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WaterSim: a simulation model for urban water planning in Phoenix, Arizona, USA

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Abstract. WaterSim, a simulation model, was built and implemented to investigate how alternative climate conditions, rates of population growth, and policy choices interact to affect future water supply and demand conditions in Phoenix, AZ. WaterSim is a hierarchical model that represents supply from surface and groundwater sources and demand from residential, commercial, and agricultural user sectors, incorporating the rules that govern reservoirs, aquifer use, and land-use change. In this paper we: (1) report on the imperative for exploratory modeling in water-resource management, given the deep uncertainties of climate change, (2) describe the geographic context for the Phoenix case study, (3) outline the objectives and structure of WaterSim, (4) report on testing the model with sensitivity analyses and history matching, (5) demonstrate the application of the model through a series of simulation experiments, and (6) discuss the model's use for scenario planning and climate adaptation. Simulation results show there are significant challenges to Phoenix's water sustainability from climate change and rapid growth. Policies to address these challenges require difficult tradeoffs among lifestyles, groundwater sustainability, the pace of growth, and what is considered to be an appropriate level of risk of climate-induced shortage.

1 Introduction

Evidence is now mounting that human-induced climate change will produce a warmer and drier future for the Colorado River Basin and, indeed, that the shift to new climatic conditions is already underway (Barnett and Pierce, 2008; Barnett et al, 2008; Seager et al, 2007). These climatic conditions are altering the region's hydrology with more winter precipitation falling as rain instead of snow, earlier snow melt, and related changes in river flows—all factors that will decrease the amount of freshwater available for human use. Results from fifteen climate models from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) predict drier conditions for the region in this century, but there is substantial uncertainty about the extent, causal mechanisms, and geographic pattern of increased aridity (Seager and Vecchi, 2010).

This uncertainty creates challenges for water-resource management. Milly et al (2008) declared that stationarity—the assumption that natural systems function within a known and unchanging envelope of variability—is "dead". They note that the stationarity assumption has formed the basis for research, modeling, training, and practice in the field of water engineering. Emphasis traditionally has been on using the historical climate record to compute probability-density functions for managing water supplies, flood risk, and infrastructure design. Climate change and its uncertainties now mean that the historical record is an inadequate guide for assessing future risk. Decision scientists approach the notion of nonstationarity from a different, yet complementary, perspective, focusing on the human process of decision making. They refer to a new class of problems, including climate change, characterized by 'deep uncertainty' (Lempert et al, 2003). Deep uncertainty occurs when there is fundamental disagreement about the driving forces that will shape the future, and the probability distributions used to represent uncertainty and key variables are in dispute. There are also wide disagreements on how to value alternative outcomes and inescapable tradeoffs. These uncertainties are unlikely to be resolved before decisions in the water sector must be made about whether to redesign infrastructure, change laws passed decades ago, develop more innovative governance structures, or build less climate-sensitive cities. In problems of deep uncertainty, the goal is not to find a single optimal solution for deterministically projecting future conditions, but to look for policy decisions that are robust; in other words, those that work well across a range of future climate conditions.

Bankes (1993) makes a useful distinction between *consolidative* modeling that is based on the known facts of a complex system and *exploratory* modeling in which models are used to investigate the consequences of varying assumptions and hypotheses about the system and its future dynamics. The latter approach openly acknowledges that there is deep uncertainty about key variables and relationships that will drive future outcomes and that important information about the situation is not available. Exploratory modeling is especially appropriate for situations in which there is a high level of system complexity—where nonlinear behaviors and feedbacks can result in unintended consequences and catastrophic events. The search for an optimum solution may not reveal the unlikely, but real, possibility for catastrophic consequences, nor will it necessarily reveal a path that would avoid such consequences. There has been considerable development of agent-based modeling as an exploratory simulation approach to deal with problems that are characterized by complexity and uncertainty (Bankes, 2002; Zellner, 2008).

Simulation modeling allows policy makers to explore 'what-if' scenarios of the future and to look for policies that perform robustly over a wide range of plausible futures. Such robust strategies are often adaptive; they evolve iteratively as new information is gained and processed. Pahl-Wostl (2002) notes the importance of the human dimension in sustainable water-resource management, asserting the need for innovation and change in the traditional process of decision making. She argues that a system's adaptability and flexibility are more important than ecological or economic performance, and that inflexible technological solutions should be replaced by adaptive ones. In these types of settings, models are important both as scientific tools and as communication devices that facilitate social learning about the future.

With these perspectives in mind, we built and implemented WaterSim, an exploratory simulation model and participatory process, to consider the future water budget of metropolitan Phoenix, Arizona, USA under conditions of uncertainty. WaterSim was designed to challenge local and regional policy makers to vary their hypotheses and assumptions about future population growth, climate change, land-use change, and regional water policy. WaterSim is shown in the Decision Theater, an immersive, visualization facility at Arizona State University where viewers are encouraged to manipulate assumptions and hypotheses about the future and discuss policy options that reduce the risk of climate change to what they believe to be socially and politically acceptable levels. In this paper we provide context and background for the model development process by describing water supply and demand conditions in the Phoenix area, outlining the objectives and structure of the model, evaluating the credibility of model outcomes, and demonstrating its functionality with simulation experiments. We conclude with a discussion of the participatory process surrounding WaterSim and the profound challenges of climate adaptation in Phoenix.

2 Background and context

2.1 Climate change and water management in the Western USA

The basis for urban growth and economic development in the arid southwestern USA is the ability to manage the natural variability in runoff from infrequent, but heavy, rainfall events. There is increasing evidence that the Southwest USA will become warmer and drier in the coming century, reducing snowpack, Colorado River flows, and urban water supplies (National Research Council, 2007). Until recently, regional water managers have been slow to embrace the need for climate adaptation and to factor the implications and uncertainties of climate change in their long-term plans. Though they acknowledge that uncertainty pervades their work, most define it in terms of seasonal and interannual variability not long-term climate change (White et al, 2008). Typically, water managers use the historical record as the basis for gauging risk and are skeptical about the predictive validity of scenarios and climate models. In addition, the impacts of climate change are long term while many water managers are faced with more immediate uncertainties such as the rate of economic and population growth, the legal status of Indian water rights, endangered-species designations, environmental permitting, and other components of the water-planning process (White et al, 2008). In a study of institutional resistance to incorporating climate-change scenarios into practice, Ingram and Lejano (2007) showed that this problem is not limited to Phoenix. Interviews with approximately forty water professionals in the West revealed inherent conservatism; they are heavily invested in established ways of doing business, skeptical of model results, and averse to public scrutiny.

2.2 Water supply and demand in Phoenix

Water is the key resource for growth in the desert city of Phoenix. It was crucial for prehistoric settlement based on irrigation agriculture, as well as for modern agricultural development and recent urbanization (Gammage, 1999; Gober, 2006). The metropolis is well endowed with a diverse portfolio of water sources, including the upland watersheds of the Salt and Verde Rivers, the Colorado River Basin (figure 1) and, when surface waters are in short supply, a vast network of underground alluvial aquifers. Over the years city leaders constructed a sophisticated water storage and delivery system to manage the Salt and Verde River flows, negotiated for a share of the Colorado River flows, and supplemented surface water with groundwater during drought periods. Today the region's municipal, industrial, and agricultural sectors use slightly more than 2.5 billion m^3 (2 million acre feet) of water with increasing shares coming from the Colorado River, through the Central Arizona Project (CAP) Canal, and effluent and a decreasing, though still substantial, portion coming from groundwater (figure 2). The region also stores excess Colorado River water underground and later recovers it through a Groundwater Savings Facility program. On the consumption side approximately 57% of water is used in the municipal and industrial sector, non-Indian agriculture consumes 33% and Native American communities use the remaining 10%, mostly for irrigated agriculture on reservation lands (ADWR, 2009).

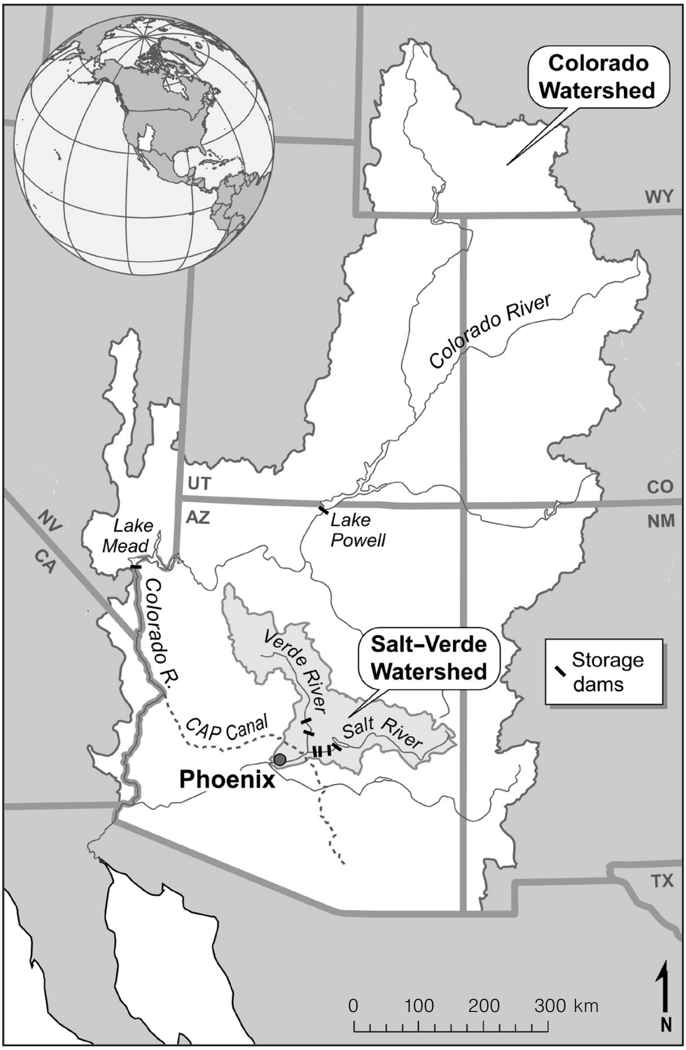


Figure 1. Phoenix, AZ depends on the upstream watersheds of the Salt and Verde Rivers and on the Colorado River Basin, via the Central Arizona Project Canal, for its surface water supplies.

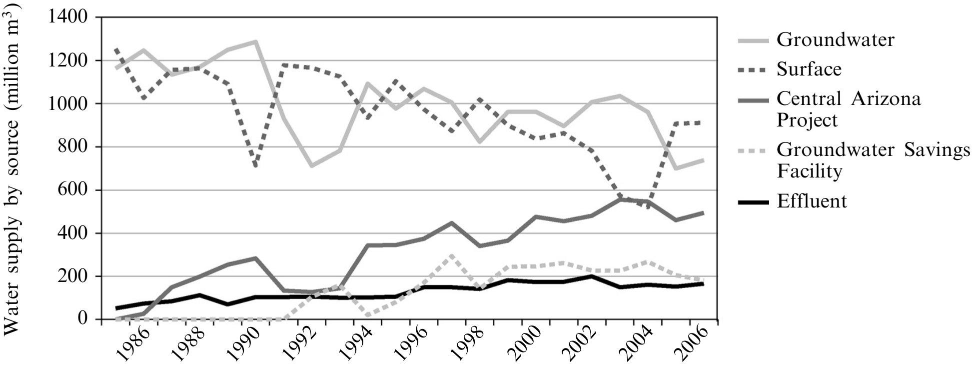


Figure 2. The Phoenix, AZ water supply by source for the municipal, industrial, and agricultural sectors combined (source: ADWR, 2009).

Climate studies have identified a range of uncertainties about the surface-water supplies from the Salt – Verde and Colorado River Watersheds. Ellis et al (2008) showed that runoff from the Salt – Verde Watersheds could vary from 50% to 123% of historical averages, on the basis of model runs using scenarios from the Intergovernmental Panel on Climate Change Third Assessment Report in 2001. Estimated future flows on the Colorado River system range from 61% to 118% of historical averages (Christensen et al, 2004). Central Arizona is particularly sensitive to even small reductions in Colorado River flows because its water rights are junior to those of California. Climate change was not a major topic of scientific debate when this 1968 agreement was put into place. In order to secure the federal loans to build the 541 km Central CAP Canal from the Colorado River to the rapidly growing cities of central and southern Arizona, CAP agreed to secondary water rights (Hirt et al, 2008). Thus, the CAP Canal will bear the full brunt from any long-term shortage in the lower basin of the Colorado River before California's supplies will be curtailed.

Water decision making in metropolitan Phoenix is highly decentralized. Decisions are made at the local level by municipalities and thirty-seven small private companies that have been granted exclusive rights by the state to sell water in rapidly growing urban-fringe areas. Each provider has a unique portfolio of water from various sources and makes individual decisions about managing supply and demand. The state regulates groundwater at the regional level, but the regulation process surrounding the ability of the Colorado River flows to recharge aquifers on a long-term basis favor local interests over regional control (Hirt et al, 2008).

2.3 Status of water modeling in the Phoenix area

The City of Phoenix, which represents about one third of the metropolitan area's total population, currently uses a simulation model for water-resource planning. The model tests water supply and demand scenarios, identifies conditions under which expanded infrastructure, backup supplies, and water-use restrictions will be needed, and can be used to develop a long-term capital funding program to achieve 'supply redundancy targets'. Included in the model are water-supply conditions, growth and water-demand projections, environmental requirements and regulations, and recharge and recovery strategies. The city uses the model for scenario planning to test the sensitivity of input variables to changing development patterns, water-use patterns, drought conditions, and other factors. Model projections show that the city can meet projected growth for the next fifty years with the current supplies in normal or moderate drought conditions, but severe conditions would necessitate significant capital investments to enlarge the infrastructure (City of Phoenix, 2005). Model results for four canned scenarios are reported in printed form. They do not support real-time stakeholder engagement in which model inputs and assumptions can be manipulated to assess the consequences of today's decisions for future water-shortage conditions. In addition, the model does not support regional-level water planning.

3 WaterSim model components

3.1 Model structure and equations

WaterSim simulates regional water supply and consumption with a focus on the consequences of policy decisions made today for long-term shortage under conditions of deep uncertainty. It facilitates policy decisions to lower the risk of climate change and to achieve water sustainability in Phoenix. In this subsection we present the structure of the WaterSim model. In subsection 3.2 we review data sources used to establish model inputs and parameters.

WaterSim projects water consumption and availability in central Arizona under varying scenarios of growth, urbanization, climatic uncertainty, and policy choices from the current time until 2030. The model uses the 'XLRM' framework (Lempert et al, 2003), which includes four types of components: (1) *exogenous uncertainties* (X) are factors that decision makers cannot control, (2) *policy levers* (L) represent potential actions that decision makers could take, (3) *relationships* (R) describe the mathematical associations between variables, and (4) *outcome measures* (M) summarize model outcomes for decision-making purposes. The specifics for each of these four components in WaterSim are shown in table 1.

Table 1. Components of WaterSim.

Exogenous uncertainties
Variability of water supply
Volume of minable groundwater
Climate-change impact on water supply
Policy levers
Groundwater management
Policy start year
Water-shortage policy
Retirement of agricultural land
Population growth rate
Relationships
Equations within the WaterSim model
Outcome measures
Water availability in liters or gallons per capita per day
Groundwater deficit

WaterSim projects a time series for the outcome measures (M) over the simulation period as a function of the policy levers (L) and exogenous uncertainties (X) using a stock-and-flow model of the system dynamics type (Sterman, 2000). With this approach, the relationships (R) among the physical and socioeconomic processes are modeled as a system of interconnected integral equations. WaterSim contains two components that exogenously project a time series for the future availability of water from the two major surface water sources, the mainstream of the Colorado River and the Salt – Verde River system. A third model component projects future demand for water as a function of projected population and land-use patterns under the assumptions of no constraints on water usage, and a fourth component models the interconnections between supply and demand.

An underlying assumption in WaterSim is that imbalances between supply and demand can be met by (1) using groundwater if demand exceeds the available surface supply or (2) storing excess surface water in the groundwater aquifers if demand is less than the surface supply. There is sufficient groundwater to cover deficits in surface water between now and 2030 under all scenarios we considered without constraining consumption below historical levels. Policy levers (L) are available to match the surface water supply and demand, if desired, by modifying demand. In particular, policies can be imposed where total water consumption is constrained to be equal to the available surface water, averaged over a time period. The implications of other policy levers that impact water demand can also be investigated, such as constraining the population growth rate or changing the rate at which agricultural land is retired and converted to other uses.

A stock-and-flow diagram using system dynamics notation summarizes the logic of the WaterSim model (figure 3). In this diagram, rectangles represent 'stocks' (state variable), and the flows into and out of these stocks are represented by 'pipe' arrows with 'valves' on the pipes representing the factors that control flows. A 'cloud' at the end of a pipe represents a flow originating or terminating outside the system that is modeled. Circles represent auxiliary variables that influence flows, with arrows showing the direction of influence. Diamonds represent model parameters that are exogenously specified. In many cases these parameters are time series or functions to specify variations in exogenous inputs to the model over the time period of the simulation.

The elements in the top-left quadrant of figure 3 represent the modeling of the water supply from the Colorado River, and the top-right quadrant represents the modeling of water supply from the Salt and Verde Rivers. For each, a time series of historic flows for the relevant river system is used to exogenously specify a flow pattern over the simulation time period. The historical time series can be modified to explore the possible effects of climate change. During a simulation run, the model imposes the legal limitations on how much water providers in the Phoenix area can withdraw in times of shortage.

While this portion of figure 3 illustrates the logic for modeling the Colorado River and Salt – Verde supplies, the actual WaterSim model logic is considerably more complicated. For example, it directly considers both major Colorado River reservoirs, Lake Powell and Lake Mead, adjusts for other reservoirs, and takes into account the complex set of rules that govern the allocation of water among the seven states under the Colorado River Compact. Accurate modeling of these allocation rules is particularly important when there are water shortages, as can occur during a drought, because Phoenix's portion of available water can be constrained quickly due to the agreements made at the time the CAP Canal was funded.

The bottom-left quadrant represents the modeling of unconstrained water demand in the Phoenix Metropolitan area for three categories of water users: commercial and other, residential, and agricultural. By 'unconstrained', we mean that this is the demand that would occur if there were no restrictions imposed on water usage, on the basis of historical use patterns by different types of users. As with the water-supply portion of this diagram, the unconstrained water-demand portion shows the overall logic, but the actual model is considerably more complicated. Specifically, it considers a variety of water-use categories and how the demand from each category will vary over the simulation period.

The bottom-right quadrant represents the logic for how water supply and demand are matched. Specifically, the total unconstrained demand for water for the various categories of water users is compared with the available surface-water supply. Demand is first fulfilled with surface water. If the demand exceeds the available surface-water supply—which it often does in simulation runs where restrictions are not imposed on water use—the additional required water is drawn from groundwater if policies are not specified to restrict demand. The impact of different policies with regard to allowed water use can be investigated by varying the policy levers. Specifically, the implications of imposing policies related to the amount of allowed groundwater overdraft can be easily simulated.

3.1.1 *Water-supply equations*

The model for water supply as a function of time, as illustrated in the upper portion of figure 3, is specified through a dynamic system that projects the volumes of water $R(t) \equiv [R_1(t), R_2(t), ..., R_n(t)]$ in each reservoir or aquifer as a function of time t,

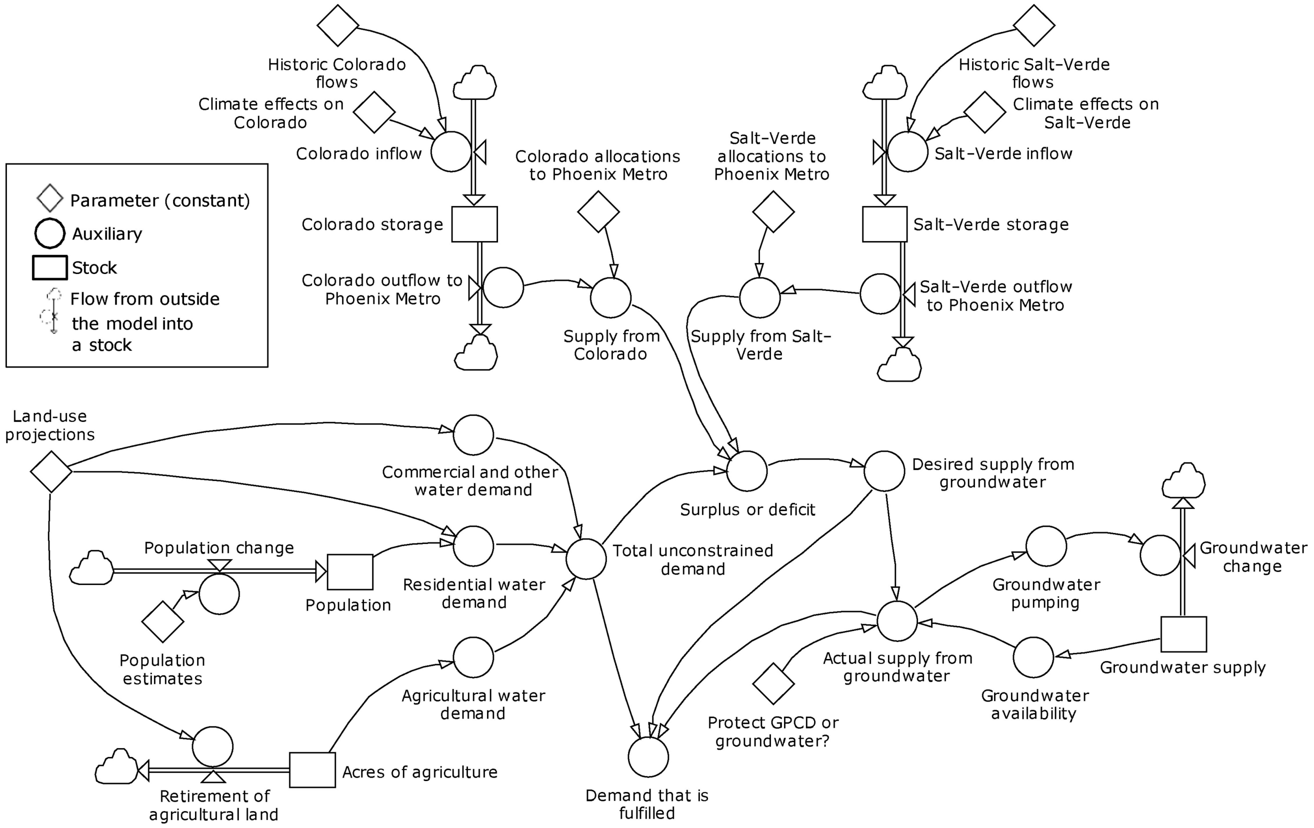


Figure 3. Simplified stock-and-flow diagram summarizing the WaterSim logic. (GPCD is gallons per capita per day.)

where the subscripts represent the n reservoirs or aquifers in the system. (Figure 3 shows two reservoirs and one aquifer, but the actual model is somewhat more complex.) Reservoir levels can increase through precipitation runoff, upstream releases, natural and artificial recharge, and recycling; they can decrease from upstream uses, downstream reservoir releases, evaporation, and loss. These factors depend on the exogenously specified climate assumptions and policy $C(t; x, l)$, where x denotes the climate scenario and l denotes the water-policy levers that are specified as parameters of the system. The initial conditions at time t_0 are the initial reservoir or aquifer volumes, $R^0 \equiv (R_1^0, R_2^0, ..., R_n^0)$. Specific hydrological rules are specified by a vector of functions $f_1, f_2, ..., f_n$, one for each reservoir or aquifer, which are functions of the reservoir or aquifer volumes, the climate assumptions, and specified policy. Thus, the dynamical behavior for the system of reservoirs and aquifers is represented by the system of integral equations:

$$R_i(t) = R_i^0 + \int_{\tau = t_0}^{t} f_i[R(\tau), C(\tau; x, l)]\mathrm{d}\tau, \qquad i = 1, 2, ..., n.$$

The available supply $S^0(t) \equiv [S_1^0(t), ..., S_n^0(t)]$ from each reservoir or aquifer depends on the water in the reservoirs or aquifers as regulated by legal limitations and entitlements. This is represented by $S_i^0(t) = g_i[R(t)](i = 1, 2, ..., n)$, where g_i represents the limitations and entitlements for that source. After calculating the available water supply for each reservoir or aquifer, these quantities are then allocated by the model during a simulation run to specific states, regions, and providers according to the water entitlements and agreements.

3.1.2 *Water demand equations*

The calculation of water demand, as illustrated in the lower-left portion of figure 3, begins with a base map that consists of an indexed collection of polygons that partitions the region into collectively exhaustive and mutually exclusive subregions. Each polygon has exogenously specified attributes for population, land use, area, and location for each time step. From this map we calculate a baseline unconstrained water demand for each polygon based on its spatial attributes and then aggregate these quantities to obtain the overall demand for the entire region. The outputs from this analysis are used to specify the unconstrained water-demand parameters for WaterSim. The projected unconstrained water demand $D^0(t) \equiv [D_1^0(t), D_2^0(t), ..., D_m^0(t)]$ for each of the m user categories is then calculated using these parameters and the projected future population and agricultural lands as calculated by integral equations analogous to those specified above for reservoir and aquifer volumes. Figure 3 shows three sectors (residential, agricultural, and commercial and other), but the actual model is more detailed.

3.1.3 *Water demand – supply matching equations*

Since there is no a priori restriction that the total surface-water supply equals the total unconstrained demand, WaterSim includes mechanisms to balance the total amount of water $S(t)$ that will actually be supplied and the total amount $D(t)$ that will actually be consumed as a function of time. Specifically,

$$S(t) = \sum_{i=1}^{n} S_i(t),$$

where $S_i(t)(i = 1, 2, ..., n)$ are the amounts supplied by each of the reservoirs or aquifers, and

$$D(t) = \sum_{j=1}^{m} D_j(t),$$

where $D_j(t)(j = 1, 2, ..., m)$ are the amounts actually consumed by each category of user. The model to calculate and balance water supply and consumption can be expressed for any time t as

$$\begin{aligned} S_i(t) &= F_i[S^0(t), D^0(t); x, l], \qquad i = 1, 2, ..., n, \\ D_j(t) &= G_j[S^0(t), D^0(t); x, l], \qquad j = 1, 2, ..., m, \\ S(t) &= D(t), \end{aligned}$$

where F_i and G_j are functions to allocate specific water supplies based on supply, demand, and the exogenously specified climate scenarios x and policy levers l. Supply and demand can be matched through a variety of approaches that depend on water conservation programs, groundwater policy, use restrictions, or economic principles.

3.1.4 *Implementation*

The WaterSim computer implementation consists of five submodels with a top-level interface that links the submodels for presentation purposes (figure 4). This modular model structure allows straightforward modification of subcomponents without needing to consider parts of the model that are not being modified and also facilitates easy testing and validation of subcomponents. A user-friendly web-based front end makes the model accessible to water planners who wish to engage in scenario planning and policy analysis (http://watersim.asu.edu/).

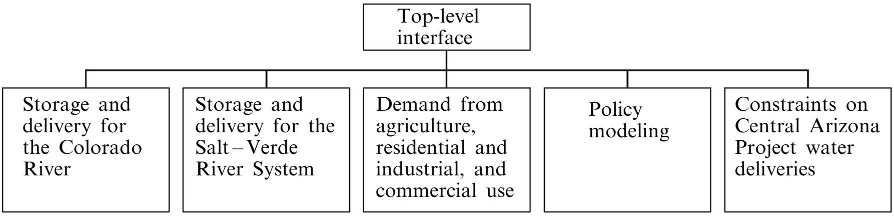
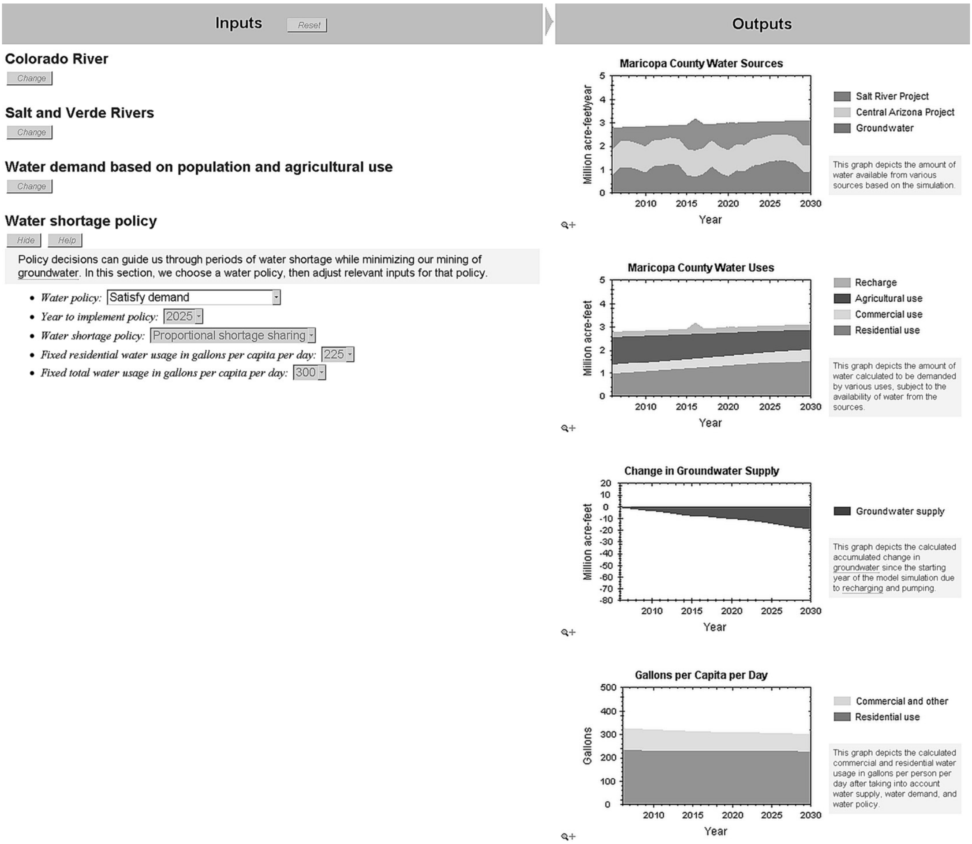


Figure 4. WaterSim model structure.

3.2 Model parameters for the Phoenix area supply and demand conditions

The initial parameters of the model, including climate conditions, growth projections, and pace of agricultural land retirement are based on the historical record and projections from previous scientific or government studies. Outputs project the distribution of water across sectors (residential and commercial) and gallons (liters) per capita per day [GPCD (LPCD)] in residential and other uses implied by these conditions (figure 5). The base-case policy assumes that groundwater supplements surface water. For Phoenix, when surface-water systems are unable to meet demand the deficit is made up by groundwater drawdown. WaterSim simulates surface-water flows using a portion of the historical flow regime for the Colorado and Salt – Verde Basins projected forward. Therefore, the outcome is determined by the index year—the base year upon which future flows are calculated. This varies greatly by whether the sequence upon which the simulation is based was a 'dry' or 'wet' sequence. In addition, the historical flow regime can be scaled up or down to represent wetter or drier conditions relative to the historical period being used for the projections. This permits the modeling of future conditions that have



Policy decisions can guide us through periods of water shortage while minimizing our mining of groundwater. In this section, we choose a water policy, then adjust relevant inputs for that policy.

- *Water policy:* Satisfy demand
- *Year to implement policy:* 2025
- *Water shortage policy:* Proportional shortage sharing
- *Fixed residential water usage in gallons per capita per day:* 225
- *Fixed total water usage in gallons per capita per day:* 300

This graph depicts the amount of water available from various sources based on the simulation.

This graph depicts the amount of water calculated to be demanded by various uses, subject to the availability of water from the sources.

This graph depicts the calculated accumulated change in groundwater since the starting year of the model simulation due to recharging and pumping.

This graph depicts the calculated commercial and residential water usage in gallons per person per day after taking into account water supply, water demand, and water policy.

Figure 5. WaterSim inputs and outputs screen.

similar variability to historical patterns but are either systematically wetter or drier over the simulated time period.

Clearly, the choice of index year, the beginning of the historical record extracted for simulation, infuses uncertainty into the modeling process because historic flow patterns are highly variable. Users can change the index year as well as the severity of drought conditions (specified as a percentage of historical runoff) and the duration of drought. The model includes nineteen scenario/model combinations downscaled to the Salt – Verde system (Ellis et al, 2008). Model inputs can be used to vary the exogenous uncertainties: for example, 'what if' a drought begins in 2010, runs for ten years, and provides 75% of the historical level of water? What would happen if a particular climate-change scenario comes to pass and flows are reduced (or increased) by a certain percentage?

Simulated future water demand is based on the future allocation of land uses and population projections. WaterSim allocates projected future population onto available land parcels and then translates the resulting residential population densities into water demand using 'water duties' or rates of water use specified by land-use type. For example, high-density residential uses have higher water duties than low-density residential uses, but per capita use rates are lower. A geographic information system is used to project population density onto the residential land-use parcels. These densities are calculated from population projections for the years 2010, 2020, 2025, and 2030 (ADES, 2006); linear interpolation is used to estimate annual population for intervening years. Future water demand is sensitive to population density because there is a rapid decline in per capita water use with higher residential densities—an obvious relationship in a city such as Phoenix where between 60% and 75% of residential water use is for outside purposes (Mayer and DeOreo, 1999). Water duties are also applied to future nonresidential urban land uses, including the remaining agricultural lands. The base case is to assume that population growth will adhere to the projections of the Arizona Department of Economic Security (ADES, 2006), and that agricultural lands will be retired by 2070. Users can modify the input assumptions to project the effects of faster-than-expected or slower-than-expected population growth and varying rates at which agricultural lands are converted to urban uses on future water conditions.

WaterSim assumes that future water scarcity is affected by policies concerning water supply and demand. The base-case policy assumes that the system must 'satisfy demand' as presently constituted and that any shortage from surface-supply deficits or growth in demand is balanced by groundwater deficit through withdrawal. WaterSim users can alter the policy to assume 'sustainable groundwater use' under which withdrawal is forced to be equal to recharge. Reductions in demand are then required to balance any deficits in supply.

4 Testing and evaluation

Debate surrounds the issue of model evaluation, with some scientific academics arguing that model results cannot be validated or proved (Konikow and Bredehoeft, 1992). Model users can, however, gain confidence in model validity with a number of testing procedures. We first explored the sensitivity of our model outcomes to changes in assumptions about future water-supply and water-demand conditions. A second testing approach examined whether key components of the system involving storage and release from reservoirs could replicate historical patterns and whether assuming historical land use produced accurate estimates of actual water consumption.

4.1 Sensitivity analyses

Sensitivity analyses were used to test the responsiveness of the model outputs to uncertainties about climate, runoff, and population-growth conditions. We explored model sensitivities within the range of scenario results produced by Ellis et al (2008) ranging from 50% to 123% of historical flows on the Salt – Verde system and estimates by Christensen et al (2004) of flows on the Colorado River ranging from 61% to 118% of historical flows. We varied population growth from zero to 300% of official projections to reflect uncertainties about growth rates. We varied our policy conditions in two separate analyses. The first assumes that groundwater levels are drawn down to satisfy current levels of demand; the second assumes sustainable groundwater use (withdrawal = recharge) requiring reductions in consumption in response to deficits in surface supplies.

Figure 6(a) shows an ensemble of WaterSim results, using the most pessimistic historical index conditions as the basis for the simulation; in other words, we based the simulation on the driest twenty-five years in the historical record. We assumed groundwater overdraft would compensate for surface-water deficits when they occur. As expected, river flow levels above 100% of historical averages do not affect overdraft conditions. Expected levels of population growth (population growth factor = 1) and no climate change (percentage of historical flows = 100%) produce a long-term drawdown of 30 billion m^3 which amounts to an annual average of 1.2 billion m^3 or about 1 million acre ft per year over the twenty-five year simulation period. This drawdown is substantially higher than recent levels of drawdown which range from 200 000 to 400 000 acre ft, or between 247 and 493 million m^3 per year (ADWR, 2009). A business-as-usual approach to water policy and population growth (with no climate change)

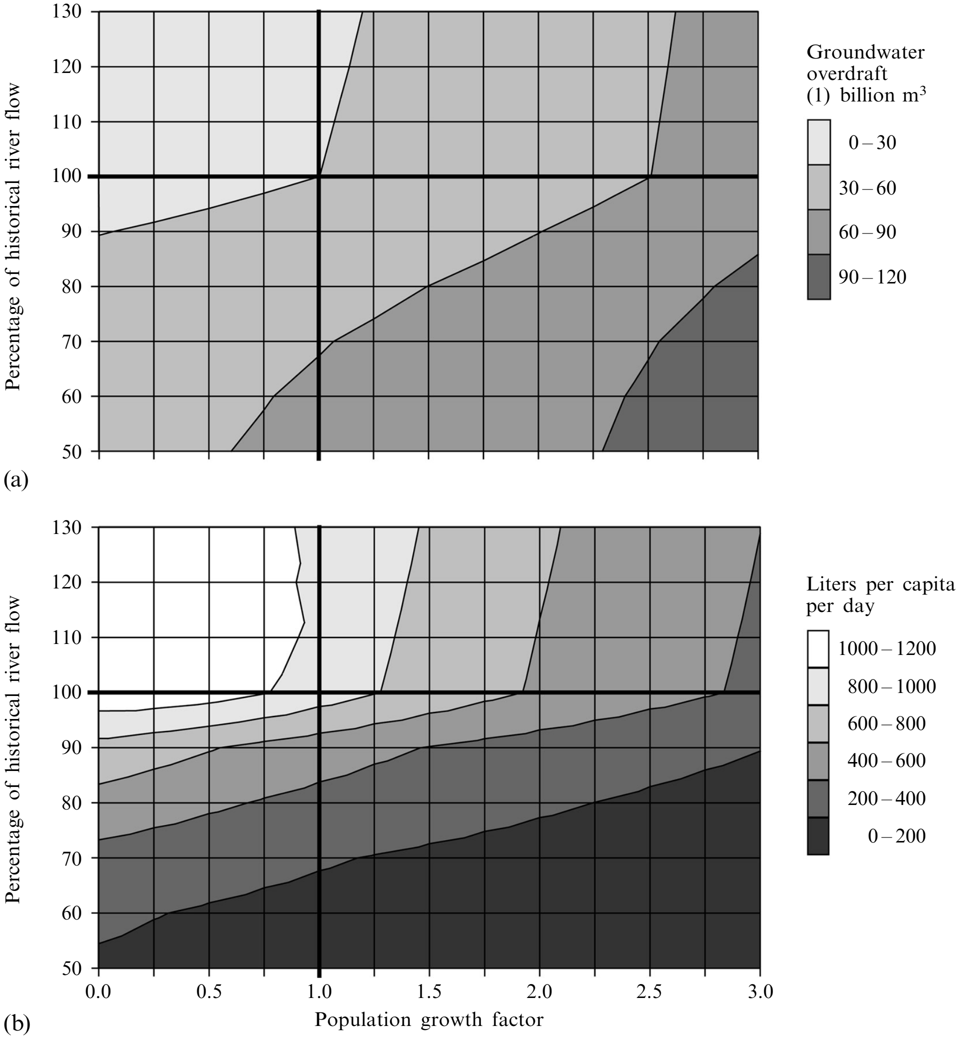


Figure 6. Sensitivity analyses of varying growth and climate conditions for (a) cumulative overdraft assuming demand satisfaction and (b) available liters per capita per day assuming five-year groundwater sustainability.

will result in unsustainable groundwater use at levels substantially above what occurs at present.

Figure 6(b) assumes that the region institutes a policy of sustainable groundwater use on a five-year-average basis. In this case, reductions in consumption would compensate for declines in surface flows, and recharge balances drawdown on a five-year basis. Per capita consumption is sensitive to changes in both population growth and reductions in river flow. The steep reduction in LPCD in the zone between 70% and 90% of historical river flows reflects the CAP's junior status in the Colorado River allocations. When flows fall below 70% of historical averages, it matters little how far they fall because Phoenix has already lost its Colorado River allocation. Above 100% of historical flows, consumption will continue at current levels. These results agree both qualitatively and quantitatively with what we anticipate would happen, and hence provide some confidence that the model accurately portrays relationships in the Phoenix water system.

4.2 History matching

We tested whether WaterSim's submodels will reproduce output patterns that actually occurred between 1970 and the present time if the input parameters are set to agree with actual historical conditions. Specifically, these analyses evaluate whether the Salt – Verde and Colorado submodels reproduce the actual levels of water in upstream reservoirs, whether actual historical retirement of agricultural land use follows a linear decline as assumed by the WaterSim water-demand submodel, and whether WaterSim's 'backcasting' estimates of municipal water demand matched observed historical levels.

WaterSim closely replicated upstream reservoir storage conditions in the watersheds of the Salt and Verde Rivers (figure 7). The relevant submodel takes projected river flows into the reservoirs and reduces them by an estimate of the amount of water lost to evaporation, the amount of dam overflow, and an estimate of the amount of water released by the dam managers to meet demand for agricultural, urban, and industrial use. The model assumes that managers will try to keep as much water as possible in storage to meet future demand subject to meeting the current demand. We ran a series of storage estimates with different start years, each set to actual conditions for that year. The variations in the reservoir storage projected by the model were somewhat accentuated relative to the actual historical values, but were otherwise similar to historical variations in storage levels.

We performed a similar test for storage in Lakes Powell and Mead in the Colorado Watershed (figure 8). There, WaterSim underestimated storage in Lakes Powell and Mead before 1985, but more closely replicated historical levels in later years. Errors occurred because Arizona was unable to take its full allotment of 3.5 billion m^3 (2.8 million acre ft) of Colorado River water during that period. The CAP Canal had not yet been built or extended to all possible irrigation districts. When the state was able to take all, or nearly all, of its allotment WaterSim's outcomes more closely matched observed storage levels.

WaterSim's demand submodel assumes that the retirement of agricultural land is a linear function of time, depending upon the number of hectares (acres) of agricultural land at the start of the run and the year when non-Indian agricultural lands will be completely retired. We examined rates of agricultural land retirement after 1985 when

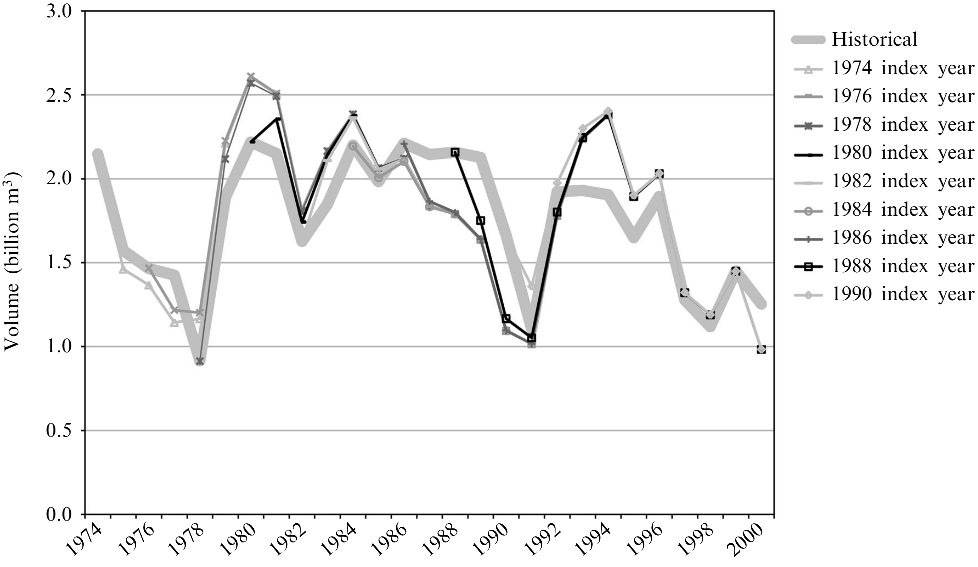


Figure 7. Submodel predictions of reservoir volumes for the Salt – Verde River system.

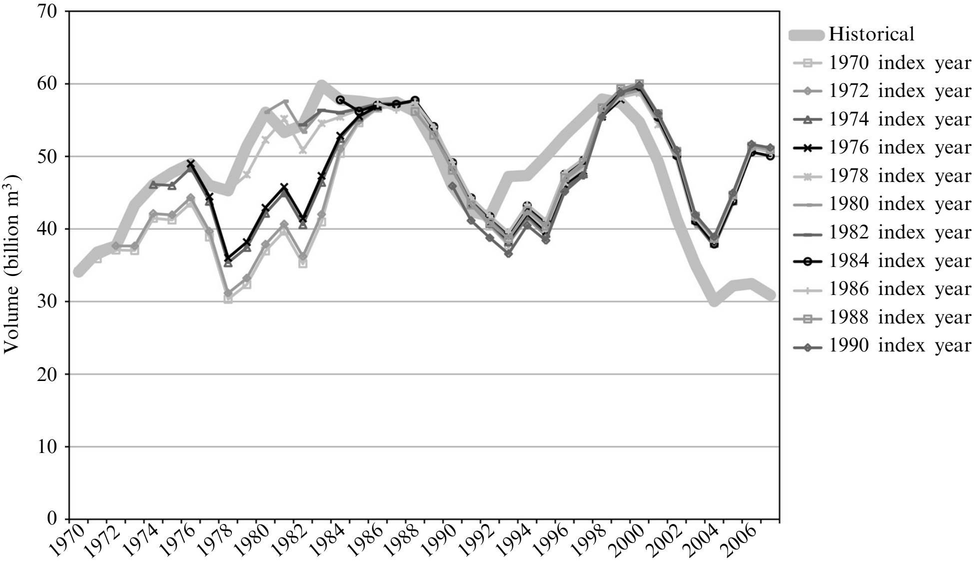


Figure 8. Submodel predictions of reservoir volumes for Lakes Powell and Mead in the Colorado River Watershed.

data on lands retired from agriculture were first collected by the Arizona Department of Water Resources. The retirement-trend line fit to this data between 1985 and 2005 has a slope of -5.6 and an r^2 of 0.97. The higher r^2 indicates that the annual land-retirement trend is very close to being linear. The slope of -5.6 means that for every year an average of 2266 ha (5600 acres) of agricultural lands are retired for other uses (mostly urban land uses). At this rate, non-Indian agricultural lands would be completely retired by around 2065, which is close to unofficial expectations by the regional planning authority that 'buildout' will occur by 2070.

One final test involved reconstructing municipal water consumption using historical data. We populated residential categories with census estimates of the population for 1985, 1990, 1995, and 2000 and estimated other land uses on a proportional basis. We used the water duties described above to estimate water use according to the type of land use and the density of residential land uses. This methodology, which is at the heart of the estimation procedure used by WaterSim's demand equations, produced estimates of municipal water consumption that matched quite closely with actual consumption, especially when we took account of the water used to irrigate local golf courses (figure 9).

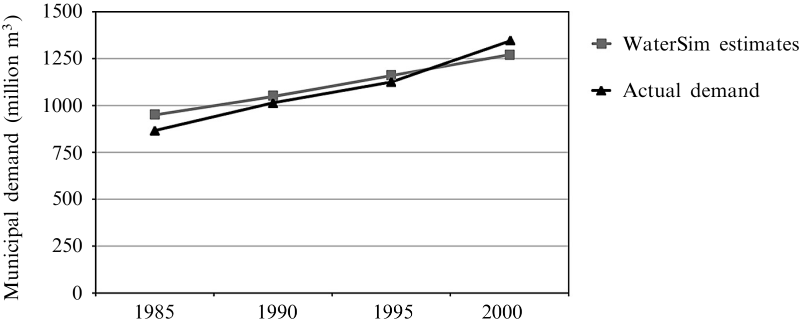


Figure 9. Actual versus estimated municipal wtaer demand in Phoenix, AZ.

5 Simulation experiments

In this section we demonstrate how the output from WaterSim varies with different input choices for six possible scenarios. These experiments are not meant to be the final word on vulnerability to climate change in Phoenix but rather examples that demonstrate the types of exploration that the model can support. The first assumes the effect of climate change on the Salt–Verde system will reduce flows to 50% of historical flows (table 2). In this scenario one of the region's surface supplies is seriously compromised while the second remains intact. Per capita water consumption is assumed to remain constant because the policy parameter is set to satisfy demand at current levels regardless of what happens to supply. Groundwater overdraft compensates for surface-water deficits over the twenty-five-year simulation period, and the cumulative drawdown is around of 18.6 billion m^3 (around 15 million acre ft) which is higher than current rates of annual drawdown which vary from 247 million m^3 to 493 million m^3 (200 000 – 400 000 acre ft) per year, depending upon available surface supplies. The model shows that unsustainable groundwater use would be required to maintain both population growth at current levels and water consumption at 848 LPCD. In this scenario, the region mortgages its future by drawing down its groundwater to maintain current levels of growth and consumption.

In the second experiment, we impose climate-change conditions on the Colorado and Salt–Verde River systems. Predictably, supplies from the Colorado are curtailed, and even more groundwater is required to maintain rapid growth and current lifestyles. Residents continue to consume 848 LPCD, and the cumulative drawdown reaches 46.0 billion m^3. More than 60% of the total water supply comes from unsustainable groundwater supplies. For perspective, this would amount to between three and six times the current rate of drawdown. Increasing the growth rate (to 150% of projected levels) in the third experiment further exacerbates the drawndown situation, increasing dependence on unsustainable groundwater to 65% of total water consumption. This scenario results in cumulative drawdown of 53.9 billion m^3 (43.7 million acre ft). This drawdown level resembles the risky conditions that prevailed prior to the 1980 Groundwater Management Act

Table 2. Results of the simulation experiments.

Change in runoff (%)		Population growth	Protection policy	Deliveries over course of simulation (billion m^3)[a]			2030 values	
Salt–Verde	Colorado			from Salt–Verde	from Colorado	from groundwater	groundwater (billion m^3 loss)	LPCD
50	100	100	LPCD/GPCD	18.6 (20.6)	34.4 (38.1)	37.3 (41.3)	28.4	848
50	70	100	LPCD/GPCD	18.6 (20.6)	16.4 (18.2)	55.3 (61.2)	46.0	848
50	70	150	LPCD/GPCD	18.6 (18.9)	16.4 (16.6)	63.6 (64.5)	53.9	848
50	70	150	groundwater	18.6 (37.9)	16.4 (33.4)	14.1 (28.7)	3.5	148
50	70	100	groundwater	18.6 (38.4)	16.4 (33.8)	13.5 (27.8)	2.8	178
50	70	50	groundwater	18.6 (38.6)	16.4 (34.0)	13.2 (27.4)	2.3	204

Note: LPCD = liters per capita per day; GPCD = gallons per capita per day.
[a] Percentages are shown in parentheses.

(http://www.azwater.gov), when subsidence resulted in damaged roads and building foundations, aquifer compactions, and water-quality problems (Connall, 1982).

The fourth, fifth, and sixth experiments point to possible sustainable paths. In these scenarios, we change the policy assumption to require five-year sustainable groundwater use by 2010. The latter recognizes sustainable use and allows pumping so long as five-year levels average 280 million m^3 (227 000 acre ft), the estimated level of recharge. To achieve five-year sustainable groundwater use, consumption would need to fall from 848 LPCD today to 148 LPCD by 2030 in order to support high growth rates of 150% of projected levels in the fourth scenario. Reductions to this level would severely curtail the number of swimming pools, require a shift from irrigated landscape to native vegetation, and limit outdoor water features such as urban lakes and fountains. They would also involve reductions in water consumption from smart growth and high-density urban forms that leverage outdoor water across a larger number of urban residents, significant reductions in indoor water use, and increases in water reuse from current levels. Substantial changes in current Phoenix-area lifestyles and attitudes toward water reuse would be necessary to attain water sustainability in the face of an accelerated rate of growth, pessimistic climate-change scenarios, and a policy that requires sustainable groundwater management. The fifth and sixth experiments demonstrate how lower levels of population growth (100% of projected levels in the fifth and 50% in the sixth scenario) reduce the need for stringent cutbacks in per capita water use and present tradeoffs between the levels of future growth and the lifestyles that can be supported in a sustainable future.

6 Concluding remarks

We developed WaterSim as part of a long-term effort to engage Phoenix policy makers and residents in a structured discussion about the choices that lie ahead with respect to water policy, given the deep uncertainties of climate change. These uncertainties will require new modeling approaches and decision processes. The traditional engineering solution for water management in the arid Southwest USA has been to design infrastructures and secure supplies to accommodate the worst-case set of conditions in the historical record. This strategy will fail if the runoff level and regimes of the future are outside the historical record. Problems of deep uncertainty, such as climate change, require us to consider a range of possible futures (climate and otherwise) beyond the constraints of the historical record. In addition, as the examples above show, we need to address value tradeoffs that are presented by climate change in a rapidly growing city. These are difficult tradeoffs between short-term lifestyle preferences and long-term sustainability. In the short term, the region can weather the effects of climate change without visible sacrifice, because of its substantial groundwater resources, but this entails tapping the equity in that precious bank of groundwater. WaterSim facilitates a discussion about the cumulative, long-term impacts of such a strategy as well as policy approaches that address the long-term risks.

The integrated nature of the WaterSim model facilitates discussions about the interconnections among water and land management, growth and sustainability, and sustainability and lifestyle. Thus it can be used to highlight critical tradeoffs among growth, sustainable groundwater use, lifestyles, and risks associated with climate change. The risks of a future of severe water shortage can be reduced substantially by limiting population growth, altering the density of growth, and restricting water use on residential and commercial lots. Further reductions could result from incentives for lowering indoor water use. Available supply could be increased by purchasing Indian water rights, changing water-allocation rules in the Colorado River Basin, and technological solutions such as desalination and cloud seeding.

Future versions of WaterSim will incorporate price and nonprice policies to study their potential to reduce water use. Nonprice interventions include landscape ordinances and building codes, irrigation-controller rebate programs, incentives to remove turf, and water-education campaigns to induce private behavior to reduce leaks, remove swimming pools, and limit shower times. In addition, our stakeholders have stressed the need to address water reuse and recharge policies and to downscale WaterSim to the individual water-provider level where participants can consider the consequences of local decisions for regional vulnerability.

WaterSim is part of an interactive process for scientific engagement with water stakeholders, the private sector, community leaders, and the public to decide how much risk the Phoenix community is willing to tolerate with respect to future water availability and how much sacrifice it is willing to make now to reduce that risk. Despite its desert location, Phoenix has a large hydraulic reach and diverse portfolio of water supplies. Its current consumption levels leave room to plan creative climate-adaptation strategies and its built environment offers opportunity for increasing density and, hence, reductions in per capita water use. The evidence from WaterSim modeling is clear. Business as usual will not suffice in the long run. Modeling results also show that adaptation can substantially reduce exposure to the risk of water shortage resulting from climate change.

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