

The paradoxical ecology and management of water in the Phoenix, USA metropolitan area.

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Abstract

One of the fastest growing cities in the US, the desert city of Phoenix has appropriated significant surface and ground-water resources from regions near and far to support not only basic needs but also various cultural amenities, such as golf courses. Rapid expansion of the metropolitan area has resulted in loss of native ecosystems including desert riparian areas, and creation of new, designed ecosystems that are frequently water-intensive. This article reviews current water resources and management practices, along with resultant ecological impacts. Future legal, socioeconomic, cultural, and environmental challenges to the sustainability of the current lifestyle are highlighted.

Key words: urban ecology, sustainability, aquatic habitat, Arizona, semi-arid ecosystem.

1. Introduction

Located in the northern Sonoran Desert of the southwestern USA, the Phoenix metropolitan area receives approximately 180 mm of precipitation a year, with an average January temperature of 12°C and an average July temperature of 34°C (Baker *et al.* 2004). Most rain is concentrated in two seasons: a summer "monsoon" season with short, intense, localized thunderstorms and a winter rainy season characterized by frontal storms of longer duration and lower intensity. Given its hot, dry climate, the area experiences an average of two meters real evapotranspiration annually. Since this is much higher than the annual precipitation, additional sources of water must be utilized for human habitation. The

city is situated in an alluvial valley surrounded by rugged mountain ranges typical of Basin and Range topography (Jacobs, Holway 2004).

Despite its arid climate, humans have lived here since prehistoric times. The valley is situated at the base of more humid upland watersheds. Dryland rivers, the Salt and Verde, provided adequate surface water to support settlement in an area where precipitation falls short of evapotranspiration substantially. The complex civilization of the Hohokam, which was based on irrigated agriculture, persisted for more than 1000 years (Fitzhugh, Richter 2004). Early modern Phoenicians in the late 19th and early 20th centuries resurrected and expanded the ancient canal system, creating vast areas of agricultural production, including citrus, dairy, alfalfa, and cotton crops.

Throughout the 20th century new tactics for stabilizing and increasing water supply to the valley included the establishment of large dams, both within the local watershed and on other distant rivers, requiring trans-boundary water transfer, and an extensive canal network throughout the region. These structural solutions essentially eliminated in-stream flow of the region's rivers, except during extreme flood events.

Now, Phoenix is one of the most rapidly growing cities in the US, increasing from approximately 300 000 in 1950 to greater than 3.7 million in more than 20 municipalities in 2004. Models predict that in 2025, the population will exceed 6 million, representing a 280% change since 1980 (Jacobs, Holway 2004), and nearly all of the undisturbed and agricultural lands will have been developed to urban land uses (Jenerette, Wu 2001). With few geographical barriers to expansion, growth has been largely in an outward direction, estimated at almost 0.8 km per year (Gober, Burns 2002). Most new construction has been the result of conversion of agricultural to residential use, but increasingly, new areas of desert are being transformed into housing developments.

Clearly, unlimited population growth rates are unsustainable due to accompanying environmental impacts and resource limitation. However,

analysts predict the population of Phoenix to level off around 7 million (Gammage 2003). Are there enough resources to support a population of this size without incurring serious environmental damage, impairing resources for future generations? Does the rate of growth affect long-term sustainability? Questions and concerns about the sustainability of Phoenix's rapid expansion are inextricably linked to sociological and ecological processes across many scales, from daily individual and household decisions to long-term climatic patterns and change. As Gammage (2003) notes, "because water's absence is the defining characteristic of a desert, its management becomes the defining activity of living in the desert." In addition to describing current socio-ecological conditions in the metropolitan area, in this article we also address future prospects for maintenance and growth of urban Phoenix, given water as a limiting resource. Phoenix is not alone in addressing these questions; Fitzhugh and Richter (2004) estimate that "41% of the world's population lives in river basins where the per capita water supply is so low that disruptive shortages could occur frequently." Evaluation of Phoenix's sustainability, and implementation of steps to achieve it, will benefit not just Phoenix and the US Southwest but also rapidly growing cities throughout the world.

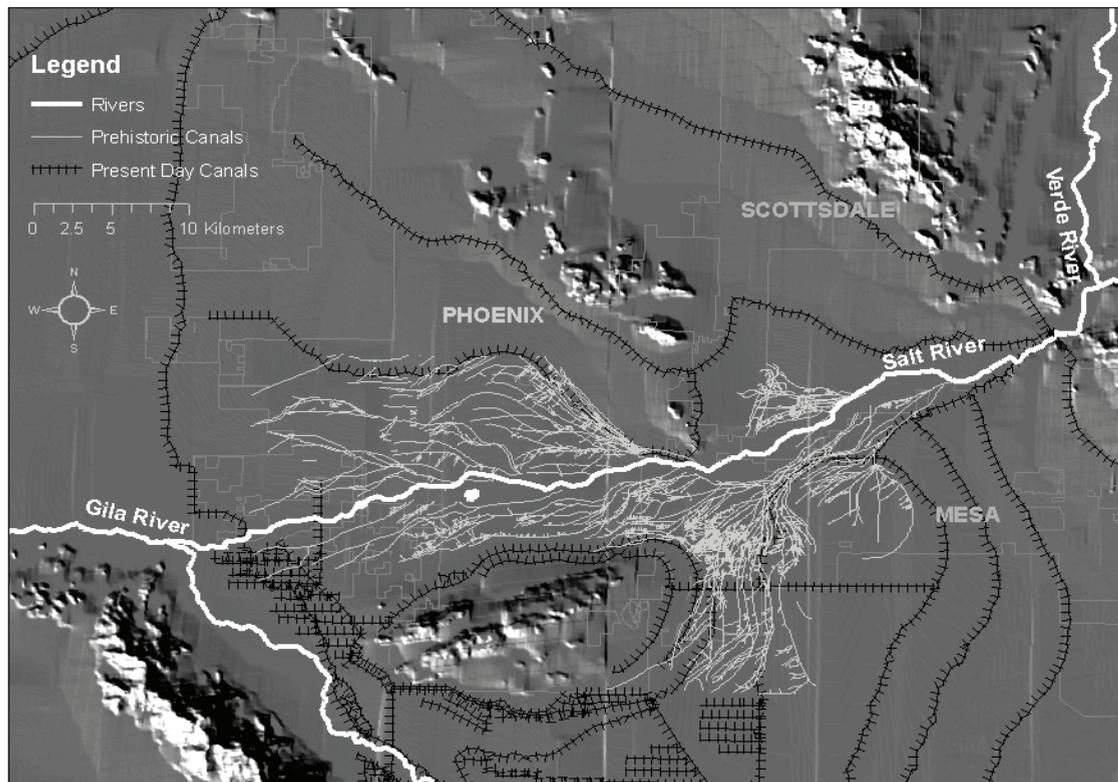


Fig. 1. Major water features in the Phoenix Metropolitan Area, including prehistoric Hohokam Canals. The Salt and Verde Rivers are tributaries to the Gila River, which in turn feeds into the Colorado River (hundreds of km away).

2. Current water resources and management

Phoenix currently has a relatively diverse array of water resources available. The valley has access to 2.8 billion cubic meters of water from its watershed, groundwater, and the Colorado River. The Hohokam were the first in the area to actively manage water resources to enhance agriculture. They built a system of canals on the north and south sides of the Salt River, just downstream from the confluence with the Verde River (see Fig. 1). When Phoenix was re-established as a farming community in the late 1800s to support area mining and military outposts, the ruins of Hohokam canals were discovered, excavated, and expanded upon (Gober 2006).

The magnitude of earlier efforts is small in comparison to the billions of m³ moved throughout the modern-day system. The transition from relatively small-scale farming to bustling metropolis, although rapid, did not occur instantaneously. Rather, changes were incremental and in response to rising pressures and opportunities. The first step was the construction of dams. Like other rivers of the American Southwest (Baker 1977), the flows of Salt and Verde Rivers are quite variable and flash flooding can have deleterious effects on settlements and agriculture. Damming the rivers reduces flooding and ensures a more stable water supply year-round. In the early 20th century, several dams were constructed along the Salt and Verde Rivers, most of them funded by the US Bureau of Reclamation (Fig. 2). There are now seven dams with six

reservoirs (one dam is for diversion only) with a total storage capacity of 4.4 billion m³ (ADWR 1999). The eventual dam and canal system, managed by what came to be known the Salt River Project (SRP), was able to supply water to greater than 800 km² of irrigated farmland (Gammage 2003). As the urban population of Phoenix grew, farms and ranches were converted to residential and commercial areas that retained the prior water rights. These land-use types use less water than agriculture, depending on landscape choice and household conservation. Today, SRP delivers more than 1.2 billion m³ per year to its service area (Jacobs, Holway 2004).

However, substantial development has occurred outside of the SRP service area, where users must find an alternate source of water. The Phoenix valley has several groundwater sub-basins that are hundreds of meters deep and have been used to supplement surface water supply since the early 1900s. The history of intensive agriculture throughout much of the area has diminished the quality of this groundwater, especially with respect to pesticides and nitrate, a component of fertilizer (ADWR 1999). For example, the median concentration of nitrate is >10.0 mg NO₃⁻-N dm⁻³ (Baker *et al.* 2004), just above the maximum limit for drinking water established by the US Environmental Protection Agency. Treatment to remove contaminants during the water-treatment process is generally considered cost-prohibitive except when no other water source is available.

Another substantial difficulty resulting from groundwater use is overdraft of the aquifer (removals > recharge). Declining water table levels have been occurring in some places since the 1940s, although early legislation (the 1948 Critical Area Groundwater Code) proved insufficient to slow the trend of increased well drilling. Arizona did not undertake serious measures to curb groundwater use until the federal government issued an ultimatum to the state in 1977: the US Secretary of the Interior threatened to eliminate funds for the Central Arizona Project (CAP), a canal being constructed to deliver water from the Colorado River in the west, eastward across the state some 450+ km and uphill more than 700 m, to the cities of Phoenix and Tucson. In response, the state created the Groundwater Management Act (GMA) in 1980, a com-

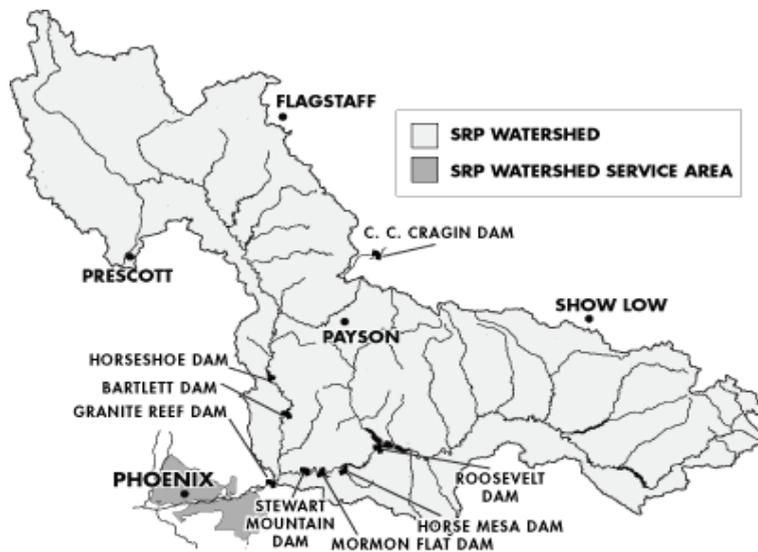


Fig. 2. Salt and Verde River Watersheds serving the Phoenix Metropolitan area. The Salt River Project (SRP) is a quasi-municipal agency that manages water deliveries from these rivers to its service area, as well as providing electricity generated by hydropower. Source: <http://www.srpnet.com/water/dams/default.aspx>

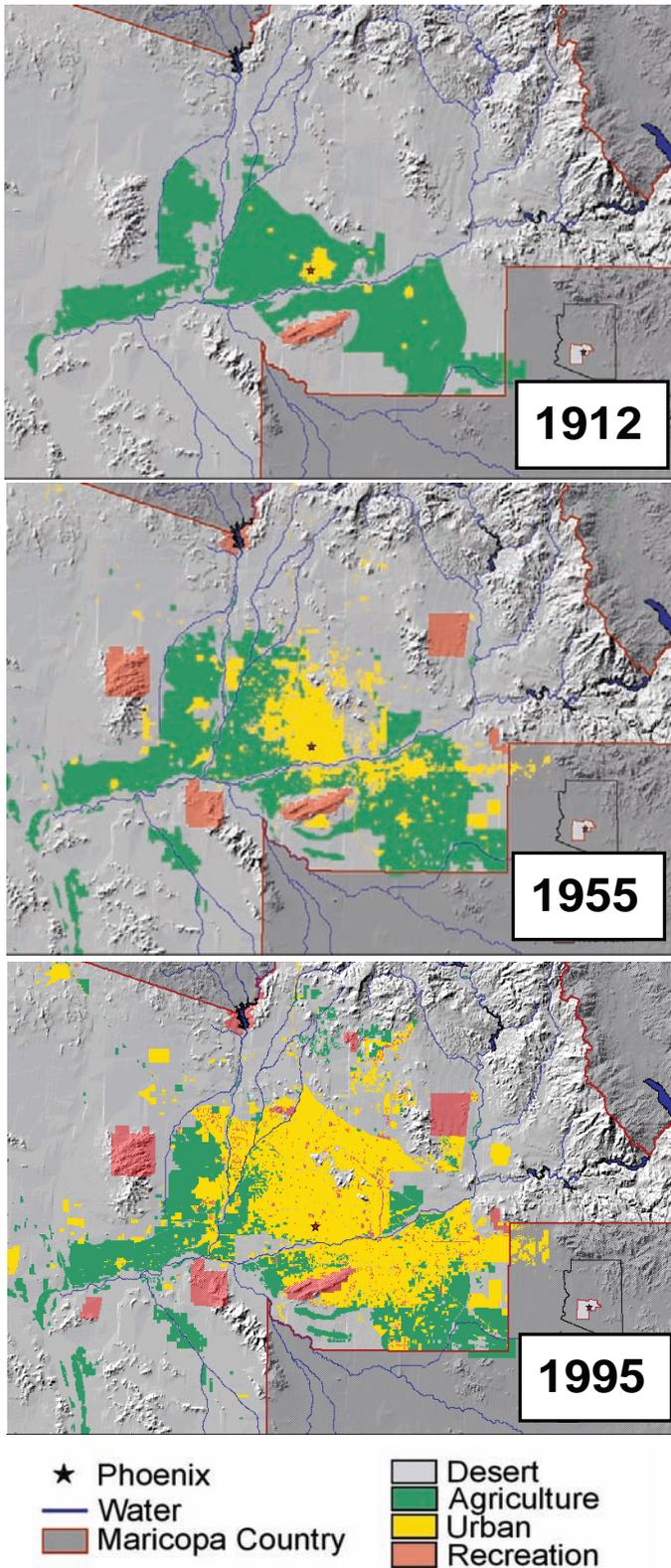


Fig. 3. Changing Land Use in Phoenix's History (After Knowles-Yanez *et al.* 1999 modified).

plex and ambitious regulatory plan to achieve "safe-yield" by 2025. As an "Active Management Area" (AMA), the Phoenix metropolitan area is subject to several management approaches, including supply- and demand-side management, as well as technical planning and assistance (Jacobs, Holway 2004). To date the GMA has had mixed success across the state. In the Phoenix AMA, the groundwater overdraft was reduced by approximately 40% between 1985 and 1995 (ADWR 1999), but 0.44 billion m^3 per year are still overdrafted today (Baker *et al.* 2004). While there have been significant reductions in the Phoenix AMA, groundwater use in the entire state of Arizona has been reduced by only 15% from 1950 to 2000 (Konieczki, Heilman 2004).

The transition from reliance on groundwater to utilizing other sources has been aided significantly by the construction of the CAP canal. In the 1960s, states in the lower Colorado River Basin, California, Nevada, and Arizona began discussing the prospect of apportioning the river water between them. With an allotment of 3.4 billion m^3 , Arizona received federal funding to build the CAP canal, designed to bring 1.7 billion m^3 to Phoenix and Tucson. The canal began deliveries of Colorado River water to Phoenix in 1985, but for the first decade Arizona appropriated less than half of its share of water. Initially intended to support agriculture, CAP water instead increasingly went to municipal and industrial users as the urban centers of Phoenix and Tucson grew and agriculture declined. Arizona only recently began to use its full share, largely due to the establishment of the Central Arizona Groundwater Replenishment District (CAGRD) in 1993 and the Arizona Water Banking Authority (AWBA) in 1996. These programs assume that water in the seven underground basins is interchangeable, and that recharge in one place compensates for pumping in other places. Under these plans, developers without access to renewable water sources (i.e., surface water) are able to pump groundwater at the development site in exchange for purchasing an equivalent amount of CAP water to be recharged at an existing recharge facility. This water is legally considered to be surface rather than groundwater. Thus urban growth can

occur at sites that otherwise would not have been able to satisfy the 100-year assured water supply criterion (Jacobs, Holway 2004).

The above description of water sources to the Phoenix area is merely a broad overview; the intricacies are extremely complex and often opaque. Although the ADWR is charged with enforcing state regulations and has a general, regional perspective on the Phoenix AMA that includes surface water sources, its primary focus is on groundwater. More than 20 municipalities and agencies in the Phoenix metro in fact make the practical management decisions; there are no standardized methods for accounting and no integrated management approaches that consider all water sources. The summary statistics for the Phoenix area for 1995 are that water sources comprised approximately 44% surface water (Salt and Verde Rivers), 39% groundwater, 12% CAP water, and 5% treated wastewater effluent (ADWR 1999).

The end users of this water supply have changed substantially over time. In the first half of the 20th century most of the water was used for irrigation of cropland. After World War II and the invention of air-conditioning, the urban population of Phoenix began to grow rapidly (Gober, 2006). The proportion of agricultural land use relative to the total area has significantly dropped over the past forty years (Fig. 3). But agricultural water demands are so high in comparison to municipal needs that even with the overall regional decline in agriculture throughout the latter half of the century,

agricultural water still represented 58% of the total water demand in 1995 (ADWR 1999), and declined to 42% in 2000 (Authors' calculations based on data from the Arizona Department of Water Resources 2005). The average liters per capita per day (LPCD) for municipal use in Phoenix has only decreased somewhat since 1980 (Fig. 4), and is still above the national average of 693 LPCD. Seventy percent of the municipal use is used for landscape irrigation (Baker *et al.* 2004), indicating not only a potential area for considerable increases in water use efficiency, but also the remarkable ecological transformation that has accompanied urban development in Phoenix. These include introduction of numerous non-native species, destruction of desert habitat and riparian areas, and construction of artificial lakes and stormwater management structures.

3. Current aquatic habitats/ecosystem services

Cultural preferences, along with the relatively easy access to a variety of water resources, have drastically changed the ecology of the Phoenix valley. Demand for agriculture and later municipal uses have had a significant impact on contributing watersheds and downstream systems. Dams on all of the major tributary rivers to the Gila River have eliminated pre-dam seasonal patterns of in-stream flow. Also, many flood mitigation efforts involved

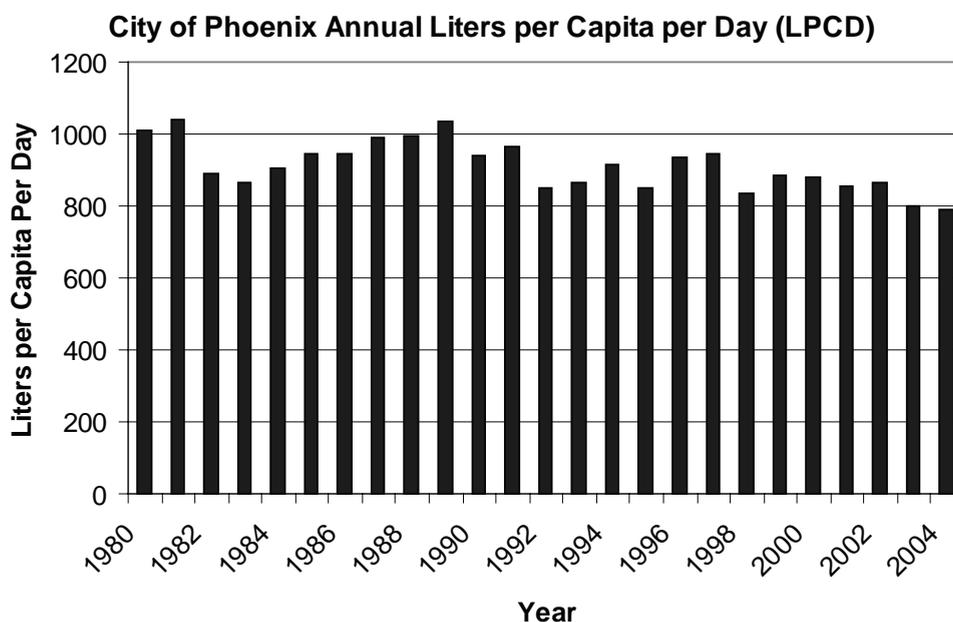


Fig. 4. Annual Averages of daily per Capita Consumption [Units: $\text{dm}^3 \text{capita}^{-1} \text{day}^{-1}$] 1980 - 2004. Source: City of Phoenix Water Services Department

hard-engineering solutions including the lining of riverways. These days, a significant amount of stormwater runoff is diverted to stormwater retention and detention basins associated with housing and commercial developments. These basins serve several roles, providing flood mitigation, groundwater recharge, and recreational areas. The built environment has eliminated many natural flow-paths, and although newer developments are designed to handle floods of a particular magnitude, flooding does still occur, especially in older neighborhoods.

Historical modifications have resulted in an overall loss of riparian areas in some places, and a general shift in riparian community composition via bank stabilization, the introduction of non-native plant species, and the decrease in total woody plant volume (Green, Baker 2003). Some river and riparian habitats exist downstream of wastewater treatment plants, in ephemeral river washes receiving stormwater runoff, and sites designated for groundwater recharge, but it is only recently that agencies have begun to consider ecological factors in management of aquatic systems in the Phoenix area. For example, the Rio Salado Project, funded by the City of Phoenix, the Flood Control District of Maricopa County, the Arizona Water Protection Fund, and the US Army Corps of Engineers (US ACE) began the "restoration" in 2001 of 240 hectares of riverbed and riparian areas in central Phoenix. They are using native riparian

species, such as cottonwood (*Populus fremontii*), willow (*Baccharis salicifolia*) and mesquite (*Prosopis* spp.), and when completed, the riparian system will include 57 hectares of mesquite bosque and 17 hectares of cottonwood/willow habitats, as well as 16 acres of wetland marsh. However, because the river flow regime has not been restored and groundwater levels have been lowered, there is not enough water naturally available to support these communities. Therefore, the project will include groundwater pumps, canals, and reservoirs to ensure adequate supply (City of Phoenix, 2005).

Meanwhile, further downstream at the 91st Avenue Wastewater Treatment Plant (WWTP), billions of liters of treated effluent are released into the Salt River annually. This nutrient-rich water supports an extensive riparian area, but little groundwater recharge is occurring because the area already has high groundwater levels. From the management perspective, this water is going to waste: a Bureau of Reclamation officer says "we just can't keep dumping it in the stream and letting it go downstream." So an \$80 million project is in the works to pipe the water northwest and uphill to the dry Agua Fria riverbed to facilitate groundwater recharge. Officials note that, in addition to recharging the aquifer, the addition of this water will help restore native riparian habitat along the Agua Fria (Landers 2004). However, no mention is made of the potential impact of water removal on the riparian communities of the Salt, which has

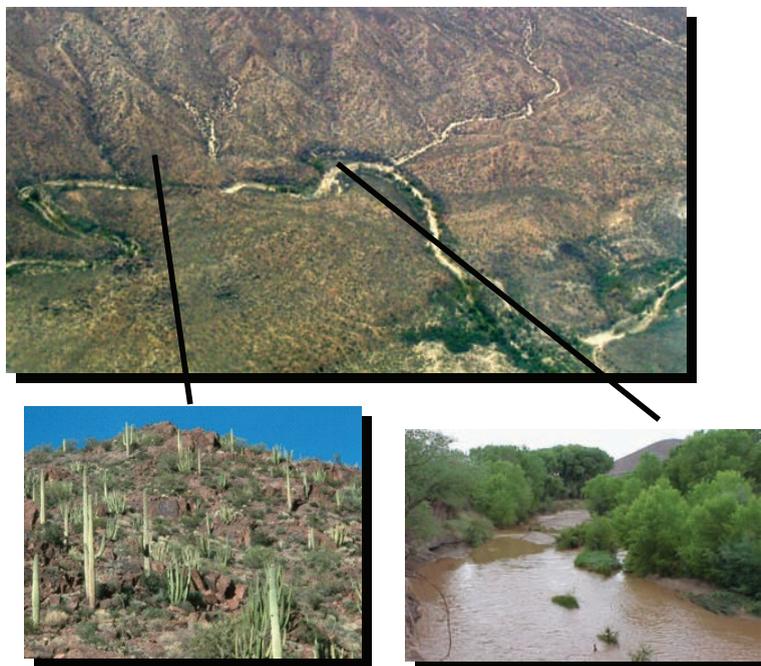


Fig. 5. Impacts of Urban Development on Riparian Habitat. Pictures of Sycamore Creek, NE of Phoenix. Natural Sonoran desert riparian areas have sinuous streams with gallery forests comprised primarily of cottonwood (*Populus fremontii*), willow (*Baccharis salicifolia*) and mesquite (*Prosopis* spp.). Upland areas typically have Saguaro cacti (*Carnegiea gigantean*) and creosote bushes (*Larrea tridentate*).

been receiving effluent from the WWTP for decades.

Thus, inevitably there are complex tradeoffs within the urban ecosystem between various water management and environmental objectives (Grimm *et al.* 2004). The culmination of historical decisions leads more and more frequently to the creation of "designed ecosystems" to satisfy particular goals: water recharge, habitat restoration, aesthetics, recreation. For example, the Phoenix metropolitan area now has greater than 650 artificial lakes (E.K. Larson, unpubl.). In Gilbert there is a Riparian Institute and "water ranch": 18 recharge ponds for treated effluent and constructed "riparian" habitat (the area is not an historical wash or river) designed to attract birds and other wildlife (Edwards 2001). The City of Scottsdale along with US ACE and Flood Control District of Maricopa County, instead of installing a concrete-lined channel in Indian Bend Wash for flood mitigation, created a series of lakes connected by streams, surrounded by a grassy floodplain including parks and golf courses (Fig. 5 and Fig. 6). All of these require substantial management efforts: water replenishment, algal control, fertilization for maintenance of grass. Current

management goals focus on desire for lush, green playing fields, and clear ponds, rather than long-term sustainability.

Very few locations throughout the urban area are typical desert aquatic habitats. Water, as a premium commodity, is moved miles to create desirable landscapes. What is desired is strongly influenced by the cultural backgrounds and experiences of stakeholders. Immigrants from more temperate climates, especially the US Midwest, represent a large proportion of Phoenix residents. With them they may bring memories of lush grasses, abundant vegetation, small ponds and lakes. Two aspects of city life reinforce the perception that such landscapes are sustainable. First, regulation of water flows via damming and reservoirs has damped the strong "pulse" regime of desert hydrology, allowing available water to support vegetation year-round. Second, before the invention of air-conditioning, the cooling effect of increased evapotranspiration was an essential way to contend with extreme summertime temperatures. Thus, throughout Phoenix's history, new arrivals have seen a steady supply of water and abundant green growth, and many were attracted in the first place by promotions of the city as an idyllic place to retire,



Fig. 6. Impacts of Urban Development on Riparian Habitat. Pictures of Indian Bend Wash, Scottsdale, AZ. Urban washes have been radically transformed. No buildings are allowed within the 100-year floodplain, instead a series of artificial lakes, streams, and wide grassy park areas provide flood abatement. Note the severe down-cutting in the stream.

famous for its golf courses. There is no reason, given that such perceptions are actively encouraged, for newcomers to think of water as a limiting resource. Essentially, many residents no longer perceive or appreciate that they are living in the desert; for them, the desert exists only outside of the city (Farley-Metzger, personal communication; Gober 2006).

Another effect of urbanization on the ecosystem is the "urban heat island." In Phoenix, the average minimum temperature has increased on average about 0.1° C per year over the past fifty years, due to nighttime attenuation of cooling by the re-radiating built structures (Baker *et al.* 2002; Brazel *et al.* 2000). Additionally, the number of "misery hours per day" (hours in which the temperature is above 38° C) has doubled since 1948 (Baker *et al.* 2002). While the only direct effects of the heat island on aquatic ecosystems are increased evapotranspiration rates and plant stress within the city, the overall demand in the city for water increases as cooling and irrigation needs rise, possibly resulting in less water availability in contributing watersheds.

4. Sustainability concerns, challenges for the future

Are the water supplies and management practices for the Phoenix metropolitan area sustainable? The crux of this question is that the answer depends on the interaction of a multitude of uncertain ecological, economic, social, and cultural variables. Assessment of these variables is ongoing, but is hampered by significant technological, organizational and informational difficulties. At the most basic level, research is still needed on human population trajectories, ecological impacts, climatic change, etc. There is a paucity of data on environmental outcomes of urban development, water use, landscaping practices, etc. at scales ranging from individual households to municipalities to watersheds to the Colorado River basin. Even well established and government-supported programs, such as the Central Arizona Groundwater Replenishment District, are based on assumptions and simplifications of the complex system that have had insufficient investigation. For example, there is no science to support the feasibility recharged surface water in one location to compensate for groundwater pumping in another, much less any investigation into resultant water quality. Given the groundwater overdraft, subsidence, and lowered water levels, does recharging work on a basin scale? Does recharged water remain perched? Is it reasonable for housing developments to recharge surface water at one location in the basin, and expect the water they pump at their

location to be "surface water" (or at least counted that way)? What are the long-term impacts of the spatial and temporal discontinuities of groundwater banking? The Phoenix Active Management Area of the Arizona Department of Water Resources, along with other research and public interest groups, are striving to address these issues with extensive data collection and modeling. After extensive research, the Governor's Water Management Commission (2001) conceded that, given the continued and projected trend of groundwater overdrafting, it is unlikely that the Phoenix AMA will achieve safe yield by the 2025 deadline. Even if it were possible to reach the goal of safe yield, Jacobs and Holway (2004) note that "the safe-yield goal... does not account for potentially diminished surface water flows or localized areas of depletion. Thus safe-yield is not necessarily synonymous with sustainability, as defined by the Brundtland Commission..."

With respect to renewable (non-groundwater) sources, new analyses continue to emerge. Some authors, such as Gammage (2003), argue that populations as high as 7 million will be sustainable as long as there is a corresponding decrease in agriculture (a water-intensive land use). His view does not incorporate any climatic variability. Morehouse *et al.* (2002) conclude that the variety of water resources available to Phoenix provide more of a buffer to short-term drought conditions than Tucson, but that "even if agricultural demand were eliminated entirely, drought conditions would still force the AMA to rely on non-renewable supplies to meet 43% of its needs." However, one of the most basic underlying assumptions about the flexibility of Phoenix water resources, that Colorado River water will provide when the Salt and Verde are experiencing drought and vice versa, was recently challenged by a joint University of Arizona/Salt River Project report. The report used tree-ring analysis to reconstruct drought cycle synchrony between the two basins, and found that only two events in the 443 years analyzed showed asynchronous flow (Hirschboeck, Meko 2005), leading the manager of water resources at SRP to opine, "our thought that the Colorado River would be able to bail us out is not a safe assumption anymore" (McKinnon 2005c).

The current political environment is also changing. The 2004 Arizona Water Settlements Act returns 800 million m³ to the Gila River Indian Community (GRIC), to compensate for lost access to surface water by appropriation by European settlers in the 19th and 20th centuries. This water will be allotted from CAP water, reducing the amount available to the cities of Phoenix and Tucson. The GRIC will lease 49 million m³ back to the municipalities and 82 mil-

lion m³, previously undistributed, will also be allotted (2004). The tribe will also have the option to lease a greater portion of their water back to the municipalities, but it is unknown if they will elect to do so, many expect they will use the water for their own agricultural needs (King 2005). The final impact of the Act has yet to be fully realized.

Additionally, the legal status of Arizona's claim to CAP water is not secure. The US Secretary of the Interior has instructed the Colorado Basin states (Colorado, Utah, New Mexico, Wyoming, Nevada, California, and Arizona) to come up with a drought and water-shortage management plan (McKinnon 2005b). Arizona, as the most junior party, could lose some of its allotment more easily than more senior states in times of crisis, and thus has started a legal defense fund in anticipation of upcoming disputes. Such clashes might not be far on the horizon, as Upper Basin states protest Lower Basin states' use of water in Colorado River tributaries that does not count in their total allotment. If the US court system were to decide that tributary flows should be included, Arizona could lose up to half of its CAP allocation (McKinnon 2005a).

Finally, accurate and precise assessment of water supply and demand for the valley remains elusive. With more than 20 municipalities and agencies making management decisions, there is an acute lack of consistency in the way that water use is calculated. On top of that, the history of western US water-rights law makes stakeholders reluctant to disclose all information, for fear that other agencies will dispute claims and annex resources. There is no good, integrative, regional understanding of actual usage; for example, in a report published by the City of Phoenix Water Services Department (1995) designed to inform city residents of future prospects, there is only tangential mention that, if the city were to assert its total allotment rights during a time of drought, other municipalities would likely suffer shortages. Such gaps in communication lead to conclusions such as Bush's (2005) that there is enough renewable water only "if the context of institutional arrangements and water entitlement is ignored." As the city is in the midst of an ongoing decade-long drought, coupled with continued rapid growth, the pressure for institutional transformation is increasing. Efforts with varying foci and scales have been initiated by several research institutes, municipal agencies, and collaborative organizations. For example, the East Valley Water Forum is a partnership of tribal, public, and private water agencies working together to assess the status of current water resources and develop plans for meeting future water needs reliably. Efforts such as these are nascent; considerable work is still needed.

Conclusions

Beyond the traditional boundaries of basic natural science, urban ecological questions pose new challenges for researchers, as they necessitate interdisciplinary work between the natural and social sciences (Grimm *et al.* 2000). Anthropological and sociological questions about what makes Phoenix Phoenix are intimately tied to the changing environmental setting. For instance, research has shown that plant diversity within the city is closely correlated with socioeconomic factors such as family income and housing age (Hope *et al.* 2003). But socio-cultural values, like ecosystems, are mutable. For the Phoenix metropolitan area, water is perhaps the foremost integrator of these issues. Adequate assessment of regional sustainability and the means to achieve it require comprehending how values, economics, and the environment feedback to one another and change over time. The Central Arizona - Phoenix Long Term Ecological Research project (CAP LTER), a nationally funded program now in its eighth year, seeks to expand and develop the necessary research tools and data to understand the long term, regional dynamics of the urban ecosystem (Grimm, Redman 2004). Key areas of research include Land Use/Land Cover Change; Climate-Ecosystem Interactions; Fluxes of Materials and Socio-Ecosystem Response; Human Control of Biodiversity; and Water Policy, Use and Supply. Additional vital insight will be provided by the newly funded Decision Center for a Desert City (DCDC), a research institute at Arizona State University focused on establishing relationships between climatic conditions and water decision making.

Phoenix was named explicitly after the mythological bird that rose again from its ashes. With its astronomical continuing growth, Phoenix again burns bright, but will it maintain enough water to prevent another incineration?

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