ASU Global Institute of Sustainability
ARIZONA STATE UNIVERSITY

ASU Decision Center for a Desert City
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Advancing Science in Support of Water Policy and Urban Climate Change Adaptation at Arizona State University's Decision Center for a Desert City: A Synthesis of Interdisciplinary Research on Climate, Water, and Decision-Making Under Uncertainty

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Technical Report
August 2013

Acknowledgements: This material is based on work supported by the National Science Foundation under Grant SES-0345945, Decision Center for a Desert City, and Grant SES-0951366, Decision Center for a Desert City II: Urban Climate Adaptation. Any opinions, findings, conclusions, and recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the National Science Foundation.

We wish to recognize important contributions to this work by investigators with collaborating projects at Arizona State University, including the Global Institute of Sustainability; Central Arizona–Phoenix Long-Term Ecological Research project; Phoenix Area Social Survey; Decision Theater; Consortium for Science, Policy and Outcomes; Center for Policy Informatics; Center for Environmental Economics and Sustainability Policy; among others.

We thank the following people for providing important reviews and input on this manuscript: Rimjhim Aggarwal, Chrissie Bausch, Hallie Eakin, Andrew Ellis, Ariane Middel, Elizabeth Wentz, and Abigail York.

Finally, we are extremely grateful to our stakeholder partners for their collaboration and support.

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Executive Summary

The Decision Center for a Desert City (DCDC) at Arizona State University (ASU)—funded by the National Science Foundation (NSF) since 2004—conducts research relevant to water resources and urban climate dynamics under multiple uncertainties. This report summarizes and synthesizes research findings and achievements of DCDC after almost a decade of research and science-policy interactions. Water resource decision-making is complicated by climate change and variability, population growth and economic development, diverse stakeholder interests and fragmented governance. While these factors generate various uncertainties and complexities for decision-makers, DCDC pursues research to create a more sustainable future. The DCDC contributes to water management and urban sustainability by conducting basic science and collaborating with policymakers and stakeholders to solve real-world problems. As detailed herein, DCDC research, education, and community outreach have made substantial contributions to improving water-resource governance and climate adaptation.

Research and Educational Outputs

Knowledge advances in publications: DCDC participants have published over 340 journal articles and book chapters since 2004. According to Google Scholar, DCDC publications have received more than 6,200 citations, and over 100 of these articles have been cited more than 10 times.

Contributions to higher education: Sixty-nine graduate students have served as funded research assistants (RAs), and these students have produced 18 PhD dissertations and 17 Master's theses. More than 70 undergraduate students have also been involved in DCDC as members of the Internship for Science-Practice Integration (ISPI), the Community of Undergraduate Research Scholars (COURS), NSF's Research Experiences for Undergraduates (REU) program, and/or as undergraduate RAs.

Leveraged funding for research: Since 2010, DCDC investigators have raised more than four-million dollars in additional funding[1] to support a rich interdisciplinary community of scholars focused on water resource sustainability and urban climate adaptation in central Arizona and beyond. This funding has enhanced linkages between DCDC and related large-scale urban sustainability projects at ASU, including the Central Arizona–Phoenix Long-Term Ecological Research (CAP LTER) program and the Research Coordination Network for Science, Engineering and Education for Sustainability (RCN-SEES).

Research and Decision Support Highlights

DCDC geographers, sustainability scientists, hydrologists, and climatologists have advanced understanding of climate dynamics, urban risks, and associated uncertainties. Uncertainties and tradeoffs regarding climate and urban systems have been identified and refined, with implications for how water resources might be better managed. Researchers have developed new statistical and analytical techniques to understand sources of variability and uncertainty in information and models that are relevant to policymaking. This research has reduced the uncertainty in information that supports both scientific research and decision-making. Specific advances include developing new indicators of drought and potential climate change, identifying the factors that drive water demands, and improving the accuracy of spatial land use/cover and water demand estimates.

[1] DCDC has received two rounds of NSF funding for periods of 2004-9 ($7,000,000) and 2010-15 ($6,499,999).

DCDC scientists and modelers have developed new knowledge and decision support tools that have begun to affect decision-making about water and climate adaptation in central Arizona. DCDC researchers have used innovative tools and concepts, such as exploratory modeling, advanced scenario planning, anticipatory governance, and adaptive capacity to address pressing challenges. Using our simulation model WaterSim, DCDC researchers are evaluating a wide range of climate impacts, urban adaptation policies, and feedbacks. DCDC investigators also collaborate with water managers, regulators, and other stakeholders to link WaterSim analyses to regional and state planning efforts. This modeling and research has shown that demand management, integrated planning, and regional exchanges are central to effectively managing water resources under a variable climate and decision tradeoffs in an uncertain future.

Working in interdisciplinary teams, DCDC researchers have highlighted diverse climatic and other uncertainties, as well as uneven vulnerabilities to risks in human-environment systems. Uncertainties and tradeoffs involve both social and ecological processes that must be understood in an integrated manner to improve urban sustainability in an unpredictable future. Uncertainties revealed by DCDC research relate to not only climate change predictions and scientific estimates, but also political and economic dynamics and expectations. Tradeoffs have also been identified among water and energy conservation, heat mitigation, and other goals or outcomes. Multi-objective planning and integrated governance across water, land, energy, and other sectors can balance those tradeoffs. Since DCDC has found significant social and spatial variation in resource use, decisions, and outcomes, including heightened risks among suburban/exurban communities along the urban fringe, targeted planning for high-risk areas or populations can help alleviate (potential) losses most effectively and efficiently.

DCDC scholars have linked urban planning, institutional analysis, and policy analysis to develop improved climate adaption strategies, including jointly addressing both water supply enhancement and demand management strategies, as well as integrated planning approaches. Their discoveries about interrelationships among urban design features, distinctive climate effects (such as urban heat island versus greenhouse-induced climate change), and outdoor water demand have identified new insights about adaptation to climate change. These insights show the potential to manage climate risks and water resources through compact urban development as well as different land use/cover designs for both urban and agricultural areas. Given complex system dynamics revealed by DCDC research, urban sustainability requires a variety of coordinated strategies.

DCDC social scientists have developed new theory and knowledge about water governance, decision-making, and potential pathways toward sustainable institutions. DCDC researchers, collaborating in multidisciplinary teams, have developed analytical frameworks for assessing sustainability of water governance systems, conducted institutional analyses to identify constraints and capacities for urban climate adaptation, and completed multi-national comparative studies on perceptions of risks, uncertainties, and (in)equities in water institutions. Overall, this research has found that risk perceptions vary considerably across entities and places, and both policy preferences and adaptive actions arehighly affected by existing institutions and historic legacies, cultural and ideological predispositions, and peer influence and the desire for social status.

DCDC science-policy scholars have developed new theory and methods to better understand knowledge exchanges, collaborations between researchers and policymakers, and best practices to link knowledge to action. DCDC science-policy studies have investigated collaborative governance processes where information exchanges among diverse stakeholders are central to decision-making. This work shows that collaborations of various sorts among science, policy, and public stakeholders, as well as across stakeholder groups enhance trust and collective insights about water and urban sustainability. Collaborative science-policy activities also improve the credibility, salience, and legitimacy of research among decision-makers.

Looking ahead. DCDC has advanced multi-disciplinary research on water resource governance and urban climate adaptation under multiple uncertainties across such fields as geography, climate science, anthropology, urban studies, decision sciences, and economics. DCDC has also engaged and informed decision-making toward more interactive pathways that aim to anticipate urban environmental change and adapt to it. Over time, DCDC's work has broadened beyond the initial focus on climate, risks, and water decisions in Phoenix, Arizona toward scenario development and evaluation, synthesis and integration, and comparative and social-ecological system studies that address more general issues. In the future, research will continue to integrate climate and other biophysical understandings of water systems with knowledge about the causes, consequences, feedbacks, and responses of human-environment systems. Additionally, as the research methods applied by DCDC to Phoenix are applied to other areas, more generally applicable insights will emerge about risks and adaptive capacities, decision processes and uncertainties, water institutions and governance, and urban stressors and sustainability. Finally, through continuing engagement with community stakeholders, DCDC will continue to produce knowledge and information about water resource sustainability and urban climate adaptation that can help decision-makers to better anticipate risks and adapt to future conditions and uncertainties.

For more information about DCDC research and related activities, visit **http://dcdc.asu.edu/.**

1.0 Introduction

Since 2004, the Decision Center for a Desert City (DCDC) at Arizona State University (ASU) has been developing policy-relevant scientific knowledge and linking that information to real-world decision-making. With major funding from the National Science Foundation, DCDC's mission is to develop "fundamental knowledge about decision-making from three interdisciplinary perspectives: climatic uncertainties, urban-system dynamics, and adaptation decisions" (**http://dcdc.asu.edu/about-us/**). This involves conducting climate, water, and decision research and developing innovative tools to bridge the boundary between scientists and decision-makers, and putting the results into the hands of those concerned about the sustainable future of Greater Phoenix. DCDC activities have involved disciplinary, interdisciplinary, and transdisciplinary research involving faculty, students, and community stakeholders, as well as workshops, public information programs, creation of educational materials, and extensive outreach activities. This report summarizes and synthesizes research results to-date.

DCDC's activities are summarized in Tables 1 and 2. These tables demonstrate quantitatively how productive DCDC's activities have been, and the rest of this report describes the research that has been conducted and what has been learned from that research.

Academic Involvement	DCDC I	DCDC II			Totals[1]
	2004-9	2010-11	2011-12	2012-13	
Students Engaged					
Graduate Research Associates	57	8	6	12	69
Other graduate students (hourly workers)	4	1	2	0	7
Undergraduate student workers & others*	17	1	2	5	22
Interns for Science-Practice Integration	*	7	6	9	22
Community of Undergraduate Research Scholars	17	4	–	–	21
Research Experience for Undergraduates	*	0	2	5	7
Other Personnel					
Post-docs	6	2	1	2	7
Senior personnel (including PIs & Co-PIs)	47	29	29	29	65
Other faculty	36	30	28	21	57

Tbl. 1 Involvement of Faculty, Students, and Staff at DCDC over Time.

Notes: DCDC has received two grants for 2004-9 (DCDC I) and 2010-15 (DCDC II). The Community of Undergraduate Research Scholars courses were not offered in 2011-13.

*The counts for DCDC I includes interns, REUs, undergraduate student workers and others.
†Totals indicate the number of unique participants and may not equal the total number across years.

2.0 Challenges Facing Cities, and the Role of DCDC

Cities face multiple, complex challenges for their long-term sustainability (Vörösmarty et al. 2000). Foremost among these is providing secure and reliable water supplies to meet residential, industrial (especially energy-related), and agricultural demands, as well as economic and ecosystem needs (Wiek and Larson 2012). The impacts of population growth, land use change, and climate variability compound the inherent challenges of water management, particularly in the face of uncertainties about the future (Gober and Kirkwood 2010; Larson et al. 2013b). Such uncertainties encompass not only scientific uncertainty about hydro-climatology and other environmental dynamics, but also uncertainties about population growth, economic development, endangered species designations, environmental permitting processes, and the status of Indian water settlements (White et al. 2008). Altogether, DCDC aims to understand water resource and other environmental decision-making under multiple forms of uncertainty. At the same time, DCDC also provides relevant information to policymakers on crucial risks to water systems and potential pathways for more effective urban governance, as well as educating teachers, students, and the general public on key issues surrounding water resources and climate (Figure 1).

Climate scientists and resource managers increasingly recognize that "stationarity is dead." That is, we cannot necessarily count on future conditions being similar to past conditions— for instance, in terms of temperatures, precipitation, stream flows, and occurrence intervals for extreme events (Milly et al. 2008; Gober et al. 2010b). As an example, consider the allocation of Colorado River water to the seven Basin States in the western U.S. Allocation decisions made in the early 1900s were based on the historic flows on record, which turned out to be higher than the trendsover the long-term past (National Research Council 2007). Thus, if changes are not made, future shortages are inevitable, particularly considering basin-wide predictions for rising aridity and diminishing flows (Overpeck and Udall 2010; Bureau of Reclamation 2012). However, the predictions for exactly what future conditions will be like vary. As a result, the details of exactly what the potential shortfall will be are uncertain in terms of the types, extent, and timing of changes, as the research summarized below demonstrates. Taking into account the substantial uncertainties surrounding climate models and projections, Wilby and Dessai (2010) stress the importance of reducing current vulnerabilities, rather than solely attempting to reduce risks and uncertainties, which may not be feasible (Gober et al. in review).

In coping with risks and their impacts, a range of choices exists for anticipating, adapting, and otherwise managing human-environmental changes and other stressors to urban water systems. Decision-makers can manage water supplies, for instance, by acquiring new water sources and building infrastructureto increase storage and deliveries, and/or they can manage demands through conservation,

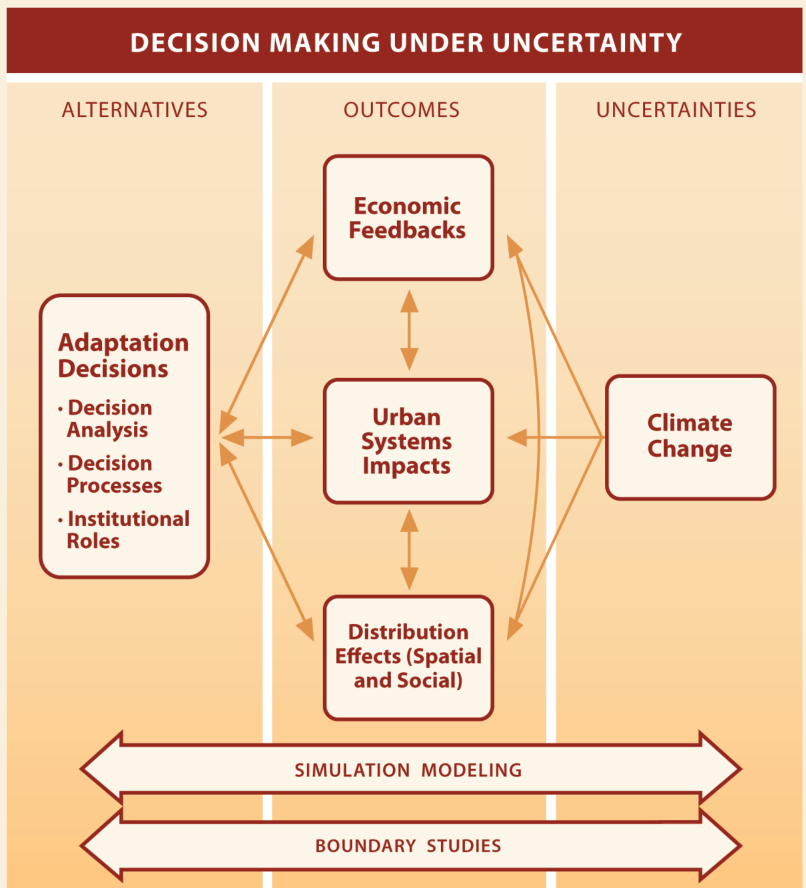

Fig. 1 Conceptional Approach for Research Activities at DCDC.

water reuse, and better matching of water supply with demand needs (Gleick 2002; Larson et al. 2009c). Such decisions and actions occur at both the individual and societal levels (e.g., from actions by individual residents or farmers, as well as by government and non-governmental entities), and at varying scales as defined by governing units (e.g., municipal, state, federal, or international) and/or biophysical units (e.g., watersheds or ecosystems; Wiek and Larson 2012). Collaboration across geographic units/scales as well as planning sectors is crucial for effectively managing water systems for several reasons. First, interconnections exist across resources or system components, as with the use of water to produce energy and the use of energy to distribute water (Wiek and Larson 2012). Second, interactions across scales are inherent because decisions and situations at one level affect those at other levels. Third, multiple stakeholders impact, and are impacted by, water resource decisions, including scientists, policymakers, special interests, and the broader public. Lastly, involvement of multiple actors with differing priorities

DCDC Products (as of June 30, 2013)	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	In press	In review	*Total*
Publications													
Peer-reviewed articles	1	13	29	28	30	20	37	26	24	13	17	17	***255***
Book chapters	1	5	13	15	4	11	4	8	12	4	5	5	*87*
Books	0	0	2	0	2	1	0	0	1	0	0	0	*6*
Non-refereed articles	0	0	0	0	2	1	2	0	3	2	0	0	*10*
Reports	0	0	3	7	3	0	1	1	3	1	--	--	*19*
Dissertations/theses	0	1	2	0	8	7	2	9	3	3	--	--	*35*
All publications	*2*	*19*	*49*	*50*	*49*	*40*	*46*	*44*	*46*	*23*	*22*	*22*	***412***
Presentations													
Inter/national meetings	1	9	17	28	29	34	35	43	33	12	--	--	*241*
Other	6	63	27	22	37	33	25	37	47	9	--	--	*306*
Posters: inter/nat'l mtgs.	0	4	5	12	6	5	6	10	12	10	--	--	*70*
Posters: other	0	2	27	14	34	18	16	22	16	29	--	--	*178*
All presentations	*7*	*78*	*76*	*76*	*106*	*90*	*82*	*112*	*108*	*60*	--	--	***795***
Outreach													
Water/climate briefings	4	6	5	5	5	4	6	7	4	3	--	--	***49***
Panel diss. (non-WCB)	0	0	0	0	4	1	1	1	0	0	--	--	***7***
Lectures (non-WCB)	2	6	4	0	3	0	0	0	0	0	--	--	***15***
Workshops	1	0	5	3	1	5	4	5	6	4	--	--	***34***
All outreach events	*7*	*12*	*14*	*8*	*13*	*10*	*11*	*13*	*10*	*7*	--	--	***105***

Tbl. 2 Various DCDC Outputs, 2004 to Present.

Notes: Some information (indicated by dashes) is not available or not applicable to in press/review products.
WCB refers to the Water/climate briefings. Also, the "other" presentations include on-campus and local events.

in decision-making processes can increase the credibility, salience, and legitimacy of these processes, which can enhance the resilience of water systems and reduce vulnerabilities to losses (Cash et al. 2003; White et al. 2010).

The co-production of knowledge (White et al. 2010, etc.) through science-policymaker interactions is another strategy to build better capacity to anticipate and cope with complex problems. Developing policy-relevant scientific knowledge, and linking that information to decisions, is a central goal of “boundary organizations” which span across both the science and policy realms (Guston 2001; White et al. 2010). DCDC has been functioning as such a boundary organization since it was founded in 2004. Collaborative activities further include developing simulation models and studying boundary organization processes, which entail discussions and collaborations with stakeholders such as water providers and resource managers. Broadly, DCDC aims to build bridges between science and policy to foster local-to-global sustainability solutions. Over time, DCDC has produced—often in collaboration with policymakers—a wealth of information and experiences on how to build trust and collaborative projects though information sharing, data negotiations, and other learning processes. After nearly a decade of work at DCDC, this report synthesizes DCDC’s state of knowledge, which is organized below into four topic areas:

1) climate dynamics in urban water systems;
2) human-environment risks and responses;
3) decision-making under uncertainty; and,
4) science-policy interactions and boundary work.

3.1 Climate Modeling and Urban Water Dynamics

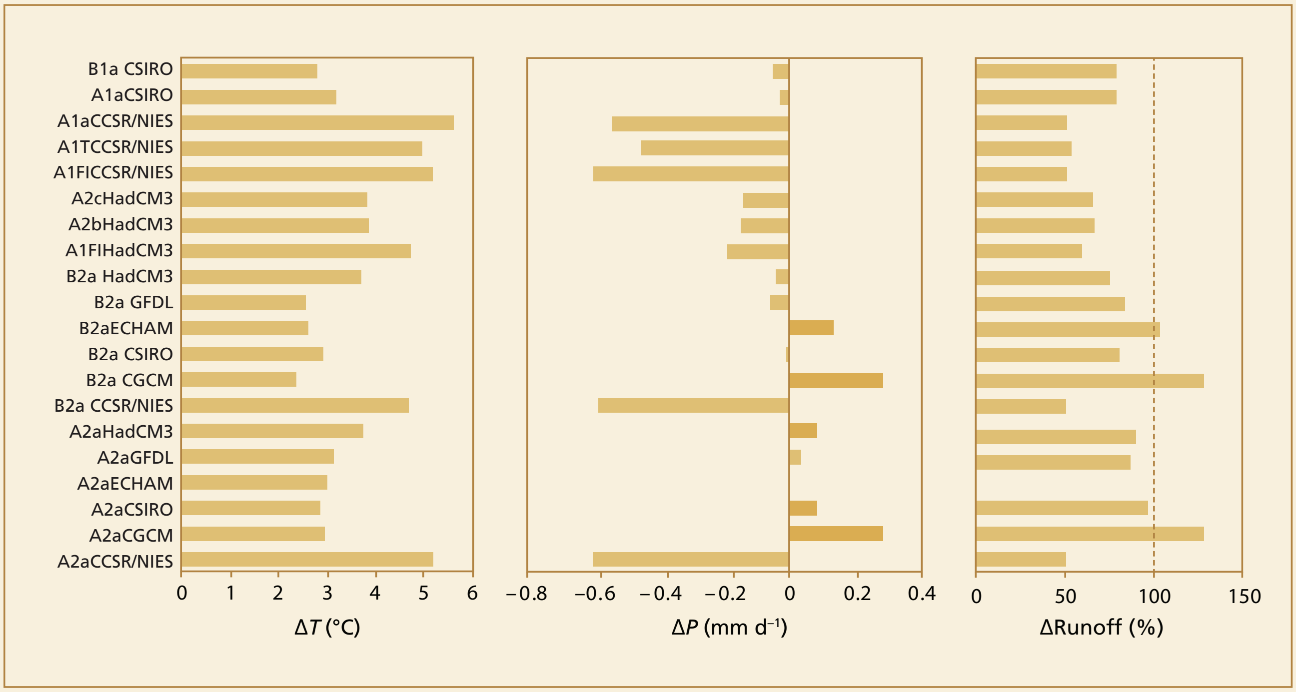

***Fig. 2 Twenty Model-Scenario Combinations Predicting Change in Temperature (ΔT), Precipitation (ΔP), and Runoff (% of historical levels) for 2050** (from Ellis et al. 2008).*

3.1.1 Climatic Effects on Water Supplies

Several DCDC studies have examined the effects of climate variability and change on water supplies as well as demands, demonstrating a range of possible impacts and uncertainties. These climate and hydrological studies were critical inputs into cross-cutting modeling efforts and vulnerability assessments (Bolin et al. 2010; Gober et al. 2010b, 2011). Ellis et al. (2008) used a water-budget model to estimate the effects of downscaled Global Climate Model (GCM) scenarios on surface water flows in the local Salt-Verde watersheds of central Arizona. The study demonstrated that runoff is sensitive to potential climate changes, although more so for precipitation than temperature. More than three-fourths of the models (16 out of 20) predicted a decline in runoff, with a mean annual runoff of 77% relative to historic flows. Altogether, the model outcomes ranged from 50 to 127% of historic runoff levels and the distribution of the outcomes resulted in an 85% chance that mean annual runoff will be below historical levels by the middle of the 21st century (Figure 2). Gober et al. (2010b) updated the analysis using model results from the Fourth Assessment of the Intergovernmental Panel on Climate Change (AR4) and found that the band of uncertainty increased from 19 to 123% of historical flows. Significant ranges in precipitation outcomes demonstrate the bands of uncertainty surrounding climate change, which are not necessarily narrowing over time.

Climatologists have also explored the large-scale synoptic processes that affect weather and climate in the Colorado River Basin in general and Phoenix in particular. Balling and Goodrich (2007) found that episodic changes in sea surface temperatures, also known as oscillations, explain only a small amount (19%) of the variation in drought occurrences in the Colorado River Basin, one of central Arizona's main sources of water. Ellis et al. (2010) analyzed the influence of teleconnections on drought, reporting that "the past century was characterized by an increase in drought coverage during the warm portion of the year almost exclusively as a result of climatic warming" (253). While La Niña is associated with a larger area of drought in the fall/winter compared to El Niño, the Atlantic Multi-decadal Oscillation (AMO) is a stronger predictor of drought in the preceding months than the Pacific Decadal Oscillation. The teleconnection-drought relationship is strongest in the southern portion of the Colorado Basin, including Phoenix and the arid Southwest. Transitions between El Niño, La Niña and neutral conditions also affect the trend toward greater variability in winter precipitation from year to year (since the 1960s). The transition from wet to dry years is most linked to transitions from El Niño to La Niña or neutral El Niño/Southern Oscillation (ENSO) events (Goodrich and Ellis 2008). The location and strength of the jet stream are primary drivers of inter-annual winter precipitation variability (Barton and Ellis 2008) and add to the complexity of climate prediction.

Other research has found a highly significant trend toward drought during the 1980-2009 period in the U.S., particularly in the Southwest and in the Colorado River Basin (Svoma and Balling 2009; Balling and Goodrich 2010). A possible explanation of droughts is relatively high surface pressure over the Salt River Basin during the latter part of 1900s, as one study showed a decline in soil moisture between 1980 to 2007 but not for 1895 to 2007 (Svoma et al. 2010). Regardless of the causes, one of the worst droughts on record was in recent decades (Goodrich and Ellis 2006). Stationarity tests of precipitation and runoff from within the Colorado River Basin support the idea that recent dryness was associated with drought rather than a changed climate, as the results did not reveal persistent reductions but rather stationary processes (Murphy and Ellis in review). This assessment also revealed that resolving anthropogenically forced precipitation and runoff trends amidst natural modes of variability will be challenging and significant uncertainties will persist in the coming decades.

While the western U.S. in general, and Phoenix in particular, can expect worsening droughts and aridity in the future, much of the rest of the U.S. will experience increases in the intensity of precipitation, particularly the Northeast (Balling and Goodrich 2011). Moreover, inter-annual variability in precipitation appears to be rising with global warming, especially in the low-sun season from October to March (Svoma and Balling 2010). Particulate matter in the Phoenix region also affects weekly precipitation patterns, as vehicle emissions suppress precipitation (Svoma and Balling 2009).

Because of climate complexities and hydrologic uncertainties, the need to monitor the onset of drought and ongoing conditions is critical for responding and adapting to changes. The Moisture Balance Drought Index (MBDI; based on Ellis et al. 2010) is particularly valuable because it characterizes the supply of moisture through precipitation relative to the temperature-driven (environmental) demand for water. Although the Standardized Precipitation Index, or SPI, does not characterize moisture availability in this way, it is still a more meaningful representation of this relationship than is depicted by the commonly used Palmer Index, and therefore both are relatively suitable in arid climates with high evaporative losses.

3.1.2 Climatic Impacts on Resource Demands

Regarding climatic impacts on water demands in Phoenix, one DCDC study demonstrated the relationship between water use and annual mean temperatures, total annual precipitation, and drought, with correlation coefficients of 0.55, -0.69, and -0.52 respectively during the 1980-2004 period (Balling and Gober 2007). Multivariate analyses of monthly, neighborhood-level data further show that annual water use is most controlled by drought, fall temperatures, and summer (monsoon) precipitation. At the household scale, others (Harlan et al. 2009; Klaiber and Smith 2013a) also found temperature and precipitation to affect residential water use. However, these climatic variables are not as strong as expected given the large amount of water used outdoors in the area (Balling and Gober 2007). These findings suggest that peoples' perceptions may be more important than actual plant needs. Additionally, behavioral practices may determine irrigation amounts more so than technology, since drip systems—which are thought to be relatively efficient—often run on timers and people do not change them in response to local weather conditions.

Another study by Balling and colleagues (2008) looked at spatial variability in how residential water demands respond to atmospheric and other conditions. They found water use in about one-third of Phoenix neighborhoods (census tracts) was not at all responsive to climatic conditions. These areas mainly housed large families and Hispanic residents. Meanwhile, 72% of one census tract's water use was explained by variation in atmospheric conditions. Water demands in high-income areas with large lots, pools, and grassy landscapes were most sensitive to changes in climate. Thus, affluent neighborhoods that use substantial amount of water outdoors will be most affected by rising temperatures due to global warming and the urban heat island (see also Harlan et al. 2009). It is important to note, however, that another analysis at the disaggregated, household scale (see Klaiber et al. in press) found that weather affects all levels (percentiles) of water use. This study demonstrates the importance of disaggregated data analysis, while also challenging other findings that suggest low-income water users are not as responsive to changing their water consumption practices. Although smaller customers' responses may not be as large, they are significantly different from zero.

Looking into the future, Balling and Cubaque (2009) modeled 50 scenario combinations outlined by the Intergovernmental Panel on Climate Change (IPCC) for the 2040-2069 period. Their study showed the high likelihood of climate-induced increases in water consumption in the near future, although the impacts varied substantially across neighborhoods (census tracts). The mean increase in water demands was estimated at 3% or more by 2050. This amounts to an average monthly increase of about 1,780 liters (470 gallons) per census tract. Nearly all of the increase (96%) is due to projected temperature changes, while the remaining variability was explained by fluctuations in precipitation. Standard deviations across neighborhoods (census tracts) demonstrate the highest variability and uncertainties among large, affluent water residences.

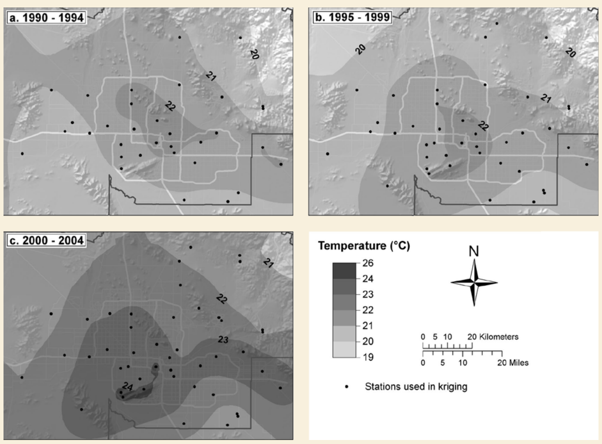

Fig. 3 Monthly Mean Minimum Air Temperature Patterns in the Phoenix Region, 1990 to 2004
(from Brazel et al. 2007).

In metropolitan Phoenix, central urban areas are 2.2 °C (4.0 °F) warmer than rural areas due to the urban heat island (UHI) effect (see Figure 3; Brazel et al. 2007). The urban heat island effect stems from the tendency for urban surfaces to absorb a larger share of the sun's radiant energy during the day and release it at night. In a spatial analysis of the intensity of UHI effects between 1990 and 2004, Brazel et al. (2007) found that agricultural developments added 0.1 °C (0.2 °F) compared to exurban sites; desert areas added 0.5 °C (0.9 °F); and urban infill areas added 1 °C (1.8 °F). The most dramatic changes occurred when farmland was converted to residential land. Minimum temperatures varied both spatially and temporally with synoptic weather conditions, development type, and number of homes built. Not only does expansion of the UHI pose heat/health-related risks (Harlan et al. 2012), but it increases demand on water resources. One study using cross-sectional data at census tract level found that a typical single-family home in City of Phoenix uses an additional 1,098 liters (or 290 gallons) per month for every 1 °F increase in the mean low temperature (Guhathakurta and Gober 2007).

Building on this work, Aggarwal et al. (2012) used longitudinal data to examine the temporal variation in UHI and its impact on water consumption in Phoenix. They controlled for the effect of unobserved ecological (e.g. soil quality) and institutional (e.g. neighborhood association rules) factors that vary across cross-sectional units but are likely to have remained relatively stable over the study period. The authors estimated that for each 1 °F increase in nighttime temperature, water use in single-family residences increased by 683.6 liters (or 180.6 gallons), which is almost 40% less than the estimates found in a previous study using cross-sectional data (Guhathakurta and Gober 2007). Even with the lowered estimate, an additional 3,338 single-family units could be added to Phoenix without incurring any additional pressures on existing water resources by reducing the nighttime temperature by 1 °F. If this occurred, almost half the new units each year—assuming a 2% annual growth rate in single-family units—could be accommodated without any additional water supplies.

In a later study, Guhathakurta and Gober (2010) explored the role of land use in mediating the effects of UHI development on residential water use. They found that impervious surfaces in residential developments increased residential water use by exacerbating the UHI. Consequently, they recommended that "smart growth" move beyond vegetation-based solutions for ameliorating urban temperatures and consider interaction between surface materials, urban water use, and UHI effects. Other research refined the relationships between land use, water demands, and UHI effects in Phoenix.

3.1.3 WaterSim

WaterSim is a systems dynamics model designed to integrate across DCDC research areas in climate, hydrology, urban design, water demand, and policy analysis. It was designed to replace traditional optimization models that have dominated water resource management and civil engineering. These modeling frameworks are poorly adapted to the uncertainties of contemporary environmental and societal change (Gober 2013). WaterSim takes an exploratory approach consistent with a decision-making-under-uncertainty framework. It allows users to explore the consequences of policy decisions and to look for robust solutions—those that work well across a range of climate futures. Theinitial versions of WaterSim (1.0-3.0) were developed between 2005 and 2007 using PowerSim for presentation in the Decision Theater, an immersive environment that includes a 260-degrefaceted screen capable of displaying panoramic computer graphics and 3D video. The next generations of WaterSim (4.0-5.0) were written as modules in FORTRAN but controlled by a Microsoft C-Sharp user interface (Gober et al. 2011; Sampson et al. 2011; see Figure 4). It captures how climate, growth, and policy choices alter water supplies (groundwater and surface water) and demands (residential, commercial, and agricultural) (Gober et al. 2011). Adaptation dynamics (i.e., policy levers) in the model include groundwater management, policy start years, water shortage polices, retirement of agricultural land, growth rates, and water use efficiencies. Exogenous uncertainties involve water supply variability, groundwater availability, and climatic effects on water supplies.

While relationships are embodied by equations (for more details on the 4.0 version, see Gober et al. 2011, Sampson et al. 2011), outcome metrics include

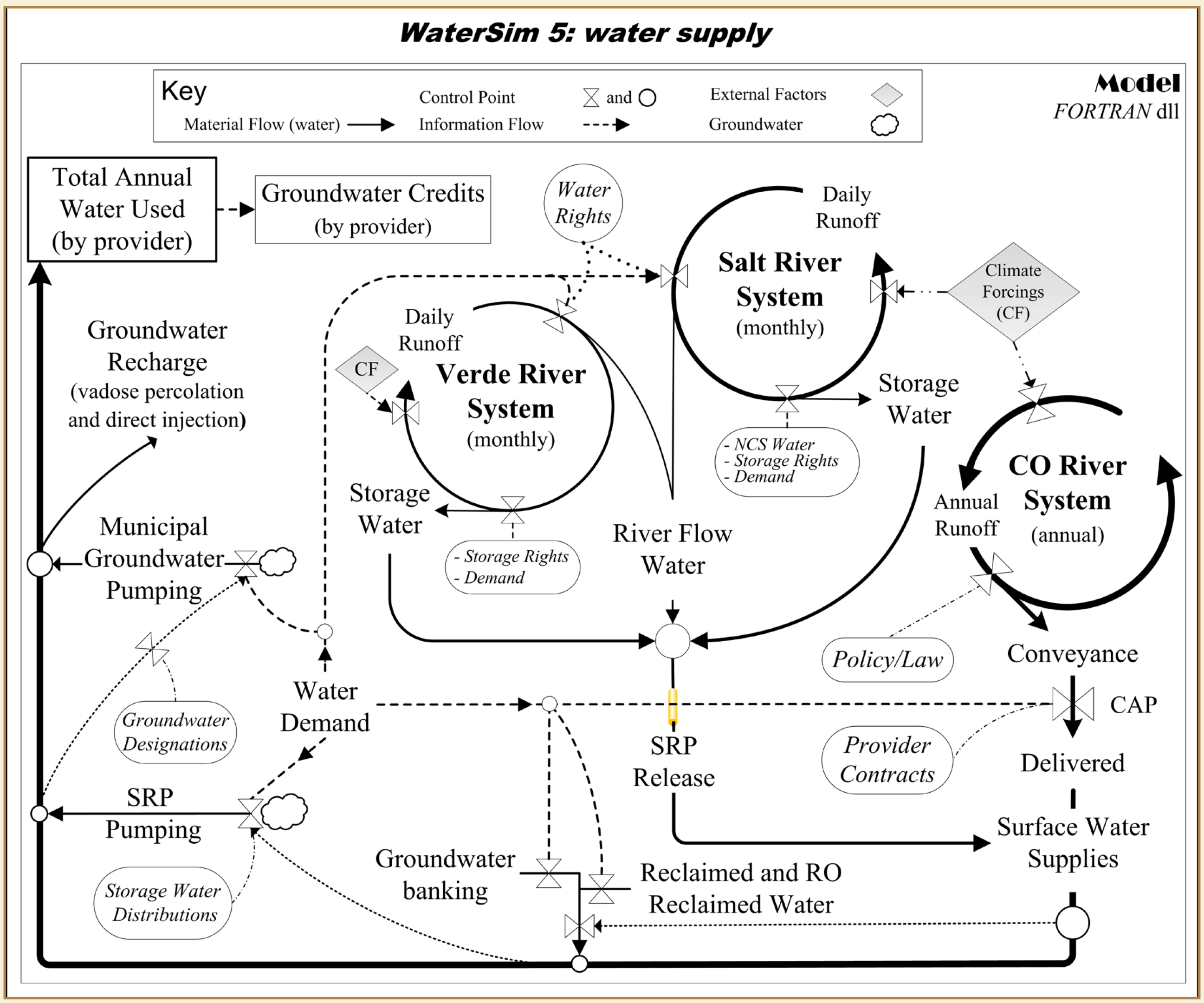

Fig. 4 ***Framework of WaterSim 5.0*** *(adapted from Sampson et al. 2011).*

water availability (in liters or gallons per capita daily) and groundwater deficits (especially relative to Assured Water Supply designations; Gober et al. in review). The model has been tested for accuracy, with results indicating more accurate simulations for regional water levels in Lakes Mead and Powell (on the Colorado River) than for the local Salt-Verde system (Sampson et al. 2011). For the latter, simulated water levels were higher than empirical estimates across 2000-2010 and, thus, predicted flows into the future are more uncertain for local watersheds than for the regional Colorado Basin. In order to validate the model, sensitivity analyses have confirmed responsiveness of the model to varying inputs about climate, runoff and growth (Gober et al. 2011). In this study, historical matching also revealed close correspondence between actual and simulated water demands over the 1985 to 2000 period.

DCDC is currently working with a 5th version of the model, which is constantly being revised to reflect stakeholder needs, data availability, and technical capacity. WaterSim 5.0 uses a mass balance approach to track local, regional, and provider-level estimates of surface water, groundwater, and water demand and use (Gober et al. in review). Simple difference equations are used to model states (e.g., reservoir storage) and rates (e.g., river flow) of water supply and water demand for the Phoenix-area water system on an annual time-step, although some of the driver variables operate at finer temporal resolutions. The current model focuses on urban water demand (indoor and outdoor) using a provider-specific representation of the water supply. This includes water treatment facilities, residential, commercial, and industrial water use from supply source to waste treatment and water reuse. We use historical estimates to model reservoir operations for surface water sources (Salt, Verde, and Colorado Rivers). Water rights for 10 local providers are used to allocate water from the Salt and Verde systems, immediately upstream from Phoenix, across providers. Groundwater rights are used to estimate provider supplies. Groundwater estimates from the Arizona Department of Water Resources (ADWR) are used to initialize provider-level credits.

WaterSim has been used to assess vulnerability of climate-related shortages or other environmental risks and tradeoffs in Phoenix (Gober and Kirkwood 2010; Sampson et al. 2011; Gober et al. in review). A study published in the Proceedings of the National Academy of Sciences concluded, for example, that the possibility of achieving groundwater sustainability by 2030 is unlikely under projected growth and unconstrained water usage (Gober and Kirkwood 2010). The authors add that adapting to urban environmental change in the greater Phoenix region is partly a matter of reducing water demands through native (desert) landscaping and fewer pools. Other studies demonstrate spatial variability in risks and uncertainties (Sampson et al. 2011; Gober et al. in review; see also the vulnerability section). Sampson et al. (2011), for example, showed different vulnerabilities to climate- and population-induced shortages based on water supply portfolios (c.f., Bolin et al. 2010). Water providers reliant on the Colorado River are

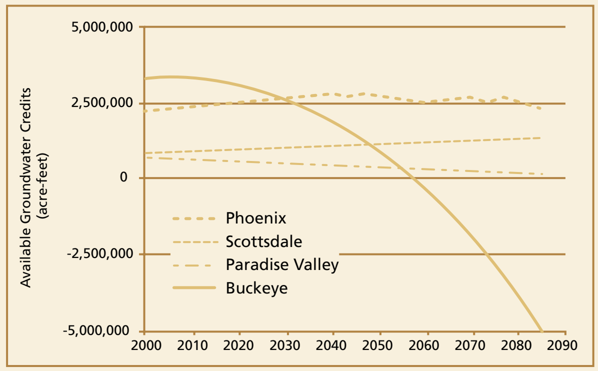

Fig. 5 Potential Future Patterns of Available Assured Water Supply (Groundwater) Credits, Assuming No Climate Change *(from Gober et al. in review).*

most sensitive to reductions in surface water, in part because of shortage-sharing agreements that set out junior rights for Arizona's allocation to the river (Gober et al. in review). In a recent WaterSim analysis, Gober et al. (in review) also identified four groundwater management archetypes among Phoenix-area communities (Figure 5): 1) robust water supplies and stable groundwater use (e.g., Phoenix); 2) recent increases in groundwater credits thanks to replenishment and water reclamation initiatives (e.g., Scottsdale); 3) possibility of slow groundwater declines over 100 years or longer (e.g., Paradise Valley); and 4) high uncertainties in the nearer term due to groundwater dependence and high growth (e.g., Buckeye).

Exploratory modeling results show potential paths to sustainability that include decreasing per capital consumption (GPCD), raising the price of water, increasing development densities, and restricting residential and commercial uses of water, especially outdoors (Gober 2007; Gober et al. 2011). A key insight from DCDC modeling exercises is that the status quo of water use and management present substantial risks and is unsustainable over the long-run (Gober et al. in review). Since uncertainties are inevitable, whether climatic, growth-related, political, or otherwise, they must be managed rather than reduced or avoided. Exploratory modeling, scenario planning, and risk assessment offer opportunities for coping with various stressors and uncertainties. As a whole, several DCDC scholars have argued that the planning paradigm should shift away from the traditional "predict and plan" model of decision-making toward anticipating and adapting to risks and perturbations through a range of choices (Quay 2010; Gober et al. in review).

DCDC researchers have also argued that integrating the social sciences in traditionally water-oriented fields of hydrology, climatology, and ecology is imperative (Gober et al. in review). Modeling sociohydrological dynamics is essential not only because people and organizations are both societal agents and targets of change, but also because they allow us to understand how knowledge and information are applied to action (Sivapalan et al. 2012). Over time, DCDC has evolved and adapted WaterSim to incorporate new system dynamics while addressing stakeholders' decision needs. Perhaps the most critical point early on focused on the salience of the model's scale, since WaterSim was originally only run at the regional level whereas policymakers need information at their jurisdictional levels (i.e., for water provider and municipal territories; Gober et al. 2011, etc.). Another planned change is to incorporate water pricing schemes into demand estimates (Gober et al. 2011). Stakeholder concerns about the model could also be addressed, for example, by adding scenarios for Native American rights and ecosystem health (see more on this later). Other dynamics that could be examined and incorporated into the model include the effects of appliance upgrades and the limits of these and other water-saving adaptations on water demands and supplies under various, potential future conditions. Nevertheless, the model has provided insights into water governance over the years, including research with stakeholders.

3.2 Human-Environment Systems: Risks, Vulnerability, and Sustainability

3.2.1 Urban Water Demands

Increasing demands on water supplies place stress on urban systems and the sustainable use of an essential resource (Chhetri 2011). Outdoor water uses are critically important to managing demands.

In Phoenix, consumption for irrigating yards amounts to approximately two-thirds of total municipal water demands (Wentz and Gober 2007). Significant progress has been made in reducing demands, especially in the central City of Phoenix, thanks largely to landscape conversions region-wide as well as appliance installations and retrofits (Frost 2013). In Phoenix, Tucson, and other southwestern cities, these savings have allowed more accounts to be served by utilities while still lowering aggregate demands overall. Yet some municipalities in metropolitan Phoenix have not reduced per capita demands, and overall water demands in some places remain high (Larson et al. 2009b). Additional information is needed on these and other demand dynamics, including topics such as the limits of conservation due to demand hardening, revenue losses, and other matters (Larson et al. 2013b). Nevertheless, DCDC has contributed much to understanding urban water demands.

At the neighborhood level, key predictors of consumption include lot size, percent pools, and percent grass (Wentz and Gober 2007; Figure 6). At the household level, Harlan et al. (2009) also found lot size and landscape type to be critical predictors of water consumption in Phoenix. Brent (2013) found, specifically, that landscape conversions—from mesic (wet) lawns to xeric (dry) conservation alternatives—reduced water consumption in the Phoenix region by 20 to 30%. Water use also increases with the number of people living in households (Wentz and Gober 2007). Both household size and pools exhibit spatial effects, indicating that census tracts are similar to those nearby based on these characteristics. Household size is less important in areas of the northeast Valley, where affluence likely leads to consistently higher rates. Meanwhile, pools had the largest effect in older, central city neighborhoods of Phoenix, perhaps due to the heat island effect leading to greater evaporative losses (Figure 6b). Although much of the analysis of water demands has been focused on single-family consumers, Wentz et al. (in press) recently examined the drivers of water use among multi-family (MFR) apartments. Three factors explained 44% of the variation in MFR water use; pool area was most influential, followed by washer/dryer and dishwasher appliances. In contrast to single-family studies, vegetation and housing age did not account for water demands, nor are water use characteristics auto-correlated for apartments in the Phoenix area (note Tempe was the specific location of this research).

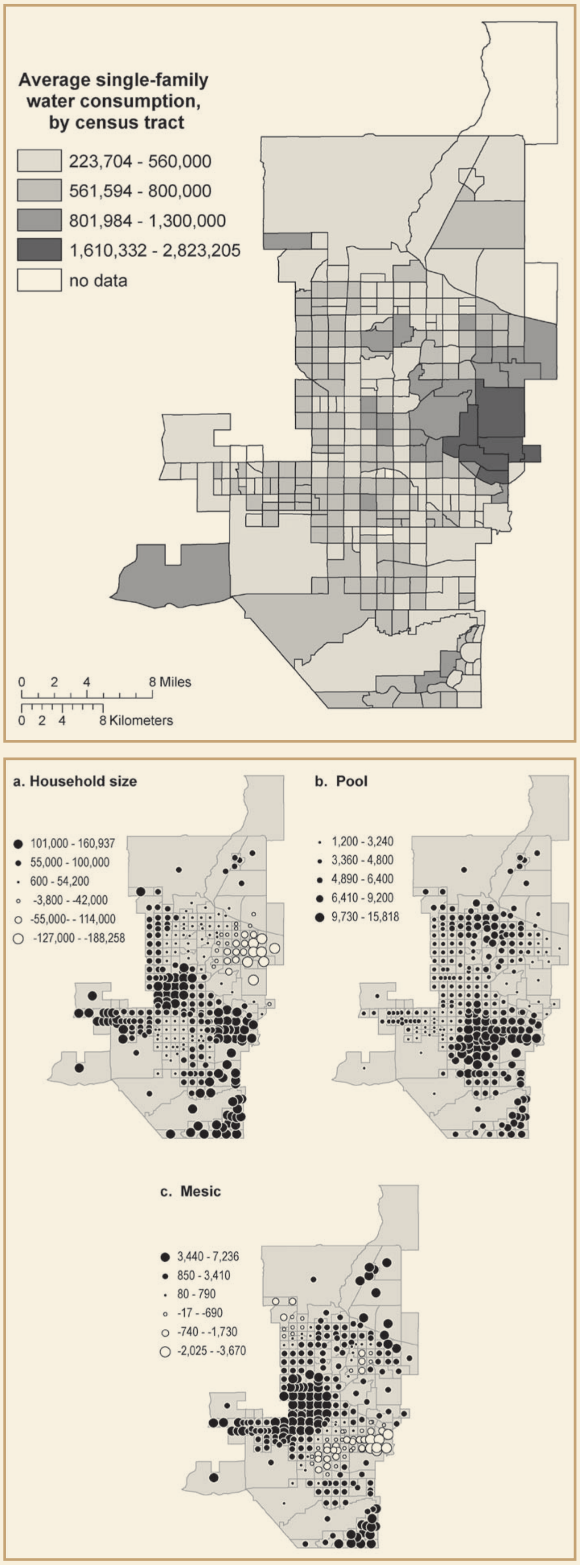

Fig. 6 (a) Single Family Residential Water Consumption for the City of Phoenix in 2000; (b) The Distribution of Certain Parameters Shown to Affect Household Water Consumption
(both from Wentz and Gober 2007).

The value of watered landscapes has been assessed by DCDC economists Klaiber and Smith (2013b), who adapted the Hausman-Taylor panel data model to estimate the revealed preferences and tradeoffs for lush landscaping. They found that residents are willing to pay for irrigated and vegetated landscapes at both the parcel and neighborhood scales, as well as for reduced nighttime temperatures. This implies that pricing mechanisms must be used wisely, which may require prices to be set higher or in ways that discourage outdoor uses specifically. A related study found that water prices do affect the likelihood of residents converting their landscapes from mesic lawns to xeric alternatives (Brent 2013). However, the responsiveness to price (i.e., elasticity of demand) was substantially lower among households who have a fervent commitment to maintaining a lush, green landscape.

Klaiber et al. (in press) estimated price elasticities seasonally and during drought periods for Phoenix, taking into account interactions with seasonal (outdoor) water use and weather conditions. Their findings suggest that water usage rates are responsive to price in both seasons, yet the effects are higher during the summer months when prices and rates of outdoor water use are both high. During dry conditions, all users (and especially large users) are less responsive to changes in price, likely because they simply pay to keep their yards green and lush. Low precipitation also increases demand in both seasons, but in the summer, the effect depends on the amount of precipitation. Overall, large users are consistently least responsive to price changes across climatic situations. These studies emphasize that different areas or sectors of society may exhibit heterogeneous responses to price signals, other policies, or still other stressors.

Several geo-spatial analyses have improved estimates and predictions for water resource demands and their management. To model an array of pricing structures across 43 local water providers in the Phoenix region, Strong and Smith (2010) developed an alternative preference-based method that examines the average residential consumers' water use response to the increasing block prices across the fragmented providers. To address problems with limited public access to household level records of water use data, Lee and Wentz (2008) developed a geostatistical approach using "soft data" and

Bayesian Maximum Entropy (BME) to estimate and map water demands while accounting for the soft data uncertainty associated with extrapolation and downscaling. The results were more accurate than classical approaches (e.g., linear kriging) that do not consider soft data. Lee et al. (2010) also used space-time variability to examine historical data and projection for future population densities. Together, these studies demonstrate that Bayesian Maximum Entropy is useful for integrating error projections for independent variables. In particular, the approach "improves accuracy up to 43.9% over other space-time mapping methods that do not assimilate the uncertain estimates" (283).

Also using BME, a similar study accounted for uncertain urban heat island data due to missing records. The results were also more accurate than traditional approaches, by up to 35.3% more than traditional kriging and 12.5% more than spatio-temporal kriging (Lee et al. 2008). Employing other geo-spatial techniques, Wentz et al. (2010 developed the space-time interpolation environment (STIE to draw upon rich spatial (e.g., satellite imagery) and temporal (e.g., weather stations) datasets. STIE involves a spatial and temporal interpolation process, in addition to a calibration process that constrains behaviors depending on the phenomenon being studied. Their Phoenix-based results show greater accuracy—at the acceptable rate of 85%—in estimating land cover than either method did alone. As a whole, developing geo-spatial and modeling techniques has proved critical not only for improving accuracies in modeling land-water dynamics, but also in reducing uncertainties surrounding the use of inadequate or incomplete data and associated data processing activities.

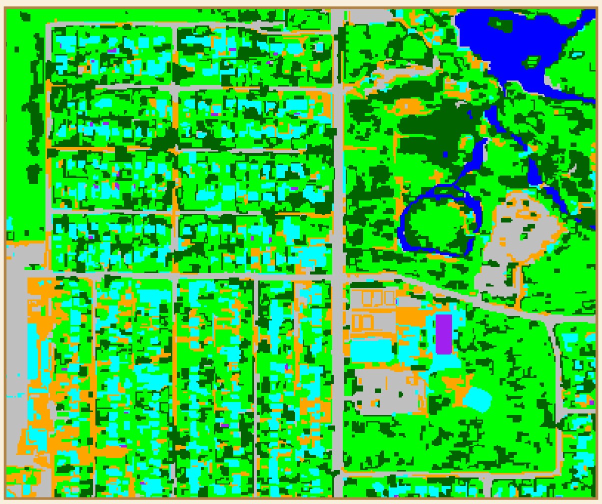

***Fig. 7 Output Map of Land Cover Using the Object-Based Approach** (from Myint et al. 2011).*

In another study associating water demands and atmospheric processes to land cover, Myint et al. (2011) developed an object-based system of land-cover classification that is more accurate than a traditional per-pixel classifier (Figure 7). This work examined five classification schemes that differentiate spatially and spectrally similar pixels at different scales. The highest accuracy (90%) was achieved with the object-based classifier (Table 3), as compared to 68% accuracy for the maximum likelihood classifier and 63% for the discriminant analysis of spectral signals. Thus, the technique developed reduces error in land cover classifications. To lessen such uncertainties in classification, the authors further recommend carefully considering which membership functions and scales best reflect each individual land class. As detailed elsewhere, the importance of context and multi-scalar interactions for understanding human-environment dynamics is a key insight derived from DCDC research generally.

Table 6
Overall accuracy, producer's accuracy, user's accuracy, and kappa coefficient produced by the object-oriented classifier – original image.

Classified	Reference								Producer's accuracy (%)	User's accuracy (%)
	Buildings	Unmanaged soil	Grass	Other impervious	Pools	Trees/shrubs	Lakes/ponds	Total		
Buildings	73	2	1	3	0	1	0	80	83.91	91.25
Unmanaged soil	6	70	0	3	1	0	0	80	94.59	87.50
Grass	6	2	68	2	0	8	0	86	95.77	79.07
Other impervious	1	0	0	87	0	0	0	88	83.65	98.86
Pools	1	0	0	1	48	0	0	50	97.96	96.00
Trees/shrubs	0	0	2	8	0	56	0	66	86.15	84.85
Lakes/ponds	0	0	0	0	0	0	50	50	100.00	100.00
Total	87	74	71	104	49	65	50	500		

Overall accuracy = 90.40%.
Overall kappa statistics = 0.89.

***Tbl. 3 Accuracy of Results for Land-Cover Classifications using Object-Oriented Method** (from Myint et al. 2011).*
Note: overall accuracy was 90.4% and kappa statistic = 0.89.

3.2.2 Urban Heat Island Dynamics

The spatial and temporal properties of Phoenix's UHI have been a longstanding interest among urban climatologists who have been affiliated with DCDC (Balling and Brazel 1987; Brazel et al. 2000; Baker et al. 2002; Hawkins et al. 2004; Chow et al. 2012a; Chuang et al. in press). Although DCDC's initial interest in climate dynamics focused on global and regional scales and asked what climate change would mean for river flows and hence Phoenix's water supply, it became apparent early in the process that small-scale climate dynamics were also significant to the region's water budget, affecting water demand through outdoor water use. Building on the earlier work of urban climatologists, DCDC researchers began to explore interrelationships among the UHI, urban design features, and water use. Results showed that adding 1,000 new homes in the area immediately adjacent to a weather station increased the average June nighttime minimum by 1.4 °C (2.5 °F) (Brazel et al. 2007), that increasing the nighttime temperature by 0.6 °C (1.1 °F) increased residential water use by 290 gallons for a typical single family home (Guhathakurta and Gober 2007), and vegetated landscaping increased water use directly through irrigation but reduced it indirectly by mitigating UHI effects (Guhathakurta and Gober 2010). Although the UHI effect is distinct from future warming due to climate change, it offers a useful natural experiment for policies and practices designed to reduce urban temperatures. Between 1997 and 2000, the average daily low temperature at the Sky Harbor weather station in the urban core was more than 5 °C (9.0 °F) higher than at a companion station 60 miles to the west (Baker et al. 2002).

The link to adaptation and policy was solidified with a question from the City of Phoenix's UHI Mitigation Task Force. A city staff member asked very simply how much water it would take to cool nighttime temperatures in Phoenix. It was becoming increasingly clear that hot summer nighttime temperatures impeded urban infill and pedestrian-oriented urban development, limited the region's capacity to attract year-round tourism, and diminished the comfort of residents who sought to be outdoors during the early evening hours. DCDC researchers experimented with a neighborhood-level energy balance model as a way to address how feasible it is to cool city neighborhoods by increasing irrigated landscaping. Using the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) model, Gober et al. (2010a) found that increasing irrigated landscaping reduces nighttime temperatures and that this relationship is nonlinear. Beyond a certain threshold, adding watered landscapes no longer improves nighttime cooling conditions. They introduced the notion of cooling efficiency or how much water it takes to produce a certain level of cooling. Middel et al. (2012b) demonstrated that efficiency tapers off at certain vegetation levels (wet fractions) around 20% (Figure 8). The latter study also showed how different land-cover types and vegetation amounts in Phoenix exhibit different heat storage capacities, and, therefore, impact the timing of sensible heat flux reversal at night. Results showed that high heat storage delays the directional change in heat fluxes toward cooling up to 3 hours, and vegetation speeds up cooling by 2 hours.

The obvious next step was to determine whether the water-temperature findings in Phoenix could be

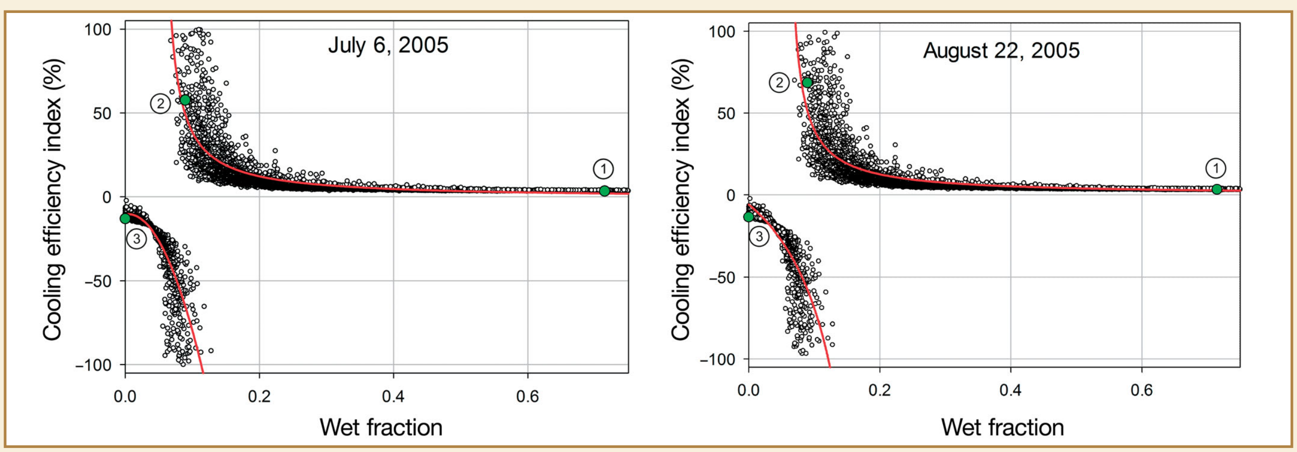

Fig. 8 Cooling Efficiency Index for the Various Local Climate Zones (LCZ) for Two Summer Days in 2005; LCZ 1: mesic open-set low-rise; LCZ 2: dry open-set low-rise; LCZ 3: bare concrete *(from Middel et al. 2012b).*

extended to other places—to ask whether vegetation and urban design features could be manipulated to cool other cities facing climate change. A team of climatologists and social scientists then collaborated with a similar team from Portland State University to produce identical experiments with LUMPS for Phoenix and Portland. Although Portland responded somewhat differently than Phoenix to land use and climate change scenarios because of its urban structure and temperate climate, many of the basic relationships translated from Phoenix to Portland (Gober et al. 2012). Although Portland is more sensitive than Phoenix to changes in climate and cools much later in the evening, the relationship between vegetated landscapes and cooling efficiency worked very similarly in Portland and Phoenix. Higher inputs of water made little difference to nighttime cooling beyond a certain threshold of vegetation density. Both cities were subjected to land use change scenarios (densification, xeriscaping, and greening) and climate change scenarios. That both cities were more responsive to land use change than to the climate change conditions suggests that cities may be able to cope with climate change through the strategic use of landscaping and higher density urban designs. A related LUMPS study added that solar radiation drives surface energy balance, and under extreme heat conditions, environmental water demands (as indicated by cumulative evapotranspiration, or ET) vary more in Portland than in Phoenix (i.e., at moderately vegetated sites; for details, see Middel et al. 2012a). This suggests that landcover configurations could be manipulated to counterbalance climate extremes, with perhaps greater effects in some places compared to others.

Chow and Brazel (2012) used the ENVI-met model to determine if it was possible to mitigate urban heat by adding xerophytic shade trees in arid neighborhoods. The effects were especially strong at the micro scale of residential lots (approximately2.5 °C; 4.5 °F) compared to the local-scale total modeling environment (approximately 1.1 °C; 2.0 °F), and during nighttime compared to daytime hours. However, xeriscaping in mesic residential areas increased heat and thermal discomfort. Another paper using ENVI-met investigated the impact of urban form, design, and landscaping on mid-afternoon micro-climate in Phoenix, thereby further demonstrating the importance of smart growth and urban designs on urban hydro-climate dynamics (Middel et al. in review). Results of this study showed that cooling is not only affected by vegetation and surface materials, but also depends on the form and spatial arrangement of urban features. At the micro-scale, spatial differences in cooling are significantly influenced by incoming solar radiation and local shading patterns. Findings also suggest that compact urban forms create local cool islands and are most beneficial for daytime cooling, especially if mid- to high-rise buildings are arranged along the direction of wind flow (which is known as the urban canyon effect).

Another line of interdisciplinary research, involving physical and social scientists, investigated the effects of the UHI on human comfort and health and on the social justice aspects of UHI development in Phoenix. In an early study, Harlan et al. (2006) investigated the relationship between neighborhood physical and socio-economic conditions on the outdoor human comfort index and found that lower-socioeconomic and ethnic-minority groups were more likely to live in warmer neighborhoods with greater exposure to heat stress. High settlement density, sparse vegetation, and no open space in the neighborhood were significantly correlated with higher temperatures. It became increasingly clear that high-income residents were using outdoor water and related landscape treatments to mitigate UHI UHI effects in a desert city. Ruddell et al. (2012, 2013) further documented the spatial variability in heat stress, showing that low-income residents were disproportionately impacted by urban heat. Combining spatial and temporal analysis, Chow et al. (2012b) showed that fewer White and Asian people, but more Latinos, lived in areas of high heat vulnerability between 1990 and 2000. A major conclusion from these studies is that UHI mitigation policies should be specifically targeted to vulnerable neighborhoods and social groups.

More recently, Harlan et al. (2012) linked heat vulnerability to heat-related deaths in the Phoenix region and found a higher than average incidence of heat-related deaths in areas of low socioeconomic status, high levels of isolation among the elderly, and little vegetation. A large proportion of deaths occurred among the homeless and in inner city areas and industrial corridors. Chuang et al. (in press) linked 911 emergency dispatch calls in Phoenix and Chicago to periods of extreme heat. The relationship between heat stress and maximum temperatures had a more sharply increasing slope in Chicago than in Phoenix suggesting that Chicago (with its more humid temperate climate) is more sensitive to increasing temperatures beyond 35 °C (95 °F). In addition, Chicago's 911 calls are more highly concentrated in periods of extreme heat, suggesting that heat is more a part of everyday life in Phoenix, but more focused on heat wave conditions in Chicago. Results have significance for emergency management practices and climate adaptation.

Finally, Ruddell et al. (2012) reported that perceptions of temperature are most strongly correlated with proximate environmental conditions. Personal experience (e.g., of heat-related health effects) tends to influence perceptions of local risks more so than those at broader, regional scales. Meanwhile, regional risk perceptions for heat were socially constructed along the lines of gender, ethnicity, and political orientation. Not only does this study demonstrate the importance of scale in UHI dynamics; it also underscores the social and spatial variability in the exposure to environmental risks.

While UHI research was prominent in DCDC's original proposal, it emerged as a centerpiece of synthetic research linking science to social science and science to policy. Research topics progressed from physical characterizations of the spatial and temporal properties of nighttime warming to policy questions about how to reduce warming through urban design and the consequences of different choices for water use, urban livability, human health, and social equity. It became increasingly clear that the UHI is more than just a physical phenomenon; it is a negative externality of large-scale urban growth with disproportionate consequences for disadvantaged populations. Also clear was the UHI's status as a harbinger of climate change both in terms the equity and health consequences a warmer city with declining cooling capacity.

3.2.3 Vulnerability and Sustainability Assessments

Several DCDC researchers have examined the vulnerability of people and places to climate and water risks including physical and social aspects of extreme heat and resource scarcity (e.g., Chow et al. 2012b; Larson et al. 2013b). One study integrating data on temperature, vegetative local population used Geographic Systems (GIS) to reveal physical the adaptive capacities of residents in certain areas. More specifically, Chow et al. (2012b) revealed two hot spots of heat vulnerability, one in urban core locations of Phoenix and other suburban cities, and another in several communities with high amounts of elderly residents. In contrast, wealthy areas in the northern portions of the Valley exhibited low vulnerability. The conversion of agricultural landto urban uses and the expansion of the UHI outward from the central city account for increases in vulnerability between 1990 and 2000 for western and southeastern parts of the Valley. As with other risks, non-White, low-income, foreign-born residents are especially vulnerable due both to heightened exposures and diminished adaptive capacity to cope with heat (see Harlan et al. 2006).

A similar spatial analysis of vulnerability to water supply shortages considered the security of water provider portfolios relative to population growth under three different scenarios (Bolin et al. 2010). This study showed substantial variability in shortfalls across providers, with smaller towns in the far southeastern, northern, and western communities of the Valley projected to experience the worst shortages. Shortages are reduced regionally under the conservation scenario, but some communities to the southwest and north remain highly vulnerable. Under the worst climate-induced shortage scenario, all communities experience some shortages, but the

Fig. 9 Diversity of Water Sources Confers Greater Security to Water Providers in Case of a Shortage *(from Bolin et al. 2010).*

Because of varying rights to diverse sources of water, spatial optimization models can be used to assess and consider water supply allocations under varying climatic futures (Murray et al. 2012). The analysis by Murray et al. shows that fringe communities are most at risk of deficits. A key point from this and other DCDC analyses is that vulnerability to future water shortage is spatially explicit and determined not only by drought and climate conditions but also by policy context. For instance, this Murray et al. analysis identified potential risk for the City of Scottsdale due to shortages on the Colorado River that would differentially affect that city, which depends heavily on Colorado River for current and future water supplies, whereas Tempe and Phoenix rely more heavily on Salt-Verde flows. Yet for most scenarios, deficits can be reduced through cooperative agreements among providers. Altogether, several studies show changing patterns of vulnerability associated with sprawl and fragmented water management, as well as other biophysical exposures and social capacities to adapt to environmental change. In yet another study, Collins and Bolin (2007) found mismatches between places that are vulnerable based on biophysical versus social conditions.

Other studies of watersheds to the north of Phoenix have underscored the politics of scale and cooperative processes for decision-making under uncertainty. In a groundwater-dependent region to the north of Phoenix around the city of Prescott, which relies primarily on non-renewable sources of water, the relatively small and rural towns and stakeholders attempt to reduce their vulnerability to shortages by developing new water supplies (Collins and Bolin 2007). This entails the importation of water, which displaces risks onto areas from which water is withdrawn or withheld, rather than decreasing risks overall. Competing descriptions of the problem and need for policy responses across government actors, citizen groups, and developers reveal claims and counterclaims about rapid urbanization and groundwater depletion (Bolin et al. 2008). As positions are taken and relationships formed, rhetoric and coalitions develop across local to broader geographic scales as well as across particular political and biophysical units depending on converging interests. On one side, some stakeholders favor importing water as a "spatial fix" to groundwater depletion so that the growth machine can continue. On the other, local actors join with national and other groups to invoke spatial and temporal dialogues over protecting ecosystems and communities, both for current residents and future generations. Thus, inter-scale interactions can be a source of collaborative adaptation (see Murray et al. 2012; Figure 10) or competitive claims and conflicts (Bolin et al. 2008).

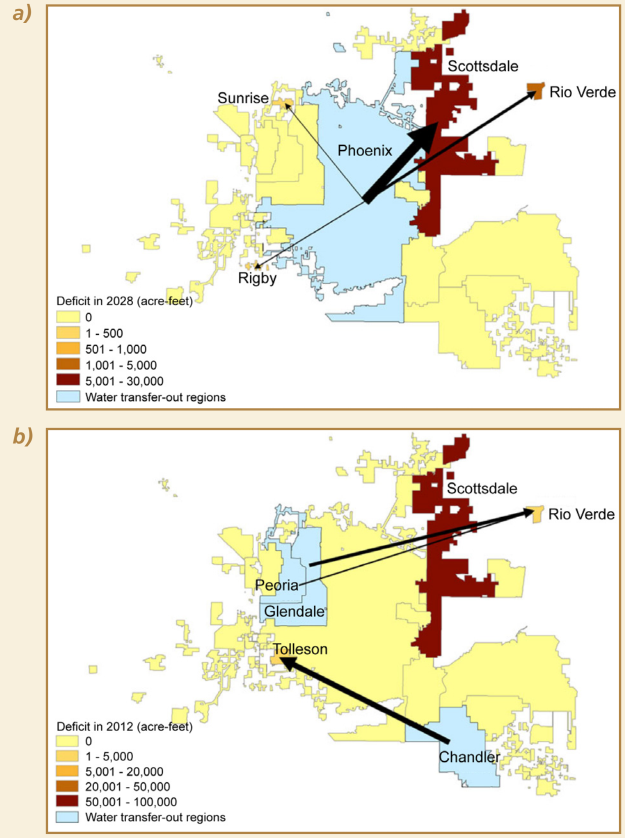

Fig. 10 (a) Arrows Show the Flow of Water as Providers at a Deficit in 2028 Obtain Water from Providers with a Surplus; (b) Regional Cooperation Helps to Alleviate Regional Deficits in 2012 with Water Reallocated from Providers with Surplus to Those in Need *(both from Murray et al. 2012).*

Several DCDC studies have conducted appraisals for water resource sustainability, identifying both successes and limitations in governance. Hirt et al. (2008), for example, detail the loopholes that have developed since the implementation of Groundwater Management Act (GMA), while a more specific empirical assessment documents how municipal conservation standards have been weakened over time, as several water providers in the region have failed to achieve "reasonable reductions" in water use despite regulatory commands to do so (Larson et al. 2009b). Since the implementation of the GMA, both residential and agricultural conservation programs have been changed from strictly mandated water-use standards to allow for voluntary best management practices (BMPs), without fully requiring or incentivizing actual reductions in water use (Larson et al. 2009b; York et al. in preparation; see also Megdal et al. 2008). Some studies link local politics and pro-growth mentalities to management strategies, which tend to focus on supply augmentation and urban development instead of demand or growth management (Larson et al. 2009c; Bolin et al. 2008; Gober et al. 2013). Both supply-augmentation and urbanization-oriented mindsets among water managers and other stakeholders appear to constrain water management options and adaptation strategies (Gober et al. 2013), inhibiting sustainable governance through a range of options (Gober 2007; Gober et al. 2011). As a whole, these studies demonstrate the need to consider the influence of political pressures and leadership, as institutional cultures and structures, on certain water management alternatives as well as their implementation and outcomes over time.

An integrative conceptual framework has also been developed to facilitate syntheses of information on the actors and rules (social system), human infrastructure (technological system), and hydrologic and ecological resources and processes (physical system) relevant for sustainable water governance (see Figure 11; Wiek and Larson 2012). Focusing on who does what with water, this interdisciplinary approach builds on research by Ostrom, Pahl-Wostl, and others in terms of guiding institutional analyses for sound governance. The framework also outlines core water resource activities (Figure 11b) and a holistic set of principles for water sustainability, as follow in brief: social-ecological system integrity and interconnectivity, resource efficiency and maintenance, livelihood sufficiency and opportunity, civility and democratic governance, intra- and inter-generational equity, and lastly, precaution and adaptive capacity.

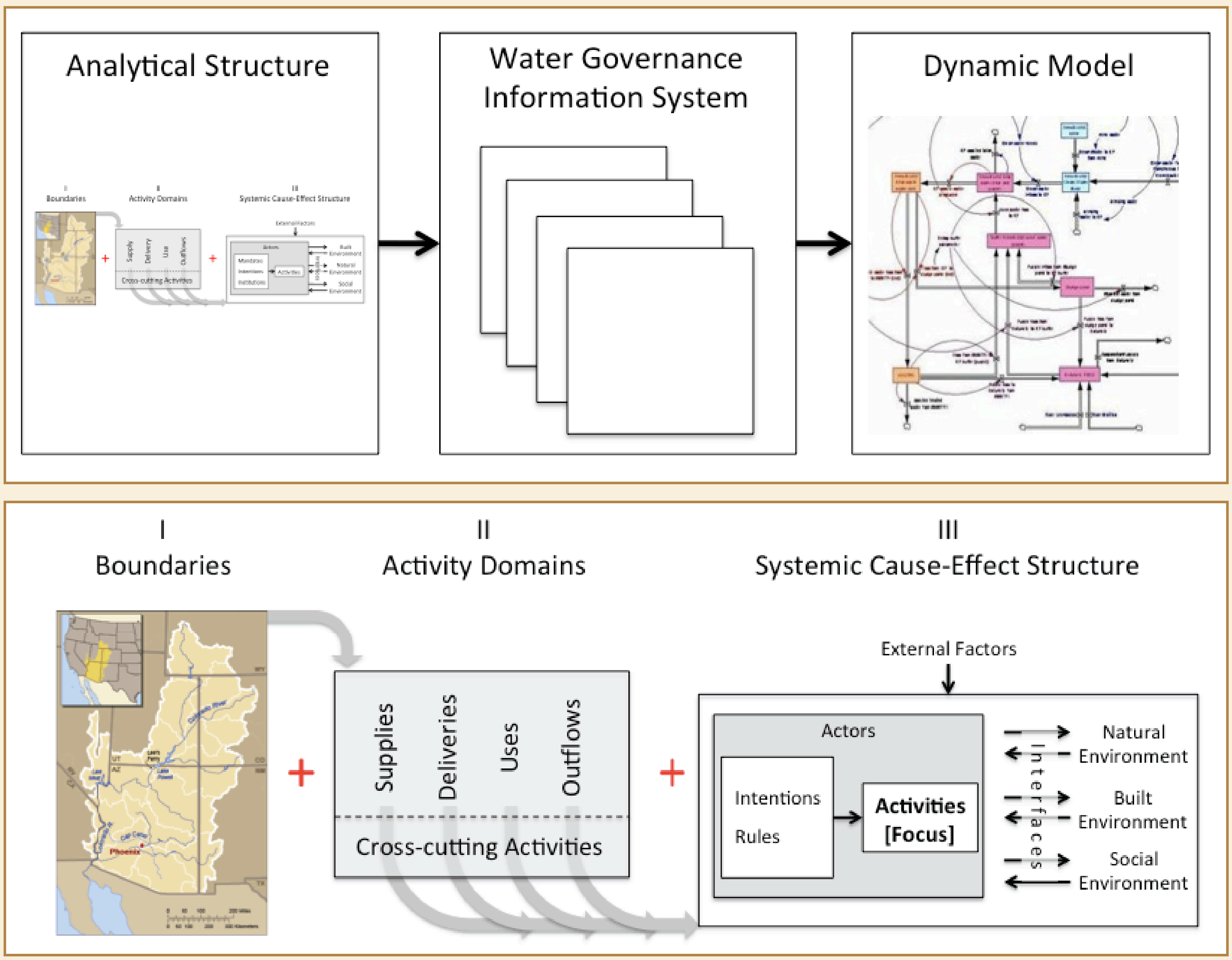

Fig. 11 (a) A Framework for the Integrated Analysis of Regional Water Governance Regimes; (b) Details of the Analytical Structure Shown in (a) *(both from Wiek and Larson 2012).*

An empirical, follow up-piece by Larson et al. (2013c) applied the framework to the Phoenix water system by synthesizing past and existing work and various sources to explain the specific supply, distribution, demand, and outflow activities in metropolitan Phoenix. The authors explained how activities affect sustainability per the broad set of principles developed for water governance, in part based on the plethora of research to-date by DCDC, the Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER) project, and other initiatives. The findings demonstrate deficiencies in the regional water system, including degraded ecosystem functions, inadequate resource maintenance (e.g., failure to meet safe yield, which means withdrawing groundwater only at rates of replenishment), inequitable outcomes and decision power, and finally, limited involvement of a wide array of stakeholders in resource planning and management. As this work aims to understand and transform the sustainability of a specific water system (that of the Phoenix area), recommendations based on this assessment were: manage interconnections across hydrologic units and resources systems (e.g., integrated land-water planning); develop decentralized projects for multiple social and hydro-ecological benefits (e.g., groundwater recharge or treatment wetlands with park facilities and habitat areas); address inequities in decision outcomes and processes (e.g., water allocations and greater public involvement); and build capacity through collaborations and learning across diverse actors and across scales and sectors.

Across two U.S. cities, another project assessed the vulnerabilities of community water systems in metropolitan Phoenix and Portland, Oregon to climate change and urbanization (Larson et al. 2013b). The study regions both exhibit common points of vulnerability for water systems into the future. These include hotter, drier summers, suburban growth, demand hardening, and limited capacities due to institutional constraints and political pressures to grow and develop (see other work, e.g., Gober et al. 2013, Hirt et al. 2008). Unique vulnerabilities also exist. While Phoenix faces more rapid growth and tradeoffs between water conservation and heat mitigation (see work by Gober et al. 2012, Middel et al. 2012a), Portland deals with exacerbated seasonal extremes in managing stormwater flows in the winters versus conserving water in the dry summers. Meanwhile, Portland is susceptible to rising irrigation demands in a warmer future, especially if investments in vegetation continue and require greater outdoor water usage to be maintained (Gober et al. 2012). Phoenix is less sensitive due to the rise of low water-use "xeric" landscapes and some water conservation achievements in recent decades (at least in some places; Larson et al. 2010, 2013b) as well as more diversified water portfolios and storage infrastructure (see Bolin et al. 2010 and Murray et al. 2012). Phoenix planners also reported more capacity in managing demands and anticipating climate changes and their implications for water compared to Portland, which has a relatively strong land use controls and smart growth initiatives that help reduce stresses on water systems. In general, these differing points mean that each region may uniquely adapt to urban environmental stressors and manage them uniquely based on their particular exposures, sensitivities, and adaptive capacities (Larson et al. 2013b).

Institutions play a key role in vulnerability and sustainability as formal and informal rules govern decisions and social interactions (Wiek and Larson 2012; York in preparation). Unique institutional contexts in Phoenix and Portland result in different pathways of adaptation to environmental change, for instance, as they are constrained by existing water and land policies respectively (Larson et al. 2013b). Additional DCDC research further explains how institutions influence the incentive structures that sway choices and guide behaviors, along with influencing expectations about the future of agriculture in the greater Phoenix region (York et al. in preparation; Bausch et al. 2013).

With attention to how institutional arrangements might guide public capacities for adapting to change, York et al. (in preparation) examine three types of agricultural programs for water management on farms: 1) municipal subsidies for using renewable surface water, as opposed to non-renewable groundwater; 2) market-based credits that allow flexibility in water use across years, rather than farmers losing conserved water to other users; and 3) voluntary Best Management Practices that allow farmers to avoid actual reductions in water use or changes in their practices. Altogether, this research has found that these programs do not necessarily reduce agricultural water demand. Rather, the current incentives shift agricultural demand to surface water flows and contribute to achievement of safe yield through a reduction in groundwater use. Nevertheless, these gains are likely threatened, as rising costs of surface water (due to increasing energy prices) and increased uncertainty over future surface water availability (due to climate change) put current reductions in groundwater pumping at risk.

Without policy changes, farmers may also resume groundwater pumping through available programs and established water rights as surface water becomes more limited. In short, although the GMA assumes a decline in agricultural uses of groundwater via conservation, this has largely been achieved through retirement of agricultural land and a shift to surface water sources. An alternative scenario is possible in which current agricultural land use continues and farmers return to exploit groundwater resources; as we discuss further below, in the face of such a scenario, the multiple benefits of farmland may warrant deliberative consideration of the role of agriculture in the region (York et al. in preparation; Bausch et al. 2013).

3.3 Adaptations, Decision-Making, and Tradeoffs

3.3.1 Drivers of Water Demands and Landscaping Practices

Reducing water consumption rates is one way to adapt to rising demands and decreasing supplies. Since outdoor water uses dominate urban water demands, irrigation and landscaping practices represent key targets for adapting to a more arid future (Gober and Kirkwood 2010; Chhetri 2011). To understand the factors influencing various water use behaviors, several studies have examined overall water consumption as well as yard irrigation and land-cover choices (e.g., Harlan et al. 2009, Larson et al. 2010), among other human decisions. As a whole, these studies show that structural factors (e.g., housing and property characteristics) often trump attitudinal factors in determining water usage. Although the influence of values, perceptions, and attitudes on behaviors is often limited, complex, and/or counterintuitive, displays of status also appear critical in decisions made about landscaping and bottled water consumption. Altogether, these findings have implications for how best to conserve water and adapt to water scarcity due to climate and other stressors.

As discussed earlier (see Wentz and Gober 2007; Harlan et al. 2009), structural characteristics of residential areas (e.g., size of lots, grass cover, pools) substantially increase household and neighborhood water use. Another important structural factor is the age of housing, since older homes tend to be less efficient due to outdated appliances and infrastructure (Larson et al. 2013a). This tendency also likely explains why newer neighborhoods with private Homeowner's Associations (HOAs) do not capture more water resources than non-HOA areas (Turner and Ibes 2011). Thus, older neighborhoods and high-income households with water-rich landscapes and large lots are critical areas for adaptive conservation efforts, particularly since affluent households use vast amounts of water to maintain amenity-drive lifestyles with water features such as pools, spas, and fountains (Harlan et al. 2009). Given uneven patterns of demand and localized effects in the factors that drive consumption overall, targeted conservation to particular actors or communities will be most effective for increasing water-use efficiency and equitable decisions and outcomes (Larson et al. 2013a). Yet some initiatives—specifically water education efforts—are unevenly distributed and emphasize middle class neighborhoods (Cutts et al. 2012), as opposed to targeting affluent areas with high rates of water use. Outreach programs also target centrally located areas, which could lead to retrofitting older homes with efficient appliances. But such conservation initiatives do not cover the fringe communities that are most vulnerable to water shortages because of less reliable supplies (Bolin et al. 2010; Larson et al. 2013b).

In order to offset the costs of structural changes in yards or households, it may be necessary to focus demand reductions on older homes in the region as well as in those with lush landscaping and large lots. In affluent areas, people may be more willing to adopt technologies such as home infiltration systems (Gartin et al. 2010). Because cost constraints do not influence residents who have expendable budgets to install low water-use landscapes or appliances, appeals to status (perhaps relative to the opportunity costs and tradeoffs in making decisions) may be more critical than financial incentives in high-income areas. Under restricted budgets or cost constraints, people have demonstrated a willingness to give up substantial amounts of outdoor water, especially compared to high-priority indoor uses for health and sanitation (Sadalla et al. 2012). Participants in this study also placed a high value on having access to a pool, but were willing to share community pools in order to conserve water.

Based on the integration of social data on perceptions with spatial data on water use rates, another study demonstrated that local areas with high usage rates but low perceptions of consumption should be targeted to increase awareness about their relatively high consumption rates (Larson et al. 2013a). High-income areas with xeric, drought-tolerant landscapes especially exhibit mismatches between perceptions and actual water use behavior, likely due to pools and other water-using amenities that lead to high rates of consumption in spite of low water-use yards. Over-irrigation is another possible explanation, since residents with automated irrigation systems, which typically operate efficient drip systems in xeric yards, may be set higher than plant needs. Further, residents appear not to adjust automated irrigation schedules based on weather patterns and climatic needs (Balling and Gober 2007).

Some experimental evidence suggests that water-intensive lawns may be associated with status-oriented views of homeowners as more family-oriented, sexually attractive, and extroverted (Sadalla et al. 2012). In this study of landscape preferences, participants with relatively strong environmental value orientations (as measured by the New Ecological Paradigm Scale, or NEP) were more willing than others to choose a low water-use (xeric) landscape as well as to consume less water and to allocate more of a capped budget to protecting native plants and wildlife (Sadalla et al. 2012). Although some studies provide evidence that people attach environmental values to water-conserving yards, other studies have found the relationship between environmental values or attitudes and water-conserving behaviors to be insignificant and even contradictory. For example, concerns about water shortages were not at all influential on landscape choices in a study of Phoenix neighborhoods (Larsen and Harlan 2006). Additionally, Larson et al. (2010) showed how environmental values are actually associated with grassy landscapes. Biocentric orientations also correlated with more frequent watering in winter months compared to residents with weaker ecological orientations (i.e., relatively anthropocentric views). Thus, the relationship between environmental values and landscape choices is tenuous at best, in part due to the social construction of "nature" by caring for yards including turfgrass and other non-native plants (Larson et al. 2009a).

A number of counterintuitive findings have emerged from DCDC's work on water use, landscaping practices, and environmental outcomes. First, the findings from Larson et al. (2010) indicate that environmental values do not result in low water-use yard choices and irrigation practices, as indicated above. Also contrary to common expectations, specifically the notion of Midwestern and other in-migrants bringing tastes for lawns to the Valley, a few different surveys have reliably demonstrated the opposite effect (Yabiku et al. 2008; Larson et al. 2009a; Sadalla et al. 2012). In other words, long-time residents of arid Phoenix prefer their grassy yards more so than newcomers, who tend to prefer desert-like 'xeric' yards. This phenomena may well illustrate a legacy effect in which the promotion of the area as a lush "oasis"—in which "the desert is a myth" (as claimed by regional booster campaigns)—has solidified in local cultural mentalities, wherein long-term residents of the Valley have become accustomed to watering the desert (Larson et al. 2009a). Finally, despite the common positioning of lawns as the "environmentally bad" option in Phoenix and in general (see Robbins 2007), residents with low water-use, xeric yards use more pesticides than do those with conventional grass landscapes (Larson et al. 2010). This behavior demonstrates yet another tradeoff in land-cover choices, since xeric yards may conserve water but they also lead to greater chemical inputs (as well as higher heat stress; Gober et al. 2012).

Contrary to other studies about residency and landscaping choices (e.g., Larson et al. 2009a; Sadalla et al. 2012), longer residence in Arizona was associated with lower water use among student residents of ASU dorms (Knox and Cutts 2010). Perhaps this difference lies in the younger sample involved in this study (i.e., college aged) or that only indoor water use was evaluated. Regardless, this study also found that perceived conservation pressures among peers lower water use. Altogether, DCDC studies support self-presentation theory (Goffman 1959), which posits that peoples' choices are made based on how they wish to be perceived and how they present themselves or are influenced by others (for more on this theory, see Larsen and Harlan 2006). Marketing messages to spur sustainable and adaptive actions should therefore rely on normative expectations and status-oriented pleas to stimulate desirable behaviors, at least for public-sphere actions (Larson et al. 2009a).

Other research has considered who consumes bottled water, and whether or not those decisions are related to risk perceptions, poor water quality, or other considerations (e.g., York et al. 2011). The most significant variables affecting bottled water consumption included lifestyle factors such as

[2] This was a collaborative initiative with the Central Arizona–Phoenix Long-Term Ecological Research (CAP LTER) project funded by NSF Grant No DEB-0423704.

socioeconomic status, being white, and having children—perhaps due to a "caregiving" effect (York et al. 2011). In their study, York et al. (2011) examined bottled water use and found that environmental concerns do not influence its consumption, but other perceptions do. While one might expect the consumption of bottled water to increase with concerns about water quality, the opposite was found; that is, drinking bottled water actually increased with positive perceptions of water quality. Another study showed, however, that residents in high-concern neighborhoods deviate from the dominant cultural model (of knowledge and beliefs), which stresses that risks are due to low investment in treatment and the desert environment. Moreover, while most people agreed that water quality can be achieved through government and household treatment and management, people living in high-concern neighborhoods more often emphasized distrust in government (i.e., as the cause of risks) and they also suggested singular solutions (e.g., drinking bottled water) (Gartin et al. 2010). In short, risk perceptions are complex and vary across groups and contexts.

3.3.2 Risk Perceptions and Attitudes in Decision-Making

To understand risk perceptions, policy attitudes, and associated decision-making processes, DCDC researchers have examined a variety of perspectives across diverse samples and stakeholder groups. Building on the tripartite framework (Dunlap and Jones 2002, etc.), three companion studies (Larson et al. 2009c, 2011a, 2011b) used data from the Phoenix Area Social Survey2 (Harlan et al. 2009) to examine affective concerns about water risks, cognitive perceptions of what causes water shortages, and conative attitudes (or behavioral intent) toward specific approaches for resource management. Overall, this and other work identifies significant dimensions along which perspectives vary, in addition to areas of divergent and convergent views among stakeholders based on their personal interests, demographic profiles, professional roles, and other factors (e.g., see also Keller et al. 2010). As explained later in this section, the context in which stakeholder views are expressed also matters, such as whether in a personal versus group situation (Wutich et al. 2010).

Concerns about environmental risks vary across different stakeholder groups, in part depending on the scale and type of risks involved (Larson et al. 2009c, 2011a, 2011b). Residents tend to worry about the safety of drinking water in their neighborhoods, for example, but not as much about local rates of water consumption (Larson et al. 2009c, 2011b). These findings, along with others, suggest that residents tend to distance environmental risks away from themselves and their local communities, unless perhaps a personal health risk is incurred (e.g., from unsafe drinking water). Safety concerns about drinking water are especially acute among women, who also tend to be more concerned about climate change (Larson et al. 2011a). However, no gender differences exist regarding attitudinal support for varying management approaches, and men and women generally agree on causal factors for water shortages (this finding is discussed further below). Most residents also express broad concerns about the impacts of regional drought, which is out of their control, as do policymakers and scientists (Larson et al. 2009c).

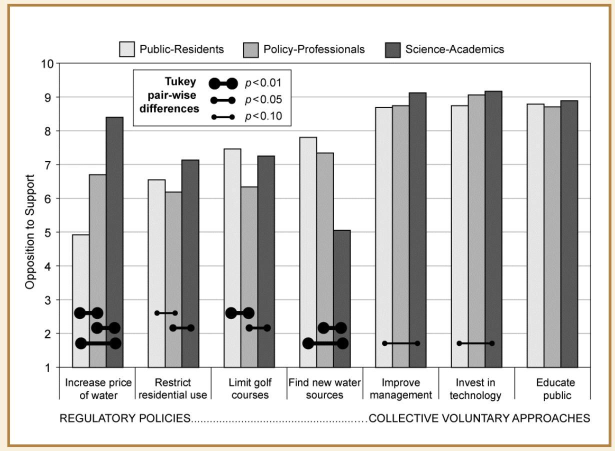

Fig. 12 Comparing Residents, Policymakers, and Scientists on their Support for Various Water Management Alternatives *(from Larson et al. 2009c).*

While the sufficiency of water supplies is of great concern across all groups, water providers worry most about cost, performance, and politics, but not about nature and environmental impacts of decisions (Keller et al. 2010). Not surprisingly, the private sector is relatively concerned about economic impacts, and environmental groups care about environmental impacts of water resource decisions. Such divergences in resource concerns reflect areas of potential conflicts in decision-making, as well as potential constraints to collaborative research or decision-making (Larson et al. 2009c, 2011a). Yet converging views also exist. For instance, an anthropological study showed a high level of "cultural consensus" among Phoenix residents in terms of how they view water quality and management (Gartin et al. 2010). Specifically, residents commonly emphasized financial and infrastructural investments and improvements, in addition to combined government and household efforts to establish acceptable water quality. Higher income people most adhered to these cultural views, and otherwise, they seem better able to adapt to water scarcity risks through the adoption of technologies.

Interestingly, policymakers are less concerned about regional water use rates than both residents and scientists, posing a constraint on regulating demand as a means of adaptive conservation (see Figure 12; Larson et al. 2009c). Findings from this study further demonstrate the supply-side orientation of water managers given their relatively strong support for acquiring more water to address shortages. By comparison, scientists stress managing demands through price-based and regulatory approaches. These diverging science-policy views present a barrier to translating knowledge about residential demands, price structures, and other aspects of conservation into water management decisions. It also explains why resource managers (policymakers) were weary of building politically unpopular pricing schemes into the WaterSim model in the early days of DCDC. Counterintuitively, water managers in this study opposed regulating residential water use more so than residents themselves. Meanwhile, both policymakers and residents show a distancing of causal factors away from residential responsibilities and policies. Instead, these groups focus on climatic sources of water shortages, especially drought. Residents also tend to blame other people and sectors for potential water scarcity risks, including new in-migrants and golf courses, thereby personally disengaging with resource problems and potential solutions.

Different views about the role of agriculture in the region exist among farmers and other stakeholders (Bausch et al. 2013). Water management policy, developed several decades ago, has shaped a pervasive belief that the urbanization of agricultural land is inevitable, leading to an expectation that "agriculture is obsolete." Yet, the farming sector plays an active role in groundwater storage for future supply, in return receiving subsidized Colorado River water (York et al. in preparation). In recent years, the combination of the slowdown in the housing market and upturn in global commodity markets has led some agricultural stakeholders to imagine farming persisting into the future. Farmers have proven adaptive to previous challenges (e.g., pest infestations) and have strong (e.g., senior) water rights, which leads some stakeholders to see agriculture as resilient. One interviewee claimed, "They can literally farm forever." Many stakeholders also see agriculture as providing real and potential benefits to the region, such as economic activity, food and water security, community, and quality of life (Bausch et al. 2013). Other DCDC research also discusses the potential for farms to provide several benefits, including acting as a buffer against temporary water shortages (Larson et al. 2013c; York et al. in preparation). These studies call into question the future role of agriculture, suggesting that there may be a need for dialogue about policies that allow adaptation through flexible water transfers as well as other benefits provided by farming (e.g., local food, open space).

A cross-national study found a similar cultural model for climate change among six counties, although Fiji and Ecuador did not share the dominant model with the others (which included a Phoenix sample for the U.S., as well as others for the U.K., Australia, and New Zealand; Crona et al. 2013). Similar to other studies in Phoenix (e.g., Larson et al. 2011a), women shared the dominate understanding of climate change as having anthropogenic causes, natural changes and impacts, and negative health effects. More highly educated people shared these same understandings. In addition, another cross-cultural study showed how institutions (norms and rules) dominate water resource decisions across countries, although Bolivia exhibited greater normative influences than in the U.S., Fiji, and New Zealand (Wutich et al. 2012a). Residents of less developed Bolivia also were concerned with interactional justices (which deal with fairness in social exchanges and actions) more so than the other countries, while distributional and procedural justices are important concerns across countries. This is largely because in Bolivia, private water truck vendors violate the normative, moral expectation that they will sell water to any willing buyer. Contrasts between developed and developing nations also included greater respective emphasis on agricultural water needs and fair water quality rules. Other culturally shared norms of justice encompass: a basic human right to water, access to safe water, entitlements to water, environmental stewardship, water markets, and fair governance (Wutich et al. 2012b). Even though these justice concerns are shared across nations, specific local situations determine how to apply institutions to meet norms about fairness.

Situational factors influence expressed views about water and how resources are managed, as seen in localized effects on perceptions (e.g., Larson et al. 2009c; Wutich et al. 2012a) and the impacts of visually displayed modeling information (e.g., Larson and Edsall 2010; Hu et al. 2012). In one study, decision-makers volunteered more opinions on self-administered questionnaires than in focus groups for highly sensitive topics (i.e., scientific validity of the WaterSim model and vulnerable communities), but not for more benign topics (Wutich et al. 2010). The exception was if decision-makers saw "gatekeeping" opportunities to share critical information or resolve pressing problems through dialogue, specifically regarding agenda setting and political uncertainty. Another study showed that cooperative decisions arose more often when research participants were given communal computer displays rather than individual ones (Hu et al. 2013). In particular, those with communal displays were more likely to invest money collectively in a community project. This finding is further supported by studies that demonstrated how visual information can lead to shared understanding by narrowing focus to specific risk factors and mitigation strategies (Edsall and Larson 2009; Larson and Edsall 2010; Hu et al. 2012). Yet Hu et al. (2012) caution that unintended consequences may arise by limiting the scope of deliberative conversations to only considerations presented in such settings. Nevertheless, Hu et al.'s interactive computer simulations with WaterSim positively impacted learning outcomes concerning the relative importance of sustainability compared to other risks. These sessions also increased awareness of the complexity of differing stakeholder interests, uncertainties about the future, and diverse policy options.

Other studies have shown that visual information can impact perceptions about risks, depending on both the nature of the risk (e.g., UHI effects versus groundwater depletion), how those risks are displayed (e.g., in a 2D PowerPoint or 3D immersive presentation), and the type of judgment involved (e.g., perceived causes of risks versus effective solutions for their management) (Edsall and Larson 2009; Larson and Edsall 2010). One study found that the immersive 3D environment affects perceptions about the severity of the heat island more so than groundwater depletion, perhaps due to experiential nature of temperature and heat relative to cross-section depictions of water we cannot see underground (Edsall and Larson 2009). Meanwhile, the visual 3D information did not alter the perceived causes of risks as much as judgments about the effectiveness of particular solutions. This suggests visual information may not gain agreement on the sources of the problems but could still advance collective decision-making regarding potential risk-management alternatives (see also Hu et al. 2012). Another analysis conducted on this same study examined the value basis of perceptions, revealing that perceptions entrenched in ideologies about the environment and politics—especially beliefs about the natural vs. anthropogenic causes of environmental risks and the effectiveness of regulatory strategies— do not change as readily as others (Larson and Edsall 2010).

3.4 Science-Policy 'Boundary' Studies

3.4.1 Interactions among Researchers and Decision-Makers

From the outset, DCDC was designed to implement the concept of a "boundary organization" (BO). A number of studies have examined science-policy dynamics including how water managers view and interact with science endeavors as well as how they frame and deal with uncertainties in decision-making (e.g., White et al. 2008, 2010; White 2013). In one paper, two divergent views emerged among water managers in an interview-based study (White et al. 2008), and these are consistent with the "engineering model" and "socio-organizational" models of knowledge transfer discussed elsewhere (Crona and Parker 2011). First, some managers—especially those trained in traditional scientific or engineering fields—view science and policymaking as distinctive spheres, wherein decisions are made rationally and information flows in a linear chain from researchers to policymakers (White et al. 2008). The second, post-normal view—held by water managers with decision-making authority—perceives science and policy as more fluid and recursive processes of interaction. The policymakers who hold the latter viewpoint may be more adept at collaborating with researchers to develop relevant knowledge, share data, create scenarios, and communicate findings to diverse stakeholders. From these interviews with water managers, a prescriptive model of the boundary interface was developed in which a variety of policy actors interface with the research community in a way that respects each other's spheres and highlights various types of uncertainty (Figure 13). This and other research advance the theoretical understanding of boundary organizations and how they impact knowledge transfer and decision-making through iterative and adaptive processes of learning (White et al. 2010; Crona and Parker 2011, 2012; Parker and Crona 2012).

Major considerations for BOs entail the need to reconcile scientific versus political pressures, different lines of accountability across sectors, the slow speed of research compared to short-term decision needs, and differing interests in basic sciences versus applied research (Crona and Parker 2008; White et al. 2010; Quay et al. 2013). Another tension arises from policymakers' primary concerns about the scientific credibility as well as the saliency and legitimacy of research (White et al. 2010), whereas DCDC investigators have been more concerned about developing interpersonal relationships for data sharing and other goals (Crona and Parker 2008; Quay et al. 2013). Perhaps this is due to the fact that DCDC researchers and stakeholders have learned much from their collaborations over the past several years (Quay et al. 2013).

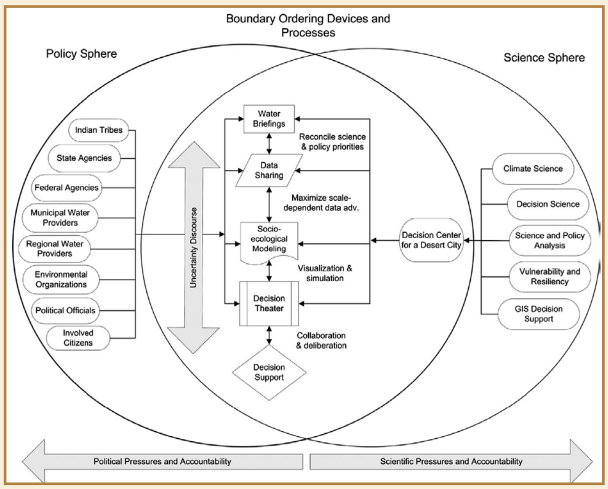

Fig. 13 The Science-Policy Interface used by Decision Center for a Desert City *(from White et al. 2008).*

A study by White (2013) found a longstanding awareness among DCDC researchers regarding the importance of how individual actors and social groups frame issues and how their perspectives play out through social processes in environmental decision-making under uncertainty. Relying on semi-structured interviews, focus groups, documents, and participant observations to describe the diagnostic and prognostic frames for water sustainability (i.e., as expressed in relation to WaterSim), the analysis identified a diagnostic frame defining the water sustainability problem as uncertain and long-term water supply shortages caused by prolonged drought, climate change impacts, and population growth. The prognostic frame defined the solutions to be urban residential water demand management, retirement of agricultural lands, and conversion of agricultural water to municipal uses to achieve safe yield of groundwater. In the initial versions of WaterSim, water sustainability was framed in fairly narrow and conventional terms of a water supply-demand balance to satisfy human uses (although as mentioned earlier, the model has been revised based on studies such as White 2013, Wutich et al. 2010, and White et al. 2010). While such framing touches on a relevant policy framework, it does not necessarily open up the discourse to novel or innovative solutions. Thus, one implication of this study is that a sustainability frame in and of itself is not necessarily a mechanism for recasting policy discourse in novel ways, unless sustainability itself is defined in comprehensive terms.

Trust and open communications in neutral spaces are central to understanding each other's needs, concerns, and interests for the successful "co-production" of rigorous knowledge as well as useful scientific information (Crona and Parker 2012). Cultural divides must also be addressed including distinctive organizational missions (e.g., for water versus land planning) and traditions among researchers and decision-makers (e.g., responsibilities to 'publish or perish' versus public duties beholden to the ultimate decisions made by elected officials) (Crona and Parker 2008; White et al. 2008; Gober et al. 2013). Two specific stereotypes to overcome are scientists' views of policymakers as narrowly focused bureaucrats, and policymakers' views of researchers as "ivory tower" academics who do not understand water management decisions (Crona and Parker 2008). As such, power relations among stakeholders and their ability to influence research or policy decisions or otherwise engage in social learning must be evaluated (Crona and Parker 2012).

As discussed earlier, DCDC research has examined how decision-makers perceive and respond to boundary objects such as the WaterSim model and other visual information (e.g., White et al. 2010; Wutich et al. 2010; Larson and Edsall 2010; Cutts et al. 2011). Cash et al.'s (2003) notions of credibility (accuracy and adequacy of evidence and logic), saliency (relevance of information to decision needs), and legitimacy (fair and inclusive consideration of stakeholders' values and interests) have been useful in evaluating decision-makers' views of scientific knowledge (Quay et al. 2013). One study on WaterSim, for example, showed how diverse decision-makers (policymakers, data analysts, and consultants) were initially skeptical about the model's credibility, salience, and legitimacy (CSL; White et al. 2010). In particular, policymakers viewed the model as more credible and legitimate than the other two groups, perhaps because WaterSim includes policy "levers" (e.g., drought and growth) that are frequently considered in resource management, or because they are accustomed to dealing with uncertainties (White et al. 2008). Yet a related study showed that policymakers critiqued WaterSim for its failure to address their interests and expertise (Crona and Parker 2008), and due to their distrust of science broadly (Crona and Parker 2012). More recent activities have addressed these deficiencies by downscaling the model to local provider territories and adding demand-side considerations, among other activities (Crona and Parker 2012). However, the political realities of certain management and adaptation strategies (e.g., limiting or controlling growth) remain a concern among decision-makers (Crona and Parker 2008).

Overall, analysis of decision-makers' critiques of early versions of WaterSim by White et al. (2010) reveal credibility problems given the lack of new tree-ring data and hydrologic information; saliency concerns because of the regional scale of the model (as opposed to depicting outcomes at the water provider level, at which decision are made; see also Crona and Parker 2008), as well as the long-term nature of scenarios and associated uncertainties; and, finally, criticisms about legitimacy since the model was seen as depicting the status quo while also excluding particular stakeholders (e.g., Native Americans and environmentalists). This research also shows how differing views about decision needs and interests result in tradeoffs across various groups and criteria. The exclusion of certain actors and values produced skepticism among some analysts and consultants, whereas policymakers were relatively positive about the conventional nature of the model. Another study of diverse group perspectives (Parker and Crona 2012) evaluated the views and interactions of university administrators, academic researchers, water managers/policymakers, and the National Science Foundation. They identified four tensions arising from varying views among these groups: interdisciplinary vs. disciplinary research, timeframes for research vs. decision needs, basic vs. applied research, and autonomy vs. consultancy.

Cutts et al. (2011) also used the CSL framework to examine water educators' reactions to and interactions with maps that depict the spatial distribution of informational products and educational efforts in the Phoenix area. Through a participatory process involving Geographic Information Systems (GIS), this study showed that water educators increasingly viewed the co-produced maps (which served as boundary objects) as legitimate and credible after they had the opportunities to 1) express their individual concerns, and 2) collectively discuss how to improve the data and how it is represented. Specific concerns included the use of an economic indicator of educational efforts, in addition to the political and budget ramifications of depicting efforts at the water provider level. Agreements then ensued to represent educational endeavors in aggregate and to use a broader indicator to identify areas of relatively high, medium, and low information. In sum, this project created an approach to engage stakeholders in mapping educational programs with point and areal data at different scales. Although the economic indicator of water information availability was not widely accepted by educators, the techniques employed showed that mapped outcomes vary depending on the use of boundaries (for census and zip code areas) and distance buffers for points (Cutts 2013).

When it comes to acquiring water knowledge, information seeking and a sense of personal efficacy are more important than attitudes, information availability, and neighborhood location (Cutts et al. 2012). Gender and homeownership respectively influence "ecological" knowledge (wherein men have more technical knowledge than women) and "procedural" how-to knowledge (wherein homeowners know how to reduce water consumption more so than renters). Though educational programs emphasize declarative, technical/ecological knowledge about topics such as groundwater, the hydrologic cycle, and natural water bodies (Cutts et al. 2008), other forms of knowledge (e.g., procedural how-to information, awareness of impacts) are known to be more effective in changing conservation and sustainability behaviors (see Frisk and Larson 2011 for a review).

3.4.2 Social Networks and Processes in a Boundary Context

Boundary studies of DCDC have employed social network analysis to examine boundary-spanning activities and challenges (Crona and Parker 2008). Results reveal a communication network of one relatively small group of main actors and nine smaller

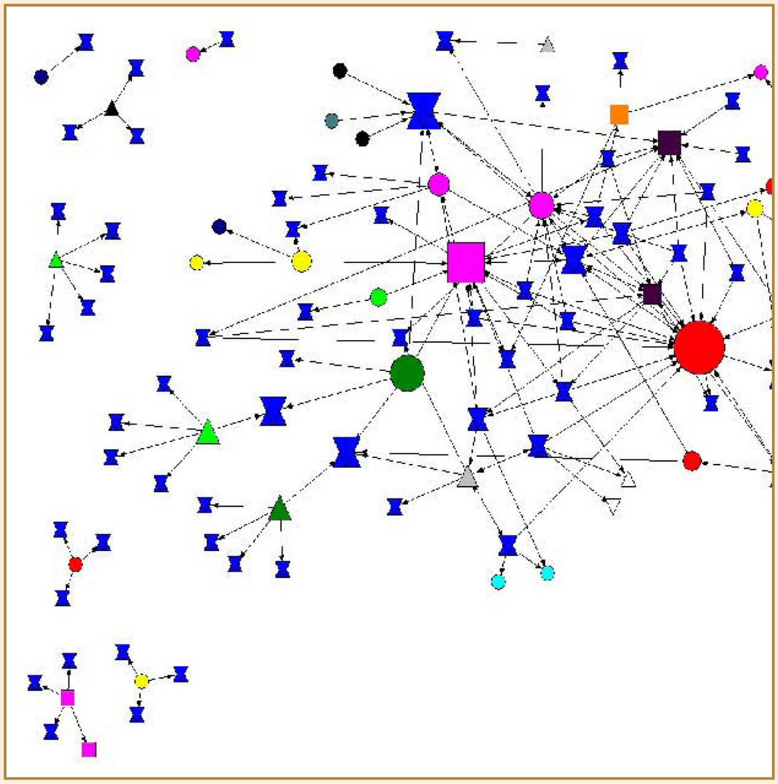

Fig. 14 Interaction Network between Policymakers and Affiliates of Decision Center for a Desert City (from Crona and Parker 2008).

This network figures illustrates:
1) Actor Positions: Faculty = circle, Staff = square, Upward triangle = graduate students and postdoctoral researchers, Other = Downward triangle; Policy member =Hour glass.
2) Betweenness Centrality: The size of the node indicates its relative degree of centrality.
3) Disciplines: Anthropology/Human Evolution and Social Change = black, Geology/Earth and Space Exploration = light grey, Ecology/Life Science = light green, Sustainability = pink, Education = teal, Planning, Policy and Community Development = yellow, Business and Economics = Dark Blue, Geography = red, History = dark green, Decision Theater = orange, Decision Center for a Desert City = purple, Mathematics and Computing = baby blue, City of Phoenix = dark grey, Other = white.

groups that have more isolated policy–university interactions (Figure 14). This study found that DCDC's early research initiatives were only moderately interdisciplinary in nature, with a lack of integration across the social and biophysical sciences. These findings have influenced ongoing and future opportunities for community engagement and transformative sustainability science, which necessitates integrative approaches to human-environment systems. Additional results from the same study also showed how the dynamics of social networks at DCDC influences the utilization of related research (Crona and Parker 2011). Specifically, direct interactions between policymakers and researchers enhance the use of DCDC information, and indirect discussions about DCDC research among policymakers themselves also increase information usage. However, the centrality of actors in the network had no effect on how knowledge is utilized, which suggests that limited interactions among researchers and policymakers still affect knowledge utilization.

Specific boundary organizing processes at DCDC include: monthly Water/Climate Briefings, where presentations and panels facilitate discussions and networking among diverse actors including faculty, students, stakeholders, and community members; the Internship for Science Policy Integration (ISPI), which brings students, faculty, and community partners together as full collaborators in research and training; data sharing among researchers, policymakers, and others to support collaborative projects and trust-building for collective interests and concerns; and, modeling, visualizations and related decision studies that offer a boundary object to develop a shared understanding of problems and improve the credibility, salience, and legitimacy of research (White et al. 2008; Larson and Edsall 2010; Crona and Parker 2012; Quay et al. 2013). According to both researchers and practitioners, the ongoing strengths of the network include: 1) network facilitation through Water/Climate Briefings and other meetings and workshops; 2) climate research of interest to decision-makers such as the Salt River Project and the Bureau of Reclamation (see earlier section); 3) modeling results (e.g., WaterSim) and visualization alternatives, including the Decision Theater as a neutral space for "de-personalizing science"; and 4) educational outreach through ISPI and regular workshops with Project WET (Water Education for Teachers) and other initiatives (Crona and Parker 2008).

Over time, DCDC has changed some of its activities and approaches to address challenges and tensions in science–policymaker interactions and to build capacity for turning knowledge into action by adapting to problems or issues as they arise (Crona and Parker 2008). One challenge is the focus of the University and NSF on basic research whereas decision-makers are more concerned with applied information. Another is that the University and NSF are pushing for interdisciplinary work while researchers tend to be disciplinary focused, in large part because of training and award structures (Parker and Crona 2012; see also Quay et al. 2013). Researchers also tend to work autonomously, rather than as consultants, which can diminish the salience of research findings to decision-makers (at least in the Phoenix area). Finally, the relatively long-term nature of research deviates from decision-makers' needs for real-time information.

The DCDC adapted to early challenges by reorganizing its advisory committees to include more academics than decision-makers (Parker and Crona 2012). In order to meet interests in research autonomy and expectations for basic research to satisfy NSF, the Center changed its advisory boards to comprise mostly academics while also hiring a community liaison from the water management community to improve the salience of research to decision-makers. Such "brokers" can help forge connections among key actors and maintain information flows across the networks of various stakeholders (Crona and Parker 2012). The DCDC has also kept a sharp focus on basic research and 'big ideas' involving broad temporal and spatial scales, which necessarily demonstrate the complexities and uncertainties of water governance in Phoenix (Parker and Crona 2012). Yet the Center has learned to listen and communicate better to meet real-world decision needs (Quay et al. 2013), for example, by responding to criticisms about WaterSim (e.g., downscaling results to the provider level; White et al. 2010; Parker and Crona 2012).

Finally, interdisciplinary research has been advanced by prioritizing integrated projects over disciplinary ones and structuring Water/Climate Briefings to facilitate multidisciplinary viewpoints on particular subject matters. A relatively new internship program (ISPI) has also been extremely successful—from the views of professors, students, and intern sponsors. Through the placement of students in appropriate internship experiences, the students have gained much experience spanning the science and policy or practitioner realms as community liaisons for DCDC and ASU's Global Institute of Sustainability (Quay et al. 2013). In fact, skeptical policymakers emerged from the first rounds of internship experiences touting their benefits and wanting to engage more in DCDC's research and educational activities. Although wary at first, the internship hosts realized just how worthwhile the experience can be for them, as well as for the students and university researchers. Further, making connections across individual projects—including through this synthesis—has been an increasing priority for the DCDC now that it has been operating for several years (Parker and Crona 2012).

4.0 Concluding Remarks

For over nearly a decade, DCDC researchers have studied the complexities involved with environmental decision-making under multiple uncertainties, including non-linear effects, thresholds, and tradeoffs. Although scientific knowledge can improve our knowledge about trends, patterns, and processes regarding water supplies and demands, as well as climatic and other impacts, recent studies underscore the limits to our knowledge on these topics about what the future holds (e.g., Ellis et al. 2008; Balling and Cubaque 2009).

Uncertainties that impact decision-making extend beyond climatic variability and change to also encompass uncertainties about the future allocation of water rights and future growth in the region (White et al. 2008). Uncertainty exists not only about climate or other urban-environmental conditions, but also because of imperfections or limitations in the current state of science (e.g., incomplete or inadequate data, modeling assumptions and simplifications; White et al. 2008, etc.). Since uncertainties about complex and future dynamics cannot be avoided, water management and planning in the 21st century requires improved paradigms for research and policymaking that explicitly account for these uncertainties (Quay 2010; Gober et al. 2010b, 2013). In particular, an adaptive approach is needed that anticipates a range of potential future outcomes and considers various adaptation strategies that will perform well regardless of exactly what happens (Quay 2010). Fortunately, water managers are accustomed to dealing with uncertainties, despite the traditional "predict a single future and plan for it" model of decision-making, and therefore this change in approach should be feasible within existing water management processes (White et al. 2008; Quay 2010).

Due to tradeoffs inherent in decisions about water and other resources (e.g., land, energy), integrated planning across sectors should be central to managing water in cities and to developing scenarios for the future (Gober et al. 2013). In the face of fragmented governance regimes and in the context of water systems that operate at multiple scales, coordination among water and other agencies, public and private sectors, and local to international scales can also help in anticipating system stressors and adapting to urban-environmental change (Larson et al. 2013b). According to Wiek and Larson (2012), moreover, multi-objective planning is a mechanism for balancing the assorted social-ecological tradeoffs that exist in making decisions about how to use, distribute, allocate, and treat water (see also Larson et al. 2013c). A range of management and adaptation choices should also be considered, as no single "one size fits all" solution is adequate for sustainable water governance (Gober and Kirkwood 2010). This means that supply augmentation or demand management alone are each likely to be insufficient for effectively addressing resource challenges into the future, partly because the former is costly and politically difficult. Meanwhile, the latter leads to lost revenues, demand hardening, and a lack of flexibility in adapting to rising water scarcity (Larson et al. 2013b).

Though the solutions to better managing urban environmental risks are not simple, we have found through DCDC that coordinated research–policy studies and related educational activities have greatly benefited scientific and community understanding of climate change, uncertainty, water governance, and urban adaptation. The collaborations and networks that DCDC has built in its role as a boundary organization have been well worth the time and effort required. We will continue to forge meaningful relationships with other stakeholders to help improve planning and management, as well as increase learning among professors, students, policymakers, and other stakeholders. Taken as a whole, DCDC activities and participants have enhanced, and will continue to enhance in the future, both basic science and real-world decision-making. By participating in DCDC activities, students are also provided with incredible professional opportunities spanning both university research and real-world practice that help prepare them to better address our challenging future. Last, but certainly not least, we have built connections and increased capacities to address these important topics, within Arizona State University and the greater community, by productively engaging with policymakers in research, educational, and community activities.

For more information about DCDC research and related activities, visit **http://dcdc.asu.edu/**.

DCDC

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