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Environmental consequences of rapid urbanization in warm, arid lands: case study of Phoenix, Arizona (USA)

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Abstract

The Phoenix metropolitan area (Arizona, USA) provides an excellent case study for examining sustainability of a rapidly growing urban ecosystem in an arid region, having grown six-fold in population in 50 years (to 3 million in 2000). The example is important, because the world's urban population will nearly double in 30 years, and most of this growth will occur in warm, arid regions. Urbanization has warmed the city by 3 °C, increasing heat stress to humans (doubling the number of "misery hours per day"; hours over 37 °C), with generally negative impact on humans and their support systems. Water and land management practices have resulted accumulation of salts (> 70% of input) and nitrogen (15-20% of input). Accumulation has increased salt and nitrate concentrations in groundwater and may have increased the salinity of soils in the urban area. Under normal hydrologic conditions, humans may adapt to gradual environmental degradation. However, we hypothesize that the resilience of the system has declined, making it vulnerable to disturbances such as severe droughts.

Keywords: sustainability, resilience, urban ecosystems, drought, water policy, urban heat island, groundwater.

1. Introduction

The World is rapidly urbanizing. The World's urban population – currently 2.9 billion – will increase to 5 billion by 2030 (FAO [1]). Most of the world's future population growth will occur in arid regions of the world, and often in the poorest areas. The number of people living in countries experiencing water stress ($1700 \text{ m}^3/\text{capita-year}$) is expected to increase ten-fold from 335 million in 1990 to 2.8-3.3 billion by 2025 (PAI [2]). Urbanization in the developed world occurred with an abundance of natural resources and human and financial capital, but in the absence of a well-developed ecological framework. With fewer resources, development of cities in the developing world will require such an ecological framework, so they can develop within the biophysical constraints imposed by nature.

This paper integrates several prior studies of the Central Arizona-Phoenix (CAP) ecosystem to illustrate biophysical problems that may limit the sustainability and resilience of the system. The CAP ecosystem is essentially the Phoenix (Arizona, USA) metropolitan area and surrounding agricultural land. The CAP system has urbanized rapidly since the 1950s and is therefore an excellent site for examining sustainability issues for rapidly urbanizing cities in hot, arid climates. Specifically, we examine the hydrologic balance, biogeochemical cycling of salts and nitrogen, and urban warming.

Modern settlement of the Central Arizona-Phoenix (CAP) ecosystem (the Phoenix metropolitan area and surrounding agriculture) was made possible by large-scale damming of rivers. At least two historical events, one technological and one political, allowed this development. The technological event was the invention of Portland cement in 1820, followed by development of large kilns in the latter part of the 19th century. Portland cement allowed the construction of massive dams of a scale that was not previously possible. The second was the infusion of huge amounts of capital, supplied as an external subsidy by the federal government to stimulate development of the western United States in the first half of the 20th century. This development was followed by worldwide construction of large dams worldwide during the 1960s-1980s.

2. Study Site

The CAP ecosystem is located in the Sonoran Desert in the southwestern United States, a region that receives an average of 18 cm/yr rainfall. Winters are mild, with an average January temperature of 12 °C and summers are hot, with an average July temperature of 34 °C. The reservoirs created by dams constructed on the Salt and Verde Rivers between 1911 and 1946 store water from high-elevation snowmelt, released as needed for agricultural irrigation and municipal use throughout the year. Modern settlement (since the construction of dams) started as irrigated agriculture. Widespread agriculture dominated the region's land development for the first half of the 20th century. The Phoenix

metropolitan area started growing rapidly in the the 1950s, with its population growing from 500,000 to over 3 million in 50 years. Urban growth is expected to continue until the population reaches 5 million in 2025 [3].

The region is being studied as one of two major, long-term urban ecosystems in the National Science Foundation’s Long-Term Ecological Research (LTER) Program. Most research presented in this paper is part of the CAP-LTER project.

3. Hydrologic Balance

Agriculture was 56% of the total demand for the region in 1995; municipal + industrial uses comprised the remaining 43%, table 1. The Salt and Verde Rivers, augmented in recent years by water from the Colorado River delivered via the Central Arizona Project Canal, supplies 1.74 billion cubic meters of water annually (ADWR, [4]). Groundwater, supplied via an extensive network of wells, supplies an additional 1.2 billion cubic meters annually. However, recharge of the aquifer (mostly by water leaching through irrigated land) supplied only 0.72 billion cubic meters. The remaining groundwater pumping was overdraft – about 15% of the total water supply. This means that groundwater was being depleted, 15 years after passage of the 1980 Groundwater Protection Act that was supposed to bring groundwater use and recharge into balance.

Table 1: Water use and supply for the Phoenix “active management area”, the Phoenix metropolitan area and surrounding agricultural land.

Water Use, billion m ³ /year		Water supply, billion m ³ /yr	
Municipal	1.02	Surface water	1.74
Agriculture	1.40	Recharge	0.72
Industrial	0.10	Overdraft	0.44
Effluent to Gila River	0.10		

Urbanization has meant a shift from agricultural to urban use. Agricultural water use has declined from about 80% of total water use in 1975 and will continue to decline to a predicted 46% in 2030. With no further conservation measures, overdraft will continue through 2030 [4]. About 70% of Phoenix’s municipal water is used for landscape irrigation, bringing per capita water consumption to 880 L/day, among the highest in the world.

Most urbanization has occurred during a wet period, leading to complacency regarding drought. This complacency is misplaced. During the late 1940s to mid-1950s a long-term drought reduced surface water flows by half for a decade. In response, farmers heavily utilized the then-abundant groundwater supply. This resulted in little noticeable drought impact, but excessive pumping substantially depleted the aquifer (Redman, per. comm.), decreasing resilience of the system to future droughts.

4. Solute Accumulation

Urbanization below dams on the Salt and Verde rivers may have created a type of urban ecosystem that probably didn't exist prior to large-scale damming of rivers – a large, mesic city in a hot desert -- one that accumulates salt. Salinity has become a problem in Phoenix and other modern cities in arid regions for several reasons. First, *source waters often have elevated salt levels*. The Salt River in Phoenix is an example, with an average TDS around 650 mg/L. Many urban areas in the southwest (e.g., El Paso) are downstream from agricultural areas, and receive water with salts concentrated by *evapoconcentration*. Second, within cities, humans add salt to wastewater. This *salt pickup* in U.S. cities is typically 300-500 mg/L (Drewes & Fox [5]). Some important sources of this salt are human excretion, chemicals used in water and wastewater treatment, household detergents and other chemicals, water softener brines, and various commercial and industrial processes. From an ecosystem perspective, these are external inputs, i.e. food and other chemicals are deliberately imported into the ecosystem by humans. These products are used, and the waste is discarded to sewers. For example, humans import sodium chloride in food, which is excreted into the sewer system. Third, 70% of the urban water supply is used for irrigation (Meyer *et al.* [6]), leading to evapoconcentration. The evapoconcentration problem is exacerbated by the fact that many residential landscapes are *deficit irrigated*, which means that less water is added than the potential for removal by evapotranspiration and there is no leaching of water from the soils profile. Under this condition salts accumulate in the root zone rather than pass through it [4]. This leads to very rapid salt buildup in soils. In El Paso (Texas, USA), for example, the electrical conductivity (EC) of soils at many sites has more than doubled over a 20 year period (Miyamoto [7]). Finally, many cities in arid lands now *recycle municipal wastewater*. Recycled wastewater is used primarily for irrigation of parks or peri-urban agricultural crops. Salinity problems associated with landscape or crop irrigation of recycled municipal wastewater have been identified in several regions (EPA [8], Miyamoto & White [9], Weber *et al.* [10]). Recycling wastewater, rather than discharging salts to rivers, retains salts within the system, contributing to long-term salt accumulation.

A *preliminary salt balance* for the CAP ecosystem (Baker *et al.* [11]) roughly quantified salt fluxes into major ecosystem components, fig. 1. Surface water was the main source of salts (1310 Gg/yr). Importation of salts to municipal water systems (not disaggregated) was about 10% of surface water input. Inputs from fertilizer, animal feeds, etc. were not quantified. Most municipal waste-water is reused, moving salts to urban landscapes, crops, and ultimately, the subsurface. There is substantial vertical movement of salts, downward from leaching through irrigated land and upward via well pumping. No more than one-third of salt inputs leave via the Gila River; two-thirds (920 gG/yr) accumulates in the system – nearly 300 kg per person per year! This is a conservative estimate, because it did not include salts that enter the ecosystem as fertilizer and animal feed. The average total dissolved solids (TDS) of well

water throughout the region has increased over the past 40 years, indicating that some salt is stored in aquifers (currently, the median TDS for 280 wells is 960 mg/L, fig. 2). The average TDS of water exiting the system via the Gila River is 3,200 mg/L, one-tenth the concentration of seawater.

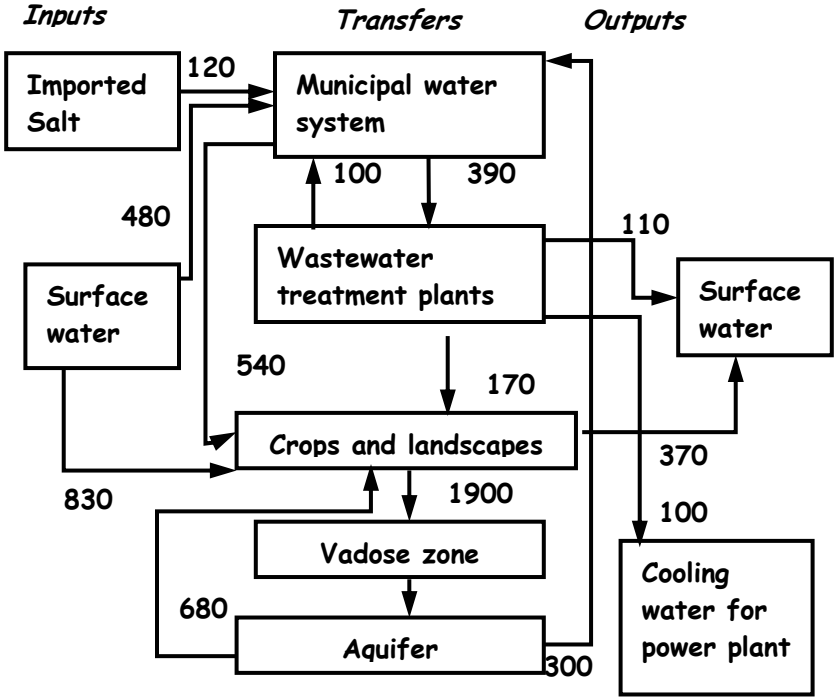


Figure 1: Preliminary salt balance for the CAP ecosystem.

Soil salinity data were collected in a unique synoptic survey of the CAP ecosystem, the *200-point survey*, which collected data on plants, arthropods, soils and other aspects of the environment (Hope *et al.* [12]). Samples included desert, agriculture, and urban sites. Electrical conductance (EC) of 1:1 soil:water solutions were higher in urban residential soils than in agricultural or desert soils, table 2. Only 1% of desert soils had a 1:1 EC > 2000 uS/cm, compared with 5% of the agricultural soils and 11% of residential urban soils. Using a rough approximation of saturated paste conductance (SPC) = 1:1 EC/0.4 (Allison *et al.* [13]), 6% of desert soils, 46% of agricultural soils, and 52% of residential urban soils had SPCs > 2000 uS/cm. At this EC, growth of many varieties of plants is inhibited (McBride [14]). These preliminary data suggest that salinization of residential soils has occurred to an extent that salt-sensitive plants are affected.

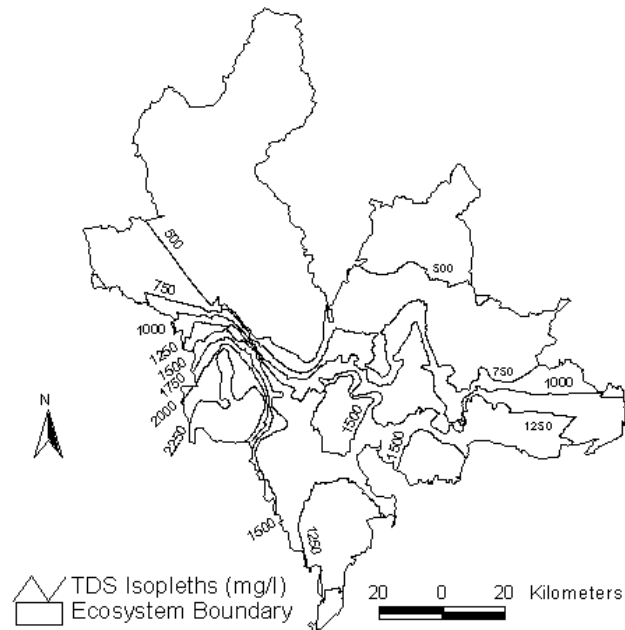


Figure 2: Salinity (TDS) isopleths for the CAP groundwater system.

Table 2: Distribution of 1:1 EC values for desert (n = 70), agricultural (n = 22) and urban residential (n = 54) in soils of the 200-point survey.

EC range	Desert, %	Agricultural, %	Residential, %
< 1000	98.6	77.2	81.6
1001-2000	0	18.1	7.5
2001-3000	0	4.5	3.8
> 3000	1.4	0	7.4

Nitrogen also accumulates in the CAP ecosystem. Unlike the situation for salts, for which the major source is surface water, most N is either deliberately imported into the ecosystem, in products such as fertilizer, and food (humans, farm animals, and pets), or inadvertently formed from combustion, which forms NO_x. A detailed mass balance (Baker *et al.* [15]) showed that 15-20% of N entering the system accumulates. One consequence of N retention is elevated groundwater nitrate concentrations. Groundwater nitrate concentrations

increased from 1960 to the late 1990s, lagging the trend in fertilizer N application rates by about 10-20 years (Xu *et al.* [16]), fig. 3.

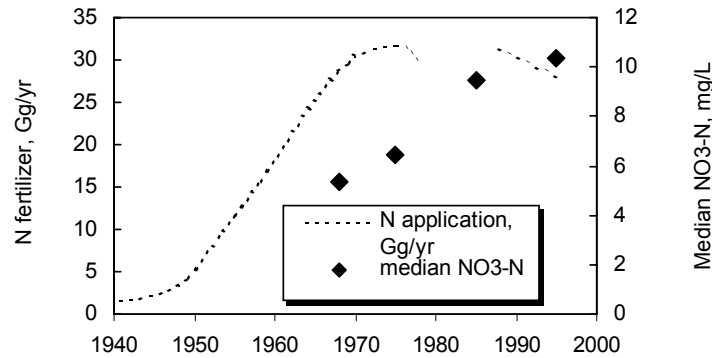


Figure 3: Trends in total chemical fertilizer N input in the CAP ecosystem and the median NO₃-N concentration of groundwater.

Salt accumulation is likely to continue as the ecosystem becomes more urbanized and agriculture declines, because surface water will continue to provide salts. Most water will be evaporated and there are few mechanisms to remove salt from an ecosystem, so salts will continue to accumulate. The situation may be somewhat different for N because N can be removed from an ecosystem by several biological and physical mechanisms, including denitrification and volatilization. If N inputs are reduced (e.g., by reduction of N fertilizer inputs), or N outputs are increased (e.g., by denitrifying a greater proportion of human sewage), N accumulation might be reduced, perhaps bringing the system into steady state (no net accumulation). A modest downturn in groundwater nitrate concentrations since 1995 suggest a downturn in N accumulation.

5. Urban Warming

Growth of the Phoenix metropolitan area has warmed the local climate [Baker *et al.* [17)]. As is often the case for urban heat islands, monthly minimum temperature have increased (by ~ 5 °C) while the maximum temperatures have remained relatively constant or declined. The mean annual temperature has increased by 3 °C. This warming has important ecological consequences. The number of *misery hours per day* – hours with an effective temperature over 38 °C – has doubled for the hottest part of the summer, making the summer climate decidedly less comfortable for humans. The lack of nighttime cooling that normally occurs in deserts has probably harmed cotton farming and dairy production in the peri-urban region. Urban warming has also increased the

duration of the warm season by about a month. Energy use for cooling in summer has increased more than energy use for heating in winter has declined, so on balance, energy use for buildings has increased on the order of 15-20%. (Baker *et al.* [17]).

The urban climate will probably continue to warm as the population of the region increases. Using a projection of regional climate change for the SW US (Spring and Hinkley [18]), estimates of Phoenix growth rates (GPRA [19]), and empirical relationship between population and magnitude of urban warming (e.g., Oke [20]), Brazel [21] determined that urban dwellers may experience a further rise in annual mean temperatures of 1.7 to 2.5 °C by 2100. Numerical modeling at the local scale using refinements of global change scenarios for the region (e.g., accurate ideas on ENSO frequencies and drought) is needed to understand the most likely climate scenarios for the 21st century.

6. Implications for Sustainability

Ecologists are now starting to view cities as ecosystems. Here we have briefly examined hydrologic, biogeochemical, and climatic aspects of an urban system, a step toward development of a broad ecosystem framework. From this perspective, we raise questions regarding sustainability. Overuse of water has depleted aquifers, groundwater is polluted with salts and nitrate, and salts appear to be accumulating in surface soils. The urban climate has become warmer, which in an already hot region is, on balance, undesirable for human well being. Do these facts mean that the urban ecosystem is unsustainable? Not necessarily. When deleterious changes are gradual, humans often adapt. For example, if soils become more saline over the period of decades, salt-sensitive landscape plants will eventually be replaced with more salt-tolerant species. If salt impairs the taste of water, more people may utilize “point of use” water treatment devices, such as reverse osmosis. We may adapt to excessive urban warming by simply cranking up our air conditioners, or perhaps taking longer summer vacations to cooler locations.

However, the system may have become less *resilient* to ecological disturbances – sudden, catastrophic event. In a desert environment, a disturbance of particular concern is prolonged, severe drought. Drought in this region would not be simply a reduction in water supply, but would most likely be accompanied by much warmer temperatures. Salinity of surface water would increase dramatically, and cities seeking to utilize larger amounts of groundwater to make up for the deficit in surface water would have to deal with contamination of salts and nitrate. Although these contaminants can be removed by reverse osmosis, the process wastes 10-20% of treated water, exacerbating the impact of the drought; and brine disposal poses an unresolved problem. Irrigation within the city would likely be curtailed, reducing evaporative cooling and further raising the temperature of the urban climate. Would the urban ecosystem sustain a major drought disturbance intact, or would such an event be a “tipping factor”, leading to permanent decline?

Currently we cannot say. We know that the Hohokum people had a successful settlement of ~50,000 inhabitants that utilized irrigated agriculture over 700 years ago, and that this civilization disappeared after a series of extreme droughts and floods around A.D. 1350 (Redman [22]). Modern Phoenix is more technologically advanced than the Hohokum, raising the question: Have we evolved, culturally, to the point that we are no longer bound by biophysical limits of nature? This seems unlikely, particularly if the constraint is water in a desert. On the other hand, modern Phoenix may be able to adapt to deteriorating environmental conditions that may allow “sustainability” under more-or-less normal hydrologic conditions. We might also reasonably infer that a severe drought might be a “tipping point” that would test the resilience of a desert city. We can also hypothesize that human activities in the current period affect resilience to future disturbance. Humans may confer resilience to their urban ecosystem (e.g., by carefully planning for extreme droughts), or reduce resilience (e.g., by continuing planning practices that overuse water and contribute to urban warming). We propose research to understand resilience of the CAP ecosystem. Such research may identify the specific conditions under which a drought might be a “tipping point”, and identify ways that resilience of the ecosystem can be increased.

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