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Decision Making Under Uncertainty: A New Paradigm for Water Resources Planning and Management

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CONTENTS

Abstract Climate change challenges water managers to make decisions about future infrastructure and the adequacy of current supplies before the uncertainties of the climate models and their hydrological impacts are resolved. Water managers thus face the classic problem of decision making under uncertainty (DMUU). The aim of DMUU is not to be paralyzed by uncertainty, but to highlight and use it to better manage risk. Strategies for DMUU include scenario planning, exploratory simulation modeling, robust decision making, and anticipatory planning and governance. These tools imply a new role for social scientists in the fields of water science and engineering and a new relationship between water science and the practitioner community. Examples are drawn from Phoenix, Arizona, and the US Southwest for DMUU support tools and strategies for science-policy engagement. Simulation experiments for Phoenix reveal challenging, but feasible, strategies for climate adaptation in the water sector for all but the most dire future climate conditions.

Key Words Decision making under uncertainty • Simulation modeling • Climate change • Scenario planning • Anticipatory governance • Robust decision making.

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1. INTRODUCTION

The growing uncertainties of climate change present formidable challenges for water engineering and planning, as presently practiced. Systems for managing water traditionally have been designed and operated assuming the principle of stationarity—the notion that natural systems function within a known envelope of variability [1]. This principle implies that relevant hydrological variables such as stream flow and annual flood peak vary according to probability-density functions based on the instrumented record. These functions are, in turn, the basis for managing risk to water supplies and building infrastructure. Anthropogenic changes in Earth's climate are altering the means and extremes of temperature, precipitation, evapotranspiration, and rates of river discharge [2]. These changes imply that the instrumented historical record may no longer be a valid basis for predicting the future and managing risk.

Climate change belongs to a class of problems characterized by "deep uncertainty." These are situations about which there is fundamental disagreement about the driving forces that will shape the future, the probability distributions used to represent uncertainty, and how to value alternative outcomes [3]. Water managers, facing long lead times to plan and implement new water infrastructure, often are required to make decisions before the uncertainties about climate models and their hydrological impacts will be resolved. They are prime candidates for *decision making under uncertainty* (DMUU). DMUU approaches reframe the climate-change question from how we can reduce uncertainty in the climate models and their application to how we can better decisions in the face of inevitable uncertainty about the climate. The idea is not to be paralyzed by uncertainty, but to draw attention to it and use it for better decision making.

DMUU approaches move away from the idea that there is a single optimal or most likely future and take into account multiple possible futures expressed as scenarios. They clarify stakeholder priorities and goals and use them as the basis for presenting choices about the future. These choices often involve critical tradeoffs, for example, between the risk of shortage and the cost of redundant infrastructure, system efficiency and distributional fairness, short-term economic growth and long-term sustainability, and water for farmers to grow food and water for city dwellers to grow decorative lawns. Societal decisions about these tradeoffs require us to ask: what is the risk, what is safe, is it fair, and who is responsible? These questions inherently involve human values, social organization, governance, participatory processes, and decision making and thus engage social scientists in research about the water system.

This chapter will focus on climate models and water resource management from a DMUU perspective. Tools for DMUU include scenario planning, exploratory simulation modeling, robust decision making, and anticipatory governance. These tools imply a new role for social scientists in the fields of water science and engineering and a new relationship between water science and engineering and water policy. I use examples from Phoenix, Arizona, and the southwestern US to show the growing risk of climate-induced water scarcity, new methods of water planning and decision making, and the application of DMUU tools in the water sector.

The chapter concludes with a discussion of the newly emerging field of sustainability science and the insight it offers for the practice of integrated water management in an age of deep uncertainty.

2. CLIMATE UNCERTAINTY AND VULNERABILITY

2.1. Sources of Climate Uncertainty

The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report in 2007 expressed high to very high confidence about climate-change impacts on freshwater systems and their management via increasing temperatures (e.g., effects of increased evaporation on water demand and decreased stream flows), sea level rise (e.g., contamination of freshwater estuaries and groundwater resources), and increasing precipitation variability (e.g., frequency and duration of droughts, floods, and severe climate events). Semiarid and arid regions are particularly prone to a variety of climate-change impacts; a warmer planet means more intense convection and precipitation at the equator which, in turn, reduces the amount of rainfall available to arid and semiarid regions at ~30° north and south latitude. Changing climate will create a host of water-related problems including droughts, floods, subsidence, shrinking glaciers, and damage to aquatic ecosystems (Fig. 8.1).

Efforts to quantify the global and regional effects of climate change use atmosphere-ocean general circulation models (AOGCMs) to simulate future (and past) climate conditions. These

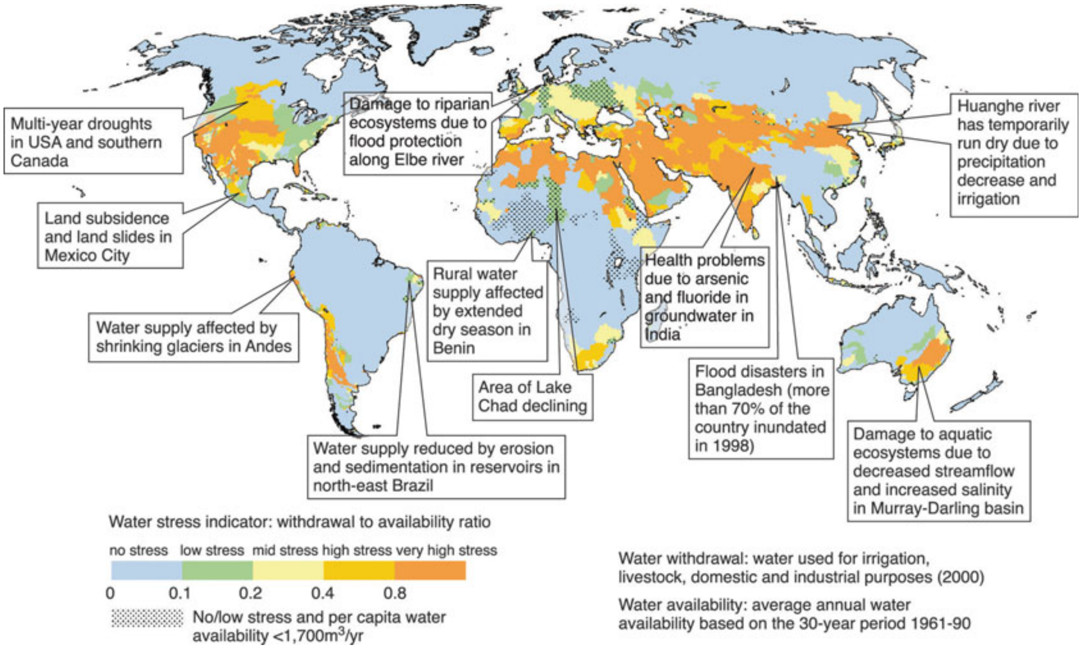


Fig. 8.1. IPCC's Fourth Assessment Report shows the range of vulnerabilities that may be affected by future climate change, superimposed on a map of water stress (*Source*: IPCC [4], Fig. 3.2).

computer models are based on differential equations that describe basic laws of physics, fluid motion, and atmospheric chemistry; the equations are solved for three-dimensional grid cells with the goal of accurately replicating atmospheric, oceanic, and land-surface processes through time. They are the primary tools for estimating future changes in temperature, precipitation, humidity, and solar radiation resulting from changes in atmospheric composition (e.g., increasing greenhouse gas emissions) and land-surface properties (e.g., increasing urbanization).

Significant uncertainties are associated with forecasts from the most widely used AOGCMs [2, 5]. These models have different resolutions in time and space, they are constructed with varying emphases on different processes, and they contain different statistical parameterizations to represent unresolved physical processes such as the formation of clouds and precipitation, ocean mixing due to wave processes, sea–ice interactions, and land-surface processes. The IPCC states "Uncertainty in parameterizations is the primary reason why climate projections differ between different AOGCMs" [2]. The inherently chaotic nature of the climate system also guarantees some level of uncertainty in model predictions.

Uncertainties about human activities further complicate modeling of the global atmospheric system. Modelers struggle with how to address human behavior with respect to fossil fuel use, development and adoption of renewable energy sources, population growth, economic development, technological innovation, and human alteration of land cover. The IPCC considers a range of storyline and scenario families and is careful to avoid statements about the relative likelihood of scenarios. Instead, they pronounce scenarios as "equally sound," without explicitly defining what this means [6].

Additional sources of uncertainty are introduced when moving from global and hemispheric to regional and local scales where climate impacts are experienced by human populations and where water decisions are made. Researchers have developed statistical and dynamical modeling approaches to "downscale" AOGCM output to higher resolutions at regional scales such as drainage basins. Uncertainties at these scales are particularly large for precipitation, given the models' problems with simulating clouds and other processes that produce precipitation. Uncertainties in model predictions appear to increase in areas of complex terrain, creating special problems in the mountainous western US [2, 7, 8].

The National Research Council reported that the US Southwest will become warmer and drier in this century, reducing snowpack, Colorado River flows, and urban water supplies [9]. Results from 24 climate models from the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4) point to drier conditions in the Southwest, but there is substantial uncertainty about the extent, causal mechanisms, and geographic pattern of increased aridity [10]. A set of downscaled model/scenario combinations from the AR4 for the Salt/Verde River Basins, immediately upstream from Phoenix and major sources of Phoenix's surface water (Fig. 8.2), revealed that future (2030) stream flow could range from 19 to 123 % of historical averages [11]. Similar results from the AR3 model/scenario combinations showed a range of 50–127 % [12]. Uncertainty about the physical systems that deliver surface water to Phoenix actually *increased* from the AR3 (2001) to the AR4 (2007) results as additional AOGCMs were developed and as climate models were linked to more and new land-use and hydrological models.

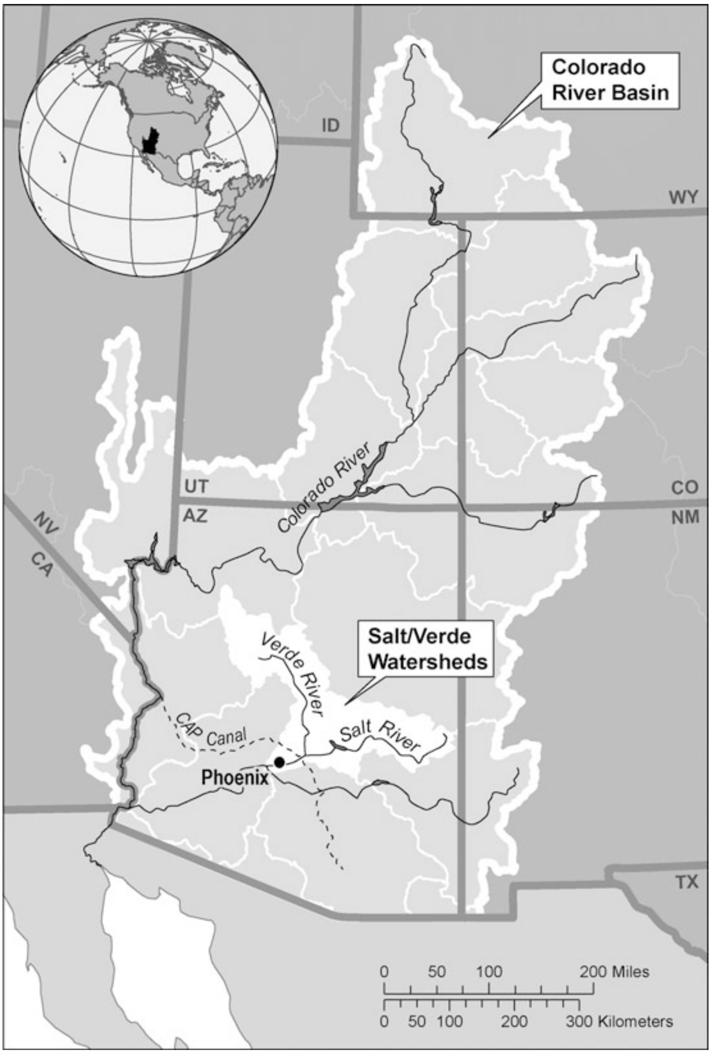


Fig. 8.2. Phoenix obtains surface water from the Colorado River Basin and Salt/Verde Watersheds.

2.2. *Stationarity Assumption*

Water systems throughout the world are designed and operated using the assumption of stationarity—the idea that natural systems operate within a known envelope of variability (Fig. 8.3). This envelope of variability is used to build and operate water infrastructure, such as dams and reservoirs, storm-water runoff systems, and wastewater treatment plants. In a seminal 2008 article in *Science*, Milly et al. declared that "stationarity is dead" [1]. There is now solid evidence in support of structural change in Earth's climate system, including a poleward expansion of the subtropical dry zone. The hydroclimate appears to have exited the known envelope of variability in some regions. And yet, records of historical variability

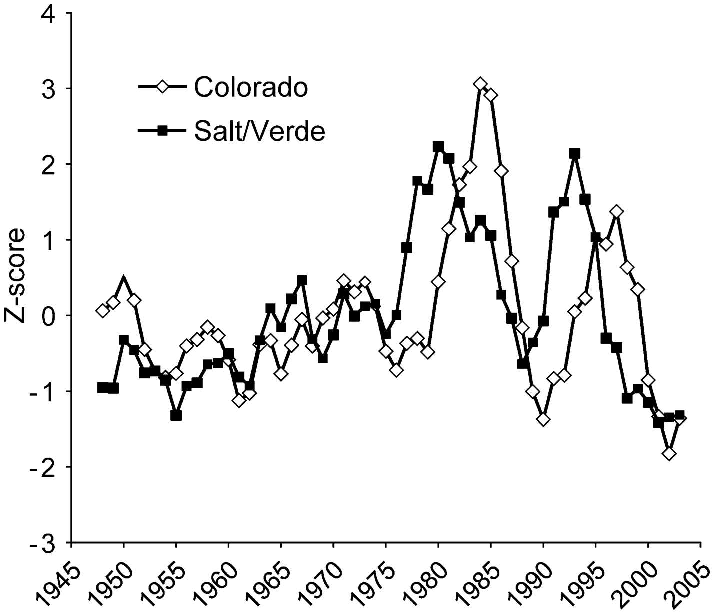


Fig. 8.3. Normalized annual flow on the Colorado and Salt/Verde River systems in *Z* scores, the number of standard deviation units from the mean annual flow.

remain the primary basis for establishing the risk of shortage, flooding, soil erosion, lake sedimentation, and ecosystem damage in water systems.

Nonstationary conditions pose significant challenges for reservoir construction and management. Reservoirs store water to account for natural variability (both seasonal and interannual) in river flows. Figure 8.4 shows the typical cumulative flow over a 10-year period in Line A. The maximum supply that the reservoir can provide in any given year is the average slope of the cumulative curve. If the flow becomes more variable, as it does in Line B, the reservoir will have to be enlarged to guarantee a given yield. This is the case even if average flows remain constant. Long periods of low flows, where the cumulative curve flattens (Line C), result in reduced yield no matter how large the reservoir. This example demonstrates the sensitivity of physical infrastructure to assumptions about future climate and the formidable challenge of infrastructure planning in an era of uncertainty. While it is possible to optimize reservoir design based on projections from a single climate model, this design will not account for all future possibilities. Rather than optimize on the basis of climate models that are still improving, water resource managers alternatively can seek solutions such as demand management that are less sensitive to any one or any one set of climate predictions [13].

2.3. *Extremes Matter!*

Extreme events that fall outside the envelope of historical variability expose individuals and communities to the risk of harm. Modern societies have adapted to the historical range of climate extremes through engineering works, building codes and floodplain maps, warning

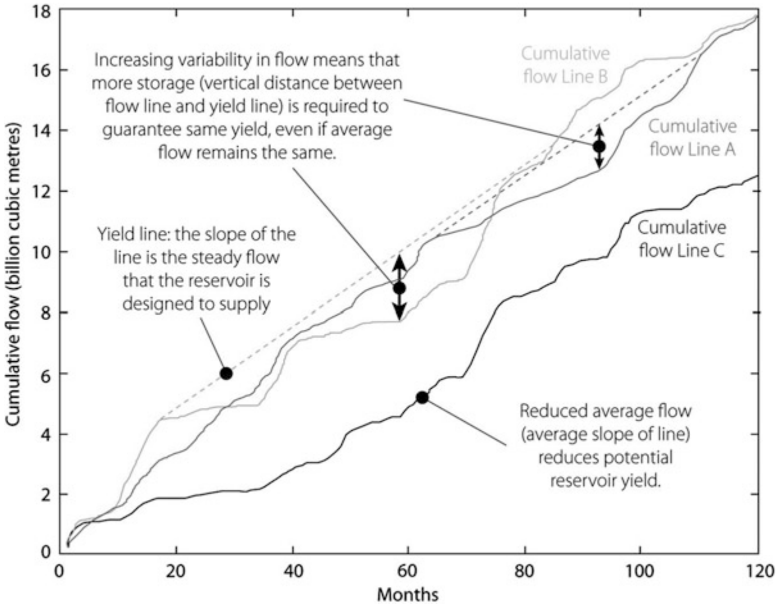


Fig. 8.4. Reservoir management in a nonstationary climate (*Source*: Krebs and Hall [13], Fig. 3).

systems, and financial instruments such as insurance programs and contingency funds. The problem is that these historical ranges are, in many cases, changing as a result of global warming. Droughts and heat waves have, over the past 40–50 years, become more intense and frequent in the US [14]. This means that many communities are experiencing climate conditions that are outside their "coping range" (Fig. 8.5). The core of the coping range contains beneficial outcomes. Approaching the critical threshold, outcomes are negative but tolerable to human societies because they have adapted to accommodate them. Beyond the critical threshold, damages and losses can no longer be tolerated, raising the risk of harm to individuals and communities. Theoretically, societies can extend coping ranges through further adaptive behaviors, but building new infrastructures, remapping floodplains, and changing human perceptions of risk take time and cost money. In an era of climate change, society will be more vulnerable to environmental harm until these adaptive behaviors are accomplished.

Ability to cope depends not only on the intensity of events but also on their frequencies (Fig. 8.6). In the upper diagram, two events of similar magnitude take place, but after the first one, new adaptation measures, such as changes in building codes, are undertaken. The second event thus has a lessened impact. In the bottom diagram, a second extreme event occurs before an area has completely recovered from and adapted to the previous one. It has a total impact in excess of what would have occurred in isolation. That is what happened during the 2003 heat wave in Europe. Anomalous hot and dry conditions affected southern and central Europe between June and mid-August 2003, raising temperatures by 3–5 °C. The warm conditions in

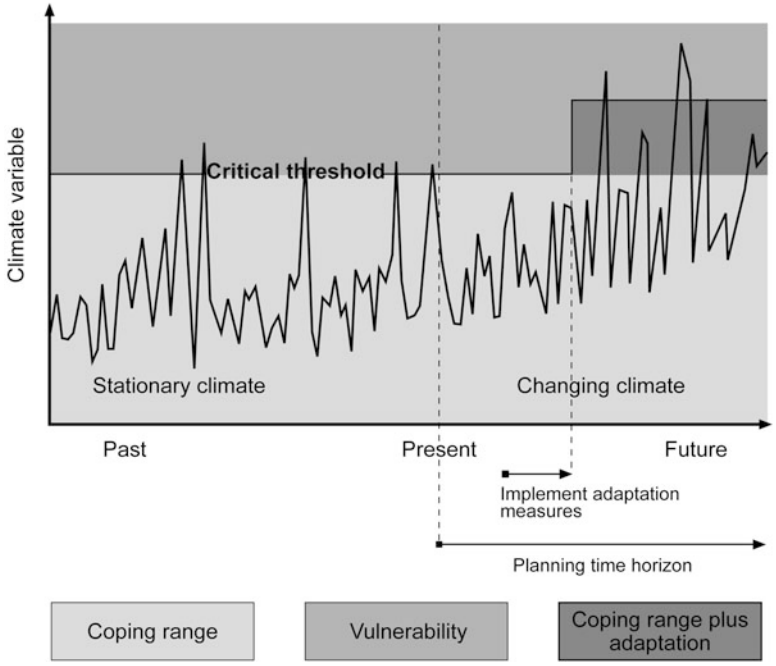


Fig. 8.5. Extreme conditions in a changed climate will fall outside of society's ability to cope (*Source*: UKCIP [15], Fig. 3.1).

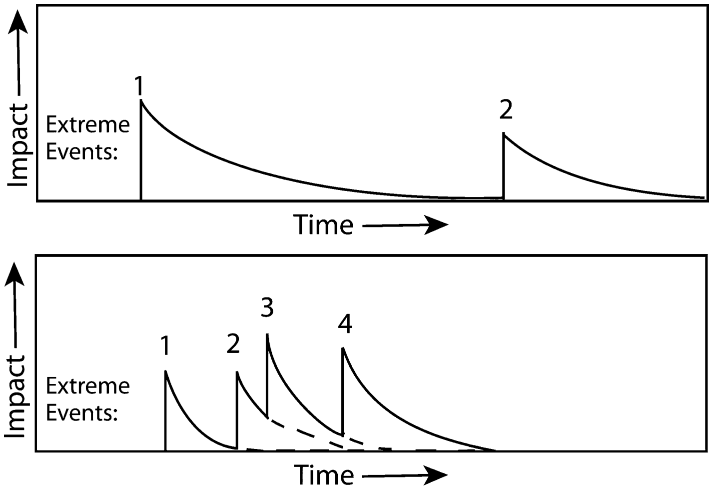


Fig. 8.6. Extreme events result in greater impact as they increase in both frequency and intensity (*Source*: USCCSP [16], Fig. 1.8).

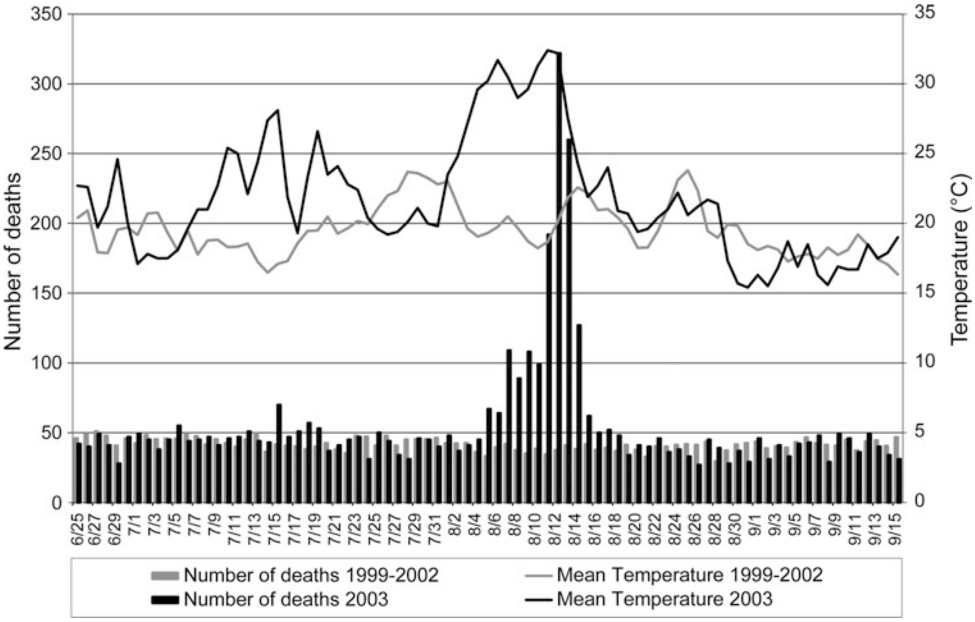


Fig. 8.7. Heat-related deaths in Paris during the 2003 European heat wave (*Source*: Vandentorren and Empereur-Bissonnet [17], Fig. 2).

June lasted throughout the month, but did not cause excess mortality until the second episode between August 1 and 13 when temperatures were more than 7 °C above normal (Fig. 8.7).

Extreme events are also the primary mechanism by which nonhuman biological species will experience the impacts of climate change. Van Vliet and Leemans have documented that “the unexpected rapid appearance of ecological responses through the world” can be explained largely by observed changes in extremes for the past several decades [18]. These climate-induced biological changes affect humanity indirectly through ecosystem services, such as water provisioning, temperature regulation, nutrient cycling, recreation, and spiritual benefits.

2.4. *Vulnerability to Extreme Events*

Study of the vulnerability of complex human and social systems to extreme events has evolved over the past several decades from one focused on physical hazards (floods, droughts, fires, earthquakes, etc.) to one that considers both physical exposure and the human ability to cope with extreme events [19]. Social scientists became more active in this field as attention turned from the physical event itself to the structure of social systems and personal characteristics that put people at risk to extreme events. A lack of coordination among public agencies, conflicts in responsibilities and mandates, political and financial priorities, and awareness of, and confidence in, available information affect the adaptive capacity of local governments [20, 21]. On a personal level, coping capacity is affected by poverty, racial and ethnic status, age (young children and the elderly are least able to cope), migration status (newcomers have less understanding of the local environment and risk than long-term residents), and housing tenure (owners have a greater stake in local outcomes than renters). Populations lacking in economic assets and access to public support systems, with diminished physical or cognitive capacities to respond to warnings, and missing strong and enduring social support systems are least able to adapt to and thus more vulnerable to physical hazards [16].

3. DECISION MAKING UNDER UNCERTAINTY

3.1. Problems of Deep Uncertainty

Standard methods of risk analysis from a variety of disciplines, including game theory, economics, operations research, and statistical decision theory, have been successfully applied to policy problems for many decades. These methods are adequate for problems in which system behavior is predictable—situations in which probability functions are known and widely used and accepted as the basis to assess risk. Increasingly, however, society is confronted with problems such as climate change, sustainable development, and the introduction of new technologies where inherent uncertainties can lead to surprising and catastrophic outcomes. Classical methods of uncertainty analysis using probabilities, statistics, and statistical decision theory are inadequate for these types of problems [22].

Deep uncertainty characterizes situations (e.g., prospects of a particular business, introduction of a new technology, water planning in the face of climate change) in which analysts do not know or cannot agree upon the key drivers that will shape the future, probability functions that represent uncertainty, and how to value who gains and who loses from key outcomes [3]. When making their arguments about deep uncertainty, decision scientists use the physical principle of nonstationarity to argue that the past is not an adequate guide for predicting the future.

DMUU methods can be used in the water sector for planning and decision making. These methods account for the fact that uncertainty will not be resolved before near-term decisions must be made about whether to build water infrastructure, acquire backup supplies, and alter urban growth patterns. They further acknowledge that water is but one component in a complex system of supply and demand, and water managers thus face multiple sources of uncertainty. Even without climate change, the Southwest would be vulnerable to water shortage due to rapid population growth and urbanization, fierce competition between urban and agricultural interests, cultural practices that rely on heavy water use to maintain oasis-type landscape treatments, and highly fragmented and rigid institutions that were set up to manage interannual variability of the twentieth century rather than twenty-first-century climate change. When queried about other sources of uncertainty, Phoenix-area water managers mention aspects of their policy setting, such as the legal status of Indian water rights, endangered-species designations, and the environmental permitting process [23].

3.2. Scenario Planning

Scenario planning is designed to cope with the uncertainty and unpredictability of the future. Scenario planners conduct group exercises and create narratives or storylines about the long-term future. These exercises often construct a small number of stories from qualitative discussions. Even quantitative analyses that produce hundreds and thousands of computer runs typically are reduced to a small number (three to four) of plausible and logically consistent stories about the future. It is important that each scenario be theoretically possible, even though some participants in the exercise believe it to be undesirable or unlikely [3]. Avoiding these rare but sometimes catastrophic outcomes is often a major concern in real-world policy situations.

Planning exercises involve a series of steps by which a set of scenarios are developed and evaluated [24]. The first step defines the decisions these scenarios are designed to inform. In the water sector, long-term planning and policy decisions include the design and construction of new water-supply infrastructure, agricultural planting patterns, water markets that allow temporary transfers of water, allocations and rate structures, and reservoir operating rules. The second step is to identify the most important and uncertain driving factors that will affect these decisions. The scenario planning group is then asked to rank key driving forces and their uncertainties. It is common for stakeholders to have differing views of the future; one goal of scenario planning is to bring these differences into the open and for stakeholders to acknowledge that a range of alternative futures is possible.

Table 8.1 lists the concerns or priorities of water stakeholders in Phoenix. Respondents to an online survey included representatives from federal and state entities, Indian tribes, local and regional water providers, private sector providers and users, and environmental organizations. They were asked to apportion 100 points across categories to reflect their level of concern about the following: (a) social and economic impacts, (b) financial and technical requirements, (c) health and safety, (d) natural and biophysical impacts, (e) political impacts and governance, (f) supply sufficiency, and (g) other legal and institutional issues. The most highly rated concern for managers in the desert city of Phoenix was the sufficiency of supply, accounting for 32 % of the total points, followed by impacts on the natural environment (16 %), health and safety (13 %), political impacts and governance (12 %), and financial and technical requirements (12 %). The overall results mask important differences across stakeholder groups, however. Representatives from local water departments and regional agencies expressed more concern for water sufficiency and safety than environmental groups who emphasized impacts on the natural/biophysical environment [25]. These results expose a critical tradeoff in urban water decisions—how to balance instream flows and biodiversity with the need to provide an adequate and reliable supply 24/7 for an ever-growing urban population.

After bringing the priorities and views of divergent groups into the open, a third step involves crafting three to four scenarios for in-depth discussion and analysis. The fourth step investigates how alternative policies and decisions work across these scenarios. This testing and evaluation process can be done qualitatively through discussion and consensus or quantitatively through simulation experiments. Scenarios are examined to determine the

Table 8.1
Concerns or priorities of water stakeholders in Phoenix, Arizona, US (adapted from Keller et al. [25])

1. Central Arizona socio-economic impacts
   - (a) Costs to the user
     - Affordability for the user
     - Informing public about costs of water
     - Investigate pricing options
     - Household versus industry pricing differences
   - (b) Impacts on the economy
     - Impact to jobs
     - Development impacts
2. Financial and technical requirements
   - (a) Costs
     - Costs of distribution and transportation
     - Other, indirect costs
     - Litigation
   - (b) Performance of the system
     - Reliability of system infrastructure
     - Infrastructure maintenance and expansion
3. Health and safety
   - (a) Meet existing standards: maintaining sampling and testing standard
   - (b) Meet existing standards: enforcing existing regulations
   - (c) Meet existing standards: planning for new threats to the supply
4. Impacts on the natural/biophysical environment
   - (a) Local environment effects on the climate (impact to local climate)
   - (b) Regional environment's natural habitat concerns
     - Riparian use of water
     - Identifying non-urban uses of water
5. Indirect/external impacts (broader impacts)
   - (a) Planning impacts: identify planning related issues
   - (b) Planning impacts: collaboration with other stakeholders
6. Political impacts and governance
   - (a) Quality of the political process (inclusion of all stakeholder concerns)
   - (b) Policy development
     - To have a collaborative process
     - Meet federal requirements
7. Sufficiency of water supplies
   - (a) Resilience of the water supply to drought and other climatic impacts
   - (b) Material requirements
     - Water supply availability
     - Acquisition of water for future supplies
     - Exchange of knowledge about water data
   - (c) Mid and long-term availability of the water supply
     - Future supply
     - Portfolio diversification

most critical outcomes and to identify "branching points" relating to the issues and policies that have the greatest impact (potentially generating crisis) on the future. Planning from scenarios involves searching for policies that are robust, that is, they will perform reasonably well across a wide range of plausible future scenarios. The goal is to minimize downside risk, given that we do not know what the future will hold.

Scenario planning processes have been criticized for their reluctance to explore rare events, failure to consider a full range of future conditions, and tendency to focus too early on one particular scenario for implementation purposes [26]. In principle, the goal of scenario planning is to open discussion to a wide range of future conditions; in practice, the process often limits community response to a single view of the future [26].

3.3. Simulation/Exploratory Modeling

Many, but not all, scenario planning processes use simulation models to represent complex human-natural coupled systems and to anticipate how they respond to various biophysical changes and policy decisions. Bankes makes a useful distinction between *consolidative* modeling which uses known facts to replicate an actual system and *exploratory* modeling which investigates the consequences of varying assumptions and hypotheses about the system and its future dynamics [27]. The former is useful in optimization and prediction, while the latter acknowledges that not all relevant and important information is available. Exploratory modeling is appropriate for situations in which there is a high level of system complexity—where nonlinear behaviors and feedbacks can result in unintended consequences and potentially 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 deep uncertainty [22, 28].

Exploratory models can be both scientific tools to investigate system behavior and communication devices to promote social learning about the system at hand. Ideally, they evolve iteratively as new information is gained and integrated into modeling activities. Robust decision making acknowledges that a range of long-term conditions are possible and that near-term strategies will be revisited as our knowledge about complex systems improves.

3.4. Elements of Robust Decision Making

Robust adaptive strategies are "comprised of *shaping actions* intended to influence the future, *hedging actions* intended to reduce vulnerability if adverse futures come to pass, and *signposts*, which are observations that warn of the need to change strategies" [29]. Hedging actions in the water sector have traditionally involved building redundancies into the water system with additional infrastructure or supply sources. Shaping actions involve conservation programs aimed at reducing demand or altering the built environment to reduce water use. In Phoenix, there is a strong relationship between urban residential densities and per capita water use (Fig. 8.8). Urban densities of 37–74 housing units per hectare require around 75 m^3 of water per person annually, compared to large-lot semirural developments where per capita

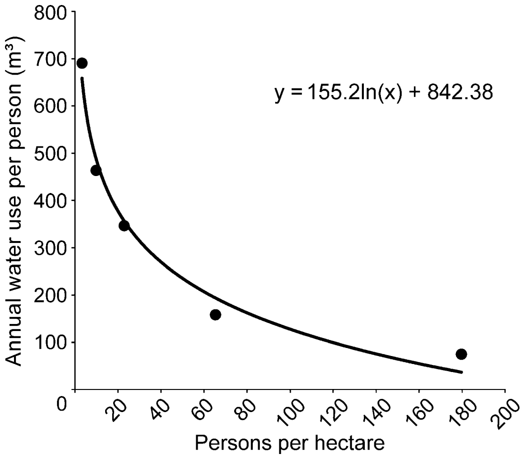


Fig. 8.8. Estimated water use needed to support residential developments of varying densities (*Source*: Gober and Kirkwood [30], Fig. 2).

water use is almost ten times higher. Adding compact residential developments would lower per capita water requirements and shape demand. Signposts involve predetermined thresholds that automatically trigger policy action. Policy change might involve an increase in price or use of block pricing, implementation of a water education program, incentives to replace turf grass with native plants, step-up in water reuse, or fixing leaks and improving water efficiency.

3.5. *Anticipatory Governance*

The planning profession has developed the idea of anticipatory governance to address problems of deep uncertainty. Guston distinguished between precaution and anticipation in dealing with complex problems of deep uncertainty [31]. Precaution is a way of acting that avoids predicted but uncertain risks; anticipation implies building capacity to respond to unpredictable and uncertain risks. Anderson argued for the need to move from prediction and prevention toward more anticipatory modes of practice [32]. Rather than trying to avoid the unknown, he urges that we anticipate surprise and plan systems that are able to accommodate a wide range of future conditions.

Feurth defines anticipatory governance as "a system of institutions, rules, and norms that provide a way to use foresight for the purpose of reducing risk, and to increase capacity to respond to events at early rather than later stages of their development" [33]. Employing the principles of anticipatory governance, the City of Phoenix utilizes a range of scenarios in its water planning process, including the possibility of moderate-to-severe water shortage, varying levels of conservation, and different development patterns (e.g., high versus low density). Over the next 8–10 years, supplies are adequate to meet even the most dire drought conditions, but action is needed to address the gap between projected demand and current supplies and thus prevent shortage beyond 2025 (Fig. 8.9). As a result of this exercise, the City is now taking steps to develop backup supplies in the form of recharged groundwater credits (excess supplies can now be banked underground and credited for use later), additional surface water from the Colorado River via the Central Arizona Project, and reclaimed water [34].

Anticipatory governance entails three steps: (a) anticipation and futures analysis, (b) flexible adaptation strategies, and (c) monitoring and action [26]. The anticipation and

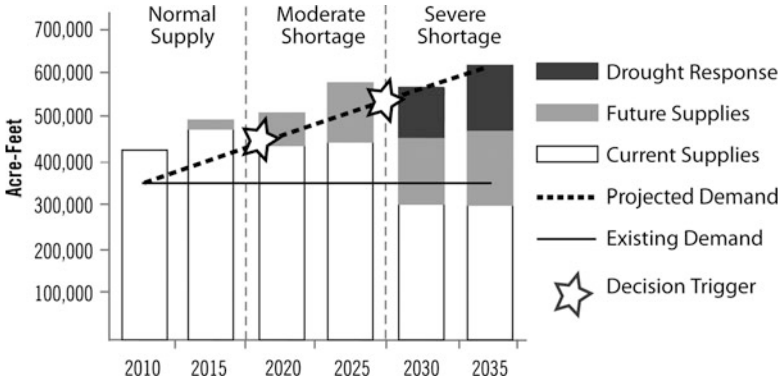


Fig. 8.9. Current projections indicate that Phoenix will be unable to meet expected demands in 2020 under shortage conditions without augmenting current supplies. Adapted from *Water Resources Plan 2005 Update* [34] based on personal communication with Steve Rossi.

futures analysis phase is quite close to robust decision making in the sense that it uses advanced computation methods to produce a large number of scenarios. Outcome spaces are then examined for robust policies; worst-case or unacceptable outcomes are identified; and sensitivity analyses of various factors are conducted. Using the range of possible futures identified in the first step, adaptive strategies are developed in the second step. Ideally, these strategies are broken into modules so that they can be implemented separately as funding becomes available and knowledge about the climate and other relevant systems increases. Critical to any adaptive strategies is the monitoring and action required in the third step. Phoenix, Denver, and New York were evaluated for their anticipatory governance procedures, but none had yet developed a structured monitoring program for long-term water planning [26].

Camacho notes that effective climate adaptation “necessitates a fundamental reformation of natural resource governance” [35]. This reformation would ask different questions about the water system. Rather than focus on the physical aspects of water systems, relevant questions would address why governance systems are unable to cope with uncertainty, why they lack capacity for cooperative behavior, why they are unable to learn from mistakes, and why information sharing is limited. More coordinated and adaptive governance systems consist of:

1. Proactive strategies that take effect before the impacts of climate change are felt rather than reactive strategies that respond to a problem at hand or seek to prevent it from reoccurring,
2. No-regret strategies that provide a net benefit irrespective of the effects of climate change,
3. Procedural strategies focused on the regulatory environment itself and how decisions about natural resource management are made [35].

3.6. *WaterSim: An Example of DMUU*

We constructed WaterSim, an integrated simulation model, to investigate the long-term consequences of climate change and policies to manage groundwater, growth, and urban development in metropolitan Phoenix [36]. WaterSim represents water consumption and

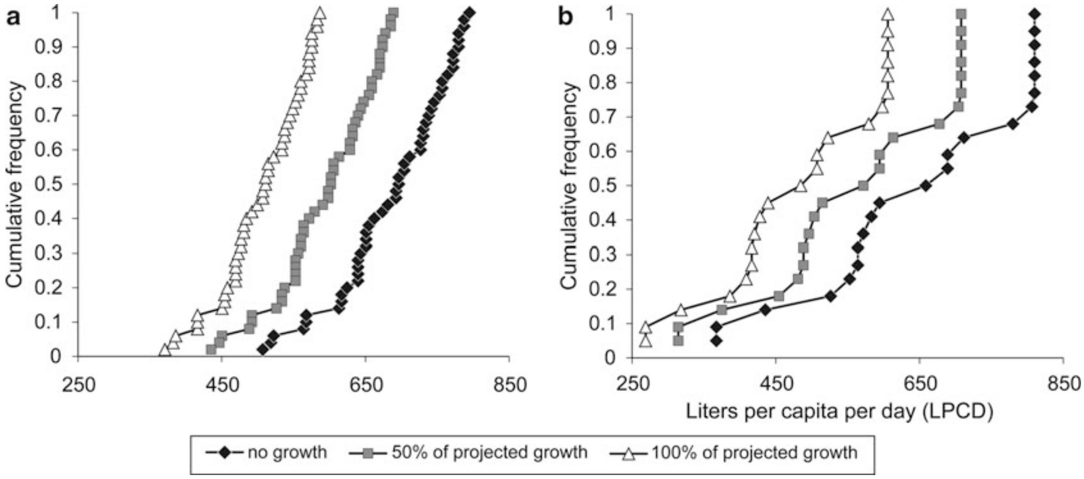


Fig. 8.10. Cumulative frequency distributions from WaterSim for LPCD in 2030—LPCD available for residential use assuming no growth, 50 % of projected growth, and 100 % of projected growth for the (**a**) Salt/Verde and (**b**) Colorado River systems (*Source*: Gober and Kirkwood [30], Fig. 3).

availability in Central Arizona from the present until 2030 and uses the XLRM framework which contains four types of components:

1. Exogenous uncertainties (X) are factors that decision makers cannot control; these are primarily associated with climate and water supply,
2. Policy levers (L) are actions that decision makers could take, such as groundwater policy, land-use planning, and population growth management,
3. Relationships (R) are mathematical or algorithmic associations among variables,
4. Outcome measures (M) summarize outcome metrics for decision- and policy-making purposes [3].

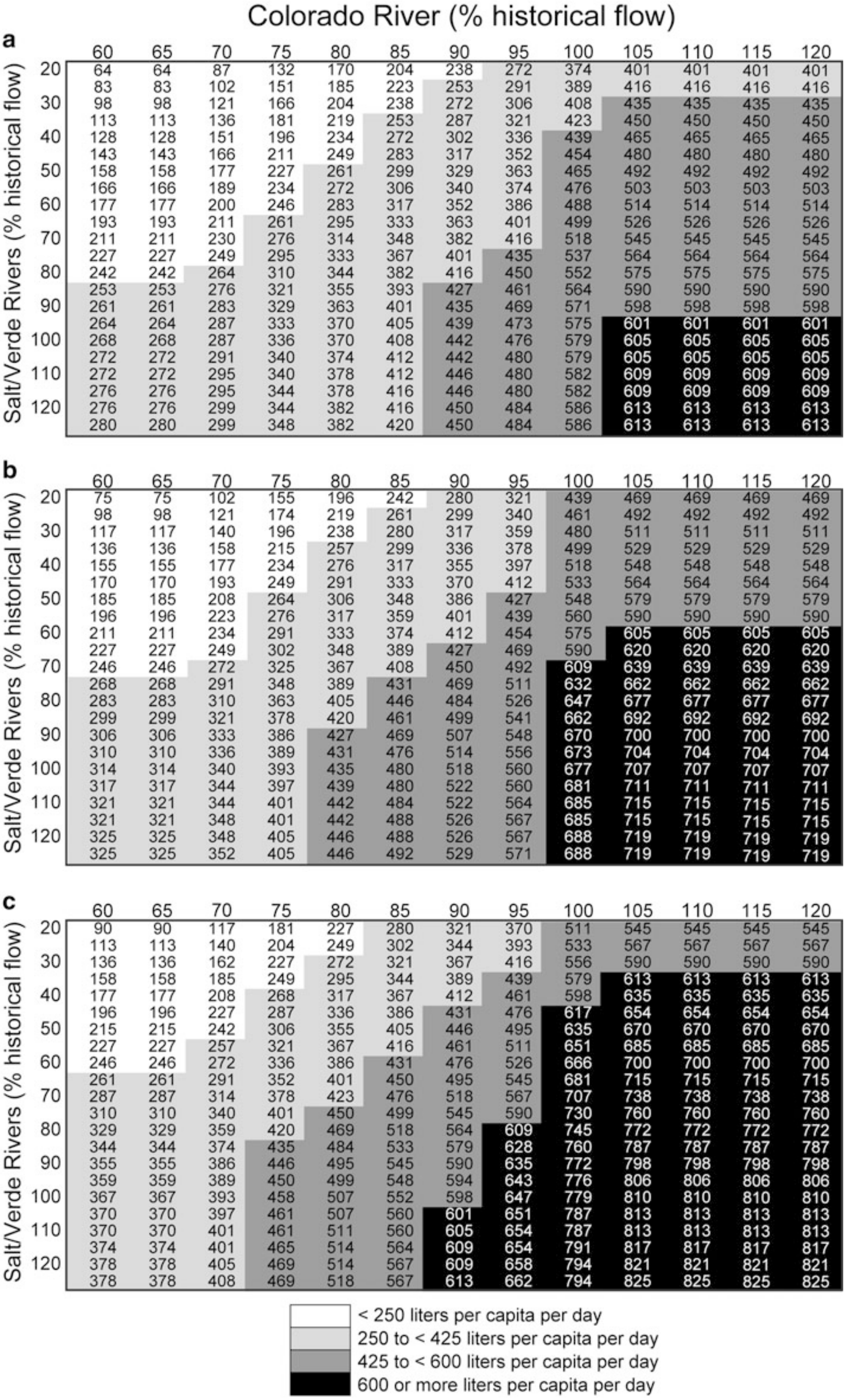
Model users can consider the consequences of policies related to population growth, while assuming that consumption is restricted to available surface-water supply plus natural recharge (Fig. 8.10). Groundwater is used sustainably in this set of model runs, assuming that withdrawal equals natural recharge. This assumption does not account for instream flows and assumes that 40 % of indoor water use is recycled. The left diagram (Fig. 8.10a) shows the effects of population-growth scenarios under varying climate-change conditions on the Salt/Verde system. The right diagram (Fig. 8.10b) shows outcomes across climate-change conditions on the Colorado River. Under the expected unconstrained growth conditions ("100 % of projected growth"), liters per capita per day (LPCD) range from 371 to 587 for the Salt/Verde system and from 269 to 606 for the Colorado system. Any of these outcomes would require reductions from today's consumption levels of 875 LPCD on a regional basis. The midpoint for the Salt/Verde system would translate into consumption levels of 511 LPCD, while the Colorado midpoint would mean consumption levels of 496 LPCD. These average conditions impose challenging but feasible restrictions on current growth patterns and lifestyles, as Tucson's 2005 LPCD was 431 and, in Albuquerque, it was 416 [37]. Limited growth would reduce the need for lifestyle sacrifices, and in the no-growth cases, modest reductions would accommodate all but the worst-case climate-model results.

Fig. 8.11. Lake Mead water levels: 1935–2010 (Data source http://www.usbr.gov/lc/region/g4000/hourly/mead-elv.html).

Central Arizona is especially sensitive to climate-change conditions on the Colorado River system because of a 1968 agreement put into place when federal funding was secured for the Central Arizona Project (CAP). In exchange for support from the California congressional delegation for a federal loan to build the CAP, regional advocates agreed to give California senior rights to Lower Colorado River allocations [38]. The consequences of this agreement have appeared only recently with persistent drought on the Colorado River Basin. In 2010, levels in Lake Mead sat at 1,082 ft above sea level [39]. These were dangerously close to the 1,075-foot mark at which the first cutbacks in delivery to CAP would be triggered (Fig. 8.11). Long-term drought would reduce Central Arizona's allocation quickly and lead to the steeply sloping lines in Fig. 8.10b. The region would more gradually lose its supply from the Salt/Verde system as shown in Fig. 8.10a. These figures and these types of analyses allow policy makers and stakeholders to explore best, worst, and mean-case climate-change conditions and then explore the effects of managing growth on output metrics (in this case LPCD). The process also highlights tradeoffs between continued growth and maintaining oasis-type lifestyles and landscape treatments (reflected in LPCD).

We used WaterSim to examine water availability under all possible runoff conditions for both systems. We considered the effect 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, Fig. 8.12a), 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. Lowering the growth rate to 50 % of the projected unconstrained level would allow the region to sustain current levels of indoor use under all but the most severe future climate conditions (Fig. 8.12b). A no-growth policy would further reduce the risk that current levels of indoor use could not be sustained (Fig. 8.12c).

We also investigated how groundwater drawdown would be affected by climate-change conditions if we assume a policy with current levels of residential water demand.



Colorado River (% historical flow)

a

Salt/Verde Rivers (% historical flow)	60	65	70	75	80	85	90	95	100	105	110	115	120
20	64	64	87	132	170	204	238	272	374	401	401	401	401
	83	83	102	151	185	223	253	291	389	416	416	416	416
30	98	98	121	166	204	238	272	306	408	435	435	435	435
	113	113	136	181	219	253	287	321	423	450	450	450	450
40	128	128	151	196	234	272	302	336	439	465	465	465	465
	143	143	166	211	249	283	317	352	454	480	480	480	480
50	158	158	177	227	261	299	329	363	465	492	492	492	492
	166	166	189	234	272	306	340	374	476	503	503	503	503
60	177	177	200	246	283	317	352	386	488	514	514	514	514
	193	193	211	261	295	333	363	401	499	526	526	526	526
70	211	211	230	276	314	348	382	416	518	545	545	545	545
	227	227	249	295	333	367	401	435	537	564	564	564	564
80	242	242	264	310	344	382	416	450	552	575	575	575	575
	253	253	276	321	355	393	427	461	564	590	590	590	590
90	261	261	283	329	363	401	435	469	571	598	598	598	598
	264	264	287	333	370	405	439	473	575	601	601	601	601
100	268	268	287	336	370	408	442	476	579	605	605	605	605
	272	272	291	340	374	412	442	480	579	605	605	605	605
110	272	272	295	340	378	412	446	480	582	609	609	609	609
	276	276	295	344	378	416	446	480	582	609	609	609	609
120	276	276	299	344	382	416	450	484	586	613	613	613	613
	280	280	299	348	382	420	450	484	586	613	613	613	613

b

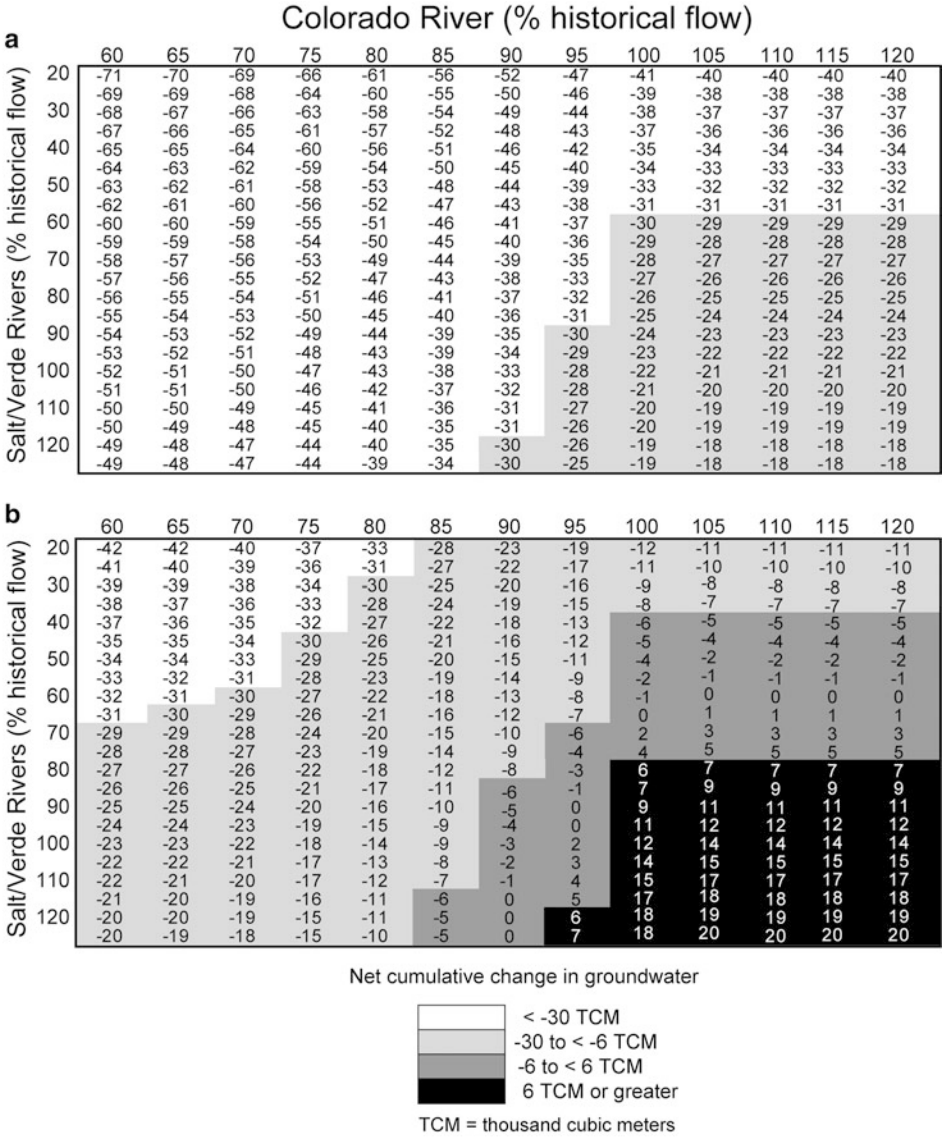
Salt/Verde Rivers (% historical flow)	60	65	70	75	80	85	90	95	100	105	110	115	120
20	75	75	102	155	196	242	280	321	439	469	469	469	469
	98	98	121	174	219	261	299	340	461	492	492	492	492
30	117	117	140	196	238	280	317	359	480	511	511	511	511
	136	136	158	215	257	299	336	378	499	529	529	529	529
40	155	155	177	234	276	317	355	397	518	548	548	548	548
	170	170	193	249	291	333	370	412	533	564	564	564	564
50	185	185	208	264	306	348	386	427	548	579	579	579	579
	196	196	223	276	317	359	401	439	560	590	590	590	590
60	211	211	234	291	333	374	412	454	575	605	605	605	605
	227	227	249	302	348	389	427	469	590	620	620	620	620
70	246	246	272	325	367	408	450	492	609	639	639	639	639
	268	268	291	348	389	431	469	511	632	662	662	662	662
80	283	283	310	363	405	446	484	526	647	677	677	677	677
	299	299	321	378	420	461	499	541	662	692	692	692	692
90	306	306	333	386	427	469	507	548	670	700	700	700	700
	310	310	336	389	431	476	514	556	673	704	704	704	704
100	314	314	340	393	435	480	518	560	677	707	707	707	707
	317	317	344	397	439	480	522	560	681	711	711	711	711
110	321	321	344	401	442	484	522	564	685	715	715	715	715
	321	321	348	401	442	488	526	567	685	715	715	715	715
120	325	325	348	405	446	488	526	567	688	719	719	719	719
	325	325	352	405	446	492	529	571	688	719	719	719	719

c

Salt/Verde Rivers (% historical flow)	60	65	70	75	80	85	90	95	100	105	110	115	120
20	90	90	117	181	227	280	321	370	511	545	545	545	545
	113	113	140	204	249	302	344	393	533	567	567	567	567
30	136	136	162	227	272	321	367	416	556	590	590	590	590
	158	158	185	249	295	344	389	439	579	613	613	613	613
40	177	177	208	268	317	367	412	461	598	635	635	635	635
	196	196	227	287	336	386	431	476	617	654	654	654	654
50	215	215	242	306	355	405	446	495	635	670	670	670	670
	227	227	257	321	367	416	461	511	651	685	685	685	685
60	246	246	272	336	386	431	476	526	666	700	700	700	700
	261	261	291	352	401	450	495	545	681	715	715	715	715
70	287	287	314	378	423	476	518	567	707	738	738	738	738
	310	310	340	401	450	499	545	590	730	760	760	760	760
80	329	329	359	420	469	518	564	609	745	772	772	772	772
	344	344	374	435	484	533	579	628	760	787	787	787	787
90	355	355	386	446	495	545	590	635	772	798	798	798	798
	359	359	389	450	499	548	594	643	776	806	806	806	806
100	367	367	393	458	507	552	598	647	779	810	810	810	810
	370	370	397	461	507	560	601	651	787	813	813	813	813
110	370	370	401	461	511	560	605	654	787	813	813	813	813
	374	374	401	465	514	564	609	654	791	817	817	817	817
120	378	378	405	469	514	567	609	658	794	821	821	821	821
	378	378	408	469	518	567	613	662	794	825	825	825	825

- □ < 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. 8.12. Scenario ensembles from WaterSim for LPCD, assuming (**a**) 100 % of projected growth, (**b**) 50 % of projected growth, and (**c**) no future population growth (*Source*: Gober and Kirkwood [30], Fig. 4).



a

	60	65	70	75	80	85	90	95	100	105	110	115	120
20	-71	-70	-69	-66	-61	-56	-52	-47	-41	-40	-40	-40	-40
	-69	-69	-68	-64	-60	-55	-50	-46	-39	-38	-38	-38	-38
30	-68	-67	-66	-63	-58	-54	-49	-44	-38	-37	-37	-37	-37
	-67	-66	-65	-61	-57	-52	-48	-43	-37	-36	-36	-36	-36
40	-65	-65	-64	-60	-56	-51	-46	-42	-35	-34	-34	-34	-34
	-64	-63	-62	-59	-54	-50	-45	-40	-34	-33	-33	-33	-33
50	-63	-62	-61	-58	-53	-48	-44	-39	-33	-32	-32	-32	-32
	-62	-61	-60	-56	-52	-47	-43	-38	-31	-31	-31	-31	-31
60	-60	-60	-59	-55	-51	-46	-41	-37	-30	-29	-29	-29	-29
	-59	-59	-58	-54	-50	-45	-40	-36	-29	-28	-28	-28	-28
70	-58	-57	-56	-53	-49	-44	-39	-35	-28	-27	-27	-27	-27
	-57	-56	-55	-52	-47	-43	-38	-33	-27	-26	-26	-26	-26
80	-56	-55	-54	-51	-46	-41	-37	-32	-26	-25	-25	-25	-25
	-55	-54	-53	-50	-45	-40	-36	-31	-25	-24	-24	-24	-24
90	-54	-53	-52	-49	-44	-39	-35	-30	-24	-23	-23	-23	-23
	-53	-52	-51	-48	-43	-39	-34	-29	-23	-22	-22	-22	-22
100	-52	-51	-50	-47	-43	-38	-33	-28	-22	-21	-21	-21	-21
	-51	-51	-50	-46	-42	-37	-32	-28	-21	-20	-20	-20	-20
110	-50	-50	-49	-45	-41	-36	-31	-27	-20	-19	-19	-19	-19
	-50	-49	-48	-45	-40	-35	-31	-26	-20	-19	-19	-19	-19
120	-49	-48	-47	-44	-40	-35	-30	-26	-19	-18	-18	-18	-18
	-49	-48	-47	-44	-39	-34	-30	-25	-19	-18	-18	-18	-18

b

	60	65	70	75	80	85	90	95	100	105	110	115	120
20	-42	-42	-40	-37	-33	-28	-23	-19	-12	-11	-11	-11	-11
	-41	-40	-39	-36	-31	-27	-22	-17	-11	-10	-10	-10	-10
30	-39	-39	-38	-34	-30	-25	-20	-16	-9	-8	-8	-8	-8
	-38	-37	-36	-33	-28	-24	-19	-15	-8	-7	-7	-7	-7
40	-37	-36	-35	-32	-27	-22	-18	-13	-6	-5	-5	-5	-5
	-35	-35	-34	-30	-26	-21	-16	-12	-5	-4	-4	-4	-4
50	-34	-34	-33	-29	-25	-20	-15	-11	-4	-2	-2	-2	-2
	-33	-32	-31	-28	-23	-19	-14	-9	-2	-1	-1	-1	-1
60	-32	-31	-30	-27	-22	-18	-13	-8	-1	0	0	0	0
	-31	-30	-29	-26	-21	-16	-12	-7	0	1	1	1	1
70	-29	-29	-28	-24	-20	-15	-10	-6	2	3	3	3	3
	-28	-28	-27	-23	-19	-14	-9	-4	4	5	5	5	5
80	-27	-27	-26	-22	-18	-12	-8	-3	6	7	7	7	7
	-26	-26	-25	-21	-17	-11	-6	-1	7	9	9	9	9
90	-25	-25	-24	-20	-16	-10	-5	0	9	11	11	11	11
	-24	-24	-23	-19	-15	-9	-4	0	11	12	12	12	12
100	-23	-23	-22	-18	-14	-9	-3	2	12	14	14	14	14
	-22	-22	-21	-17	-13	-8	-2	3	14	15	15	15	15
110	-22	-21	-20	-17	-12	-7	-1	4	15	17	17	17	17
	-21	-20	-19	-16	-11	-6	0	5	17	18	18	18	18
120	-20	-20	-19	-15	-11	-5	0	6	18	19	19	19	19
	-20	-19	-18	-15	-10	-5	0	7	18	20	20	20	20

Fig. 8.13. Scenario ensembles from WaterSim for groundwater drawdown, assuming (**a**) 100 % of projected growth and current levels of pools, irrigated landscaping, and urban densities and (**b**) 50 % of projected growth, no pools, no irrigated landscaping, and higher densities (*Source*: Gober and Kirkwood [30], Fig. 5).

Groundwater has been the historical bank account from which providers tap when surface supplies are in deficit. Under currently projected population growth conditions and unconstrained water usage, it is not possible to achieve groundwater sustainability in 2030 under any climate scenario (Fig. 8.13a). At current consumption levels, drawdown would become quite severe if the pessimistic climate scenarios were to occur. At current drawdown rates of between 250 million m^3/year and 600 million m^3/year, cumulative drawdown ranges from 6 billion to 14 billion m^3 over the course of the simulation. Current growth patterns produce more extreme drawdown situations; the more pessimistic the climate-change conditions, the more severe drawdown levels are. Policy action of some kind is necessary to achieve long-term groundwater sustainability, although it is possible to justify some overdraft while society learns to cope with new climate conditions.

Figure 8.13b shows the impacts on cumulative groundwater drawdown of restricting population growth to 50 % of projected levels and eliminating irrigated outdoor landscaping and private backyard pools. These policies would achieve groundwater sustainability under normal (100 %) surface flows and would substantially reduce drawdown for all but the most severe climate futures.

4. HUMAN FACTORS IN THE WATER SECTOR

4.1. *Water Planning as a Social Process*

The predict-and-plan model of water management in which well-defined problems are solved with technological solutions, such as wastewater treatment and water-supply augmentation, has tended to treat human actors as separate from the environmental and technical problem at hand [40]. The socioeconomic system is typically seen as an external boundary condition—the number of people to be served, the nature of their land uses, rules that govern reservoir management, etc. The complexities, feedbacks, and uncertainties in modern water systems require that humans and their social organizations and political institutions be fully integrated into water science. The use of DMUU strategies, the search for robust solutions in water planning, and analysis of system vulnerabilities recognize that humans and nature are elements of an inherently coupled system. Critical vulnerabilities often occur in the intersection points of the human and physical system, for example, when governance systems are incapable of dealing with climate-induced changes in water supply.

While climate mitigation efforts such as emission standards, carbon markets, and incentives for renewable energy are within the purview of federal authority, climate adaptation often occurs at the local and regional level where climate impacts will be felt and relevant decision making occurs. Adaptation efforts require participatory processes that reveal the needs of diverse stakeholders for climate and hydrological information and decision support and consensus building among these diverse stakeholders. Social scientists, particularly decision scientists, have played a mediating role in translating the products of water science into tools to support decision making in the water sector.

Jacobs et al. conducted an information-gathering workshop with water stakeholders and found that the availability of more information is often not the major impediment of good decisions [41]. The more relevant question is how much information is enough and how to develop and sustain participatory networks that reveal the answer to this question. Workshop participants noted that effective knowledge systems mine both practical experience and scientific knowledge to focus on common solutions to reduce the risk from climate change. Stakeholders emphasized robust solutions—those that reduce risk, no matter what the future climate conditions.

4.2. *Boundary Science*

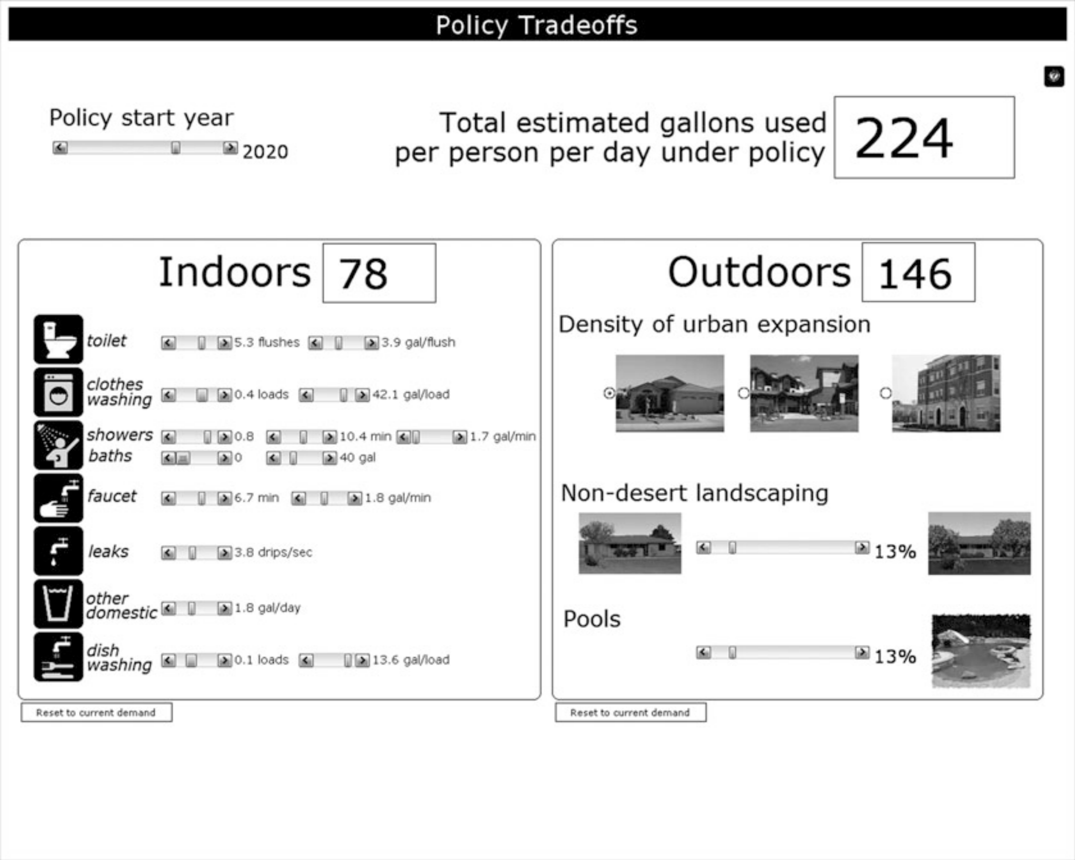
Scholars in the field of science and technology policy studies have systematically examined the process of science-policy engagement, now known as “boundary science,” for best practices. Cash et al. have identified the attributes of knowledge systems that support decision making in the environmental realm [42]. They note the emergence of boundary organizations that sit at the interface of science and policy and are responsible to both. In-depth analysis from case studies of boundary organizations reveals that efforts to use science to support policy and decision making are more likely to be effective when they manage the boundary between science and policy in ways that balance credibility, salience, and legitimacy. Credibility embodies the adequacy of technical advice and scientific arguments. Salience deals with the relevance of the assessment to the needs of decision makers, and legitimacy speaks to the perception that scientific and technological experts have been respectful of stakeholders’ divergent values and beliefs, unbiased, and fair in their treatment of opposing views. Water managers in Central Arizona gave high marks to WaterSim for its legitimacy, believing that it was produced from unbiased and objective data, modeling efforts, and scientific relationships, but lower marks for credibility and salience. The model had not yet included all relevant components of the regional water budget and thus was not yet deemed useful for decision making [43].

Participatory environments for science-policy engagement are hampered by differing perceptions of the relevant problem and its solutions. Scientists, water professionals, and the public at large have fundamentally different views of the problem of potential water shortage in Phoenix [44]. Survey results show that scientists viewed the possibility of climate-induced water shortage as a demand management problem—the key issue is how water is used, not supply constraints. The city can solve its water problems through conservation and urban design. Water managers tended to emphasize supply-side constraints and focused on how to obtain additional supplies from farmers, desalination, and infrastructure augmentation. The general public saw potential shortage as someone else’s problem—why should today’s households conserve water to protect the profits from new development on the urban fringe? These differing perceptions present profound challenges for participatory processes that aspire to link science with decision making for climate adaptation in the water sector and beyond.

4.3. *Decision Theater*

Visualization is increasingly used to facilitate social learning and decision making. Visualization caves and decision theaters create an immersive experience in which participants feel part of the model development and scientific process. Arizona State University’s 3-D, immersive Decision Theater enables WaterSim to be seen, experienced, and manipulated by water stakeholders and the public at large (Fig. 8.14). The model and its user interface have evolved as an iterative process (WaterSim 5.0 is now in development) in response to user criticism and suggestions. Users requested less emphasis on the climate conditions that are outside of their control and more opportunity to manipulate policy conditions that are within their purview (Fig. 8.15).

Fig. 8.14. The author leads an interactive session of WaterSim in Arizona State University's Decision Theater. Photo credit: Dustin Hampton.



Policy Tradeoffs

Policy start year 2020

Total estimated gallons used per person per day under policy 224

Indoors 78

toilet 5.3 flushes 3.9 gal/flush
clothes washing 0.4 loads 42.1 gal/load
showers 0.8 10.4 min 1.7 gal/min
baths 0 40 gal
faucet 6.7 min 1.8 gal/min
leaks 3.8 drips/sec
other domestic 1.8 gal/day
dish washing 0.1 loads 13.6 gal/load

Reset to current demand

Outdoors 146

Density of urban expansion ⊙ ○ ○

Non-desert landscaping 13%

Pools 13%

Reset to current demand

Fig. 8.15. Policy screen for WaterSim interactive display in Decision Theater.

5. SUSTAINABLE WATER SYSTEMS

The seminal and enduring definition of sustainability comes from the Brundtland Commission Report in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [45]. While it has been easier to define sustainability as an intellectual concept than as an operational tool, there is growing agreement that a sustainability perspective includes an awareness of complex systems thinking, foresight analysis, decision making under uncertainty, stakeholder engagement, and interdisciplinary approaches to real-world problem solving.

When these ideas are applied to the water sector, it is clear that the current practice of water management and water science will need to evolve to meet the challenges of water sustainability. Not only do we need to treat the water sector as a complex human-natural coupled system, include water professionals in the coproduction of knowledge, and incorporate DMUU support tools, but also consider the fact that water is not a stand-alone resource. It is connected to land (low-density development encourages high per capita water use), food production (virtual water is exported via food crops), and energy (the so-called energy-water nexus). Water and energy, particularly in arid regions, are linked resources. Energy is used to pump, move, and treat water. Water is used to turn turbines, wash inputs, and cool equipment. It is anticipated that as climate changes, water resources will be altered; potentially reducing their quality, quantity, and accessibility. This in turn will require increased energy inputs to purify water of lower quality or pump water from greater depths or distances. Thus, the effects of climate change for the water sector may appear indirectly in the amount of energy it will take to deliver and treat water and keep the city cool.

The concept of sustainability challenges us to look at water holistically, to consider the hidden vulnerabilities that occur because water is linked to other resources such as energy, land, and food production. This new approach to water science is interdisciplinary; it requires analysis of how complex human and biophysical systems function at a range of scales and new tools for risk assessment and decision support that incorporate notions of decision making under uncertainty.

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