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Water resources, climate change, and urban vulnerability: a case study of Phoenix, Arizona

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This paper examines the security of water resources in Phoenix, AZ, under different scenarios of climate change, consumption patterns, and reductions of available surface water. Phoenix constitutes a key site for examining the projected effects of climate change on water resources in the US West. Water providers in Phoenix rely on a mix of water sources to deliver to their customers. These include groundwater, water from the Salt and Verde River watersheds, water from the Colorado River, and effluent (water reuse). Water providers in Phoenix vary in terms of their access and rights to different sources of water for municipal delivery. As a result, providers differ in terms of their exposure to cut-backs in available water. To assess vulnerability to climate change and reduced water resources available for delivery, we consider two primary questions. (1) Based on current water provider portfolio mixes, what is the current relative security of each provider's mix of water sources? (2) Using three different climate change scenarios for the Western USA and projected growth-related demand increases, what patterns of water supply vulnerabilities are likely to manifest themselves in 2030? We map projected supply shortages and discuss implications for the vulnerability of people and places and mitigation strategies.

Keywords: vulnerability; climate change; urban growth; water resources

1. Introduction

The Phoenix, AZ metropolitan region has been among the fastest growing urban areas in the USA. Sprawling over two counties and comprising some 26 cities, its population now exceeds 4 million, and prior to the 2007 financial slump and housing bubble collapse, it was growing at a 3% annual rate (Figure 1). Located in a water-poor, hot desert environment, the metro area has supported its growth by hydromining local fossil water aquifers and securing surface water supplies from increasingly distant sources. Today, municipal water providers rely on some combination of four primary sources of water: regulated groundwater pumped from local aquifers; surface water from the Salt and Verde Rivers delivered by the Salt River Project (SRP); Colorado River water delivered by the Central Arizona Project (CAP); and treated effluent used in various non-residential applications. Renewable water from the Salt/Verde and Colorado Rivers has supported much of Phoenix's explosive growth over the last two decades as water managers attempt to

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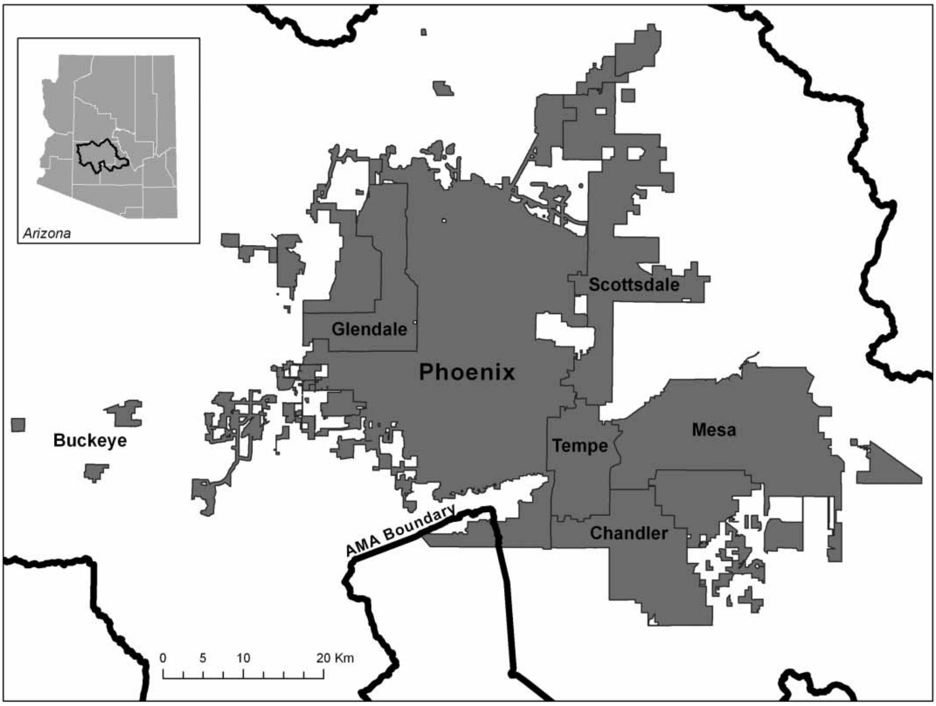

Figure 1. Study area map.

wean the region from overdependence on declining groundwater. However, the latest global and regional climate models from the Inter-governmental Panel on Climate Change (IPCC) indicate that the western USA is undergoing a long-term trend to a warmer and drier climate regime (Milly *et al.* 2005, Seager *et al.* 2007). Predictions of significantly reduced flows from both the Salt/Verde and Colorado River watersheds by 2030 cast considerable doubt on the long-term reliability of the metro area's surface water supplies to support its burgeoning suburbs (Figure 2).

The particularities of Arizona's water laws, its groundwater management system, patterns of urban development, and projected trajectories of growth will interact to shape the spatial distributions of water shortages should the IPCC climate models prove accurate. In this paper, we examine how these factors are likely to produce an uneven social geography of water insecurity in metropolitan Phoenix by 2030. This unevenness is produced by variations in water providers' service areas, the mix of water sources in their "portfolios",[1] the seniority of their rights to water, and anticipated future demands on their services. Water providers mediate between biophysical risks of declining water resources on the one hand and the differential social vulnerabilities of consumers on the other (Collins and Bolin 2007).

To investigate how these effects are likely to manifest themselves, we have two primary goals in this paper. First, based on current water provider portfolios, we map and discuss the relative security of each provider's resource mix. Second, we examine three different scenarios of climate change-induced water availability declines in the context of increasing growth-related demands. We map the spatial patterns of anticipated shortfalls for 2030 by water provider service area. We conclude by discussing the social implications of

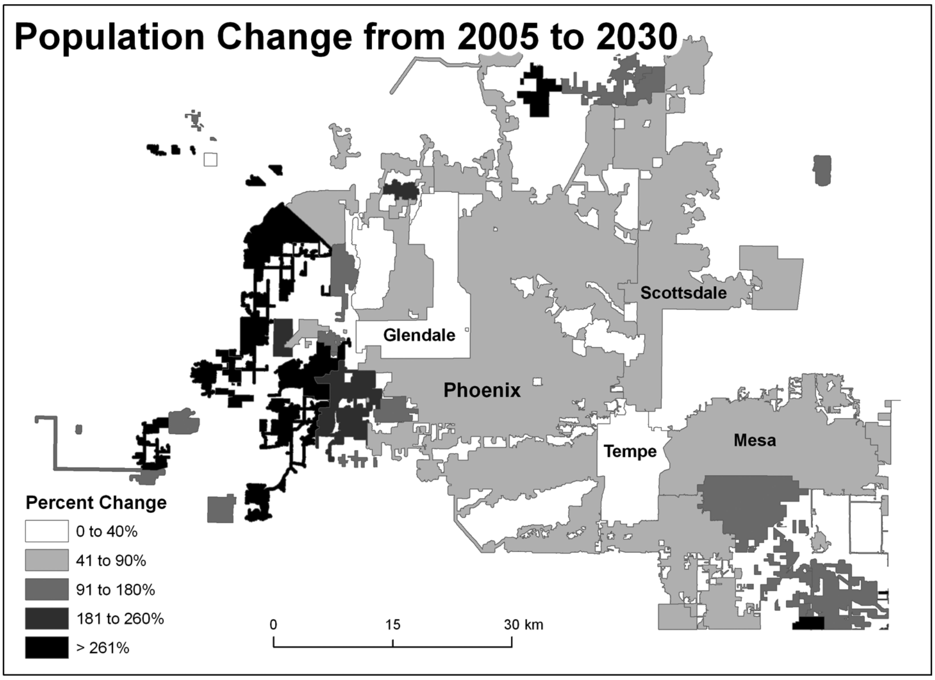

Figure 2. Projected population change 2005–2030.

future water insecurity and the options for mitigating project impacts. We begin by presenting a brief overview of the legal framework and management system for water resources in metro Phoenix.

2. Arizona Water Law and Active Management Areas

Much of metro Phoenix's current water resource profile and its groundwater management system can be traced to the 1922 Colorado River Compact (CRC), a federally brokered interstate agreement that allocated the putative flow of the river among the seven western states that border on the river[2] (Wiley and Gottlieb 1985). The CRC allocated a total of 15 million acre feet (maf) to member states (7.5 each to Upper and Lower Basins), with another 1.5 maf owed to Mexico. However, the assumption that there was 16.5 maf to distribute was based on an uncharacteristically wet period in the early twentieth century (Reisner 1993). Current estimates indicate that over the last 450 years, the average annual flow of the river has been 13.8–14.6 maf, nearly 2 maf under that allocated. More importantly, since 2000, the river has averaged less than 9 maf (Powell 2008), raising significant concerns about whether such surface flows can now, or in the future, be considered a "renewable" supply.

Of the three Lower Basin states, California receives 4.4 maf, Arizona 2.8 maf, and Nevada gets the remaining 300,000 acre feet. Due to a legal dispute with California, Arizona delayed signing the CRC for decades; thus because of the doctrine of prior appropriation, Arizona ended up with junior rights to Colorado River water. While Arizona secured legal rights to a share of Colorado River water, it could not physically get the water to its major population centres of Phoenix and Tucson, until construction of the CAP canal in the 1980s. The state's primary growth area, in the Salt River Valley agricultural region surrounding Phoenix, was more than 500 km distant and 400 m above the elevation of the Colorado River (Kupel 2003).

As early as the 1930s, water from the SRP and its local system of canals could not satisfy growing demands of urban and agricultural development in the Phoenix region (Maguire 2007). To support increasing consumption, fossil groundwater was increasingly used, resulting in an accelerating decline in central desert aquifers (Reisner 1993, Kupel 2003). With growing demands from the post-war housing boom, groundwater mining increased at a dramatic pace, and by the 1970s, there was an annual overdraft of 2.5 maf, causing land subsidence, infrastructural damage, and surface fissures over wide areas from Phoenix to Tucson (Sheridan 1995, p. 348). The spatial fix for the growing depletion problem was the Colorado River, but access to Arizona's distant allotment depended on large-scale federal funding for a canal and energy projects to pump the water overland and uphill to Phoenix and then Tucson.

The CAP was the Bureau of Reclamation's plan to move water to Phoenix. However, political support for the CAP was mixed at best, and Congressional funding for the project was not forthcoming through the Arizona boom years of the 1960s and 1970s. The CAP was typical of the grandiose, technocratic and capital-intensive federal water projects historically favoured in the arid West (Reisner 1993). Included in the original CAP legislation were provisions for an aqueduct from the Colorado River to the Phoenix area and new dams on the Colorado River to generate the large amounts of electricity necessary to pump water uphill and move it more than 500 km to Arizona's two major urban areas (Wiley and Gottlieb 1985). However, both the cost of infrastructure and, more importantly, the flooding of Grand Canyon National Park by proposed hydroelectric dams produced

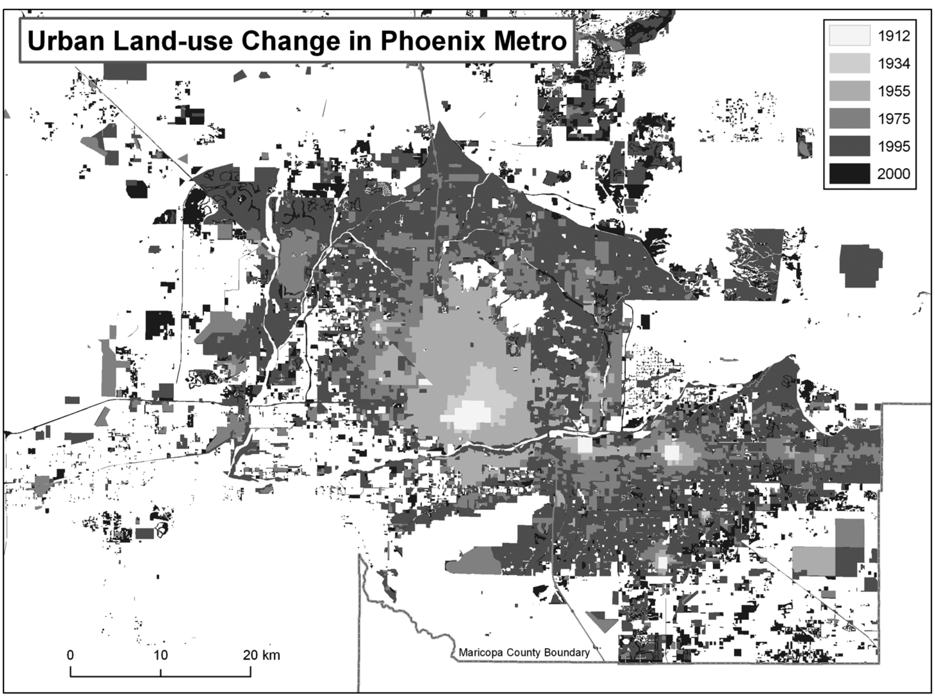

Figure 3. Expanding urban land use in Central Arizona 1912–2000.

large-scale opposition to CAP, and funding remained stymied in Congress until 1980 (Gottlieb 2005) (Figure 3).

Although the post-war boom in Arizona was fed by "cheap wages, easy zoning, and pro-business tax structures", it ultimately depended on the two things Phoenix has always depended on for growth: the federal government and water (Sheridan 1995, p. 340). The Carter administration made passage of CAP contingent on Arizona enacting groundwater conservation measures to staunch the rapid depletion of its aquifers. Momentarily setting aside its *laissez faire* political culture, the state responded to federal pressure with the passage of the Groundwater Management Act (GMA) in 1980. The GMA, and the creation of the Arizona Department of Water Resources (ADWR) to implement policy, was the state's regulatory concession to the federal government to acquire federally subsidised water for Phoenix (Reisner 1993). The GMA created Active Management Areas (AMAs), zones where groundwater use is restricted in order to maintain aquifer levels (see Figure 4: AMAs in AZ). After GMA passage, the $5 billion CAP authorisation went forward, funding the construction of an aqueduct that would, by the 1990s, carry up to 1.5 maf of water from the Colorado River 560 km (335 miles) across desert and mountain to Phoenix and then south to Tucson (Carter and Morehouse 2001). Equally important, the GMA created a market for federally subsidised CAP water by enacting policies to restrict use of cheaper groundwater in CAP service areas (Kupel 2003).

The three urban AMAs of Phoenix, Tucson, and Prescott have a "goal" of achieving safe-yield groundwater use by 2025. However, there is little evidence that any will achieve it by the deadline, and the Prescott AMA has already been declared out of safe yield (ADWR 2005, Collins and Bolin 2007, Bolin *et al*. 2008). Safe yield refers to

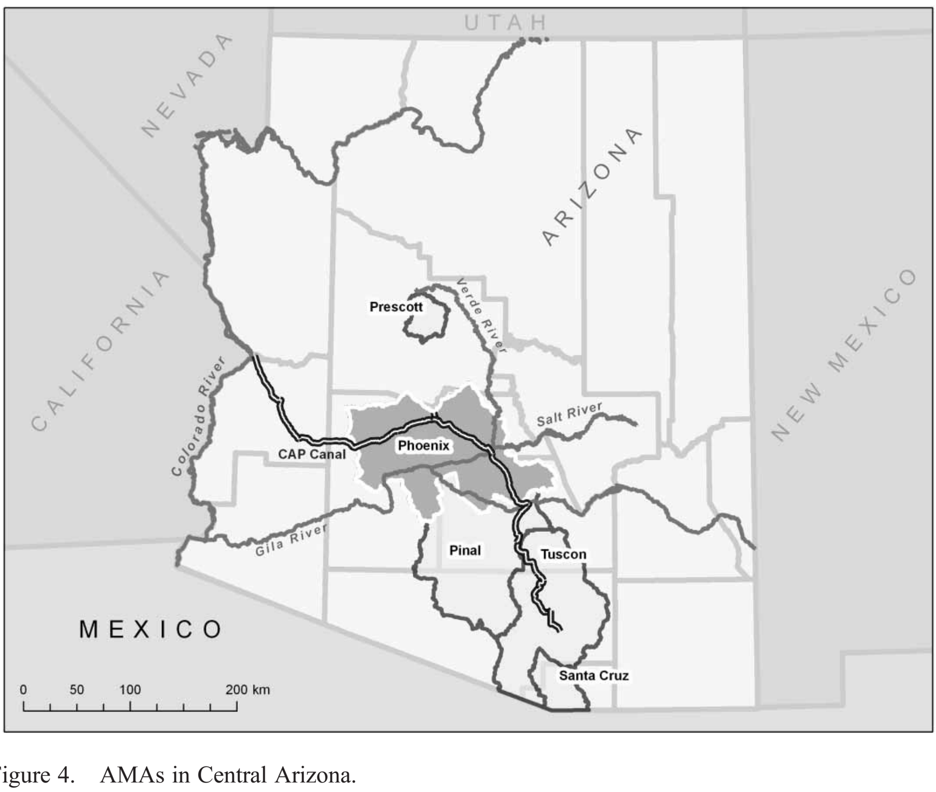

Figure 4. AMAs in Central Arizona.

"a long-term balance between the annual amount of groundwater withdrawn in the AMA and the annual amount of natural and artificial recharge" (ADWR 2004). To attain the elusive goal of safe yield, AMAs are subject to a variety of statutes designed to regulate and reduce groundwater use. Critical for Phoenix's growth-dependent economy, under the GMA, any new subdivision in an AMA has to demonstrate an assured water supply (AWS), that is, physical and legal access to a sufficient quantity of water to last 100 years[3] and the provision of the infrastructure to deliver it. Failure to prove access to an AWS will prevent a subdivision getting approval for construction.

The AWS rule was modified in 1995 to require that the water supply for new subdivisions be primarily from renewable sources (Carter and Morehouse 2001). However, since renewable water sources are not physically available on the urban periphery, this requirement can only be met through "paper water" accounting procedures. Areas without physical access to renewable water can enrol in the Central Arizona Groundwater Replenishment District (GRD) to satisfy the AWS rule by other means (Avery *et al.* 2007). Under the aegis of the CAP, the GRD allows enrolled members to continue to pump groundwater, which is to be offset by the purchase of an equivalent amount of (presumably) available surplus CAP water that will then be recharged somewhere in the Phoenix AMA. Homeowners in GRD-enrolled developments are liable for an annual fee to purchase surplus renewable supplies as offsets. On paper, there is no net loss of groundwater, even though one aquifer can be legally drawn down while another is theoretically "replenished" in a different location (Hirt *et al.* 2008). The GRD substantially undermines the goals of the GMA and can be seen as a major concession to developers, in that it facilitates building irrespective of secure supplies (Jenkins 2006). The result, as we discuss below, is that new developments on the urban periphery are 100% dependent on groundwater, in spite of any safe-yield mandate.

An elaborate system of groundwater rights and permits was created under the GMA with the purpose of preventing water tables from dropping more than 1000 feet below the surface of the land (Avery *et al.* 2007). AMAs have various provisions that leave certain types of groundwater withdrawals outside the state regulatory system. While the GMA prohibits groundwater irrigation of *new* agricultural lands, a system of grandfathered rights allow previously irrigated lands to continue in production and for those water rights to be sold if the land is retired from agriculture. Such exemptions and water rights transfers leave significant groundwater extraction activities unconstrained by state management tools and complicate attempts to develop realistic "water budgets" for the AMA. Currently, the Phoenix AMA pumps 250,000 acre feet in excess of safe yield, a figure that is expected grow in some calculations to 450,000 acre feet by the 2025 deadline (Maguire 2007).

3. The Phoenix AMA and its water providers

The Phoenix AMA overlays seven groundwater sub-basins, receives an annual average precipitation of approximately 200 mm, and uses an annual average of 2.3 maf of water. Of this, 1.4 maf is from renewable sources (CAP, SRP, and treated effluent), and 900,000 acre feet (37% of the total) is from groundwater (these amounts vary by availability year to year). In 2000, of the total water consumed within the AMA, municipal uses took up 47%, industrial 6%, and non-Indian agriculture 46% (ADWR 2004). Within the AMA, the SRP is the oldest water provider, its roots dating to shortly after the founding of Phoenix.

The SRP was established in 1903 to deliver water to agricultural lands of the Salt River Valley Water Users Association located in the area around Phoenix. The US Bureau of Reclamation constructed Roosevelt dam in 1911, the first of seven dams on the Salt River system, and transferred ownership to the SRP in 1917. While the SRP captured nearly all the flow from the Salt and Verde River drainages, demand began outstripping supply prior to World War II (Maguire 2007). This was exacerbated by the limited spatial extent of the SRP service area in relation to new agricultural and urban growth areas. Currently, SRP delivers 1 maf of water to a service area of 557 km^2 (348 sq mi). Within metro Phoenix, SRP delivers water to municipal providers in Chandler, Gilbert, Glendale, Mesa, Peoria, Phoenix, Tempe, and Scottsdale, with 10% of its water going to agriculture (Figure 5).

Since the late 1980s, the CAP has been the other major source of surface water in the Phoenix AMA, with deliveries to various local providers (Figure 5). CAP water has also helped facilitate a recent tribal water rights settlement. The Gila River Indian Community, a reservation on the southern border of the metro area, was awarded rights to 653,000 acre feet of water in 2004, with rights senior to those of Arizona (Hirt *et al.* 2008). As we discuss further below, in the event of declared shortages on the river, CAP water users, in the absence of other agreements, would be the first to experience reduced deliveries due to Arizona's junior rights status in the CRC.

There are over a hundred large and small water providers operating in the Phoenix AMA (Table 1). The largest providers, supplying in excess of 50,000 acre feet annually over substantial service areas, are typically the municipalities themselves, including the cities of Phoenix, Mesa, Tempe, Chandler, and others. At the other end of the range, there are numerous small providers delivering a few thousand acre feet to various outlying communities. The large providers serve older municipalities and generally have senior rights to SRP water. Newer developments on the urban periphery are supplied by a

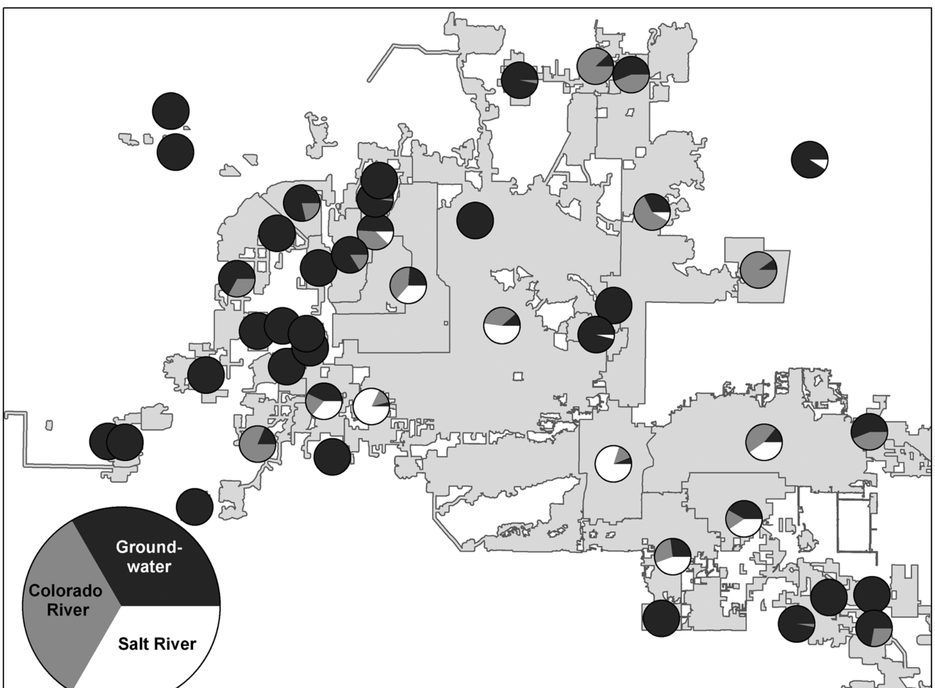

Figure 5. Water sources per provider.

Table 1. Central Arizona water providers (2000–2005).

Water provider	2000–2005 Total use acre feet[a]	Average annual acre feet[b]
Phoenix	2,048,620.53	341,436.76
Mesa	804,193.29	134,032.22
Scottsdale	532,610.73	88,768.46
Chandler	487,611.53	81,268.59
Tempe	369,135.03	61,522.51
Glendale	321,720.43	53,620.07
Gilbert	310,579.81	51,763.30
Salt River Project	243,538.56	40,589.76
Peoria	152,323.99	25,387.33
Goodyear	141,831.39	23,638.57
Avondale	140,065.38	23,344.23
Arizona-American – Sun City	83,102.73	13,850.46
Arizona Water Company – Apache Junction	66,945.39	11,157.57
Arizona-American – Paradise Valley	55,593.71	9265.62
Arizona-American – Agua Fria	49,738.83	8289.81
Roosevelt Water Company	49,235.07	8205.85
Sun City	45,824.42	7637.40
Arizona-American – Sun City West	44,536.60	7422.77
Litchfield Park	41,842.35	6973.73
Chaparral City	41,513.90	6918.98
Pima Utilities	40,268.25	6711.38
City of Surprise	27,503.38	4583.90
El Mirage	27,470.35	4578.39
Apache Junction Water Facilities District	26,799.72	4466.62
Queen Creek	22,470.78	3745.13
Arcadia Water Company	22,386.12	3731.02
Sun City West	22,142.33	3690.39
Tolleson	20,548.05	3424.68
Johnson Utilities	19,557.66	3259.61
Chandler Heights ID	18,273.82	3045.64
Rio Verde	15,913.58	2652.26
Citizens Utility	15,692.83	2615.47
Peninsula Ditch Company	15,276.41	2546.07
Roosevelt ID	14,360.22	2393.37
Sunburst Farms ID	12,877.90	2146.32
Paradise Valley	11,091.48	1848.58
Luke Air Force Base	10,383.15	1730.53
New River Water Company	9912.00	1652.00
Turner Ranches Water & Sanitary Company	8611.43	1435.24
Cave Creek	8349.34	1391.56
Rose Valley	7627.80	1271.30
Berneil	7333.37	1222.23
Buckeye	6853.58	1142.26
H2O	6810.56	1135.09
Carefree	6322.88	1053.81
Other small providers	62,833.41	10,472.24
Grand total	6,498,234.07	1,083,039.01

[a]This is the sum of use from 2000 to 2005.
[b]This is the sum of 2000–2005 usage divided by 6, to produce a yearly average.

patchwork of municipal and privately owned small providers, many of which are dependent solely on groundwater through the GRD (Figure 5).

4. Vulnerability and water insecurity

Over the last few decades, the Phoenix metropolitan region has experienced high rates of population growth with a widely dispersed urbanisation pattern, thus increasing municipal demands and complicating water distribution infrastructure. Given that access to surface water is differentially available across space and that climate change will have uneven impacts on supply sources, the metro area is characterised by a uniquely variegated landscape of intra-urban risk to future water scarcity.

The concept of vulnerability is used in human geography to analyse processes of environmental change and its implications for humans and their settlements. The term is deployed in IPCC reports to refer to the susceptibility of a system to climate change and its inability to cope with the consequences (Adger 2006). This, and other approaches to vulnerability analysis, converges on vulnerability being the likelihood that people and places will experience harm due to exposure to environmental perturbations (Turner *et al.* 2003, Wisner *et al.* 2004). Vulnerability comprises hazard exposure (in this case, climate change), the probability of harm from hazard impact, and the coping capacity of those affected by impact (Cutter *et al.* 2000, Collins and Bolin 2007). An assessment of vulnerability to water resource declines needs to consider the likely effects of climate change and demand change on water resources regionally, the current relative exposure of water provider institutions to supply shortfalls, and how these might play themselves out among residents served by those institutions. Water providers with their differential ability to obtain water for consumption mediate the relationship between people and water in particular places. Thus people's vulnerability, based on conventional measures (poverty, minority status, income, etc.), is contingent on providers' abilities to supply adequate, affordable, and reliable water into the future (Collins and Bolin 2007). In the following scenarios, we focus our analysis first at the provider scale to determine future patterns of water insecurity in the metro area. We turn to possible future geographies of social vulnerability in the conclusion, drawing from our scenario analysis and demographic trends in Phoenix.

5. Water demand, growth, and climate change impacts

Population growth is expected to lead to increased stress on Phoenix AMA water supplies, assuming future growth resembles past growth. Between 1980 and 2000, population growth in the AMA was over 100%, and at the height of the housing boom in 2006, the metro region was adding 60,000 new houses annually (Jenkins 2006). The Phoenix AMA, spread over 5646 square miles (14,623 km^2) and currently inhabited by approximately 4 million people, is projected, in some scenarios, to reach 11 million by 2050. Water use patterns have been changing towards increased municipal use, decreasing agricultural use, and greater use of surface water and treated effluent. *Per capita* water consumption in the AMA has remained relatively stagnant at around 220 gallons per day (gpcd), although it is spatially variable across the region and has been increasing in some communities (Hirt *et al.* 2008). The growth in water consumption still exceeds conservation-derived savings, and overall municipal demand continues to rise.

Historically, municipal demand has been offset by declining agricultural use as farmlands were converted to suburbs. However, much recent development in the Phoenix

AMA is not on agricultural lands, undermining the long held assumption in the AMA that agricultural water would support new urban growth (Hirt *et al.* 2008). Indeed, many of the high growth areas are on desert lands on the urban periphery and are 100% groundwater-dependent, a trend likely to increase in the future (Jenkins 2006). While the expendability of agriculture is still something of a mantra for Phoenix developers and city boosters, there are important, although seldom acknowledged, arguments for preserving agriculture lands, particularly in the face of climate change. Specifically, 25% of the agricultural water used is incidentally recharged into aquifers; agricultural open space helps mitigate urban heat islands; agricultural land can be a buffer against water shortages by fallowing; and, unlike household consumers, agriculture can use treated effluent (Maguire 2007). In addition, agriculture is a source of local food production and provides employment to sustain rural communities.

Given the critical role of the Colorado River in supporting the urban growth in Phoenix and the West, the paleo-climatic record and derived river flow data are not encouraging, with ample evidence that the river is subject to enduring droughts with dramatically reduced flows (Webb *et al.* 2004, Powell 2008). The majority (60%) of the detrimental changes already seen in climate-related trends in Western US snowpack, river flows, and winter temperatures between 1950 and 1999 are attributed to anthropogenic climate change (Barnett *et al.* 2008, p. 1). There is broad consensus among recent climate models that the Southwestern USA will be drier and warmer in the twenty-first century and that this transition is already underway. If these models are correct, the "levels of aridity of the Dust Bowl era will become the new climatology of the American Southwest within a time frame of years to decades" (Seager *et al.* 2007, p. 1181).

The IPCC projects that average annual temperature in the Southwest could rise by 4.5–9°F during this century, which is likely to increase the annual number of extremely hot days, heat waves, and projected demand for water and power (Lenart *et al.* 2007). Seager *et al.* (2007) found that almost all climate models they tested show a drying trend in the American Southwest throughout this century. The drying trend is unprecedented and unlike any climate state seen in the instrument record. Other climate model runs have predicted 10–30% decreases in runoff in mid-latitude Western North America by 2050 (Milly *et al.* 2005; Barnett and Pierce 2009). These changes will reduce mountain snowpack through higher snow lines, shorter winters, and earlier snow melt in the Spring, resulting in reduced stream flows. As mountain snows provide 75% of Western stream runoff, these changes could be critical for the 60 million residents of the Pacific and Intermountain West who rely on these surface flows (Powell 2008). Stationarity, the idea that natural systems fluctuate within an unchanging envelope of variability, can no longer be the default assumption in water resource planning[4] (Milly *et al.* 2008).

Projected anthropogenic increases in temperature are likely to exacerbate water shortages (Service 2004, Kerr 2007). Warmer temperatures and reduced snowpack in the Colorado River Basin (CRB) will lead to reduced runoff and potential significant disruption of water storage and delivery arrangements (Barnett and Pierce 2008, Powell 2008). Since water allocations under the CRC already exceed the mean annual flows, virtually all simulations indicate that precipitation declines will reduce flow below current consumptive uses within 20 years, exacerbated by increasing power and water demands as a result of warmer temperatures (Hoerling and Eischeid 2007). Currently scheduled water deliveries from the Colorado River cannot be sustained even if climate change effects reduce runoff by just 10% (Barnett and Pierce 2009). Modelled climate change effects show a reduced flow on the Colorado River, ranging from 1.5 to 4.5 maf in the next 30–50 years. If current CRC allocations are maintained, there is a 50% chance that live storage (the reservoir space from which water can be removed by gravity) in Lake Mead will be gone by 2023 and a 50% chance that water levels in Lake Mead will be below power pool elevations by 2017 (Barnett and Pierce 2008).

The Salt and Verde River system, which forms a major source of water for the Phoenix AMA, is also at risk of severe shortages from projected climate change. Based on the averaged results of six climate change scenarios in Ellis *et al.* (2008), the Salt/Verde river system could see a 23% reduction in runoff from higher regional temperatures by 2050. These estimates do not include potential climate change effects on watersheds from increased wildfires, beetle infestations, and the resulting large-scale decline in forest cover, phenomena already becoming increasingly prevalent in the West (Powell 2008). Combined with reductions in Colorado River flows, these changes will produce increased stresses on renewable water availability in the Phoenix AMA.

Climate change implications for groundwater management and use are equally grim. Desert groundwater, which now exists in regional aquifers, may have moved into its location thousands of years ago and is therefore described as "fossil" water and its extraction is considered "mining". As the snow line retreats, more precipitation falls as rain, snowmelt occurs earlier in the year, and the mountain snowpack declines, it is likely that groundwater recharge will also fall (Powell 2008). This has serious implications for the entire system of groundwater management in Central Arizona and calls into question the notion of AWS and ADWR's assumption that CAP is a reliable long-term supply (Lenart *et al.* 2007).

Recognising the growing risks, in late 2007, an interstate group of Colorado River water users negotiated a number of interim shortage sharing agreements (McKinnon 2007, USBR 2007). Under the new CRB interim agreement, the following measures are proposed: (1) Lakes Powell and Mead will be managed in tandem and allocation reductions will be based on reservoir levels; (2) states will be allowed to "bank" unused water in Lake Mead; (3) Arizona may be facing CAP cuts of 17%, possibly by 2010; and (4) non-Indian agriculture and groundwater recharge will be first in line for cuts. These proposals do not, of course, override the historic provisions of the CRC, which over-allocated the river to begin with.

6. Mapping future resource insecurity

In assessing resource insecurities, we consider two questions. (1) Based on current average water portfolio mixes, what is the relative security of each provider's portfolio? and (2) using different climate scenarios for the Colorado and Salt/Verde watersheds and projecting increased demands based on population increases, what patterns of institutional risks appear likely to manifest themselves in 2030? We map patterns of projected resource shortfalls and discuss options for mitigating impacts under three different scenarios of increased residential demand and climate change.

The three broad scenarios used here are as follows. (1). A business-as-usual (BAU) scenario, which uses mean climate model estimates for declines in CAP and SRP deliveries, coupled with projected increases in consumer demand based on population estimates. In this scenario, if safe-yield groundwater pumping is observed, there will be substantial shortages in some areas. (2) A conservation scenario, which is identical to BAU except *per capita* residential consumption is brought down to 177 gpcd, the rate in Tucson in 2005. Such conservation savings would necessitate wholesale changes in household use patterns and landscaping, although they would avoid the resource shortfalls of BAU. (3) A worst-case scenario projects losses of 96 and 50% of CAP and SRP deliveries, respectively, requiring sharply reduced deliveries and groundwater overdraft well in excess of safe yield. [As junior rights holder on the Colorado River, in the case of a severe shortage, Arizona could lose its entire CRC allotment, without other interventions (Carter *et al.* 2000).]

6.1 Data inputs

We used the following sources of publicly available data to construct our estimates and scenarios:

- population projections to 2030 for municipalities in Maricopa County from MAG;
- current (2005) *per capita* consumption figure for metro Phoenix derived from average of major municipal providers in the region;
- AMA-wide water provider portfolios for 2005;
- *per capita* water consumption figures for Tucson at 177 gpcd (Tucson Water Department 2004);
- groundwater overdraft (2005 baseline) for the AMA at 250,000 acre feet;
- projected climate change-induced reductions in surface water supplies: CAP allocation to Central Arizona reduced by 17% based on December 2007 shortage sharing agreements among Colorado River water users;
- potential worst-case reductions in CAP allocations to Arizona at 96% of the presently allocated 1.5 maf;
- climate change-induced reductions in Salt/Verde flows: SRP availability reduced by 23%, as per the average of climate change models downscaled to watershed scale;
- climate models predict a worst-case reduction of up to 50% in Salt/Verde runoff.

6.2 Building scenarios

Three major components were used to construct scenarios of demand and supply to 2030.

1. Demand (BAU) projected for the AMA based on *per capita* consumption and population projection estimates for 2030. Estimated residential demand of each of the water sources in 2030 is as follows (in acre feet): SRP 578,603; CAP 669,279; and groundwater 1,005,603.
2. Supply changes (derived from averaged climate change effects) project a 23% decline in SRP supply (223,757 acre feet lost) and a 17% reduction in CAP supply (255,000 acre feet lost) by 2030.
3. Worst-case supply projections suggest runoff reductions of up to 50% on the Salt/Verde watershed (residential deficit of 92,175 and the loss of all SRP agriculture) and near complete loss CAP flows (1,440,000 acre feet lost, including Tucson deliveries). Under the worst-case scenario, groundwater overdraft will be in excess of 356,603 acre feet of safe yield by 2030.

In addition to the main supply and demand scenarios mentioned earlier, two potential mitigating factors were considered. The first is conservation reductions in *per capita* water use across the Phoenix AMA to Tucson levels (177 gpcd). The second factor is the so-called agricultural buffer. Non-Indian agriculture in Arizona has the most junior rights to CAP water, and significant portions of its current 408,137 acre feet entitlement could be diverted to meet residential needs in the event of declared shortages – *if* that land is still in agricultural production. Groundwater also remains a significant, if unsustainable, pool to draw upon in the event of shortages, despite the mandated safe-yield obligations for 2025. In 2000, groundwater supplied 35% of the Phoenix AMA's requirement, and overdraft was estimated at 250,000 acre feet annually. As noted, a complex trade in "paper" water has been developed as part of the GRD to balance spatial and temporal inequalities in surface water access and to enable outlying communities to continue to grow while pumping groundwater. This system will likely face severe pressures as CAP flows decline, and groundwater levels, far from achieving safe yield, will fall further as water users try to meet their needs (Jenkins 2006).

6.3 Mapping resource risks

Our projections suggest that major water delivery shortfalls are likely under BAU demand scenarios (Figure 6), with more moderate shortfalls under the conservation scenario (Figure 7). These shortfalls increase substantially under worst-case supply conditions (Figure 8), although in all cases shortfalls exhibit an uneven geography according to provider service areas.

Areas in the Phoenix AMA at risk of future scarcity are characterised by one or more features in combination: high rates of projected population increases to 2030 (as much as 250% over the next 25 years in some cities by MAG estimates) and provider portfolios that are either 100% groundwater or with a mix of CAP and groundwater. Geographically, these areas are located on the urban periphery, particularly on the current western and

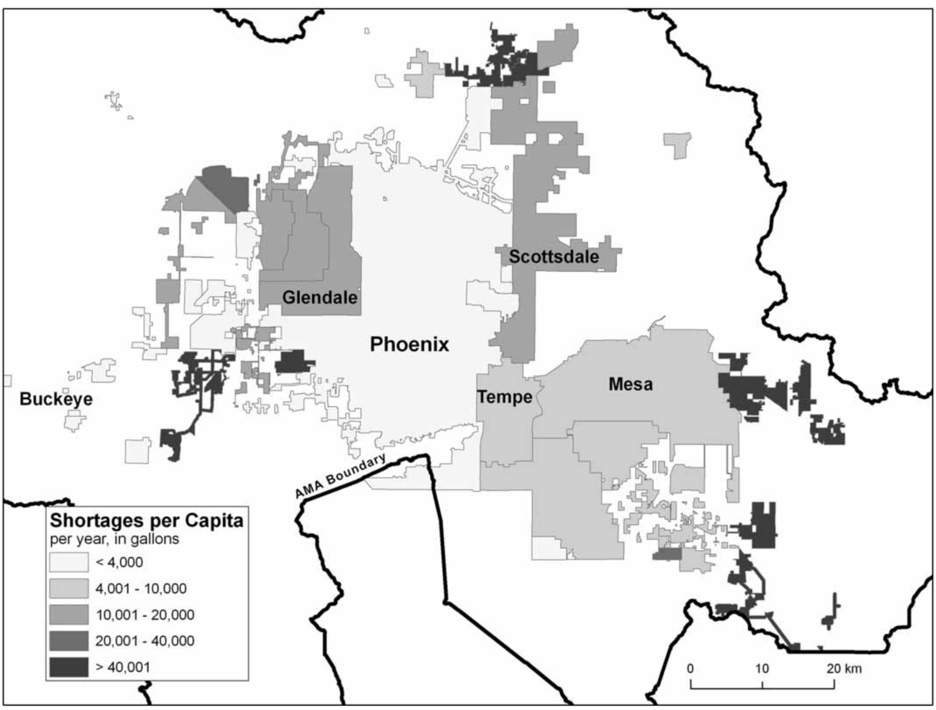

Figure 6. Projected water shortages *per capita* (BAU).

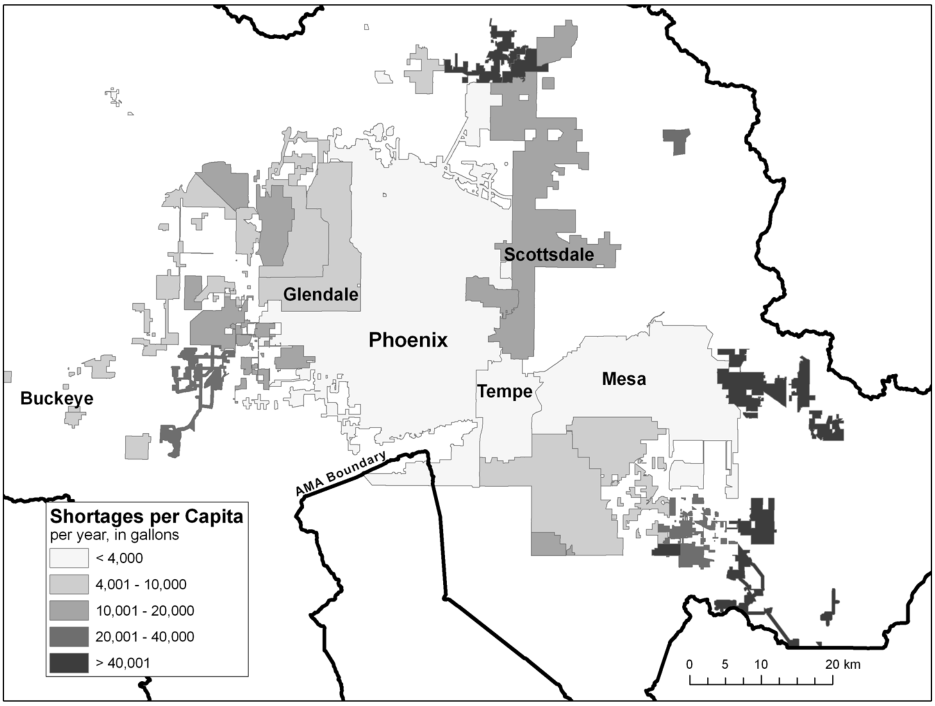

Figure 7. Projected water shortages *per capita* with household conservation.

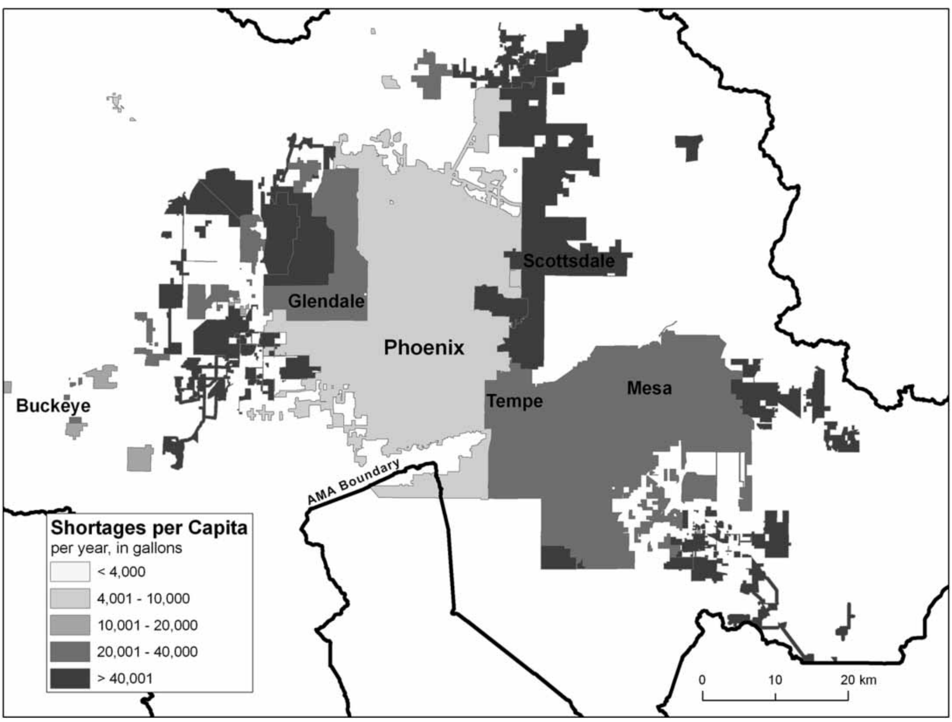

Figure 8. Projected water shortages *per capita* (worst case).

northern fringes of the metro area as well as areas in Pinal County to the east. Older cities have relatively secure claims on water from the SRP, although most use some groundwater in their mixes.

In this analysis, we find that provider exposure to water scarcity is a variously combined outcome of four intersecting factors: (1) reduced runoff on the Colorado and Salt/Verde systems; (2) Arizona's junior rights status with respect to CRC allotments; (3) continued reliance on unsustainable groundwater mining; and (4) the water mixes and projected demand increases in respective provider service areas. As scarcity increases, we would expect competition for increasingly unavailable surplus CAP water to drive costs up substantially in GRD areas first (e.g. Jenkins 2006). The root causes of vulnerability to water scarcity can, therefore, be found both in biophysical systems that determine surface and groundwater availability and in the social, economic, and historical arena of institutions, people, and places that differ in their abilities to cope with declines and price increases under conditions of scarcity.

7. Geographies of resource insecurity and social vulnerability

The scenarios presented here are an effort to sketch some alternative futures of resource stress for the region. Of course, they are limited in that they rely on models and projections and cannot take all potential processes (e.g. large-scale political economic dynamics and small-scale household and neighbourhood interactions) into account. Nevertheless, these scenarios provide an important means to understand the vulnerability of people to shortages in what is expected to be a hotter and drier future. Critical to our discussion is both Phoenix's history of rapid growth and the overdependence of the city's economy on the housing sector. Herein lies a central contradiction. As the region grows, it pushes to the very edge of available water resources, absorbing agriculture, and using growth revenues to acquire new water sources (Jenkins 2006). Yet, if it stops growing, as it has as of 2007, the regional economy plunges into crisis, with growing unemployment, skyrocketing foreclosures, and state and local governments starved of operating revenues (Reagor 2009). Without growth, water resources are under less stress, but the economy slides into crisis. With growth, the housing-dependent economy improves, but environmental quality and water resources are at increasing risk. Whether the city will resume its space consuming growth fueled by housing speculation is a matter of conjecture. The presence of 80,000 unsold homes, the highest rate of foreclosures in the West, and the structural crisis in the US economy all suggest that it may not, at least not at the rate of the 2000–2006 housing bubble frenzy (Inglis and Thompson 2009). Some of the largest recent failures have been in developments on edges of the metro region, areas with high foreclosure rates, declining property values, and costly commutes to increasingly unavailable jobs (Inglis and Thompson 2009). Nevertheless, developers are still planning for vast new developments such as Superstition Vistas, a massive new groundwater-dependent exurb, which could add 1 million people to the eastern edge of the city, more than 50 miles from the urban core to be accessed by miles of new freeway (Dougherty 2009).

These recent dynamics have implications for water resources and new forms of social vulnerability. As noted in our discussions of the BAU and worst-case scenarios, the areas most susceptible to resource shortfalls exist on the groundwater-dependent urban periphery. This finding contrasts with recent hazard studies that focus on traditional indicators of vulnerability (poverty and minority status at the census tract level), all of which point to central areas of Phoenix, south and west of the central business district (e.g. Grineski *et al.* 2007), as being zones of concern. Phoenix environmental justice research has shown that, in these central areas, poor Latinos and African-Americans are disproportionately exposed to toxic hazards and air pollution (Bolin *et al.* 2002). Conversely, these areas use relatively little water and are served by secure water providers. Our scenario analysis suggests a change in the spatialisation of vulnerability: those most vulnerable to resource declines are more likely to reside on the urban periphery in developments distant from the urban core and in farming communities being consumed by sprawl.

As the current economic crisis has revealed, the urban periphery is an area of risk for the marginal middle and working classes, both Latino and Anglo. Due to a litany of unscrupulous lending practices and bad consumer judgements, thousands of residents of new homes in these exurbs have slipped into foreclosure, while shopping centres and developers declare bankruptcy (Inglis and Thompson 2009). Whether this will cause a rethinking of urban sprawl or is just a temporary slowdown until a sprawl cycle resumes cannot be known. These areas of clustered foreclosures are typically groundwater-dependent with properties enrolled in the GRD. Homeowners are thus liable for fees to the GRD for renewable supplies to offset groundwater use. Under current economic conditions, literally thousands of homeowners cannot make mortgage payments, much less pay additional water fees which could be levied. Should sprawl resume at former rates, outlying GRD areas could become a new zone of the socially vulnerable where those who “drive ’til they qualify” in the search for affordable housing face high transportation costs, poor job opportunities, and exposure to GRD fees, which could balloon up to $2000 or $3000 annually as increasingly scarce water gets bid up by intra-urban competition (Jenkins 2006).

Will such outlying areas increasingly become regions of resource risk for economically distressed households as water prices rise and availability declines? Will these far flung exurbs become the West’s new ghost towns as a century of climate change and aquifer depletion render them uninhabitable? Water has never been seen as a limiting factor in Phoenix growth, and a triumphalist attitude prevails regarding the availability and security of water supplies (e.g. Kupel 2003). Indeed, at the height of the boom, water managers would talk of building desalination plants for California’s use and taking that state’s entire CRC allocation to fuel waves of growth in Arizona, constructing additional CAP canals and pipelines to carry the newly available surpluses (Jenkins 2006, Davis 2007). In this techno-imaginary, the feasibility, cost, environmental objections, and energy requirements for such unsustainable Promethean schemes would somehow be met to support unlimited exurban growth in Arizona. For city boosters, climate change, if it is a concern at all, is something that only looms in the distant future.

Without resorting to desalination plants and new CAP canals, our scenarios have shown that moderate near term shortages can be managed by reducing consumption. Mitigating, even partly, the projected socio-ecological impacts will require moving towards more realistic water consumption practices. Progress towards these ends would require one or more of the following changes. (1) Reducing residential *per capita* water use (particularly outdoor use). Metro Phoenix’s *per capita* use of fresh water remains unsustainably high, and, perversely, water pricing in Phoenix is less than half the unit cost of water in Seattle (Portland Water Bureau 2007). Water use could be reduced through public awareness of shortage issues, steeply tiered pricing, regulatory disincentives, and penalties, although such strategies go against the standard view that water is not a problem in Arizona. (2) Water conservation through reuse and recharge using small-scale water harvesting and recharge programmes would improve groundwater viability. (3) Increasing agricultural use efficiency of irrigation water through improved technologies and crop choices. However, if agriculture is eliminated, then systemic risks increase without the buffer it provides. (4) Changing the extent and form of urban growth away from the materials-and-energy intensive model and towards high-density, mixed use, neighbourhoods developed from within the existing urban core residential areas. This will likely speed the demise of the already stressed exurbs and, like advocates of growth limits, would encounter deep political opposition. Climate change implications for water availability, when combined with population growth projections, patterns of urbanisation, and existing institutional arrangements should be the cause for immediate concern and long-term planning. How these challenges are approached will determine the viability of urban settlements and people's vulnerability over the coming decades.

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Notes

1. Portfolios refer to the particular mix of water sources individual suppliers obtain on a yearly or long-term basis. The actual content of portfolios may vary on a yearly basis depending on the availability of water from different sources for purchase by year. Some providers rely exclusively on groundwater as they lack physical access to Salt/Verde or Colorado River water.
2. The Upper Basin states are Colorado, Wyoming, Utah, and New Mexico; the Lower Basin states are California, Arizona, and Nevada. In addition, Mexico is by international treaty entitled to another 1.5 maf.
3. Both the 100-year supply figure and the 2025 safe-yield attainment date appear to be arbitrary figures selected at the time of the relevant legislation (Maguire 2007). Terms like "sustainability" or "in perpetuity" had no political purchase in these deliberations.
4. Critically, the Bureau of Reclamation does not use climate change models in planning for future water use and storage on the Colorado River system, choosing instead to plan based on known past flows (Powell 2008).

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