also experienced sustained drought. The new reality of sustainable water supply must also be examined in conjunction with source of fresh water supply, relentless drought, urban sprawl, public health, and water quality issues. Also, existing water systems must continue to meet traditional needs such as irrigation of agricultural land, hydropower generation, and domestic consumption, while also providing for emerging needs such as recreational uses, water quality standards, and maintaining the health of the aquatic system (NRC, 2007).

Excluding riparian ecosystems, there are three major water demand sectors in the Phoenix AMA: agricultural, municipal, and industrial. By far the greatest amount of water is applied in agriculture sector followed by municipal use. Table 1 shows the Phoenix AMA's water consumption for 1995 and projected demand for 2025 by sector. Overall demand is projected to rise from 2.3 maf in 1995 to over 2.9 maf in 2025, an increase of more than 20 percent, mostly due to rising demand for water from urban population growth. According to the Third Management Plan of the Arizona Department of Water Resources, TMP-ADWR (1999), if the Phoenix AMA does not implement new efficiency policies, these projections will translate to approximately half a million acre-feet of excess groundwater extraction by 2025, thus compromising the AMA's goal of reaching "safe yield," or no net groundwater withdrawal.

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[1] Western United States water publications make use of the measure "acre-foot" rather than the more widespread metric equivalents for water volumes. Because all of the water demand and supply units are reported in acre-foot, unless mentioned specifically acre-foot will be the primary unit of measure followed in this paper. Note that one acre-foot equals 325,851 gallons.

[2] Refers to water from sources such as streams, canyons, natural channels, floodwater, wastewater, lake water, and recycled water.

Sector	Demand Characteristics	1995 (af)	2025 (af)
Municipal	- Residential, commercial and institutional uses - Irrigation for parks, & others	869,962	1,395,725
Agriculture	- Indian and Non-Indian demand for growing crops	1,333,885	1,360,743
Industrial	- Industrial, commercial and institutional uses	83,088	137,628
Riparian	- Riparian areas	48,000	48,000
Total water demand		**2,291,935**	**2,942,096**
Population projection		**(2,549,931)**	**(6,256,500)**

Table 1: Water demand by sector, Phoenix AMA, 1995 (actual) 2025 (estimated)

Source: TMP-ADWR, 1999

3. Climate change and water resources

The problem of climate change due to buildup of greenhouse gases further complicates the issue of water supply and demand in the region. Among others, the expected impacts of climate with respect to water resources are higher evaporation, change in the regional patterns of rainfall, snowfall, and snow melts, and changes in the intensity, severity, and timing of major storms (Nash and Gleick, 1993; NRC, 2007). The instrumental record of climate shows that during the 20^{th} century average temperature increased by 0.37 ^{0}C across the U.S., 0.56 ^{0}C across the western U.S., and 0.79 ^{0}C in the Colorado River Basin (CORB) area (Folland et al., 2001). In the CORB, winter temperatures increased more than summer temperatures and are most pronounced at medium to high elevations (Stewart et al., 2005; Barnett et al., 2008).

Several studies have examined the possible impacts of climate change on the Colorado River Basin and its subbasins using both empirical and General Circulation Models (GCMs). In general all studies predict an increase in temperature by the end of 21^{st} century, the disagreement however, lies in the specific details of change in precipitation, its impacts on seasons, and the range of temperature change. For example, Revelle and Waggoner (1983) used empirical models to assess the impact of hypothetical climate change in the CORB catchments. They concluded that a 4^0F change in temperature coupled with 10% decrease in precipitation would result in 24% decrease in river flow. Consistent with this study, Nash and Gleick (1991) also show that an increase of temperature by 2^0F and decrease of precipitation by 10% would reduce aggregate runoff by 20% in the CORB. Of the range of scenarios tested by Nash and Gleick (1993), the net impacts of climate change by 2025 would result in the reduction of runoff in the range of 8-20%. In their study Christensen et al. (2004) estimated a reduction of annual runoff by 14% in 2010-39, 18% in 2040-69, and 17% in 2070-98. A sensitivity

analysis of Salt and Verde Rivers by Ellis et al. (2008) show a significant reduction in the flow of Salt and Verde Rivers. For example, by 2050, the combined effects of 2.9^0C (5.4^0F) temperature change and 10% reduction in rainfall would results in a 37% decline in the flow of these rivers.

Although there is a large and an unspecifiable degree of uncertainty associated with climate models and is inherently associated with the structural configuration of the models, overall decrease in runoff can potentially strain the CORB system's ability to meet the competing demands driven by population growth, irrigation, environmental needs, and power generation. This is especially true given the high sensitivity of the CORB due to over-allocation of water resources (Barnett et al., 2004). Based on the review of studies, for the purposes of this paper I select a mid-range decrease of 15% in the flow of Colorado and Salt/Verde Rivers due to the effects of climate change. The net effects of climate change on the reduction of surface water flow by 2025 would be in the range of 187,368 to 245,020 af, with average being 216,194 af.

The climate change projections that drive the conclusions of most studies were generated using Global Circulation Models (GCMs). Because of their low resolution, GCMs are prone to creating large errors in the simulation of complex climatic phenomenon that operate at regional and local levels (Shackley et al., 1998). Many fundamental hydrologic processes occur on spatial scales smaller than most climate models are able to resolve. We thus know much less about how the hydrologic cycle will change than we would like in order to make appropriate decisions about managing regional water systems. These uncertainties greatly complicate the planning for the future and have contributed to the ongoing debate over how to respond to the problem of climate change (Schneider and Kuntz-Duriseti, 2002).

4. Ranking stressors and discussions

Using the results of the foregoing analyses, I have tabulated and ranked stressors according to two criteria: a) projected water lost due to system's inefficiency, and b) water lost due to biophysical impacts (stress) on the system. This analysis has required a number of assumptions based on the review of literature. In particular, many of the case studies and examples mentioned in this paper refer to areas that are decidedly different from the Phoenix AMA. This problem was further complicated by lack of data at the scale of the Phoenix AMA. However, I have sought to ensure that comparative studies are closely aligned with that of the Phoenix AMA in terms of biophysical and demographic characteristics.

Three other assumptions also embedded in the rankings. First, I used the population growth projection of the Maricopa Association of Governments (2003) which is basically a linear extension of historical growth trends. Obviously, such trends may or may not continue unabated into the future. Second, I do not try to account for technological change that could increase efficiencies. This assumption means that my standard state estimates are conservative, and that feasible savings on the demand side are likely to end up being higher. Finally, the projections used in the rankings assume no changes in water policies.

Table 2 illustrates the ranking of stressors based on additional water used from increased population and lost due to the system's inefficiency, as well as through

biophysical stress. The stressors are tabulated under the categories of municipal, agricultural, and biophysical. Expressed in acre-feet, Table 2 shows that largest stress on water resources occurs in outdoor landscaping under the municipal category. The significant loss of water due to rise in temperature and simultaneous reduction in precipitation due to global warming in the Colorado and Salt/Verde River basin, the largest supplier of surface water to the Phoenix AMA, ranks it as the second most important stressor. This is closely followed by the stress on water resources from inefficient agricultural use. Indoor water use is ranked fourth among the stressors discussed in this paper. This ranking is not surprising given that efficiency standards and innovation of technologies in saving water has focused on this sector. Water demand due to UHI ranked fifth, about 70% less than water lost through inefficiency in outdoor water use. This estimate is conservative because it only accounts for household demand, due to a lack of studies that take into account the effects of UHI in open water bodies in the Phoenix area. But even this information would not plausibly lift UHI out of last place.

Stressors		Difference between baseline vs standard case by 2025
Projected water lost (af) due to inefficiency	**Municipal**	**328,180**
	Indoor water use	88,830
	Outdoor water use	239,350
	Agriculture	**127,022**
Water lost due to biophysical stress	**Biophysical**	**241,551**
	Additional demand due to UHI	25,357
	Reduction of surface water flow of Colorado and Salt/Verde Rivers due to the effects of climate change	216,194

Table 2: Ranking of stressors based on projected water lost due to inefficiency in water use and added stress due to biophysical changes, 2025

Conclusion

An important revelation of this paper is that reduction in individual and system-wide water demand not only decreases stress on water resources but avoids unnecessary cost on water supply infrastructure and extends the ability of existing supplies to meet current and growing demands. More generally, the ranking suggests that outdoor water use and agriculture are comparably fertile targets for efficiency gains from technical and management perspectives. The scientific knowledge to develop more intelligent demand management methods, which are valuable for domestic and agricultural water use, are

some of the dimensions that this ranking offers in the pursuit for solutions by decision makers. The creation of water management policies reflecting the best practices are also critical for effective water resource management. While the question of what approaches and sectors are adoptable from a political and policy perspectives would be the subject of a different study, the ranking suggests that water use in outdoor irrigation and agricultural practices can be reduced substantially. Likewise, the literature review on climate change indicates that the loss of water is in the range of half of the available saving that could be achieved on the demand side and therefore suggests that adaptation to the impacts of climate change for Phoenix AMA is manageable.

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