Vulnerability assessment of climate-induced water shortage in Phoenix

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Global warming has profound consequences for the climate of the American Southwest and its overallocated water supplies. This paper uses simulation modeling and the principles of decision making under uncertainty to translate climate information into tools for vulnerability assessment and urban climate adaptation. A dynamic simulation model, WaterSim, is used to explore future water-shortage conditions in Phoenix. Results indicate that policy action will be needed to attain water sustainability in 2030, even without reductions in river flows caused by climate change. Challenging but feasible changes in lifestyle and slower rates of population growth would allow the region to avoid shortage conditions and achieve groundwater sustainability under all but the most dire climate scenarios. Changes in lifestyle involve more native desert landscaping and fewer pools in addition to slower growth and higher urban densities. There is not a single most likely or optimal future for Phoenix. Urban climate adaptation involves using science-based models to anticipate water shortage and manage climate risk.

water sustainability | climate change | decision making under uncertainty | simulation modeling

Global warming has profound implications for the future climate of the American Southwest and the region's already overallocated water supplies (1–5). Results from 15 coupled climate models from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (6) predict drier conditions for the region in this century and little prospect for return to the moister climate that prevailed before the 1997/1998 El Niño (7). Using tree-ring records, Woodhouse et al. (8) argue that the mid–12th-century drought, whose severity and duration exceeded anything in the historical record, can be used to exemplify the severe droughts that may occur in the future. Given the likelihood that climate change will diminish the Southwest's water supplies, we need to know how vulnerable people are to that risk and how best they can adapt.

The study of human vulnerability to environmental risks grew out of natural-hazards research (9, 10). Harm to human populations stems not only from physical exposure but also from a population's sensitivity to a hazardous event and capacity to cope with shocks and stresses (11–13). The concept of sustainability enlarges and redirects vulnerability analysis to consider interacting stressors functioning at varying scales in a complex system (11, 14). It infuses vulnerability research with a longer-term perspective and awareness of the importance of system resilience—the ability to bounce back after disturbance. In the process, the focus moves beyond any particular hazardous event to the preparedness of systems to cope with a range of long-term environment risks, one of which is climate change. With respect to preparedness, Guston (15) makes a useful distinction between precaution and anticipation. Precaution is a way of acting to avoid predicted but uncertain risks; anticipation implies building capacity to respond to unpredictable and uncertain risks.

Our research uses a water-balance simulation model, Water-Sim, to assess the vulnerability of Phoenix, Arizona to long-term water shortage induced by global climate change. In this paper, we (*i*) summarize key human stressors on water supplies—why the Southwest would be at risk even without climate change, (*ii*) discuss the capacities of water-management systems to anticipate and cope with climate uncertainties, and (*iii*) apply principles of decision making under uncertainty to the risk of long-term water shortage. The Phoenix study offers lessons in how climate information and models can be integrated into water decisions and tradeoffs faced by decision makers in adapting to climate change.

Human Stressors on Water Supply in the American Southwest

Twentieth-century development of the Southwest was based first on irrigated agriculture and later, on large-scale urban development. The Southwest's arid and semiarid climate is highly variable in runoff from infrequent, but often heavy, rainfall events. Historically, this variability was managed by building dams, reservoirs, and canals for flood control and water supply and by transporting water over long distances to the points of human settlement and economic development (16, 17). Rapid growth adds pressure to this system of water provision, because augmenting supply through infrastructure is increasingly difficult (4, 18–21). The seven states of the Colorado River Basin (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) will add 23 million new residents between 2000 and 2030, and this accounts for 29% of the nation's total population growth (22). Growth will occur at a time when the nation's major dam-building era is over and the downstream environmental costs of dam construction are more fully understood (4, 23, 24). Population growth will intensify competition for scarce water resources, particularly between municipal and agricultural users. That competition is already reflected in a decrease in irrigated farmlands of more than 809,000 ha in the seven states of the Colorado River Basin between 1997 and 2007 (25). The amount of water used by the agricultural sector in the Greater Phoenix Area declined from 1.3 billion m^3 in 1990 to 1.2 billion in 2000 and 0.9 billion in 2006, because farmland was retired and municipal water use rapidly increased (Fig. 1). Transfers from agricultural to urban water use raise questions about the use of potable water to grow urban lawns, the potential for agriculture to buffer cities from shortage in the case of long-term drought, and the viability of exporting water through water-intensive crops such as hay, rice, and cotton from a rapidly urbanizing arid region (26).

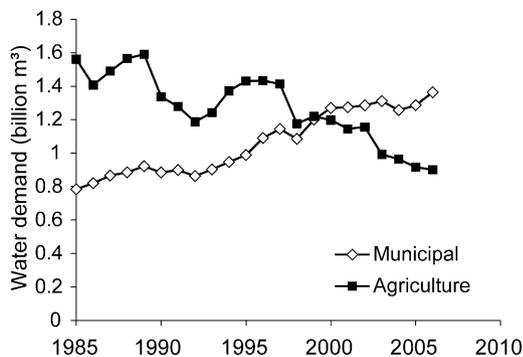Almost 92% of the Southwest's population lived in urban areas in 2000 compared with 79% for the nation as a whole (27).

Fig. 1. Municipal and agricultural demand in billion cubic meters from 1985 to 2006. Source is the Arizona Department of Water Resources (http://www.azwater.gov/AzDWR/WaterManagement/Assessments/default.htm).

The low-density, sprawling pattern of new development in many Southwestern urban areas results in high per capita water use. In the Phoenix area, for example, urban densities of 37–74 housing units per ha require around 75 m³ of water per person annually compared with large-lot residential estates of 2.5 dwelling units per ha, where per capita water use is almost 10 times higher (Fig. 2). Outdoor water use is substantial in many of the cities of the region, comprising as much as 75% of residential use (28).

Decision Making Under Uncertainty

Climate uncertainty tests the capacity of human institutions to anticipate and plan. Milly et al. (29) argue that most systems for managing water assume stationarity—the idea that natural systems function within a known envelope of variability. Interannual variability in water availability around a stable mean is assumed; the mean and variability are derived from the empirical record and used as the basis for managing risk. Deep uncertainty refers to nonstationary situations where there is substantial disagreement about the forces that shape the future, appropriate models to describe them, probability distributions for key uncertainties, appropriate variables and parameters, and methods to evaluate alternative outcomes (30). Increasingly, simulation models are used to investigate general trends, system dynamics, and implications of policy decisions on a system's future state (31). Simu-
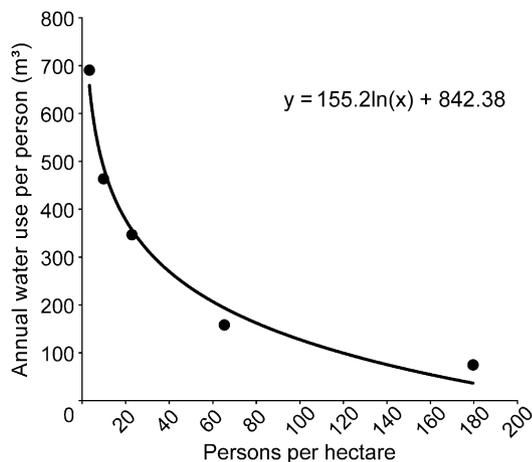

Fig. 2. Estimated water required to support residential densities. Water duties from Salt River Project (2003) Canal Available Capacity Report, table 2, 1995 Urban Water Duties in Acre Feet/Acre. Population densities based on land-use classifications from Maricopa Association of Governments 1995 Land Use Classifications (http://www.mag.maricopa.gov/).

lations allow analysts to ask what-if questions. What are the long-term consequences of implementing a growth-management policy? What policies would be effective across a range of future climate conditions?

Using WaterSim for Climate Vulnerability Assessment: A Case Study of Phoenix

Phoenix is both physically exposed to climate change and socially vulnerable to its consequences. Although Phoenix receives an average of only 193 mm (7.59 inches) of rainfall annually, its dryland rivers, the Salt and Verde, are fed by more humid mountain watersheds to the north. The city also receives water from the Colorado River Basin through the Central Arizona Project (CAP), a 541-km aqueduct. In addition to these surface sources, water in storage in alluvial aquifers historically provided an important reserve during arid periods and potentially, serves as a source for dealing with the uncertainties of drought and climate change. Severe groundwater overdraft in the 1960s and 1970s led to the Arizona Groundwater Management Act of 1980, which mandated safe yield (withdrawals = recharge) by 2025 (32). Critics charge that loopholes in implementation and enforcement have undercut the goal of safe yield (33).

We used an integrated simulation model, WaterSim, to investigate the long-term consequences of policies to manage groundwater, growth, and urban development in Phoenix. It simulates water consumption and availability in Central Arizona from the present until 2030. WaterSim uses the exogenous uncertainties, policy levers, relationships, measures (XLRM) framework, as presented by Lempert et al. (30), to process the analysis. It has the following components. (*i*) Exogenous uncertainties are factors that decision makers cannot control; these are primarily associated with climate and water supply. (*ii*) Policy levers are actions that decision makers could take, such as groundwater policy, land-use planning, and population-growth management. (*iii*) Relationships are mathematical or algorithmic associations among variables. (*iv*) Measures for evaluating success are the metrics that present model outcomes as they relate to policy making.

Exogenous Uncertainties. Important inputs to WaterSim are future runoff conditions of the Colorado and Salt/Verde River Basins. Downscaled climate-model/scenario combinations from the IPCC AR4 (6) present a range of possible future climate conditions in the Salt/Verde Watershed (34) and the Colorado River Basin (3). Studies consider 50 runoff scenarios for the Salt/Verde system and 22 for the mainstream of the Colorado River. Scenarios show a range from 19% to 123% of the historical mean flow for the Salt/Verde system and from 61% to 118% for the Colorado River.

Analysis of 5-yr running means of runoff for the two systems shows a r^2 of 0.28, suggesting a tendency for the two systems to function in tandem. Hirschboeck and Meko (35) also found synchronization of high and low stream flows in the Colorado River Basin and Arizona rivers in instrumental and paleoclimate records. We address uncertainty about the interrelations between future runoffs in the two systems in two ways: first, we consider the impact of climate variation on each system alone, assuming that the runoff for the other system remains at its historical level; and second, we examine the combinations of future runoff scenarios for the two systems. We use a starting year of 1954 for the simulations, because the subsequent period is the best representation of average conditions in the two systems. The historical flows for the two rivers systems are projected forward from the simulation baseline year of 2006. Then, the runoffs resulting from projected flows are determined in the simulation for each climate scenario by applying a climate-adjustment factor to the baseline flow for each year and for each of the two systems to account for the climate-model ranges reported above.

The rate of population growth over the simulation period is exogenously specified by official projections (36), but potential variations in this baseline growth pattern are specified as policy levers. Unconstrained water demand over the simulation period is based on projected land-use patterns (37) and the relationship between residential density and per capita water consumption as presented in Fig. 2.

Measures for Evaluating Success. We use two metrics to assess outcomes from each combination of scenario and policy: (*i*) the amount of water available for urban residential uses measured in terms of liters per capita per day (LPCD) in 2030, and (*ii*) the cumulative groundwater deficit in 2030. Groundwater calculations take account of natural recharge and water stored underground for future use.

Policy Levers. We consider sets of policy levers: (*i*) managing residential water consumption directly by requiring (or not requiring) that residential demand be constrained to available surface water and indirectly by imposing constraints on residential use by restricting water-intensive vegetation and swimming pools, and (*ii*) population growth management by allowing the projected population growth rate or restricting growth to 50% of the projected growth rate or no growth at all.

Relationships. The simulation model is composed of five submodels with a top-level interface that links the submodels and provides input/output capabilities. The submodels represent (*i*) storage and delivery for the Colorado River, (*ii*) storage and delivery for the Salt and Verde system, (*iii*) water demand, (*iv*) policies to address deficits in supply, and (*v*) legal and physical constraints on water delivery to Phoenix through the Central Arizona Project. An annual time step is used for the simulation. The storage and delivery submodels adjust the available surface water dynamically over the simulation period by taking into account the effects of water rights assigned to other states, the capacity of the reservoirs, and evaporation in addition to any changes caused by assumed climate variations. The water-demand submodel calculates demand over the simulation period from agriculture, residential, and industrial and commercial uses. The policy submodel adjusts water use based on policy choices about population growth, conversion from agricultural to other land uses, urban density patterns, groundwater withdrawal policies, and per capita water use.

Single-System Variability. We first asked what the range of uncertainty in the climate scenarios means for residential water consumption, assuming that only one of the two surface-water systems deviates from historical flows and assuming a policy of groundwater sustainability (no groundwater drawdown) with no restriction on population growth. Results are presented in cumulative frequency distributions, with each point representing the LCPD implied by its climate-model/scenario combination when groundwater sustainability is imposed for three different growth policies. The range of possible outcomes is between 371 and 587 LPCD for the Salt/Verde system based on the 50 outcomes (Fig. 3*A*) and between 269 and 606 for the 22 scenario/model combinations for the Colorado River system (Fig. 3*B*). Current consumption on a regional basis is 875 LPCD. Water supplies in Phoenix are highly sensitive to reductions in the Colorado River flows, because a 1968 agreement negotiated in Congress to win approval of the CAP mandated junior river rights to the CAP (33). CAP has the lowest priority of the Lower Colorado River allocations, and its use would be the first to be curtailed under shortage conditions (32).

Upper ranges of both distributions correspond to model results with runoff of more than 100% of historical averages. The Colorado River line levels off after 100%, because CAP has
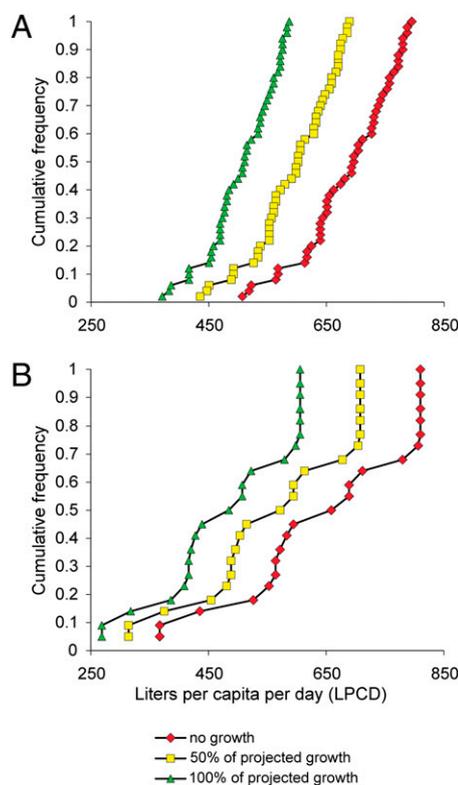

Fig. 3. Cumulative frequency distributions (ogives) of WaterSim results for available LPCD in 2030 under scenarios of no growth, 50%, and 100% of projected growth under climate-model/scenario combinations for the (*A*) Salt/Verde Rivers and (*B*) Colorado River. Source of population projections is the Maricopa Association of Governments (http://www.mag.maricopa.gov/).

a set allocation in times of surplus. The midpoint for the Salt/Verde model/scenarios would require a reduction to 511 LPCD; the Colorado River midpoint translates into a reduction to 496 LPCD. Reductions to these levels would be challenging but feasible, given that cities in similar climatic conditions are at or below these levels now. The 2005 LPCD in Tucson was 431; in Albuquerque, it was 416 (38). Runoff levels for the most pessimistic of the scenarios would limit consumption (371 for the Salt/Verde scenario/model combinations and 269 for the Colorado combinations) to about the current level of indoor water use (265 LPCD). Climate adaptation entails a choice between lifestyle and sustainable growth. Limiting growth would reduce the need for lifestyle sacrifices to achieve sustainable groundwater use. In the no-growth case, modest reductions in consumption levels would accommodate all but the most pessimistic of the climate-model results.

Two-System Variability. We also used WaterSim to investigate water availability under all available runoff conditions for both systems. First, we considered the impact of policies related to population growth, assuming that consumption is restricted to available surface-water supply plus recharge. Under the expected unconstrained growth conditions (100% of projected growth), there are future climate conditions that would require substantial reductions in consumption below 425 LPCD and many to below 250 LPCD, which is slightly below what is now used for indoor purposes (Fig. 4*A*). Lowering the growth rate to 50% of the projected unconstrained level would allow the region to sustain a lifestyle similar to Tucson and Albuquerque under the midpoint climate scenarios (Fig. 4*B*). A no-growth policy would
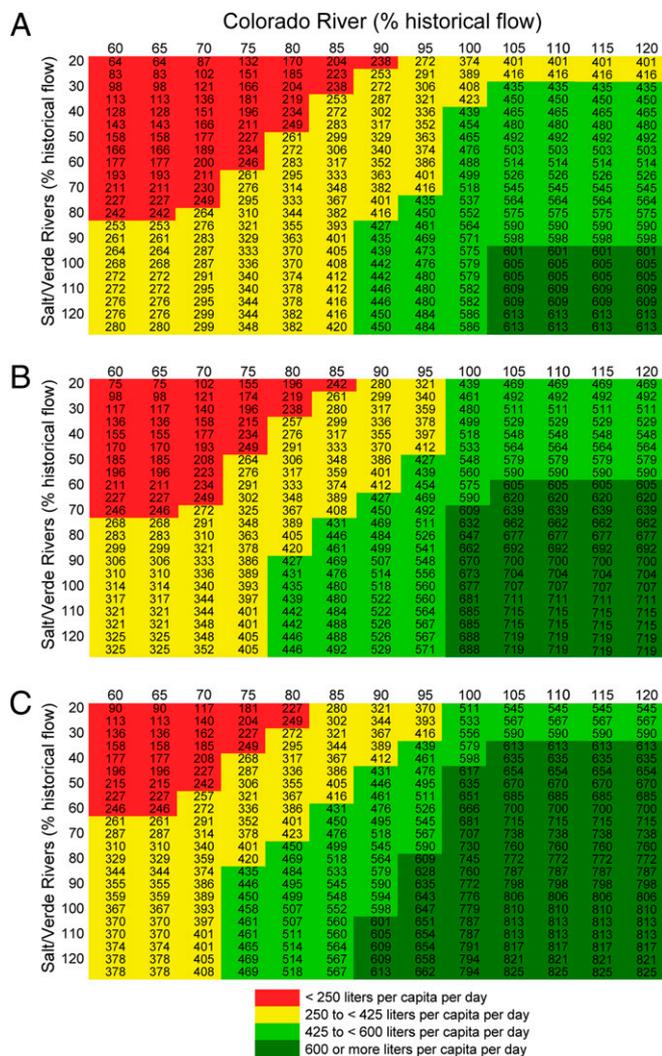
Fig. 4

Colorado River (% historical flow)

Salt/Verde Rivers (% historical flow)

A, B, C — data grids (columns: 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120; rows: 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120)

Legend:
- < 250 liters per capita per day
- 250 to < 425 liters per capita per day
- 425 to < 600 liters per capita per day
- 600 or more liters per capita per day

Fig. 4. WaterSim results for available LPCD under combined runoff conditions for the Colorado and Salt/Verde Rivers for (A) 100% of projected growth, (B) 50% of projected growth, and (C) no growth.

Fig. 5

Colorado River (% historical flow)

Salt/Verde Rivers (% historical flow)

A, B — data grids (columns: 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120; rows: 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120)

Net cumulative change in groundwater

Legend:
- < -30 TCM
- -30 to < -6 TCM
- -6 to < 6 TCM
- 6 TCM or greater

TCM = thousand cubic meters

Fig. 5. WaterSim results for cumulative groundwater change (thousand cubic meters) under combined runoff conditions for the Colorado and Salt/Verde Rivers with (A) 100% of projected growth with current levels of mesic landscape and private backyard pools and (B) 50% of projected growth and elimination of mesic landscaping and private backyard pools.

Summary and Conclusions

There are a variety of demand-oriented options that might have been included (e.g., the effects of water-conservation programs such as refitting indoor toilets and other appliances, restricting the use of turf grass on residential and commercial properties, restricting outdoor water, using rate structures to reduce water use among high-volume users, and fixing leaks, which account for 19% of indoor water use in Phoenix) (28). On the supply side, one might consider the effects of water reuse technologies, purchasing Indian water rights, changing the rate at which agricultural lands are converted to urban purposes, desalination, and cloud seeding. There are many paths to achieving water sustainability in Phoenix and other cities of the Southwest; we considered only growth limits, land-use change, and groundwater management.

Our analysis shows the value of moving from precaution to anticipation in water planning. Simulation results show that there is a wide range of uncertainty about how much water will be available for Phoenix from the Colorado and Salt/Verde systems. Designing a system to supply enough water for business as usual in the most pessimistic climate-change scenarios would be very expensive and perhaps, physically impossible. Ignoring those scenarios and designing for a best guess case could leave Phoenix vulnerable to water shortage with little time to adapt. Our modeling framework provides a way to translate the products of climate science and the principles of decision making under uncertainty into policy-oriented analysis for sustainable climate adaptation.

lessen the risk that water supplies would not sustain current levels of indoor use (Fig. 4C).

Next, we investigated how groundwater drawdown would be affected by climate-change conditions if we assume satisfaction of the demand at current levels, using groundwater to compensate for any shortage in surface supplies. Under currently projected growth conditions and unconstrained water usage, it is not possible to achieve groundwater sustainability in 2030 under any climate scenario. Cumulative drawdown would become severe if the pessimistic climate scenarios were to occur (Fig. 5A). At current drawdown rates (between 250 million m³/yr and 600 m³/yr), cumulative drawdown ranges from 6 billion to 14 billion m³ over the course of the simulation. Climate-change conditions and current growth patterns produce more extreme drawdown conditions. Policy action of some kind is necessary, even without climate change, to prevent groundwater drawdown. Fig. 5B shows the result of restricting residential water use by limiting growth to 50% of projected levels and eliminating irrigated outdoor landscaping and private backyard pools. These policies achieve groundwater sustainability under normal (100%) surface flows and substantially limit drawdown for all but the most severe climate futures.
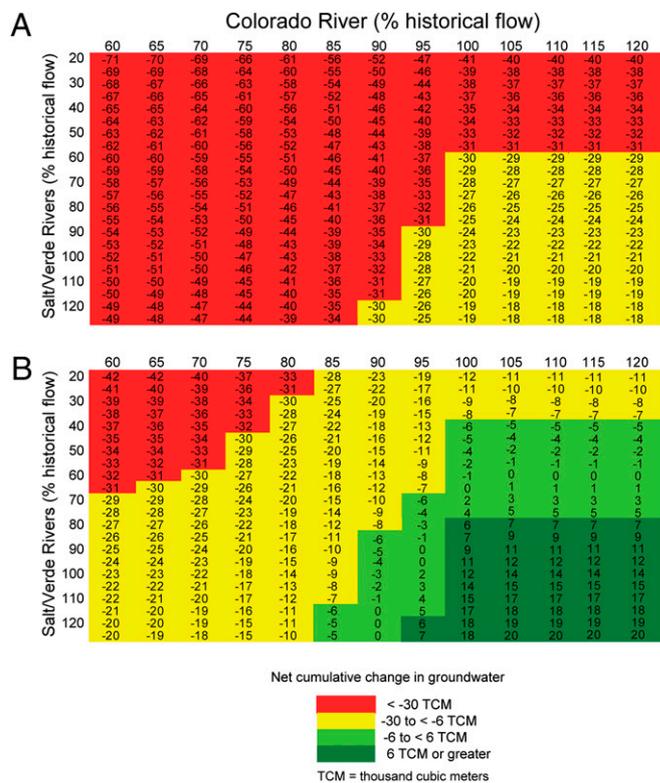
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