Water-demand management: assessing impacts of climate and other changes on water usage in Central Arizona

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ABSTRACT

Planning for sustainable water management in the arid region of the southwestern USA is challenging mostly due to only partial understanding of factors converging around water supply and demand. Some of the factors that prompt concern about the adequacy of water resources are: (a) a growing urban population seeking a range of services, including the need to preserve and enhance aquatic ecosystems; (b) dwindling water storage due to multi-year drought conditions; and (c) the prospect of human-induced climate changes and its consequences in the hydrologic system of the region. This study analyzes the potential for water saving in the Phoenix Active Management Area (AMA) of Central Arizona, which includes the city of Phoenix, one of the fastest growing metropolitan areas in the country. Based on an extensive literature review and secondary data analysis, this paper investigates multiple factors that place increasing strain on current water resources, and attempts to extend this analysis to 2025. Outdoor water use within the residential landscape is the most important factor that strains water resources in Phoenix AMA. Any gain in efficiency through agricultural water demand management would not only improve the availability of water for other uses in the AMA, but would facilitate adaptation of the agricultural system to climate and other ongoing changes.

Key words | central Arizona, climate change, multiple factors, sustainability, water-demand management

INTRODUCTION

Planning for sustainable water management in the arid region of the southwestern USA is challenging mostly due to only partial understanding of factors converging around water supply and demand. Some of the factors that prompt concern about the adequacy of water resources are: (a) a growing urban population seeking a range of services, including the need to preserve and enhance aquatic ecosystems; (b) dwindling water storage due to multi-year drought conditions; and (c) the prospect of human-induced climate changes and its consequences in the hydrologic system of the region. Emerging water quality concerns due to urban runoff and other non-point pollution is further complicating the calculus of the region’s water portfolio. Surprisingly, no water authority at the local level has ever made a comprehensive effort to investigate the real potential for water demand management through conservation and water-use efficiency. Yet, this information is vital for meeting growing urban needs, maintaining health of the ecosystem, reducing the dependency on the Colorado River, and attaining the ‘safe-yield’ goal, for example, set by the Groundwater Management Act (GMA) of Arizona. More importantly, water-demand management is necessary to adapt to changing conditions brought about by the factors discussed above.

This study quantifies the water-saving potential through conservation and technological efficiency in two sectors: municipal and agricultural. It also explores the alteration of the hydrologic systems of the region, consistently highlighted in climate studies of the southwestern USA, an area at the forefront of climate change research. For the
purpose of this study the hydrologic system is analyzed as a biophysical process. This paper will quantify the effect of climate change on the supply of water resources in the Phoenix Active Management Area (AMA), one of the fastest growing metropolitan areas in the country. Based on an extensive literature review and the analysis of secondary data, this paper assesses the effects of multiple factors that places stress on the current water resources and attempts to extend this analysis up to 2025 for Phoenix AMA. The purpose of this paper is to: (a) explore the value of demand management as a support for decision making for sustainable water use and (b) assess the significance of water-saving potentials to minimize the vulnerability of water resources to multiple factors. Where applicable, the paper also discusses some of the challenges that society faces in capitalizing on the water-saving potential. It is important to note that, while the focus of this paper is on the water-resources management of Phoenix AMA, the findings may have implications for other parts of the country facing similar conditions.

The biophysical and socio-economic contexts of the Phoenix AMA are first presented, followed by an overview of the AMA’s water supply and demand portfolio along with the discussion of the basis for the analysis of demand management. The possibility of water supply augmentation through efficiency is then elaborated, and the value of analysis of stressors for decision making under the current situation in the Phoenix AMA is described. Finally, the conclusions from this study are presented.

**Phoenix AMA: biophysical context**

The Phoenix AMA, located in Central Arizona, is one of five AMAs in the state (Figure 1). In 1980, Arizona enacted the GMA (i.e. the Groundwater Code) to sustainably manage and conserve its groundwater. The GMA established the Arizona Department of Water Resources (ADWR) and four AMAs: Pinal, Phoenix, Prescott and Tucson. Later, the Tucson AMA was split to form a fifth AMA, Santa Cruz. The AMAs are mandated by the GMA to establish a long-term management goal for groundwater supplies (Connall 1982) and develop policies to promote sustainability of water resources. The Phoenix AMA covers 14,623 km² (5,646 square miles). It consists of seven groundwater sub-basins and includes a large portion of Maricopa County and smaller sections of Pinal and Yavapai Counties.

Located primarily in the subtropical desert, the climate of the Phoenix AMA is semi-arid and is characterized by low precipitation, hot summers, and mild winters. The average daytime temperatures during the hottest month of July consistently hover between 38 °C (100 °F) and 43 °C (110 °F), with little relief during the night, when temperatures rarely fall below 27 °C (80 °F). In the winter, daytime temperatures for January, the coolest month, are between 16 °C (60 °F) and 21 °C (70 °F), and night-time lows can be below freezing (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 also has 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 rainfall averages 18–20 cm (7–8 in.) across the Phoenix AMA, with a significant spatial variation (ADWR 1999). The rainfall is bimodal, with summer monsoons rains from July to mid September, and winter rainfall from November through mid April. From the perspective of groundwater hydrology, winter rainfall is vital because of its longer duration and lower intensity (hence reducing surface runoff), 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 (Kiladis & Diaz 1989; Andrade & Sellers 1988; Allen & Ingram 2002; Hidalgo & Dracup 2002; McPhee et al. 2004).

In recent years several La Niña phases of ENSO have occurred with widespread droughts in the region. Multi-decadal fluctuations in ocean temperatures (e.g. AMO – Atlantic Multi-decadal Oscillation and PDO – Pacific Decadal Oscillation) are also associated with abnormally 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 & Oweis 1999; Enfield et al. 2001). During the 20th century, multiple cycles of PDOs were observed. For example, extended
periods of drought associated with cool PDO were observed from 1890–1924 and 1947–1976. Likewise, a period of extended wetter conditions associated with warm PDO lasted from 1925 to 1946 and 1977 to 1996 (Meko et al. 2007). In recent years, the PDO may have switched to a cool phase that can bring extended periods of drought to the southwestern USA (McCabe et al. 2004). Tree-ring records of Colorado River streamflow show periods of extended drought years in the 1580s, the early 1620s to 1630s, the 1710s, the 1770s, and the 1870s (Hirschboeck & Meko 2005). A drought year means less snowpack in the watershed of the rivers and therefore reduced supply of surface water, leading 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.

The Colorado River, one of the major sources of water in the southwest, serves approximately 30 million people and irrigates 1.4 million hectares (3.5 million acres) of agricultural land in seven states and Mexico. The river is governed by what is arguably the most complex legal structure of any river in the world. Much of the current water management plans in the basin were devised during the relatively benign climate of the early and mid-20th century. However, the basin has observed the most warming of anywhere in the lower 48 states during the last 30 years (Barnett et al. 2004). With increased climate warming and evaporation, Colorado River runoff may decrease in the order of 15–20% by the middle of the 21st century (Christensen et al. 2004; Milly et al. 2005; Christensen & Lettenmaier 2007; Seager et al. 2007; Ellis et al. 2008). The cumulative effects of multiple factors that are converging to stress the water resources in Phoenix AMA and the possible effects of climate variability and change may result in impacts that are beyond the present experiences of communities.

**Phoenix AMA: overview of water demand and supply**

Approximately 2,837 million m³ (2.3 million acre-feet) of water is used annually in the Phoenix AMA, primarily from four major sources: (a) local rivers; (b) Colorado...
River; (c) groundwater; and (d) effluent water. The Gila River, along with four principal tributaries – the Salt, Verde, Agua Fria, and Hassayampa Rivers – forms the primary source of surface water for the AMA. Based on historic data, average surface water availability from these rivers is a little over 1,233 million m³ (1 million acre-feet) annually. Of the 3,453 million m³ (2.8 million acre-feet) of Colorado River water to which Arizona is entitled, the Phoenix AMA receives less than 617 million m³ (0.5 million acre-feet) through the Central Arizona Project (CAP) and is managed by the Central Arizona Water Conservation District which pumps water from the Colorado River at Lake Havasu for delivery to Maricopa, Pinal, and Pima Counties. Although it is becoming a key component of Arizona’s water security plans for the future and is currently used for many other purposes such as agriculture, lawns, and industrial cooling, effluent water represents a small fraction of the total water supply; and in 1995 it was reported to be only 353 million m³ (286,000 acre-feet) (ADWR 1999). For this reason, effluent is not used as a resource in this analysis and will not be discussed further.

Groundwater is a critical component of Arizona’s water resources which remained unregulated until 1948, when the Critical Groundwater Code was implemented. The primary goal of this Code was: (a) to slow the rate of groundwater depletion, (b) limit the expansion of irrigated acreage, and (c) place restrictions on new agricultural wells (Fletcher 1992). Areas declared as ‘critical’ were restricted from having new wells drilled or from bringing in additional irrigation land. However, because existing wells could be replaced and even deepened, groundwater depletion of critical areas was slowed but not stopped (Schlager 1995). The failure to place any limits on the amount of groundwater that could be pumped remained a fundamental weakness of the Code and was further weakened by its inability to institute any mechanism to enforce it. In 1951, during a brief water supply crisis, the Groundwater Management Commission drafted a follow-up bill but the legislature failed to pass it (Connall 1982). And again in 1977 some amendments were added to the bill, but none of these addressed the core issue of pumping limitations (Hirt et al. 2008), an essential requirement to address the challenge of overdraft. Still the report by Groundwater Management Commission, which gave birth to the GMA, continues to serve as a guide for managing groundwater in the AMAs. The act attempts to achieve and maintain ‘safe yield,’ defined as a long-term balance between the amount of groundwater withdrawn in an AMA and the annual amount of natural and artificial recharge in the AMA (ADWR 1999). The quantity of groundwater withdrawals and its quality are regulated by the Arizona Department of Water Resources and the Arizona Department of Environmental Quality respectively.

The 1922 Colorado River Compact apportioned water among the Upper (Wyoming, Utah, Colorado, and New Mexico) and Lower (California, Arizona and Nevada) Basin states, with each receiving 9,251 million m³ (7.5 million acre-feet). In addition, the 1944 USA–Mexico treaty guaranteed an annual flow of not less than 1,850 million m³ (1.5 million acre-feet) to Mexico. As widely documented, when the Colorado Compact was negotiated, the average flow of the river was estimated to be about 22,202 million m³ (18 million acre-feet) (Christensen et al. 2004), the wettest period in the past 12 centuries (Woodhouse et al. 2005). A revised estimate of the flow at 20,106 million m³ (16.3 million acre-feet) was made later. Yet the Mexico Treaty obligation allocations at a total 20,352 million m³ (16.5 million acre-foot) indicates that the legal entitlement to the river’s water remains greater than the average flow of the river. It must be noted here that a 2005 tree-ring based assessment estimated that during the period between 1521 and 1964 the mean annual flow at Lees Ferry was about 17,516 million m³ (14.2 million acre-foot) (Hirschboeck & Meko 2005), a figure that is considerably lower than earlier estimates.

Along with the seemingly complex situation arising due to over-allocation of Colorado River water, communities need to grapple with new challenges. The combination of rapid population growth, increased environmental concerns, a rise in manufacturing and service industries, and the effects of possible climate change have imposed new challenges on water management in the AMA (Megdal et al. 2008). It is noteworthy that, over the past 30 years, the lower Colorado River basin has witnessed a significant increase in temperature of 0.61 °C (1.1 °F) per decade with no visible change in rainfall pattern (Ellis et al. 2008). The new reality of sustainable water management must also be examined in conjunction with sources of freshwater
supply, relentless drought, continuing urban sprawl and water quality issues. In addition, existing water systems must meet traditional needs such as irrigation of agricultural land and hydropower generation 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. Table 1 shows the Phoenix AMA’s water consumption by sector for 1995 and projected demand for 2025. According to the Third Management Plan of the ADWR, ADWR (1999), the overall demand for water is projected to rise from 2,827 million m$^3$ (2,334,935 acre-feet) in 1995 to over 3,629 million m$^3$ (2,942,096 acre-feet) in 2025, an increase of more than 20%. This is attributed to urban population growth. If the Phoenix AMA does not implement new efficiency policies, these projections will translate to approximately 600 million m$^3$ (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 (ADWR 1999; Holway et al. 2006).

Following ADWR (1999), municipal water is defined as all non-irrigation uses of water supplied by a city, town, and private water companies covering the irrigation district. It comprises residential and non-residential water uses and is projected to become the largest consumer, growing from 37% of total water use in 1995 to 47% in 2025 (Table 1). Residential demand includes interior and exterior use at single and multi-family dwellings. Interior water use can vary according to the efficiency of appliances and water-use practices of residents. Exterior water use is determined by the type of residential landscape, irrigation practice, and lot size. Non-residential use predominantly includes commercial and institutional water use. On average, about 67% of municipal water is used for the residential sector in the Phoenix area. The remaining 33% is used by public operations such as city parks, public schools, public colleges and universities, and everyday government operations. Water demand in the municipal sector is closely tied to population growth and may go up by 60% to nearly 1,722 million m$^3$ (1,395,725 acre-feet) in 2025 (ADWR 1999). Therefore, any program to enhance efficiency in municipal water use will be a critical component in the effort to achieve and maintain ‘safe yield’ in the Phoenix AMA.

While urbanization is replacing agriculture to some extent, the latter still accounts for more than half of the total water use. Agriculture will continue to be an important part of the total groundwater usage in the Phoenix AMA through 2025. Although agricultural water use is expected to remain at about 1,645 million m$^3$ (1,333,885 acre-feet) between now and 2025, ADWR (1999) projects that net area under crop will increase by 10% within the Indian communities. Moreover, crop water demand shifts with increase in temperature regimes as the crop consumptive use per irrigated acre becomes higher with higher temperature. Demand for agriculture water is also influenced by several factors, including number of acres under crops, types of crops grown, irrigation efficiency, agricultural trade policies, federal farm program(s), and market value of crops. Vast quantities of water consumed in agriculture mean that any gain in efficiency can substantially alleviate pressure in water resources. The agricultural sector uses such a large percentage of the groundwater in the Phoenix AMA, that

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**Table 1** | Water-supply portfolio by sector: Phoenix AMA, 1995: (actual); 2025 (estimated)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Demand characteristics</th>
<th>1995*</th>
<th>2025*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal</td>
<td>Residential, commercial and Irrigation for parks &amp; others</td>
<td>1,073 (869,962)</td>
<td>1,722 (1,395,725)</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Indian and Non-Indian demand for growing crops</td>
<td>1,645 (1,333,885)</td>
<td>1,678 (1,360,743)</td>
</tr>
<tr>
<td>Industrial</td>
<td>Industrial, commercial and institutional uses</td>
<td>102 (83,088)</td>
<td>170 (137,628)</td>
</tr>
<tr>
<td>Riparian</td>
<td>Riparian areas</td>
<td>59 (48,000)</td>
<td>59 (48,000)</td>
</tr>
<tr>
<td><strong>Total water supplied</strong></td>
<td></td>
<td><strong>2,880 (2,334,935)</strong></td>
<td><strong>3,629 (2,942,096)</strong></td>
</tr>
</tbody>
</table>

*Values are expressed as million m$^3$ (acre-feet).

the water-efficiency program is critical in attaining the goal of ‘safe yield’ by 2025.

Research shows that there is a potential gain from transfer of water from low value use (e.g. agriculture) to high value use (municipal) as water commands substantially high prices in urban uses. This has prompted a general expectation that the vast amount of agricultural water can be transferred to municipal and industrial usage. In monetary terms, the transfer of water from agricultural to urban usage may seem like a win-win proposition as it offers a cost-effective way of meeting municipal water demand in the future (NRC 2007) and may seem comforting to policymakers. However, it has its limitations which have been well recognized in the 1992 report of the National Resource Council (NRC). One of the major concerns is the loss of agricultural return flow that supports local ecology. Therefore, it is important to consider the ‘third party’ effects of such water transfer.

Agriculture has long been seen by policymakers as a source of resiliency. In Arizona’s dry and highly variable climate with periodic droughts, maintaining regional agriculture may be critical for the resilience of the entire water system. During droughts, agricultural water can be diverted to more pressing needs. Agriculture currently serves as an emergency water bank, buffering the supply against annual fluctuations in water availability. If agriculture were to be largely replaced with domestic and industrial usage of water, those sectors would suffer shortages during periods of drought. The location of agriculture is critical to the effectiveness of the agricultural buffer because transporting water from distant agricultural lands will require expanding current infrastructure. Therefore, reallocation of water from agricultural use to urban and industrial usage to justify growth may turn out to be an urban myth.

Unlike municipal and agricultural sectors, the industrial sector is diverse. It includes water use in power plants, sand and gravel facilities, animal industries, and manufacturing facilities in the AMA. While industrial usage comprises a small proportion of the total demand, it is increasing steadily over time. According to ADWR (1999), total industrial water usage is projected to grow from 102 million m³ (83,088 acre-feet) in 1995 to about 170 million m³ (137,628 acre-feet) by 2025. As the industrial sector is very diverse, it also makes it difficult to have technical expertise related to best management practices. More importantly, as the preponderance of industrial water demand is met through mining groundwater, the demand is projected to rise from 8% of the AMA’s groundwater use in 1995 to 11% by 2025 (ADWR 1999).

Another important but under-recognized component of demand is the need for water required to maintain ecosystem functioning (NRC 2001). Until now, addressing the human dimensions of water use has been the major focus of water planners. Neglect of ecosystem needs over the years has led to a state of steady deterioration of the riparian environment (Morrison et al. 1996) and could potentially have significant adverse effect on the ecosystems of the region.

**Basis for analysis of water-saving potentials across various sectors**

Water resources in a rapidly growing urban center are typically subjected to a variety of factors that can impair the sustainability of water supply in the future. These factors are intimately linked and when combined will increase vulnerability of water resources to change. An obvious factor that stresses water resources at the local level is population growth. Nowhere is this more crucial than in the arid landscapes of the southwest where limited water supply restricts structural solutions to meeting increasing demand for water (Ingram et al. 2008a). During the decade of 1990 to 2000, Arizona’s population grew by nearly 1.5 million. About 1.2 million of these new residents live in the two metropolitan areas of Phoenix and Tucson. Estimates show that each year Arizona adds about 195,000 people, raising statewide water demand by about 30.8 million m³ (25,000 acre-feet) annually (Eden et al. 2008). Beyond the obvious increase in demand for household water use, the growing population also seeks water for recreational and maintenance of riparian ecosystems (NRC 2007).

At a more macro level, the recent multi-year drought that began in 1997 has raised concerns about sustainability of water in the southwestern USA. This is further compounded by the uncertainty associated with the possible alteration of hydrologic cycle due to the effects of climate change. In general, increase in temperature in the Colorado
River basin will increase the rain to snow ratio, shift peak runoff in the spring, increase evapotranspiration, and reduce stream flow (Christensen et al. 2004; Christensen & Lettenmaier 2007; Seager et al. 2007), constraining the already over-allocated water resources. Accelerating water demand punctuated by multi-year drought and the prospect of the reduction of Colorado River flow due to climate change along with impairment of water quality raises the concern of sustainability of water resources in the region.

This paper recognizes that water resources in the Phoenix AMA are subject to multiple factors that collectively stress its supply and demand. Also, given the large uncertainties typically associated with efforts to quantify the impacts of climate change in the hydrological systems at the local level, an obvious approach to the analysis of water-saving potential is by looking at the areas of strength in relation to causes and effects. It is argued that understanding of the sensitivity of water resources to various factors will provide insights on the social processes that shape the vulnerability of water resources to current and future change.

Following Pielke et al. (2000), who demonstrated that demographic and socio-economic changes will be 20 to 60 times more important than climate change in contributing to economic losses related to natural hazards (e.g. tropical cyclone) over the next 50 years, this paper undertakes the ‘first-order’ analysis of water-saving potential of water resources to major water stressors. Specifically, based on detailed literature review, this paper quantifies the net effect of each stressor on the supply and demand of water resources in the Phoenix AMA. For example, from a demand management perspective, the 60–70% of all water used by single family residences in the southwestern United States for landscape irrigation constitutes an important stressor. Research shows that residents who convert from turf grass to a more desert friendly xeriscaping landscape can realize up to 30% savings in annual household water demand (Sovocool et al. 2006). Theoretically, by converting the turf-dominated landscape to xeriscaping landscape, a single family residence in the Phoenix AMA can reduce their demand for water significantly.

For the purpose of this paper, stressors are characterized as any biophysical, chemical, or anthropogenic factors that can adversely affect water demand and supply in the region. They can be located within both human and natural origins. Human-induced stressors include pressure due to population growth, demand for maintaining economic and recreational needs, additional demand for water due to the effects of the UHI, impairment of water quality, and institutional conflicts. Natural stressors include persistent droughts, seasonal variations, and changes in the hydrological regime due to the effects of climate change. Some of these stressors are of local origin while others are regional and global in origin. The analysis of water-demand management, therefore, is complicated by the interaction of various stressors that operate at different temporal and spatial scales (WERF 2004; Adams 2005; Bates et al. 2008).

In this paper, the analysis of water-demand management is carried out through investigating the direct ties between stressors and net effects on water resources by comparing a ‘baseline’ scenario with respect to a more desirable state of affairs, an ‘alternative’ scenario. The baseline scenario expects continuation of the existing water-use practices (usually less efficient) in the foreseeable future. It provides a basis to quantitatively demonstrate the water-saving potential against the alternative scenario(s), assuming no specific interventions are made to increase water-use efficiency. This is also the condition referred to as the ‘business as usual’ scenario as it does not incorporate any water-efficiency measures beyond those that exist currently.

The alternative scenario is based on documented best practice(s) for water-use efficiency by the end users. It includes the practices that are aimed at managing water demand through efficiency and conservation. The outcome is then compared against the same sectors using baseline scenarios. For the purpose of quantitative comparison, this paper, where possible, proposes two alternative scenarios, each in various enclaves, mediated by different contexts and circumstances for specific sectors in question. Each alternative scenario is treated independently and assumed to represent the best practice by the end users at the Phoenix AMA. For example, a study of 18,000 single family residential properties in the Las Vegas metropolitan area found a 76% reduction in water application per square foot among the households that changed from turf landscape to xeric (appropriate to local climate) landscape (Sovocool et al. 2006). For managing water demand in the arid southwest, this can be considered as a desirable state of affairs and
certainly a best case scenario. The alternative scenario is meant to serve as an example of a plausible demand management strategy, and not as a comprehensive analysis of any water-management policy. The alternative scenario takes a ‘weight-of-evidence’ measure to establish a reasonable basis for comparison with the baseline scenario. In order to determine the potential for water-demand management, each water-demand management measure is associated with the water-efficiency factor. The quantitative estimate obtained through the use of water-efficiency factors for each scenario is compared to determine the water-saving potential due to the adoption of efficient measures.

In addition, a significant decrease in Colorado River runoff is anticipated for the future due to impending climate change. Most studies indicate that, over the next 30–50 years, the flow of the Colorado River may decrease anywhere from 6 to 30% (Christensen et al. 2004; Milly et al. 2005; Christensen & Lettenmaier 2007; Seager et al. 2007), an equivalent of 1,233–5,550 million m³ (1.0–4.5 million acre-feet) per year. If the estimates hold, by 2030, discharge from Lees Ferry (which separates the upper from the lower basin) may be insufficient to meet current consumptive water demands. This may increase competition among municipal, agricultural, industrial, and environmental users (Bates et al. 2008). In order to estimate possible water losses due to a decrease in the flow of river water, two scenarios (moderate and extreme) of water flow are created. While hypothetical, these water-supply scenarios will help understand the total water budget of the AMA.

Based on the supply of and the demand for water resources, the analysis of the water-saving potential of the Phoenix AMA can be located within three categories: (a) municipal, (b) agricultural, and (c) biophysical. Operating at various levels, these can impact water resources in single, cumulative, or synergistic ways.

Analysis of water-use efficiency by category

Municipal category

In the last two decades, some of the fastest growing metropolitan areas of the southwestern USA have made a significant progress in water-use efficiency. For example, Gleick et al. (2003) demonstrated that residents of California could reduce their indoor water demand by almost 40% simply by replacing water-inefficient toilets, washing machines, showerheads, and dishwashers, and by reducing the leaks in the water-supply systems. The savings proposed are cost effective and have important co-benefits such as saving energy and decreasing the amount of waste water created. Likewise, Southern Nevada Water Authority, which includes Las Vegas, was able to reduce per capita water consumption by 13% during the period between January 2003 and December 2005. Net water consumption went down even when some 250,000 new residents were added (Sovocool et al. 2006). This is attributed to a combination of factors including the upgrading of household equipment and conversion from turf to a xeriscapic landscape. Water savings through conservation and efficiency gains are practical as well as cost effective and offer significant potential for demand management in the future. To best assess and compare existing municipal water-consumption rates and potential savings due to increased water-use efficiency (technological and managerial), this paper addresses indoor and outdoor residential water usage separately. Together, they are not only the largest consumers of municipal water but also provide direct indicators of demand management, and are most affected by many water conservation programs.

Indoor water use

The end user data collected for the Residential End Uses of Water Study (REUWS 1999) provides information about water-use characteristics for over 1,188 homes across 12 cities in North America and Canada. In the REUWS study, indoor water-use averages 262.3 L (69.3 gallons) (including leakage) per capita per day (LPCD), ranging from 216.1 LPCD (57.1 GPCD) in Seattle, Washington, to 316.0 LPCD (83.5 GPCD) in Eugene, Oregon. The same study shows the average daily indoor water use of 500.9 LPCD (79.5 GPCD) for Central Arizona (Phoenix, Scottsdale and Tempe), accounting for 32% of residential water consumption (Mayer & DeOreo 1999a).

Over 100 water-efficient appliances are available in the market that can result in permanent indoor water-use savings if applied appropriately (Vickers 2000). To illustrate the importance of water-efficient appliances for reducing indoor water use, this section focuses on four key indoor
appliances – flushing toilets, washing machines, showerheads, and faucets (see Table 2). The comparison is based on the quantitative breakdown between appliances that are considered water inefficient but are still in use and those that meet water-efficient standards as set by the 1992 Energy Policy Act of the federal government.

Flushing toilet

On average, a person uses about 71.9 L (19.0 gallons) of water per day for flushing toilets. This is one of the indoor appliances where the most waste occurs through leaks and inefficient products. Although the 1992 Energy Policy Act requires that newly installed toilets not exceed 6.1 L (1.6 gallons) per flush, in Phoenix, the REUWS study shows the average per flush volume was 12.9 L (3.4 gallons). As shown in Table 2, by upgrading to ultra low flush (ULF) toilets that use only 6.1 L (1.6 gallons) per flush, the daily average toilet water use could be reduced by 35.6 LPCD (9.4 GPCD). Over the course of a year, a person could save 12,933 L (3,417 gallons) of water. One of the public concerns with respect to toilets with lower volume per flush is that people would double or triple flush, thereby defeating the objective of saving water. However, a study by Mayer & DeOreo (1999b) comparing ULF and conventional toilets showed the same frequency of flushing for both, resulting in a water saving of over 60% in the ULF toilets.

Washing machine

Average daily per capita use of water for washing clothes across households in Phoenix is 46.6 LPCD (12.3 GPCD), accounting for 21.6% of residential indoor water use. As shown in Table 2, a washing machine with a low water factor uses 30–35% less water per load than a conventional machine (http://www.energystar.gov). By replacing a water-inefficient washing machine, on average, a person could potentially save as much as 6,219 L (1,643 gallons) of water annually.

Showerhead

The installation of high efficiency showerheads is a relatively low-cost way for individuals to save water. According to the REUWS study, average daily per capita showerhead water usage was 46.6 LPCD (12.3 GPCD), accounting for 15.6% of residential indoor water use. As shown in Table 2, by replacing commonly used showerheads (11.4–15.1 L or 3–4 gallons/min) with low-flow ones (9.5 L or 2.5 gallons/min), a person would save 26.9 L (7.1 gallons) of water per shower. This translates into a net saving of 9,807 L (2,591 gallons) of water per person per year.

Faucet

Faucets are important components of residential water use. Based on the REUWS study, a person uses an average of 37.8 L (10.0 gallons) of water is used for faucets/day, accounting for 15.7% of total indoor water use in Phoenix. Ordinary kitchen and bathroom faucets use up to 15–19 L (4–5 gallons) of water per minute. As shown in Table 2, by installing high efficiency (7.6 L or 2.0 gallons/min), yet inexpensive faucets, a person can save up to 13,815 L (3,650) gallons of water per year.

Table 2 | Comparison of the baseline and standard appliances/fixtures in outcome of water use per person per day in the Phoenix AMA

<table>
<thead>
<tr>
<th>Indoor water use by scenarios: Baseline (BA) vs. Standard (ST) case</th>
<th>Water use/day (BA)</th>
<th>Water saving/day (ST)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flushing toilets</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA 12.9 L (3.4 gallons)/flush × 5.2 flushes/person/day</td>
<td>67.0 (17.7)</td>
<td>35.6 (9.4)</td>
</tr>
<tr>
<td>ST 6.1 L (1.6 gallons)/flush × 5.2 flushes/person/day</td>
<td>31.4 (8.3)</td>
<td></td>
</tr>
<tr>
<td><strong>Faucets</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA 17.0 L (4.5 gallons)/min × 4 min/person/day</td>
<td>68.1 (18.0)</td>
<td>37.8 (10.0)</td>
</tr>
<tr>
<td>ST 7.6 L (2.0 gallons)/min × 4 min/person/day</td>
<td>30.3 (8.0)</td>
<td></td>
</tr>
<tr>
<td><strong>Showerheads</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA 13.2 L (3.5 gallons)/shower × 7.9 min/shower × 0.9 shower/person/day</td>
<td>94.2 (24.9)</td>
<td>26.8 (7.1)</td>
</tr>
<tr>
<td>ST 9.5 L (2.5 gallons)/shower × 7.9 min/shower × 0.9 shower/person/day</td>
<td>67.4 (17.8)</td>
<td></td>
</tr>
<tr>
<td><strong>Washing machines</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA 154.8 L (40.9 gallons)/load × 0.30 load/person/day</td>
<td>46.6 (12.3)</td>
<td>18.2 (4.8)</td>
</tr>
<tr>
<td>ST 94.6 L (25 gallons)/load × 0.30 load/person/day</td>
<td>28.4 (7.50)</td>
<td></td>
</tr>
<tr>
<td><strong>Net indoor saving</strong></td>
<td>118.4 (31.5)</td>
<td></td>
</tr>
</tbody>
</table>
The residents of Central Arizona have been improving their water-usage efficiency by replacing some of the retired and inefficient technologies with those of more modern and efficient ones – a good example includes the low-flow toilets. This is especially true after the 1992 Energy Policy Act requiring that the water-efficiency standard be applied to plumbing fixtures in all new and renovated housing after 1994. For substantial numbers of houses built prior to 1994 in the Phoenix AMA that could have standard plumbing fixtures resulting in inefficient use of water, the installation of current generation of technologies in water appliances could reduce water wastage significantly.

According to the population data prepared by the Maricopa Association of Governments (MAG) for the CAP (2003), the population of the Phoenix AMA in 2025 is estimated to be 6,256,500, with a net growth of 3,706,569 between 1995 and 2025. To illustrate water-demand management during the period between 1995 and 2025, two separate scenarios of water usage have been constructed: (a) alternative scenario; and (b) baseline scenario. The alternative scenario assumes an incremental (logistic) adoption of water-efficient appliances between 1995 and 2025, i.e., slow adoption at the beginning followed by accelerating and decelerating adoption, ultimately leading to saturation. The baseline scenario assumes that during the same period, 80% of the population in the base year (i.e. 1995) did not change their appliances.

Based on the growth trajectory of the Phoenix AMA during the period of the mid 1990s, it is estimated that in 1995 approximately 20% (509,986) of the Phoenix AMA’s population was already living in new or remodeled houses and had installed water-efficient plumbing fixtures. The remaining 80% (2,039,945) of the population did not have water-efficient plumbing fixtures. Accordingly, 20% of the Phoenix AMA population in 1995 was assumed to be using 157.5 L (41.6 gallons) LPCD of water with the remaining 80% of the population using 275.9 L (72.9 gallons) LPCD of water for indoor purposes, translating into a net indoor water usage of 190,343 acre-feet in Phoenix AMA. In 2025, following the assumptions of the alternative scenario, all residents become water efficient and use only 156.3 L (41.3 gallons) LPCD of water, translating into 289,438 acre-feet of water for indoor purposes. Following this scenario, during the 30-year period from 1995 to 2025, the population of Phoenix AMA increases by 145% while during the same period indoor water use increases by only 35%. This implies that if current water use in Phoenix AMA becomes as efficient as the existing technologies permit (see Table 2), the AMA could save as much as 122 million m³ (99,095 acre-feet) of water annually by 2025. Even without further improvements in technology, the analysis shows that indoor residential water usage could significantly be reduced. With continual advancement in efficiency, newer appliances and fixtures may have even better water-use rates than those discussed here.

Outdoor water use

A substantial amount of water in Phoenix AMA is used outside of homes to irrigate lawns and gardens. According to REUWS, the average outdoor water usage for single family residents in Tempe, Phoenix, and Scottsdale accounts for 63% of their total water consumption. Outdoor water use rises to a maximum during the summer when water supply is low, hence residential landscape use plays a large role in water demand management. Unlike most indoor water usage, much of the outdoor water is lost to evaporation and transpiration and thus is no longer available for capture and reuse (Gleick 2005). A multi-year survey of 72 households in the Phoenix metropolitan area reveals that actual outdoor water usage is highly variable, and depends only partly on the type of landscaping used (ADWR 2003). Poor irrigation scheduling– watering too often, too long, and at the wrong time of day – are some of the factors leading to excess water usage in the residential landscape (Vickers 2001). Knowing when and how much water is needed and adjusting irrigation schedules according to changing weather conditions is critical in managing water demand as well as in optimizing plant health (Epstein 2000). There are a range of choices available for managing water demand for landscape purposes. Following Gleick (2005), landscape water demand management options can be described as: (a) management practices, (b) hardware improvement; and (c) landscape design.

Management practices

Activities that involve caring for outdoor lawns and plants on the basis of available scientific knowledge constitute
the basis for management practices. The potential to reduce water in landscape irrigation is large because it consumes a significant amount of municipal water, and because simple changes such as choice of plants and irrigation methods can greatly reduce landscape water demand. Efficient water management involves a range of activities including irrigation scheduling based on knowledge of plant water needs. A field study that compared outdoor water-usage patterns in two single family housing units (approximately the same size) planted with a mix of low water-use plants found a difference of 32.9 L/ft²/month (8.7 gallons/ft²/month) between households (825,130 L or 218,000 gallons/year) (Martin 2001). As illustrated by Beard (1973) and Kneebone et al. (1992), the common perception that the application of more water translates into better quality (growth) is not necessarily true. In fact, studies show that under some level of restricted irrigation (or deficit irrigation) plants do not visibly show difference in vigor (Qian & Engelke 1999; Kirda 2002). This deficit irrigation strategy has been successfully applied in many agronomic, horticultural, and turf grass species. Studies on turf grass show that reducing irrigation by 20–40% below the recommended rate results in no reduction in quality or physiological condition (Fu et al. 2004; DaCosta & Huang 2005). In fact, moderately deficit irrigation is associated with better quality growth (Jordan et al. 2003; Fry & Huang 2004).

**Hardware improvement**

Most water-efficient hardware devices ensure that water is applied only when and where it is needed. As a move towards increasing outdoor water efficiency, increasing numbers of homeowners install automatic irrigation systems. Although automatic irrigation systems do offer the potential for more efficient use of water, research shows mixed results. Most homeowners do very little to adjust their irrigation schedule in response to seasonal changes in plant water requirements (Courtney 1997). Indeed, one study suggests that automatic irrigation systems actually lead to increased water waste (Vickers 2001), instead of enhancing efficiency.

Recent technological advances in evapotranspiration monitoring, rain sensors, soil moisture sensor, and similar devices can augment the efficiency of irrigation systems. For example, a large, interconnected information system can help reduce the excess use of water in outdoor lawns. The most well known system is the California Irrigation Management System (CIMIS), which uses information generated at about 100 computerized weather stations throughout the state to help industrial, commercial, and residential property owners determine optimal timing and quantity of irrigation. CIMIS users reported an average of 13% savings in applied water.

**Landscape design**

According to the ADWR (1999), a typical household consumes 548.8 L (145 gallons) of water/day for outdoor irrigation. Water-wise xeriscapinglandscape, if designed and maintained properly, could save a significant amount of water compared to a conventional landscape with turf grass (Martin & Stabler 2002); this type of landscaping can be practiced anywhere in the world (Vickers 2001). Studies of residential properties that have been partially or fully converted to xeriscaped landscapes have reported actual water savings of 20–50% for several years (Nelson 1994; Epstein 2000), but savings could be higher. Studies suggest that more than 70% of the water used irrigating landscape could potentially be saved by careful selection of native plants suited to a semi-arid environment (Smeal et al. 2006). One of the most comprehensive studies of landscaping in southern Nevada shows water savings of 76% resulting from replacing turf grass with xeriscaped landscapes (Sovocool et al. 2006), resulting in an annual saving of over 340,650 L (90,000 gallons) per household. Likewise, another study shows that single family residences that are water-wise could potentially save as much as 40–45% water (DaCosta & Huang 2005).

Based on prevailing landscape design and water-use practices, this paper proposes three separate scenarios to quantitatively demonstrate the characteristics of landscape water use. They are: (a) best case scenario, (b) business as usual scenario; and (c) intermediate scenario. The best case scenario assumes that by 2025 all housing units in the Phoenix AMA will adopt xeriscaping landscaping and be water efficient, thereby saving 70% of outdoor water use, as in the case of Las Vegas. The business as usual (water intensive) scenario assumes that the residents of the Phoenix AMA will not change their landscape preference (i.e. turf dominated landscaping) but upgrade their irrigation hardware.
This technological fix would result in a 13% reduction in their outdoor water usage by 2025. But the reality is that most people are likely to make partial changes in the landscape as they become more and more aware of the constrained water situation. This anticipated change in behavior warrants looking beyond the two scenarios to an intermediate one that could be more realistic. This intermediate scenario assumes only partial conversion to xeriscapic landscaping but with the implementation of water-wise management practices such as deficit irrigation discussed earlier. Based on the review of the studies conducted across different parts of the country, full implementation of this practice may save 40–45% of outdoor water by 2025.

According to the MAG (MAG-CAP 2003), total housing units in the Phoenix AMA are estimated to be 1,075,500 in 1995, of which 85% (914,175) are estimated to be single family residential (SFR) units. If the current trends of growth persist, by 2025 the number of SFR will increase to 2,445,500. On average, excluding the water use for swimming pools or cooling, a typical SFR in the Phoenix AMA uses 549 L (145 gallons) of water a day for landscape irrigation (ADWR 1999). To illustrate the landscape water-consumption patterns, using the three scenarios as a basis, this paper demonstrates the landscape water-saving potentials for SFR units only. As shown in Table 3, while there is a significant variation, all three scenarios demonstrate potential for some degree of water saving. According to the assumption of best case scenario, if all the SFR units in the Phoenix AMA adopt xeriscapic landscaping and become water efficient, approximately 343 million m³ (278,040 acre-feet) of water will be saved annually by 2025 (see Table 3). In other words, they will use only 165 L (43.5 gallons) of water a day. Likewise, following the assumption of the intermediate scenario, the SFR units in the Phoenix AMA will save 196 million m³ (158,880 acre-feet) of water annually by 2025. Each SFR will use 329 L (87 gallons) of water a day.

Agriculture has been the predominant user of water in Arizona in the 20th century. In the Phoenix AMA, agricultural

### Table 3

<table>
<thead>
<tr>
<th>Number of SFR* units at year 1995 and 2025, Phoenix AMA</th>
<th>1995 – 914,175</th>
<th>2025 – 2,445,500</th>
</tr>
</thead>
<tbody>
<tr>
<td>(SFR × 549 L (145 gallons)/day/SFR) × (365)/AF</td>
<td>183 (148,481)</td>
<td>490 (397,200)</td>
</tr>
</tbody>
</table>

**Landscape water use by scenario**

- **BAU**: Technological fixes in landscape irrigation will save 15% water
  
  \[= (183 \times 0.13) = 24\]
  
  \[= 148,481 \times 0.13) = 19,303\]

- **Best case**: Xeriscapic landscape in all SFR units will save 70% water
  
  \[= (183 \times 0.70) = 128\]
  
  \[= (148,481 \times 0.70) = 103,220\]

- **Intermediate**: Partial conversion to xeriscapic landscape will save 40% water
  
  \[= (183 \times 0.40) = 73\]
  
  \[= (148,481 \times 0.40) = 58,983\]

**Agriculture category**

Agriculture has been the predominant user of water in Arizona in the 20th century. In the Phoenix AMA, agricultural
water demand is categorized separately for Indian and non-Indian use. Out of 132,213 hectares (326,695 acres) of non-Indian agricultural land, approximately 65,479 hectares (161,797 acres) (49.5%) was cropped in 1995, using 1,368 million m³ (1,109,105 acre-feet) of water (ADWR 1999). Agricultural land for three Indian communities was estimated to be 14,944 hectares (36,925 acres) in 1995. Since water users in Indian communities are not subject to the conservation requirement or acreage restriction in agriculture, water use for agricultural irrigation purpose is not included in the analysis. According to the ADWR (1999), agricultural water use is projected to increase in the future. It should also be noted that the annual water use by Indian communities was estimated at 277 million m³ (224,780 acre-feet) in 1995. With almost half of the total crop acreage, cotton is one of the principal crops grown on the non-Indian agricultural land. In 1995, approximately 32,281 hectares (79,766 acres) of cotton, about 12,113 hectares (29,932 acres) of alfalfa, and 9,428 hectares (23,298 acres) of cereals were grown in the Phoenix AMA. Farmers use different methods to irrigate their crops including flood, sprinkler, and drip systems, with flood being the dominant mode (Postal 1992).

Flood irrigation is simply the application of water by gravity flow to the surface of the field. It is mostly used in field crops where the entire field is flooded or water is fed into small channels (furrows). Although it has a number of important advantages, it is also criticized for its inefficiency. In Arizona, flood irrigation is justified for flushing salts and chemicals from agricultural land, and a recent estimate by the US Geological Survey showed that about 81% (http://www.agcensus.usda.gov/Publications/2002/FRIS/index.asp) of irrigated agriculture is under flood irrigation. According to Salas et al. (2006), the average water-use efficiency factor (defined here as the volume of irrigation water beneficially used divided by the volume of irrigation water applied) associated with flood irrigation depends on various factors and can range anywhere from 50 to 75%. For the purpose of this paper the water-efficiency factor associated with flood irrigation is estimated to be 60%.

Introduced in the 1930s, the sprinkler irrigation system is slowly gaining momentum in the southwestern US agriculture. In a sprinkler irrigation system, water is delivered to the field through a pressurized pipe system and is distributed by rotating sprinkler heads or spray nozzles. A recent estimate by the US Geological Survey puts 16% of agricultural land under sprinkler irrigation (http://www.agcensus.usda.gov/Publications/2002/FRIS/index.asp). The water-use efficiency factor associated with sprinkler irrigation is determined by several factors including wind speed and direction. Following Salas et al. (2006), the average water-use efficiency factor associated with sprinkler irrigation system is 80%.

Drip irrigation is defined as a low-pressure, low-volume irrigation system and includes surface and sub-surface drip. It is also known as micro-irrigation. Although sprinkler and drip irrigation are known for their water-use efficiency, installing these systems requires an expensive upfront investment. A recent study by Thompson et al. (2009) shows only about 3–4% of irrigated land is under drip irrigation systems. As with other irrigation systems, the water-use efficiency factor associated with drip irrigation is highly variable, ranging from 80% to over 95%. It is determined primarily by the root zone, type of crops, and depth at which drips are set. According to Salas et al. (2006), the average water-use efficiency factor associated with drip irrigation is 90%.

It is argued that increasing agricultural water efficiency is a necessary condition in light of current and future challenges. The water that is saved through efficiency could be redirected for agricultural production, to support new urban and industrial activities, to restore stressed ecosystems, and to recharge groundwater aquifers. Several options have been proposed to improve the efficiency of water-use in agriculture. Based on Cooley et al. (2009) and Morrison et al. (1996), three technological and managerial scenarios could be considered in the Phoenix AMA: (a) efficient irrigation technology, (b) regulated deficit irrigation, and (c) crop adjustment and or retirement.

Efficient irrigation technology

By improving irrigation efficiency through new and innovative irrigation technologies, such as sprinkler and drip systems, on-farm water demand can be significantly reduced (Murphy 1995). A well known example of efficient irrigation is that of Arizona-based Sundance Farms. Sundance Farms has been growing cotton, wheat, and, recently, alfalfa with buried drip lines placed 20–25 cm
(8–10 in.) below the soil in every row of crops so the drip lines are undisturbed. The drip irrigation system has worked well on alfalfa, reducing water use by one-third and increasing yield one-third of a ton per acre per cutting, compared to flood irrigation (Blake 2009). In order to quantify the demand for water in the Phoenix AMA in the year 1995, this study assumed that 3% of crop land was under drip irrigation, 17% under sprinkler irrigation and the remaining 80% under flood irrigation. This is in line with what has been estimated for Arizona by the USGS. As pressure to make agricultural systems more water efficient increases in the future, more farmers will choose to install water-efficient technologies. So by 2025, it is assumed that about 20% of crop land will be under drip irrigation, 40% under sprinkler irrigation, and the remaining 40% under flood irrigation. While there is no basis for this projection, in recent years Arizona has undertaken a concerted effort to increase irrigation water-use efficiency. As shown in Table 4, by making irrigation systems more water efficient, such as by changing the flood irrigation systems to sprinkler and/or drip irrigation; the Phoenix AMA could save between 57.7 and 157.8 million m³ (46,630–127,901 acre-feet) of water by 2025.

**Regulated deficit irrigation**

In recent years, water scarcity and interest in maximizing crop quality have induced a number of innovative approaches to water-demand management in agriculture (Goodwin & Boland 2002; Cooley et al. 2009). Deficit irrigation, defined as the application of water below full crop evapotranspiration requirements, is one such approach (Chaves et al. 2007). A growing body of literature shows that consumptive water use can be reduced in some fruit and cereal crops without negative impacts on yield (Polaris Institute 2008). In fact it may even increase yield in some cases. A study by FAO on deficit irrigation in semi-arid climates around the world shows potential for water saving with little impacts on crop yield and quality (Goodwin & Boland 2002). The choice of crop accompanied by better cultivars is equally important for increasing water use efficiency in agriculture (Stirzaker 2003; Passioura 2006). Agronomic practices such as the incorporation of organic materials in the soil, use of mulch, and tillage practices all contribute

### Table 4 | Comparison of agricultural water demand by irrigation types and crop, Phoenix AMA, 1995 and 2025

<table>
<thead>
<tr>
<th>Crop Type and acreage under each crop by year</th>
<th>Water use million m³ (acre-feet) by irrigation systems and associated water-efficiency factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crop Type</strong></td>
<td><strong>Water use million m³ (acre-feet) by irrigation systems and associated water-efficiency factor</strong></td>
</tr>
<tr>
<td>Cotton</td>
<td>1995 (70.766) 1/8 (3.76 × 296 = 296) [239,936] 0.8 182 [148.223] 0.4 27 [22,198]</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>1995 (71.789) 1/8 (3.76 × 296 = 296) [107,971] 0.8 182 [148.223] 0.4 27 [22,198]</td>
</tr>
<tr>
<td>Cereal</td>
<td>1995 (23,298) 1/8 (3.76 × 296 = 296) [239,936] 0.8 182 [148.223] 0.4 27 [22,198]</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>2025 (70.766) 1/8 (3.76 × 276 = 276) [239,936] 0.8 182 [148.223] 0.4 27 [22,198]</td>
</tr>
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<td>2025 (71.789) 1/8 (3.76 × 276 = 276) [107,971] 0.8 182 [148.223] 0.4 27 [22,198]</td>
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</tr>
</tbody>
</table>

Notes: (a) Acreage under each crop for year 1995 obtained from ADWR (1999). (b) Percentage of area under each irrigation system is based on data from USGS for AZ. (c) Acreage for year 2025 is projected to decline by 10% from base year of 1995. (d) Following Salas et al. (2006), average water use efficiency factor associated with flood, sprinkler, and drip irrigation is 60, 80, and 90%, respectively. (e) Crop specific water requirements were based on ADWR (2000). (f) All values rounded to three significant figures.
to water-use efficiency (Zhang & Oweis 1999). Water saving associated with deficit irrigation depends on many factors, including soil and climate, crop types, and the sensitivity of crop growth stages to water stress.

Research shows that crops such as wheat and barley are more efficient with water when they are marginally stressed (Oweis & Hachum 2003). For example, wheat production can be maintained with 20–40% less water provided other management practices are in place. Likewise deficit irrigation has been found to improve the water-use efficiency of cotton. Study by Basal et al. (2009) show no change in seed and lint yield when irrigation water was reduced to 75%. The effect of deficit irrigation in alfalfa is mixed, however. For example, large-scale field trials conducted in the Klamath Basin and the Sacramento Valley of California in 2003 reveals severe yield losses when deficit irrigation was practiced. A similar study from Yuma, Arizona shows that alfalfa yields did not recover after irrigation was withdrawn in the summer. In contrast, a study from Maricopa, Arizona, shows no severe loss on the yield of alfalfa with deficit irrigation. Soil type appears to be a determining factor, as severe yield loss occurred on the sandy soil of Yuma and not on the loamy soil in Maricopa (Ottman et al., 1996; Orloff et al., 2003).

While it appears that more research is needed to determine the optimum level of deficit irrigation in alfalfa, for other crops there is strong research to suggest the value of deficit irrigation in water-demand management in agriculture. The ADWR (1999) assigns an irrigation requirement of 6,553 m³ per hectare (2.15 acre-feet per acre) for cereal crops. The total area under cereal in 1995 was estimated at 9,429 hectares (23,298 acres) and it is estimated to be 8,486 hectares (20,968 acres) in 2025 (see Table 4). Without deficit irrigation, farmers will use 62 million m³ (50,091 acre-feet) of water in 1995 and 56 million m³ (45,081 acre-feet) in 2025. With more practice of regulated deficit irrigation, about 40% of this water can be saved. This amounts to a net saving of 22 million m³ (18,032 acre-feet) annually by 2025. The saving would be even larger in cotton, amounting to 92 million m³ (74,980 acre-feet) and 83 million m³ (67,482 acre-feet) in year 1995 and 2025 respectively. Just by following deficit irrigation practices, farmers of the Phoenix AMA could save as much as 105 million m³ (85,514 acre-feet) of water annually by 2025.

### Adjusting cropping patterns

Like elsewhere around the world, farmers generally try to maximize their net profit, and select crops and growing methods that help them do that. These decisions are influenced by subsidy policy, legal rights to water use, and other considerations discussed earlier. Thus, restructuring agricultural practices to minimize water application is a complex issue (Morrison et al. 1996; Cooley et al. 2009). The discussion in this section is intended to shed light only on the potential for reduced agricultural water use, given that policy and economic environments reward such reductions.

Some crops have much greater water requirements than others. By shifting toward the production of more water efficient crops, the agricultural sector potentially could save current and future water demands in the Phoenix AMA. Since plant water requirements in the Phoenix AMA are met by irrigation, water saved from crop shifting can reduce groundwater withdrawals as well as consumptive usage. Crop adjustment also may provide economic advantages to the farmers. According to Morrison et al. (1996), farmers can cut their water demand by approximately 50% by switching from water demanding crops such as cotton and alfalfa to vegetables and increase net crop revenue in the process. For example, economic return to per unit water consumption is significantly greater in vegetables than in alfalfa and cotton. Estimated economic return from per acre-foot of water uptake for vegetables is US$1,495 but is much lower at US$95 for alfalfa.

For the purpose of quantitative analysis, this paper assumes a scenario of gradual transition from field crops (e.g. alfalfa) to vegetable crops, shifting 20% of irrigated field crop acreage to irrigated vegetable crop acreage by 2025. It is worth noting that, when the net area under irrigated agriculture is changed, it adjusts from more water-demanding field crops to less water-demanding vegetables. For example, by shifting 20% of its alfalfa area to vegetables, the Phoenix AMA would be able to save about 28 million m³ (22,575 acre-feet) of water annually by 2025. The choice of shifting from field crops to vegetables is justified on the grounds that it is happening currently and may likely to continue in the future. In addition, agricultural land use of seasonal crops such as vegetables is more flexible than...
permanent crops (orchards and vineyards) and can be easily shifted (or fallowed) in response to changing climatic or market conditions (Cooley et al. 2009).

Water savings achieved through demand management in agricultural irrigation systems, such as through the use of water-efficient technology and agronomic practices, are real (Gleick 2003). Although the total irrigated crop area remains relatively unchanged, except for the normal decline due to urbanization, the water use will decline by 262 million m$^3$ (212,675 acre-feet) annually by 2025. Water saving at this level will address the problem of groundwater overdraft in the Phoenix AMA, and appropriate agricultural policies may help rebalance the groundwater hydrology while maintaining, and even increasing, economic productivity and profitability.

**Biophysical stressors**

Increases in average night-time temperatures, persistent drought, and possible alteration of hydrological cycles are some of the biophysical stressors that can have direct effect on the supply and demand for water. For example, UHI effects may increase pan evaporation rates of swimming pools, requiring frequent refilling. Rising temperatures due to greenhouse effects may exacerbate the UHI effects, leading to further loss through evaporation. Climate change and variability may alter the hydrological cycle and reduce the supply of water into the system. These stressors on water supply create a different analytical challenge for understanding the future of water in the Phoenix AMA. This paper consider two biophysical stressors: (a) UHI and (b) climate change due to global warming.

**Urban heat island**

With the documented gradual increase in average night-time temperatures in Phoenix and surrounding areas due to urbanization, the impact of the UHI effect on water demand has emerged as a significant concern (Guhathakurta & Gober 2007). The UHI phenomenon in the Phoenix metropolitan area has been studied since the mid-1980s, with research showing that, in the last 50 years, average night-time temperature, in parts of the Phoenix metropolitan area has increased by as much as 6.5 °C (11.7 °F) (Cayan & Douglas 1984; Balling & Brazel 1986; Brazel et al. 2000; Stabler et al. 2005; Gelt 2006).

While studies on the relationship between UHI, energy consumption, and water use are now beginning to appear, quantitative assessments of household water demand are less studied (Guhathakurta & Gober 2007). Significantly higher temperatures extending longer into the evenings may increase residential water consumption. Accounting for other factors that lead to increased water use, Guhathakurta & Gober (2007) show that a typical single family home in a census tract impacted by the UHI effect consumes an additional 5798.6 L (1,532 gallons) of water a month in summer when compared to similar households not directly affected by the UHI. During the five months of the summer period, the effects of UHI alone on water demand could be as much as 71 million m$^3$ (57,488 acre-feet) by 2025 (provided all 2,445,500 single family units were affected by UHI).

**Climate change due to global warming**

In addition to the ongoing challenges discussed thus far, the problem of climate change due to buildup of greenhouse gases further complicates the issue of water resource management 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 (NRC 2007). The instrumental record of climate shows that, during the 20th century, average temperatures increased by 0.37 °C (0.67 °F) across the USA, 0.56 °C (1.0 °F) across the western USA, and 0.79 °C (1.4 °F) in the Colorado River basin (CORB) area (Folland et al. 2001). In the CORB, winter temperatures increased more than summer temperatures and were most pronounced at medium to high elevations (Stewart et al. 2005; Barnett et al. 2008).

Concerns regarding the consequences of climate change on the flow of Colorado River water date back to at least the 1970s (NRC 2007). Several studies have examined the possible impacts of climate change using both empirical and general circulation models (GCMs). In general, all studies predict an increase in temperature by the end of 21st century; the disagreement however, lies in the specific details
of the change in precipitation and the flow of Colorado River water. Climate change, together with increasing water demand from population growth and associated socio-economic development, will result in impacts that are beyond the institutional experience of the region and may exacerbate conflict among water users (Barnett et al. 2008; Bates et al. 2008; Ingram et al. 2008b). Increase in temperature alone will stress the supply of water resources in the CORB and decrease of rainfall will exacerbate this condition (Christensen & Lettenmaier 2007; McCabe & Wolock 2007; Seager et al. 2007). A study by Milly et al. (2005) using values from 12 different GCMs shows a decrease of runoff over the interior western USA during the 21st century. Almost all models agree in the decrease of runoff to around 10–30% in southern Europe, the Middle East, mid-latitude western North America, and southern Africa. Another study of western North America arrives at similar conclusions (Christensen et al. 2004). The study concludes that, relative to the 1950–1999 baseline, the CORB will warm by 1.4 °C (2.5 °F) by 2025 and 2.2 °C (4.0 °F) by 2050. According to this study, average temperature changes of 1.0 °C (1.8 °F), 1.7 °C (3.1 °F) and 2.4 °C (4.3 °F) and precipitation changes of −3, −6, and −3% are predicted for the CORB for the periods 2010–2039, 2040–2069 and 2070–2099, respectively. These temperature and precipitation changes will lead to runoff reductions of 14, 18 and 17% for each of the three periods respectively (see Table 5).

In their most recent paper, Christensen & Lettenmaier (2007) employed downscaled versions of 11 different GCMs to assess the impacts of climate change on the water resources of the CORB. For each of the 11 GCMs, two emissions scenarios (IPCC SRES A2 and B1) were represented. Results for the A2 and B1 climate scenarios were divided into period 1 (2010–2059), period 2 (2040–2069), and period 3 (2070–2099). The mean temperature changes averaged over the 11 ensembles for the CORB for the A2 emission scenario ranged from 1.2 °C (2.2 °F) to 4.4 °C (7.9 °F) for periods 1–3, and for the B1 scenario from 1.3 °C (2.3 °F) to 2.7 °C (4.6 °F). Precipitation changes were modest, with ensemble mean changes ranging from −1 to −2% for the A2 scenario, and from +1 to −1% for the B1 scenario. Runoff changes mostly were the result of a dominance of increased evapotranspiration over the seasonal precipitation shifts, with ensemble mean runoff reductions of −1, −6, and −11% for the A2 ensembles, and 0, −7,

<table>
<thead>
<tr>
<th>Study</th>
<th>Scenario driven change in climate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ΔTemp (°C)</td>
<td>ΔRainfall (%)</td>
</tr>
<tr>
<td>Christensen et al. (2004)</td>
<td>P1 (1.00)</td>
<td>P1 (−3)</td>
</tr>
<tr>
<td></td>
<td>P2 (1.70)</td>
<td>P2 (−6)</td>
</tr>
<tr>
<td></td>
<td>P3 (2.40)</td>
<td>P3 (−3)</td>
</tr>
<tr>
<td>Milly et al. (2005)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Christensen &amp; Lettenmaier (2007)</td>
<td>A2</td>
<td>A2</td>
</tr>
<tr>
<td></td>
<td>P1 (1.23)</td>
<td>P1 (−1)</td>
</tr>
<tr>
<td></td>
<td>P2 (2.56)</td>
<td>P2 (−2)</td>
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<tr>
<td></td>
<td>P3 (4.45)</td>
<td>P3 (−2)</td>
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<tr>
<td></td>
<td>B1</td>
<td>B1</td>
</tr>
<tr>
<td></td>
<td>P1 (1.28)</td>
<td>P1 (−1)</td>
</tr>
<tr>
<td></td>
<td>P2 (2.05)</td>
<td>P2 (−1)</td>
</tr>
<tr>
<td></td>
<td>P3 (2.74)</td>
<td>P3 (−1)</td>
</tr>
<tr>
<td>Ellis et al. (2008)</td>
<td>(2.4–5.6)</td>
<td>(−0.6 + 0.3 mm/day); average 0.1 mm/day</td>
</tr>
</tbody>
</table>
and ~8% for the B1 ensembles (see Table 5). Overall decrease in runoff potentially can strain the CORB system’s ability to meet the competing demands driven by population growth, irradiation, environmental needs and power generation (Barnett et al. 2004). This is especially true given the high sensitivity of the CORB due to over-allocation of water resources.

A sensitivity analysis of change in average temperature and annual flow of the Salt and Verde Rivers in Arizona was tested using a suite of climate models by Ellis et al. (2008). They estimated the projected changes in temperature and rainfall for the time slice of 2020 and 2050. Based on the projected outputs of the models, on average the region is expected to warm by 1.4 °C (2.5 °F) by 2020 with 8.77 mm drop in annual rainfall. The net implication of this is a reduction in the flow of Salt and Verde Rivers. For example, about an increase in temperature of 1.0 °C (1.8 °F) would result in a 6% decrease in runoff. Likewise, a 10% decrease in precipitation would result in a 20% decrease in runoff. By 2050, the combined effect of 2.9 °C (5.4 °F) temperature change and 10% reduction in rainfall would result in a 37% decline in the flow of these rivers (see Table 5).

As most of the surface runoff is derived from snowmelt, the water resource in the western USA is also sensitive to changes in winter temperature. This may be a reason why most of the work on hydrology of the western USA is focused on changes in observed snowpack. Mote et al. (2005) analyzed time series of snow water equivalent (SWE) in the Pacific Northwest and shows long-term decrease in snowpack, and increasingly early snowmelt over the western USA. Stewart et al. (2005) analyzed changes in the timing of spring snowmelt runoff across the western part of the nation. Shifts in seasonality of precipitation and stream flows have been observed across several regions of the western USA (Dettinger & Cayan 1995; Rajagopalan & Lall 1995; Cayan 1996; Hamlet et al. 2005; Stewart et al. 2005).

While studies acknowledge that decadal scale variability may have contributed to the observed trends, it is argued that this variability alone could not explain patterns of changes in SWE over the period analyzed and this pattern was attributed to a regional trend of warming. Notwithstanding considerable regional variability in SWE, a study by Mote et al. (2005) also demonstrated coherent regional scale warming signals throughout the western USA. Likewise the study by Barnett et al. (2008) shows a significant shift in regional hydrology associated with decreased snowpack and accompanied by an increase in minimum temperature during winter and a change in center timing of river flow. Although hydrological shifts at decadal scale are expected due to the nature of decadal scale variability, the recent trend in increased streamflow variability is a major concern for water managers, as it tends to diminish the reliability with which water demands can be satisfied. About 70% of the annual runoff into the CORB comes from the permanent snowpack of the Rocky Mountains and the remaining 30% comes from accumulated snow during the winter and spring melts (Christensen et al. 2004). This is certainly not welcoming news for those living in the western USA.

There is a large and an unspecified degree of uncertainty associated with these climate models, and is inherently linked with the structural configuration of the models. The climate change projections that drive the conclusions of most studies were generated using GCMs. Because of their low resolution, GCMs are prone to creating large errors in the simulation of complex climatic phenomena 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. Thus we 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 planning for the future and have contributed to the ongoing debate over how to respond to the problem of climate change (Schneider & Kuntz-Durisetti 2002). Yet, it also is worth noting that the body of research conducted in the last 30 years collectively points to a drier future with higher rate of evapotranspiration-reduced snowpack, and a reduction of annual runoff and river flow in the western half of the USA.

The CORB is highly sensitive to runoff reductions due to an almost complete allocation of river flow for consumptive usage. Studies conducted in the 1990s suggested a large decrease in Colorado River flow, but more recent studies show a modest decline. Some even suggest no change or a
small increase in river flow. The studies that consider only a change in temperatures show a decrease in river flow, while the studies that consider change in both temperature and precipitation show a greater variability in the outcomes of river flow. It is apparent that there is a large degree of uncertainty with respect to the change of river flow in the CORB. Most studies, however, assert a likely decrease in the order of 0–14% for the time slice of 2010–2039 and 10–50% for 2050 (see Table 5). Although no study shows values for 2025, it is safe to say that the net effects of climate change on the flow of the Colorado river would be in the order of anywhere from 0.00 to 484 million m$^3$ (392,000 acre-feet).

### Groundwater Management Act and the prospect of water sustainability: a discussion

While the GMA and the institutions associated with it have been regarded as an innovative approach to address groundwater overdraft (Jacobs & Holway 2004), the Act has been weakened by the inability of its related policies to enforce the goal of GMA (Hirt et al. 2008). For example, the First Management Plan of the ADWR was vague on enforceability and was also silent about the fees or penalties that water providers might face if their conservation targets were not met (ADWR 1984). Although neighboring cities such as Tucson and Las Vegas successfully made a transition to reduce their water use, especially for outdoor purpose, the water providers in Phoenix did not have any incentives to actively embrace the notion of water conservation (Jacobs & Holway 2004). In response to this resistance and due to the lack of compliance, in the mid 1990s ADWR developed a different model of conservation, substituting the regulatory framework of LPCD-based water use reduction targets with a suite of agreed-upon best management practices (Hirt et al. 2008). The creation of such an alternative program, in fact, allowed high rates of water consumption to continue and pushed the notion of sustainable water management even farther into the future, exemplifying the lack of political and institutional will to address Arizona’s groundwater overdraft challenges (ADWR 1999).

Despite the claim that Central Arizona is moving towards a path to sustainable water future (Jacobs & Holway 2004), scholars argue that the goal of attaining ‘safe yield’ set by the GMA remains unrealistic (Hirt et al. 2008). Though the arrival of CAP water in 1986 eased the supply of water in the Phoenix AMA, progress in managing the demand has been slow. At an average of 890 LPCD (235 GPCD), the Phoenix AMA has the heaviest water user in the nation (ADWR 2007). It is 38% higher than Tucson, its neighboring city (Copenhaver 2005). Currently, there is no AMA regulated LPCD usage. Although water providers are authorized by ADWR to adjust LPCD usage to meet the need of supply and demand, this allocation depends greatly on the water portfolio of each provider. For example, the city of Phoenix has a 855 LPCD (226 GPCD) usage and holds allocations from the Salt River Project, CAP and Groundwater, while the city of Queen Creek has a 473 LPCD (125 GPCD) usage that comes from groundwater only. So cities with diverse portfolio of water available to them seem to have higher GPCD usage.

As discussed earlier, while the GMA was designed to sustain groundwater supplies for the future, the 1948 Groundwater Code and its subsequent amendments did not place any limits on the amount of groundwater that could be pumped by users. Therefore it is likely that the total water supplies may decrease in the future, making demand management a key priority. Yet a resolution to the demand management appears to be far from over. Current complex institutional arrangements and the governance structure in the Phoenix AMA are not helping to make necessary progress in reducing water demand. According to Hirt et al. (2008), the ongoing legislative amendments, consumer resistance, and nervous regulators are the reasons for slow progress in demand management.

In the Phoenix AMA, groundwater overdraft has declined in the two decades between 1980 and 2000. However, with rapid population growth and the failure of conservation regulations, it is projected that the overdraft will rise in the foreseeable future, contrary to the fundamental goals of the GMA. According to ADWR, based on the current water use scenario, groundwater overdraft will rise by over 50% between 1995 and 2025, making it impossible to reach “safe yield.” Continuous growth of population and ongoing changes in climate may exert additional stress on the existing portfolio of water in the Phoenix AMA. Deepening wells and pumping more groundwater to meet the demands of growth or to augment shortages from the impacts of climatic stress are not sustainable solutions.
Pumping groundwater to balance a lack of surface water supplies during times of drought has become more challenging in terms of increasing drawdown and may be legally problematic in light of the AMA’s goal of ‘safe yield’ and sustainable groundwater use. Therefore, demand management should be a crucial part of a calculus of sustainable water management. Although agricultural water use in the Phoenix AMA will continue to decrease in the future, the urban and industrial water use will continue to grow. This shift towards transfer of water from farms to cities (Hirt et al. 2008) warrants a careful consideration of demand management. Paradoxically private ownership of water and an irrational water-pricing mechanism are posing significant obstacles to water-demand management. According to a report by the US Bureau of Reclamation (2003), the region may face a water supply challenge as early as 2025 which may affect the local economy and natural resources.

The focus of this paper was to analyze the water-saving potential of the current Phoenix AMA and, through extensive literature review and secondary data analysis project this analysis till 2025. The analysis 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, this paper consciously sought to ensure that comparative studies were closely aligned with that of the Phoenix AMA in terms of biophysical and demographic characteristics. Three other assumptions embedded in the analysis of this paper included: (a) a linear extension of historical population growth trends (such trends may or may not continue unabated in the future); (b) assumptions of no change in technology, indicating that the estimates based on alternative scenarios are conservative, and that water savings are likely to be even greater than what has been presented; and (c) an assumption that no changes in water policies will occur exerting significant pressure on water-consumption behavior.

Many options are available for improving the efficiency of water use. This paper illustrated the evidence-based practices showing potential for water saving without compromising on the quality of water usage. Both the municipal and agricultural sectors show the potential for significant water saving based on actual experience. Using the results of the foregoing analyses, this paper tabulated and ranked the stressors according to two criteria: (a) estimated water saving through demand management and through improving the system’s inefficiency; and (b) anticipated water loss due to biophysical impacts (stress) on the system. The analysis clearly illustrates that appropriate water demand management and efficiency improvements can save significant amounts of water. Yet these improvements often entail significant investment, which can be a barrier to implementation. Still desirable policies can help reduce these barriers. A number of proven technologies and management practices can improve water use efficiency. Strengthening and expanding the use of such technologies would certainly help manage the water resources more sustainably.

Table 6 summarizes the net water saving through different conservation and efficiency measures. Following the discussions in the earlier sections, they are tabulated under the categories of municipal, agricultural, and biophysical. Expressed in acre-feet, Table 6 shows that water resource in the Phoenix AMA is sensitive to stress from outdoor landscaping under the municipal category, and has the potential for the most savings. This is closely followed by the stress on water resources from inefficient agricultural use. The loss of water due to a rise in temperature and a simultaneous

<table>
<thead>
<tr>
<th>Factors that stresses water resources</th>
<th>Annual water saving potential by 2025, million m³ (acre-feet)</th>
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</thead>
<tbody>
<tr>
<td><strong>Potential saving from municipal sector</strong></td>
<td></td>
</tr>
<tr>
<td>Indoor water use</td>
<td>122 (99,095)</td>
</tr>
<tr>
<td>Outdoor water use</td>
<td></td>
</tr>
<tr>
<td>a. Best practice scenario</td>
<td>345 (278,040)</td>
</tr>
<tr>
<td>b. Intermediate scenario</td>
<td>196 (158,880)</td>
</tr>
<tr>
<td>c. Business as usual scenario</td>
<td>64 (51,636)</td>
</tr>
</tbody>
</table>

| **Potential saving from agricultural sector** | 262 (212,675) |

| **Potential loss from biophysical change** | 71–484 (57,488–392,000) |
| Additional demand due to UHI | 57,488 |
| Reduction of surface flow in Colorado and Salt/Verde Rivers due to climate change | 0.00 to 392,000 |
reduction in precipitation, due to global warming, in the CORB, the largest suppliers of surface water to the Phoenix AMA, ranked as the third most important stressor. There is, also, a potential for savings in indoor use but the amount is not as great as other categories. This is not surprising given that efficiency standards and technology innovation have been focused for this sector.

While climate variability and change may have negative consequences in both the supply of and demand for water, this paper clearly shows that there are other significant factors which have more direct impact on water resources (and vice versa). Indeed, this paper demonstrates that local factors such as use of inefficient technologies, practice of water-demanding landscaping, land-use change, and the persistence of water-intensive agricultural practices are seen to influence water supply more significantly than climate change. While water-consumption patterns are clearly related to its supply, they are also determined by a host of other factors such as population growth, household use, landscaping preferences, availability and use of water-conserving technologies, and overall pricing. However, the impacts of these variables on decision making about water use are not well documented. This paper is an initial attempt to address this shortcoming by synthesizing existing literature on water-resource management in Central Arizona. This has been accomplished by analysis of the sensitivity of water resources to multiple factors so as to facilitate decision making in water management in Central Arizona. In so doing, the paper also has identified gaps in the current research portfolio and decision making.

**CONCLUSION**

Water-use efficiency is becoming an increasingly important factor that can help Arizona not only adapt to impending climate change but also manage its growth trajectory in the future. Lack of comprehensive estimates of actual water usage poses a serious challenge in the study of water issues in Arizona. The failure to provide a comprehensive account for water use contributes directly to the failure to manage it sustainably. This study demonstrates that with existing knowledge, technologies, and institutional infrastructure, Arizona can address water supply constraints and improve its long-term sustainability. Given changing social, economic, and hydrologic conditions in the southwestern region of the country, a more holistic water demand management approach is needed. This is important to address the concerns of reaching ‘safe yield’ as stated by the GMA and to adapt to the potential impacts of climate change.

An important revelation of this paper is that reduction in individual and system-wide water demand not only decreases sensitivity of water resources to change but also extends the ability of existing systems to meet current and future demands. More generally, the analysis of water-saving potential suggests that outdoor water use and agriculture are comparably fertile targets for efficiency gains from technical and management perspectives. It is acknowledged that municipal water savings estimated for this paper are inextricably linked to population growth. Any change in population will have implications for those estimates. Although conventional wisdom suggests that water saving from agricultural sector is available for other uses, it may not happen in the real world due to the limitation of infrastructure and legal rights among the users.

The scientific knowledge to develop more intelligent demand management methods, which are valuable for outdoor and agricultural water use, are some of the dimensions that this paper offers in the pursuit for solutions by decision makers. The creation of water-management policies reflecting the best practices is critical for effective water-resource management. While the question of what approaches and sectors are adoptable from political and policy perspectives would be the subject of a different study, the ranking of water use in this study suggests that outdoor irrigation and agricultural practices can be reduced substantially. Likewise, the estimated loss of water due to change in local hydrological regimes is in the range of half of the potential savings that could theoretically be achieved by managing demand, thereby suggesting that vulnerability to climate change for Central Arizona can be reduced.

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