



DCDC I Final Report

Decision Center for a Desert City
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DCDC I Final Report	
Table of Contents	
I. Introduction to DCDC	3
II. Findings of Research Activities	17
III. Education and Development	22
IV. Outreach Activities	26
V. Contributions	33
VI. Partner Organizations	35
VII. DCDC Participants	41

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I. Introduction to DCDC

In 2004, the National Science Foundation (NSF) established the Decision Center for a Desert City (DCDC) at ASU to advance the scientific understanding of water decision making in the face of climate uncertainty and other environmental risks, using Phoenix as an experimental research and outreach laboratory. We structured DCDC as a boundary organization at the interface of science and policy to play a translational role, converting the products of climate science into tools for better decision making under uncertainty. To date, DCDC efforts have resulted in: (1) a critical mass of basic research, including over 200 articles, books, and book chapters, 75 of them appearing in 2009 and 2010; (2) WaterSim, a dynamic water-simulation model that serves as an important basis for community engagement, a point of articulation for interdisciplinary research, and an experimental setting to study decision making under uncertainty; (3) a network of relationships with regional water managers and resource decision makers; and (4) a significant and growing set of comparative and collaborative partnerships linking our Phoenix case study to climate adaptation efforts nationally and globally.

As the mission of DCDC evolved to focus on urban climate adaptation, our vision of knowledge production, science-policy engagement, and community outreach matured. We conceptualized research, learning, and outreach as synergistic activities as feeding upon and reinforcing one another rather than as discrete activities. Our priority was on discoveries at the intersection of basic and applied research in what has come to be called Pasteur's Quadrant. We sought to maintain a balance between new data collection and analysis and synthetic activities that integrate existing data, models, and knowledge. Attention increasingly was focused on feedbacks and nonlinearities that produced unintended consequences and revealed hidden vulnerabilities in complex urban resource systems, as for example, when cities seek to solve their warming problems with increased water use for vegetated landscaping (Gober et al. 2010a) or when unsustainable land use practices lead to unsustainable water use (Quay and Gober 2011).

Climate research and policy making over the past 20 years have revealed that fundamental disagreement about the underlying natural and social forces that shape the future and uncertainties associated with climate modeling will *increase rather than resolve* over time. As we more fully understood this reality, we built capacity to address multiple potential futures through scenarios, simulation modeling, anticipatory governance, and the principles of decision making under uncertainty.

Research Activities

Simulation Modeling: WaterSim

We built and implemented WaterSim, a simulation model, to investigate how alternative climate conditions, rates of population growth, and policy choices interact to affect future water supply and

demand conditions in Phoenix. WaterSim represents supply from surface and groundwater sources and demand from residential, commercial, and agricultural user sectors, incorporating the rules that govern reservoirs, aquifer use, and land-use change. The development of WaterSim was documented in Gober et al. (2011) and Sampson (2011). We always planned that WaterSim would evolve as our understanding increased, and thus, our modeling efforts were responsive to feedback from stakeholders and the research and instructional needs of DCDC participants.

During the latter years of DCDC I, WaterSim 4.0, was expanded to investigate inputs and outputs at the water-provider level and restructured as a multi-language library to make future modifications more straightforward to implement. Scaling to the water-provider level was implemented in response to stakeholder inputs that water decision making in the Phoenix area occurs primarily at the local scale. WaterSim 4.0 is comprised of: (1) a Microsoft C# interface; (2) a C# library module; and (3) a simulation model written in FORTRAN that houses the rules and algorithms to model water supply and demand, all at the water provider-level.

The model runs simulation using an annual time-step, but monthly estimates can be generated for many of the principal output variables. WaterSim 4.0 produces water supply and use patterns for 33 Phoenix Metropolitan Area water providers. Other improvements in version 4.0 include: (1) expansion of the Salt-Verde reservoir operations sub-model to include a more robust estimate of reservoir release based on provider designations, and inclusion of new conservation space allocations; (2) the addition of a city infrastructure module that tracks water movement among the various city “elements” such as surface water treatment plants, water supplies, residential and commercial water use (indoor and outdoor), and waste water treatment plants, to name a few; (3) new modules to estimate the total dissolved solids (TDS) of the water resources used by water providers; and (4) an approach to estimate the electricity used in moving the Central Arizona Project (CAP) water along the CAP aqueduct to Phoenix.

Decision Science and Policy

The goal of DCDC’s decision-science program was to investigate and develop decision analytic frameworks for complex problem formulation for water resource management. The decision science team, led by Craig Kirkwood from the W. P. Carey School of Business and Robin Keller from the University of California-Irvine’s Merage School of Business, conducted basic research on decision making and incorporated integrated methods of prescriptive decision analysis within DCDC’s larger research program. Their article in *Systems Engineering* presents an approach for efficiently assessing stakeholder perceptions of evaluation concerns in the first stage of problem structuring for decisions involving complex systems (Keller et al. 2010). This research used output from a Web survey to assess the appropriateness of a set of evaluation concerns for water policy including an analysis of variations among stakeholder group priorities. While the specific outputs from this study are directed at Central Arizona water resources decision making, the basic approach can be used in other policy settings.

Keller, Kirkwood, and former UC-Irvine postdoc Jay Simon also completed and submitted for publication research to develop and implement new decision-analysis methods for problems with geographically varying outcomes (Simon et al. in review at *Operations Research*). This research developed new quantitative results and applied results to illustrative applications in water resource decision making and other policy-oriented settings. Decision research also integrated decision analysis concepts into climate and WaterSim research. These efforts resulted in publications that explicitly addressed climate uncertainties through scenarios and multiple evaluation attributes. Relevant publications include Gober et al.'s (2010b) presentation of a new paradigm for long-term water planning in the *Annals of the Association of American Geographers* and Gober and Kirkwood's (2010) *Proceedings of the National Academy of Sciences* study of water sustainability in Phoenix.

Human-Climate Interactions in the City

Building on previous urban heat island research and a growing interest in the interactions between urban energy and water, DCDC researchers broke new ground in their understanding of urban resource systems and climate impacts on them. Central to this research is how to redesign cities to accommodate climate impacts. An early focus on water expanded to the energy and carbon impacts of various urban designs. DCDC-funded planner Subhrajit Guhathakurta, engineer Eric Williams, and graduate student Stephane Frijia quantified the tradeoffs between high-density, high-rise buildings that save land and energy for transportation, and low-density, low-rise buildings that have less embedded energy and more benign direct climatic impacts but engender more automobile travel. Collaborating with DCDC postdoctoral fellow Ariane Middel, they refined ideas and methods for a successful proposal to the Civil Infrastructure Systems (CIS) Program at the NSF. The ongoing funded project aims to clarify how urban form, land-use patterns, and type of structures influence a city's energy needs and greenhouse gas emissions. The analysis tracks the evolution of a network of energy use as an area develops and accounts for life cycle impacts in construction and manufacturing processes, end-of-life buildings, roads, and vehicles. This project illustrates DCDC's role as an incubator of interdisciplinary research about urban climate adaptation. It was focused on a critical tradeoff for decision making, linked DCDC's longstanding interests in human-climate interactions to life cycle analysis, and leveraged a relatively modest DCDC investment in exploratory research into a freestanding, long-term research initiative.

Geographers Patricia Gober, Anthony Brazel, and Kelli Larson and postdoctoral fellow Ariane Middel collaborated with colleagues at Portland State University (PSU) on a NOAA-funded project to investigate land/water interactions in Phoenix and Portland. Resulting research addressed tradeoffs and feedbacks inherent in water-conservation programs designed to curb outdoor water use. Managers seeking to reduce outdoor water use face a difficult choice because a watered landscape ameliorates temperature in many cities, particularly those with hot, dry climates. The Phoenix-Portland project uses a neighborhood-level, energy balance model, Local-scale Urban Meteorological Parameterization Scheme (LUMPS), to estimate latent heat (energy used to evaporate water) and derive nighttime and daytime cooling rates across almost 200 Census block groups in each of the two cities. Results pinpoint where and when outdoor water provides the most efficient urban cooling

and estimates how much additional water is needed to retain existing temperatures under climate-change scenarios. A workshop to share results with Portland water and land managers was held in October 2010. Other LUMPS research projects include: Middel et al.'s (2011a) study of the effects of land cover mixes on surface energy balance in the *International Journal of Climatology*; Middel et al.'s (2011b) review of land-cover modification scenarios in the *Journal of Urban Technologies*; and Myint et al.'s (2011) methodological piece about remote sensing techniques for land-cover classification in *Remote Sensing of Environment*. Two additional articles from the project currently are under review, with several others in preparation. The PSU-ASU collaboration was an example both of leveraging DCDC funding with support from other sources and transferring what we have learned about climate adaptation in Phoenix to other cities.

Governance and Cooperation as a Climate Adaptation Strategies

Fragmented and outdated water governance is a significant barrier to climate adaptation in Phoenix and indeed across the western US. Western water rights and the institutions that evolved to administer them grew out of the settlement patterns and climate conditions of the 19th and early 20th centuries. Many of these legal frameworks and water institutions are ill-equipped to manage water in an era of growing uncertainty and complexity. Coordination and cooperation will be required to manage 21st Century water systems, and thus DCDC's interests turned toward the effects of cooperation (or the lack of it) as a climate adaptation strategy.

Geographers Alan Murray, Patricia Gober, Sergio Rey, and Luc Anselin, modeler David Sampson, and graduate student Paul Padegimas developed a spatial-optimization model to support water-supply allocation between providers when some are in deficit while others are in surplus. The model uses output from WaterSim 4.0 at the provider level to examine the impacts of cooperation on deficit conditions for 33 providers under varying climate-change scenarios. This paper is under review at *Water Resources Management*.

The Morrison Institute for Public Policy - with funding from DCDC, the Lincoln Institute of Land Policy, and the Sonoran Institute and under the leadership of DCDC I PI, Grady Gammage - assessed water security in the Sun Corridor of Central Arizona. This effort allowed DCDC to expand our network of collaborators to include Lincoln and Sororan Institutes and challenged us to conceptualize water security as a larger regional issue. Furthermore, the report demonstrates our commitment to improving the linkages between basic scientific research and public policy deliberation. The resulting report, *Watering the Sun Corridor* (Gammage et al. 2011), designed for public consumption and policy analysis, concludes that, although the region is unlikely to run out of water in the near future, difficult choices lie ahead "about how to strike the right balance between population growth and lifestyles." DCDC's research program and decision tools were and continue to be explicitly focused on this choice—how to understand it from a scientific standpoint and how best to represent it to decision makers.

Environmental Economics: Water Demand Research

Economist Kerry Smith led an active and productive research program centered on water-demand and the valuation of energy-water interactions. With respect to the latter, Smith organized a conference on April 19–20, 2010 on Economic Evaluations of Water/Energy Interactions for Policy, which was co-sponsored by DCDC and the Center for Environmental Economics and Sustainability Policy (CEESP). The objective was to evaluate the methods used in water management, including integrated river management, water and energy policies, and project evaluation. Conference participants considered the economic evaluation of dam removal for large and small river systems, issues associated with planning an assessment for the Klamath River, methods used in evaluating benefit and costs for large-scale projects, and aspects of the interactions between water and energy policies.

Smith, working with postdoctoral fellows Aaron Strong and Allen Klaiber (now faculty members at the University of Iowa and Pennsylvania State University, respectively) and undergraduate research fellow Michael Kaminsky developed a new method to estimate the price elasticity of water demand by residential customers. The strategy exploits temporal variation in water rates due to cost changes over time. It does not require the detailed assumptions associated with a mixed discrete/continuous structural demand model such as presented in Olmstead et al. (2007). In addition, Klaiber and Smith completed preliminary hedonic property value models for Maricopa County that indicate subdivisions with significant mesic vegetation yield higher land values than xeric subdivisions. In 2010, Smith and colleagues published articles on these and related topics in a variety of top scientific and policy-oriented outlets including: NBER Working Papers Series, “Valuing ecosystem services in general equilibrium” (Carbone and Smith 2010); *Environmental and Resource Economics*, “Behavioral economics and benefit-cost analysis” (Smith and Moore 2010); *Resources for the Future Issue Brief*, “Pre-positioned policy as a public adaptation to climate change” (Smith 2010); and *Land Economics*, “Reconsidering the Economics of Demand Analysis with kinked budget constraints” (Strong and Smith 2010).

Smith also negotiated a data-sharing agreement with the water departments for the Cities of Phoenix and Tucson and is working on agreements with Scottsdale, Peoria, and Mesa. The goal is to assemble a dataset of water use from a variety of local water providers so that the effects of various price and non-price policies can be examined systematically.

Environmental Psychology: Why People Make the Decisions They Do

A team of psychologists at ASU, including Susan Ledlow, Ed Sadalla, Douglas Kenrick, and Steven Neuberg, employ an evolutionary perspective to demonstrate that people make decisions according to a set of principles that were functional in the environment in which human cognition, emotion, and behavior evolved (Kenrick et al. 2009). Evolutionary models suggest that people make unsustainable resource decisions because sustainability was not an issue in the environment to which humans adapted. Humans evolved with strong tendencies to focus on consequences that were immediate and certain. These ideas are applied to assumptions regarding economic rationality and utility

optimization. While traditional economic models assume a rational decision maker, “functional” approaches focus on evolved motives and the ecological context in which decisions are made.

In the final year of DCDC I, they studied water use in the Phoenix area, where water is relatively inexpensive and conservation efforts rely more on persuasion than pricing to change water consumption behaviors. The research was designed to explore which water uses are regarded as necessities (that would be more difficult for people to curtail), and which as luxuries (that would be easier for people to curtail). To that end, they conducted an experiment on residential water consumption choices, using a “tradeoff” paradigm to explore the relative perceived values of different water choices. Research questions were: (1) what are the perceived necessities associated with water usage; (2) what aspects of water usage are regarded as relative luxuries; (3) are there sex differences in perceived necessities and luxuries; and (4) how does “environmental orientation” influence the perception of luxuries and necessities?

Science-Policy Interactions and Boundary Organizations Research

Science policy interactions and boundary organizations research examined the co-production of knowledge and policy for environmental decision making. Our approach drew upon theoretical perspectives from science and technology studies, political science, and sustainability science. Research activities explored three interconnected domains: *boundary work*, or the boundary-ordering devices, processes, and methods that link science and policy; *boundary organizations*, or institutional forms positioned in the overlapping space of scientific research and political decision making and public action; and *boundary objects*, hybrid constructs that integrate elements from scientific and political worlds to facilitate the negotiation and exchange of multiple types of knowledge and action.

In an article in *Science and Public Policy*, White et al. (2010) examined decision makers’ assessment of the credibility, salience, and legitimacy of WaterSim as a boundary object. Overall, decision makers were critical with respect to the credibility of the knowledge and informational assumptions imbedded in the boundary object; they were skeptical about the salience of the boundary object to their immediate decision making needs; and they were fairly evenly divided about the boundary object’s legitimacy. This research demonstrated divergent perceptions of credibility, salience, and legitimacy between different decision making groups as well the likelihood that tradeoffs exist between credibility, salience, and legitimacy in the design and functioning of boundary objects. The line of research facilitated the redesign of WaterSim to better address decision-maker needs.

In a *Field Methods* article, Wutich et al. (2010) compared focus groups and individual responses for gathering information from decision makers on sensitive topics such as competence, risk, and gate-keeping. Decision makers were more reticent in focus groups than in individual responses for the discussion of very sensitive topics *unless* the group discussion provided an opportunity to make real progress on water policy problems. The study suggested that multi-method research may be appropriate for research on sensitive issues. In an article in *Environmental Science and Policy*, Larson et al. (2009b) examined divergent perspectives on water resource sustainability among three groups

at the science-policy nexus: the general public, policy experts and scientific experts. This study identified differences in affective environmental concern, cognitive risk perceptions, and policy attitudes between the samples.

Boundary organizations researchers studied the co-production of science and decision making through a series of collaborative scientist-manager workshops on scenario construction, uncertainty, climate modeling, and water management in Phoenix (described in Outreach Activities). Researchers Arnim Wiek and Kelli Larson examined Phoenix water management stakeholder perceptions and cross-perceptions, developed a conceptual model of the water governance structure, and created a set of sustainability principles and challenges for regional water governance (Wiek and Larson in review at *Water Resources Management*). DCDC researchers Dave White and Katja Brundiers, along with former Decision Theater Director George Basile and Senior Manager Sandra Epstein, developed an international collaboration with researchers from Tecnológico de Monterrey, Mexico. This collaborative project integrated watershed observation, hydrological flood modeling, and stakeholder engagement in the San Juan River Basin. The collaboration includes the Centro del Agua para America Latina y el Caribe (CALCA) FEMSA Foundation and the Inter-American Development Bank (IBD).

During the course of DCDC I funding, we evolved in a number of directions to: (1) more fully collaborate with stakeholders to co-produce knowledge (e.g., Gober et al. 2010a included three staff members from the City of Phoenix Water Services Department); (2) expand the range of boundary processes studied to include scenario construction and sustainability assessments (Gober and Kirkwood 2010; Quay 2010); (3) map diversity of stakeholder perceptions (Larson et al. 2009b; Parker and Crona in review at *Social Studies of Science*); (4) foster international collaborations such as one with Tecnológico de Monterrey to model and develop scenarios for the San Juan River Basin in Mexico, and; (5) transfer lessons from DCDC to other boundary organizations.

Vulnerability, Resilience, and Risk

DCDC supported two lines of vulnerability research, one focused on the risk of water shortage and the second on vulnerability to heat stress, both extensions of the water/temperature mediation research described in the human-climate interaction section above. Sociologist Bob Bolin, DCDC postdoctoral fellow Mohan Seetharam, and graduate student Brian Pompeii used a spatially explicit version of WaterSim to examine the security of local water systems under scenarios of climate change, population growth, and consumption patterns. Individual water providers differ in physical exposure to climate change based on their supply sources and in social vulnerability based on different consumption patterns and rates of growth. The root causes of vulnerability to water scarcity are found both in biophysical systems that determine surface and groundwater availability and in the social, economic, and historical aspects of institutions, people, and places. Thus, different adaptive abilities will be required to cope with declines in water availability and price increases under conditions of scarcity. Bolin et al. (2010) appears in the journal *Local Environment*.

A growing body of DCDC research focused on vulnerability to heat stress in Phoenix. The expanding and intensifying urban heat island partly motivates this work, but takes on added significance as climate change threatens to increase temperatures further. DCDC postdoctoral fellow Darren Ruddell, with geographer Anthony Brazel and students Desiree Hoffman and Omayya Ahmed, documented warming winters, hotter summers, and more intense heat-wave conditions between 1896 and 2009 (Ruddell et al., in review at *Climate Research*). Geographers Winston Chow, Wen-Ching Chuang, and Patricia Gober developed an index of vulnerability based on physical exposure to heat stress and adaptive capacity of the population to cope and showed that the city's minority populations became more vulnerable to excessive heat between 1990 and 2000 (Chow et al. 2011). Other recent studies have shown the highest risk of exposure to extreme heat is among elderly, minority, and low-income residents (Ruddell et al. 2010). Recent work also links increasing temperatures to perceptions of discomfort and health concerns (Ruddell et al. 2010; Ruddell et al. 2011).

Climate Modeling: Fine Tuning and Evaluation

Climate scientists developed a deeper understanding of the physical processes that underlie drought conditions in the Southwest. Ellis et al. (2010) used a hydroclimatic index to create a historical record of drought coverage and analyzed the linear trend and relationships with key climate teleconnections. Svoma et al. (2010) linked with regional and hemispheric teleconnections with soil moisture trends in the Salt River watershed; Svoma and Balling (2010) studied trends and patterns of precipitation variability; Balling and Goodrich (2010) used advanced spatial analytical methods to characterize the recent extended drought in the Southwest and found a strong regional focus on the Colorado River Basin; and Balling and Goodrich (2011) studied the variation in precipitation intensity in the Southwest.

With the arrival at ASU of hydrologist Enrique Vivoni in the School of Earth and Space Exploration, we expanded DCDC's natural-science team to include a hydrological component. Vivoni is developing a distributed hydrological model of the Salt/Verde basins using a Triangulated Irregular Network (TIN)-based Real-time Integrated Basin Simulator (tRIBS). Results of this modeling effort allow for a more spatially explicit assessment of the effects of climate change on these major water sources and integration of the effects of changing land-use conditions on upstream watersheds. Vivoni is also conducting hydrological modeling in the San Juan River Basin in Mexico as part of the collaboration with Tecnológico de Monterrey, as researchers and stakeholders collaborate to develop and Integrated Basin Observatory that links hydrological modeling, socio-economic analysis, and decision support.

Environmental and Cultural History: The Context for Water Decision Making

Historian Paul Hirt, geographer Kelli Larson, and graduate student Annie Gustafson collaborated on a series of papers that defined the historical and cultural context for water decision making and pinpointed the limits of current water institutions and governance systems for long-term water

sustainability. Their most recent effort, published in the *Journal of Policy History*, explored the systematic weakening of provisions of Arizona's Groundwater Management Act, a much-heralded law to end groundwater overdraft by 2025 (Larson et al. 2009a). Their historical analysis documented how the Arizona Department of Water Resources, the state legislature, and municipal water providers systematically eroded conservation standards and made inadequate progress toward reducing urban water demand. Their paper argued that the prevailing culture of consumption remains firmly in place in the form of high water-use rates, weakened regulations for reducing water demand, perpetual attention to the use (not conservation) of renewable water, and continued searches for additional water supplies to support growth and economic development. Their work is a reminder of deep-rooted historical traditions and cultural barriers that confront decision makers who seek climate-adaptation strategies.

In the final year of DCDC, Hirt and graduate student, Dan Killoren, conducted a qualitative, longitudinal analysis of the process used to negotiate American Indian water rights. Research findings will contribute to a better understanding of the group dynamics, planning tools, and policy innovations that were critical to the negotiation and settlement process (Killoren 2011). Case studies and best practices drawn from the research will provide water managers, policy makers, and researchers with examples of successful conflict resolution mechanisms that can improve water resource management and policy in the future.

Education Activities

We integrated DCDC research into learning materials and educational programs, engaging a variety of formal and informal education partners. Monica Elser, education team leader, worked with The University of Arizona's water-education programs (Project Wet, Cooperative Extension, and the Water Sustainability program) to deliver two-day Advanced Water Educator Workshops on the following topics: water management (2006), climate change and decision making (2007), water reuse (2008), the energy-water nexus (2009), and water and the future of agriculture (2010). Annual workshops attracted about 25 participants from the region's water education community. DCDC served as the host agency, and each year several DCDC researchers participated in the event.

We continued to work with area students on urban sustainability as related to the urban heat island (UHI), and in collaboration with the NSF-funded GK-12 Sustainable Schools program on water use and conservation in neighborhoods, schools, and homes. We also shared our research products by delivering learning modules directly to students. These modules were based on WaterSim on the Web, the Southwest Water Information Project Atlas, and an urban-sustainability unit that challenges students to design an urban environment to mitigate UHI effects. DCDC also developed and implemented sustainability-learning modules in area high schools and partnered with ASU's School of Sustainability and its Sustainable Schools Program. In February 2009, we developed and presented a mobile, touch-screen application of WaterSim at the NSF exhibit site at the AAAS meetings in Chicago. Over 100 visitors, including journalists, scientists, and leaders of other institutions, visited the booth to test-drive WaterSim and ask questions. Information based on

research by DCDC scientists continues to be incorporated into activities/lessons that the GIOS education-outreach team implemented. In addition, a team of scientists led by Ajay Vinze from the College of Business developed a sustainability exercise based on WaterSim for use in the ASU Executive MBA program.

Activities for graduate and undergraduate students were integrated into DCDC research projects, and DCDC faculty members mentored students. In addition, undergraduate students participated in the Community of Undergraduate Research Scholars (COURS) seminar taught by Margaret Nelson, Vice Dean, Barrett, The Honors College at ASU. This seminar helped students integrate their disciplinary training with the knowledge and skills needed for interdisciplinary collaboration. More specifically, students were required to: (1) craft a clear statement of the broader impact of their work, drawing from the many disciplinary perspectives; (2) build skills that enable them to think across disciplines and produce solution-based research; (3) conduct an original research project in conjunction with a faculty or postdoctoral mentor; and (4) present research in a capstone poster session at the end of each academic year. Poster sessions held in conjunction with DCDC water-climate briefings, drew between 50 and 75 ASU faculty and community partners each year.

Graduate students worked as research assistants with faculty members and were required to participate in the interdisciplinary Community of Graduate Scholars (CGS) seminar also taught by Vice Dean Nelson and DCDC staff member Katja Brundiers. The goals of CGS were to enhance interdisciplinary research and build collaborative work skills. Graduate students worked on various activities during the period of DCDC I funding including: visiting other DMUU centers and sharing insights into their work; organizing a DMUU student poster session at the 2007 and 2011 AAAS meetings; and organizing panel discussions at DCDC Water-Climate Briefings.

To date, DCDC has employed seven postdoctoral fellows: three geographers (Tim Collins, Mohan Seetharam, Darren Ruddell), a planner (Ariane Middel), an economist (H. Allen Klaiber), a civil engineer (Seung-Jae Lee), and a psychologist (Athena Aktipis). Our postdoctoral mentoring activities have focused on professional and career development and designed to help fellows: (1) participate in community-based research about decision making under uncertainty; (2) deepen expertise in their discipline and in interdisciplinary collaborative research; (3) gain an understanding of the role of a tenure-track faculty member in an American university; (4) mentor undergraduate and graduate students; (5) build a network of collaborators and coauthors; (6) establish an independent research program; and (7) participate in the social and cultural life of a comprehensive research university. Postdocs forged research programs with faculty members and students and produced a critical mass of journal articles related to DCDC's mission. Tim Collins is now an assistant professor at the University of Texas at El Paso. Mohan Seetharam works for the Conservation Governance and Policy Ashoka Trust for Research in Ecology and the Environment in India. H. Allen Klaiber is an assistant professor in the Department of Agricultural Economics and Rural Sociology at Pennsylvania State University. Seung-Jae Lee is a postdoc at the National Renewable Energy Laboratory in Golden, Colorado. Darren Ruddell holds a faculty position in geography at the University of Southern California.

References

- Balling, R.C. and G.B. Goodrich. 2010. Increasing drought in the American Southwest? A continental perspective using a spatial analytical evaluation of recent trends. *Physical Geography* 31(4):293-306.
- Balling, R.C. and G.B. Goodrich. 2011. Spatial analysis of variations and trends in precipitation intensity in the USA. *Theoretical and Applied Climatology* 104(3-4):415-421.
- Bolin, B., M. Seetharam and B. Pompeii. 2010. Water resources, climate change, and urban vulnerability: A case study of Phoenix, Arizona. *Local Environment* 15(3):261-279.
- Carbone, J.C. and V.K. Smith. 2010. Valuing ecosystem services in general equilibrium. National Bureau of Economic Research Working Paper 15844.
- Chow, W.T.L., W. Chuang and P. Gober. 2011. Vulnerability to extreme heat in metropolitan Phoenix: Spatial, temporal and demographic dimensions. *The Professional Geographer*. DOI:10.1080/00330124.2011.600225.
- Ellis, A.W., G.B. Goodrich and G.M. Garfin. 2010. A hydroclimatic index for examining patterns of drought in the Colorado River Basin. *International Journal of Climatology* 32(2):236-255.
- Gammage Jr., G., M. Stigler, S. Clark-Johnson, D. Daugherty and W. Hart. 2011. *Watering the Sun Corridor: Managing Choices in Arizona's Megapolitan Area*. Morrison Institute for Public Policy, Arizona State University.
- Gober, P., A.J. Brazel, R. Quay, S. Myint, S. Grossman-Clarke, A. Miller and S. Rossi. 2010a. Using watered landscapes to manipulate urban heat island effects: How much water will it take to cool Phoenix? *Journal of the American Planning Association* 76(1):109-121.
- Gober, P. and C.W. Kirkwood. 2010. Vulnerability assessment of climate-induced water shortage in Phoenix. *Proceedings of the National Academy of Sciences USA* 107(50):21295-21299.
- Gober, P., C.W. Kirkwood, R.C. Balling, A.W. Ellis and S. Deitrick. 2010b. Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm. *Annals of the Association of American Geographers* 100(2):356-372.
- Gober, P., E.A. Wentz, T. Lant, M.K. Tschudi and C.W. Kirkwood. 2011. WaterSim: A simulation model for urban water planning in Phoenix, Arizona, USA. *Environment and Planning B* 38(2):197-215.

- Keller, L.R., C.W. Kirkwood and N.S. Jones. 2010. Assessing stakeholder evaluation concerns: An application to the Central Arizona water resources system. *Systems Engineering* 13(1):58-71.
- Kenrick, D.T., V. Griskevicius, J.M. Sundie, N.P. Li, Y.L. Li and S.L. Neuberg. 2009. Deep rationality: The evolutionary economics of decision making. *Social Cognition* 27:764-785.
- Killoren, D. 2011. American Indian water rights in Arizona: From conflict to settlement, 1950-2004. PhD Dissertation, Arizona State University.
- Larson, K., A. Gustafson and P. Hirt. 2009a. Insatiable thirst and a finite supply: Assessing municipal water conservation policy in greater Phoenix, Arizona, 1980-2007. *Journal of Policy History* 21(2):107-137.
- Larson, K.L., D.D. White, P. Gober, S. Harlan and A. Wutich. 2009b. Divergent perspectives on water resource sustainability in a public-policy-science context. *Environmental Science and Policy* 12(7):1012-1023.
- Middel, A., A.J. Brazel, P. Gober, S.W. Myint, H. Chang and J. Duh. 2011a. Land cover, climate, and the summer surface energy balance in Phoenix, AZ and Portland, OR. *International Journal of Climatology*. DOI:10.1002/joc.2408.
- Middel, A., A. Brazel, B. Hagen and S.W. Myint. 2011b. Land cover modification scenarios and their effects on daytime heating in the inner core residential neighborhoods of Phoenix, AZ, USA. *Journal of Urban Technology* 18(4).
- Murray, A., P. Padegimas, P. Gober, L. Anselin, S. Rey and D. Sampson. In review. Spatial optimization models for water supply allocation. *Water Resources Management*.
- Myint, S.W., P. Gober, A. Brazel, S. Grossman-Clarke and Q. Weng. 2011. Per-pixel versus object-based classification of urban land cover extraction using high spatial resolution imagery. *Remote Sensing of Environment* 115(5):1145-1161.
- Olmstead, S.M., W.M. Hanemann, and R.N. Stravins. 2007. Water demand under alternative price structures. *Journal of Environmental Economics and Management* 54:181-198.
- Parker, J. N. and B.I. Crona. In review. All things to all people: Boundary organizations and the contemporary research university. *Social Studies of Science*.
- Quay, R. 2010. Anticipatory governance: A tool for climate change adaptation. *Journal of the American Planning Association* 76(4):496-511.

Quay, R. and Gober, P. 2011. A cautionary note for Sun Corridor water planners. In: *Watering the Sun Corridor: Managing Choices in Arizona's Megapolitan Area*, 18. Morrison Institute for Public Policy, Arizona State University.

Ruddell, D.M., S.L. Harlan, S. Grossman-Clarke and A. Buyantuyev. 2010. Risk and exposure to extreme heat in microclimates of Phoenix, AZ. In *Geospatial Techniques in Urban Hazard and Disaster Analysis*, eds. P. Showalter and Y. Lu, 179-202. Springer-Verlag.

Ruddell, D., S.L. Harlan, S. Grossman-Clarke, and G. Chowell. 2011. Scales of perception: Public awareness of regional and neighborhood climates. *Climatic Change*. DOI:10.1007/s10584-011-0165-y.

Ruddell, D., D. Hoffman, O. Ahmad and A. Brazel. In review. An historical analysis of threshold temperatures in Phoenix, AZ. *Climate Research*.

Sampson, D.A., V. Escobar, M.K. Tschudi, T. Lant and P. Gober. 2011. A provider-based water planning and management model—WaterSim 4.0—for the Phoenix Metropolitan Area. *Journal of Environmental Management* 92(10):2596-2610.

Simon, J., C.W. Kirkwood and L.R. Keller. In review. Preferences for decisions with geographically varying outcomes: Theory and illustrative applications. *Operations Research*.

Smith, V.K. 2010. Pre-positioned policy as public adaptation to climate change. Issue Brief 10-07:1-19. Resources for the Future.

Smith, V.K. and E. Moore. 2010. Behavioral economics and benefit cost analysis. *Environmental and Resource Economics* 46(2):217-234.

Strong, A. and V.K. Smith. 2010. Reconsidering the economics of demand analysis with kinked budget constraints. *Land Economics* 86(1):173-190.

Svoma, B.M. and R.C. Balling. 2010. United States' interannual precipitation variability over the past century: Is variability increasing as predicted by models? *Physical Geography* 31(4):307-318.

Svoma, B.M., R.C. Balling and A.W. Ellis. 2010. Analysis of soil moisture trends in the Salt River watershed of Central Arizona. *Theoretical and Applied Climatology* 102(1-2):159-169.

White, D.D., A. Wutich, K.L. Larson, P. Gober, T. Lant and C. Senneville. 2010. Credibility, salience, and legitimacy of boundary objects: Water managers' assessment of a simulation model in an immersive decision theater. *Science and Public Policy* 37(3):219-232.

Wiek, A. and K.L. Larson. In review. Water governance, people, and sustainability – A systems approach. *Water Resources Management*.

Wutich, A., T. Lant, D. White, K.L. Larson and M. Gartin. 2010. Comparing focus group and individual responses on sensitive topics: A study of water decision-makers in a desert city. *Field Methods* 22(1):88-110.

II. Findings of Research Activities

Exposure to WaterSim

WaterSim serves as a key point of engagement with regional stakeholders and the public-at-large as well as an experimental object to study how scientific visualization affects perceptions and policy development. Erik Johnston from the ASU School of Public Affairs and Ajay Vinze from the WP Carey School of Business asked: (1) whether and to what extent exposure to WaterSim increased knowledge about water supply and demand in metropolitan Phoenix and (2) how two different IT-facilitated interaction environments influenced collaborative behavior in resource-dilemma scenarios. Their findings revealed that, after interacting with WaterSim, participants' knowledge about water supply and demand increased from 3.35 to 4.63 on a scale of 5, a statistically significant learning outcome. Subjects who interacted with a shared display of WaterSim in the Decision Theater showed higher collective orientation than people interacting with a laptop version of the model. Results underscore the value of WaterSim in promoting learning, joint understanding, and collective action toward shared environmental challenges.

Decision Making Under Uncertainty

Formal decision methods were used to structure the critical tradeoffs between short-term lifestyle and long-term sustainability in water resource decisions. In the March 2010 issue of the *Annals of the Association of American Geographers*, Gober et al. (2010) proposed a new paradigm for water planning that would incorporate the deep uncertainties associated with climate change and future water-supply conditions in the Southwest. Climate-model results for the Salt/Verde Basins were downscaled and used as inputs to WaterSim, and a decision framework was used to organize results. Simulation experiments showed that: (1) current levels of consumption cannot be supported without unsustainable groundwater use under most climate model scenarios; (2) feasible reductions in consumption would allow the region to weather the most pessimistic of the climate projections; (3) delaying action reduce long-term sustainability of the groundwater resource under some climate scenarios; and (4) adaptive policy with appropriate monitoring to track groundwater provides sufficient warning that the need for use restrictions is approaching and avoids the need for drastic, ad hoc actions.

Gober and Kirkwood (2010) investigated the impacts of climate-change conditions on both the Salt/Verde and Colorado River systems and clarified the risks associated with climate change and how well different management strategies would address these risks. Results show that policy action will be needed to attain water sustainability in 2030, even without reductions in river flows caused by climate change factored into the analysis. There is not a single most likely or optimal future for Phoenix, but rather a set of tradeoffs that decision makers must confront about how best to manage risk in the face of uncertainty about future conditions.

Energy Implications of Urban Densities

Subhrajit Guhathakurta, Eric Williams, and Stephane Frijia quantified energy impacts of varying urban designs using data about the built environment, energy use, and transportation patterns. A preliminary study of 52 Census tracts in Phoenix showed that single-family homes represent 33% of livable space, but account for 55% of total electric power consumed while townhomes comprise 45% of livable space but account for only 18% of electrical power consumed.

Smart Design for Urban Climate Adaptation

In an article in the *Journal of Planning Education and Research*, Guhathakurta and Gober (2010) used path analysis to examine interrelationships and feedbacks among residential land use, the urban heat island, and water use in Phoenix. They found that (1) impervious surfaces contributed to increased water use by exacerbating the urban heat island and (2) larger lots containing pools and mesic vegetation increased water demand both directly to support pools and vegetation and indirectly by reducing diurnal temperature variation which increased water demand. They concluded that smart design of urban environments needs to move beyond simplistic water and vegetative solutions for mitigating uncomfortably hot temperatures to consider interactions among surface materials, land use, urban heat island, and water use.

Residential Water Demand

Three important results emerged from Kerry Smith's team on the empirical analysis of the elasticity of water demand (Klaiber et al. in review at *Economic Letters*; Smith in press with NBER, University of Chicago Press). First, there are clear differences in price responsiveness by size of water user. Second, there are pronounced seasonal differences in price responsiveness. Finally, there is some evidence of differences in price responsiveness with the level of seasonal precipitation. Especially dry seasons (low precipitation) exhibit somewhat less price responsiveness. This research led to two papers and multiple presentations at national and international meetings, and results that can inform urban water pricing policies.

Water as a Luxury or Necessity

The environmental psychology team conducted an experiment using a tradeoff paradigm to explore the relative perceived values of different water choices. Results from this study indicated that most respondents considered several indoor water uses as necessities while outdoor water uses tended to be regarded as luxuries (depending on the participant's duration of residence in the Phoenix area). Water for native plant and animal protection was considered a luxury by both males and females. Subjects who scored high on the *New Environmental Paradigm*, a measure of environmental orientation, were more likely to spend money for native plant and animal protection. Results of this study indicated that in residential settings, some types of outdoor water uses may be more easily curtailed than some types of indoor water use. Regression analysis revealed that longer duration of

residence was related to the idea of outdoor watering as a necessity. Policy ramifications are that campaigns to shift from high- to low-water use landscape treatments may be more successful among recent migrants than long-term residents.

Heat Stress and Disadvantaged Urban Populations

Multiple studies using a variety of modeling and empirical techniques document that Phoenix's disadvantaged populations are disproportionately exposed and vulnerable to increasing heat stress. Darren Ruddell, Sharon Harlan, Susanne Grossman-Clarke, and Alexander Buyantuyev used a Weather Research and Forecasting (WRF) model to simulate air temperature thresholds for excessive heat exposure and conducted a social survey about perceived temperatures and heat problems during Summer 2005 (Ruddell et al. 2010, *Geospatial Techniques in Urban Hazard and Disaster Analysis*). Results showed that the highest exposure to extreme heat was among elderly, minority, and low-income residents. Winston Chow, Wen-Ching Chuang, and Patricia Gober constructed maps of vulnerability to extreme heat in Phoenix in 1990 and 2000 and related these maps to demographic changes in the city (Chow et al. 2011). The total population of Phoenix residents living in heat vulnerable areas rose by 16% from 1990 to 2000, with Hispanics growing by 153%, followed by African Americans at 48%. The number of highly vulnerable, non-Hispanic whites decreased from 285,000 to 228,000, a drop of 20%.

Spatial Optimization Modeling for Water Supply Allocation

Geographers Alan Murray, Patricia Gober, Sergio Rey, and Luc Anselin, modeler David Sampson, and graduate student Paul Padezimas developed a spatial-optimization model to support water-supply allocation between water providers when some are in deficit while others are in surplus (Murray et al. in review at *Water Resources Management*). The model uses output from WaterSim 4.0 at the provider level to examine the impacts of cooperation among 33 providers under various climate-change conditions. Results show that cooperative agreements would reduce spot shortages at the provider level that would occur even without climate change. Cooperative behavior would substantially reduce deficits if climate change were to moderately reduce river flows in Phoenix's major source regions, but have little effect under the most pessimistic scenarios because there are few surpluses available for reallocation.

Drought Monitoring and Prediction

Ellis et al. (2010) used a hydroclimatic index to create a historical record of drought coverage and analyzed the linear trend and relationships with key climate teleconnections in the Colorado River Basin (CRB). An increase in drought conditions during warm portions of the year is exclusively the result of climatic warming. In recent decades, a significant increase in drought coverage occurred earlier in the year, during the spring, primarily as a function of warming, but in combination with a decline in precipitation for a significant portion of the Basin. The El Niño (La Niña) phase of the El Niño-Southern Oscillation (ENSO) phenomenon is associated with a smaller (larger) area of drought

during fall and winter, and the ENSO phase during the preceding six months is a significant predictor. The area of drought within the Colorado River Basin is larger (smaller) during the warm (cold) phases of the Atlantic Multi-decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO), although the relationship with the PDO is weak. Monthly AMO values for the two years preceding drought provide minor predictability. Decadal averages of drought coverage closely follow those of both the AMO and PDO index. However, the nature of the PDO-drought relationship is reversed over the two halves of the historical record, possibly indicating a dominance of the AMO over the PDO in influencing drought in the region. Teleconnection-drought relationships are stronger for the southern portion of the basin. Trends in drought coverage, the current phases of the AMO and PDO, climate-change projections of regional warming, and the likelihood of continued rapid population growth could result in significant water resource problems in the Colorado River Basin.

References

- Chow, W.T.L., W. Chuang and P. Gober. 2011. Vulnerability to extreme heat in metropolitan Phoenix: Spatial, temporal and demographic dimensions. *The Professional Geographer*. DOI:10.1080/00330124.2011.600225.
- Ellis, A.W., G.B. Goodrich and G.M. Garfin. 2010. A hydroclimatic index for examining patterns of drought in the Colorado River Basin. *International Journal of Climatology* 32(2):236-255.
- Gober, P. and C.W. Kirkwood. 2010. Vulnerability assessment of climate-induced water shortage in Phoenix. *Proceedings of the National Academy of Sciences USA* 107(50): 21295-21299.
- Gober, P., C.W. Kirkwood, R.C. Balling, A.W. Ellis and S. Deitrick. 2010. Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm. *Annals of the Association of American Geographers* 100(2):356-372.
- Guhathakurta, S. and P. Gober. 2010. Linking urban heat islands to water use in Phoenix: A path analysis. *Journal of Planning Education and Research* 30(1):40-51.
- Klaiber, H.A., V.K. Smith and M. Kaminsky. In review. A new strategy for estimating price elasticity with increasing block rates. *Economics Letters*.
- Murray, A., P. Padegimas, P. Gober, L. Anselin, S. Rey and D. Sampson. In review. Spatial optimization models for water supply allocation. *Water Resources Management*.
- Ruddell, D.M., S.L. Harlan, S. Grossman-Clarke and A. Buyantuyev. 2010. Risk and exposure to extreme heat in microclimates of Phoenix, AZ. In *Geospatial Techniques in Urban Hazard and Disaster Analysis*, eds. P. Showalter and Y. Lu, 179-202. Springer-Verlag.

Smith, V.K. In press. How can policy encourage economically sensible climate adaptation? In *The Design and Implementation of U.S. Climate Policy*, eds. D. Fullerton and C. Wolfram. NBER, University of Chicago Press.

II. Education and Development

K-12 Education

In conjunction with the University of Arizona's Water Resources Research Center, DCDC hosted 35 teachers at the fifth annual Advanced Water Educator Workshop on July 17–18, 2010. The workshop focused on the water and the future of agriculture, covering four topics: (1) water rights and regulations; (2) infrastructure and change; (3) economics, agriculture, and growth; and (4) the sustainability of food production. In previous years, the Advanced Water Educator Workshops dealt with: water management (2006), climate change and decision making (2007), water re-use (2008), the energy-water nexus (2009). The workshops averaged 25 participants and included K-12 teachers and education coordinators at water agencies and NGOs.

Undergraduate Education

We have funded 17 REU students to participate in ASU's Community of Undergraduate Research Scholars (COURS) program sponsored by Barrett, The Honors College during the duration of DCDC I. Facilitated by DCDC PI and Barrett, The Honors College Vice Dean Margaret Nelson, COURS included students from DCDC, the Southwest Consortium for Environmental Research and Policy, the Integrative Graduate Education and Research Training program in Urban Ecology, the Biocomplexity Project, and other NSF-sponsored projects. COURS students met weekly for multidisciplinary discussions of research, participated in a range of research activities related to their respective projects, and prepared research posters for presentation at a capstone event hosted by DCDC. The COURS program epitomized DCDC's goal of linking undergraduate education to research and decision making in a collaborative and interdisciplinary context. Stakeholders expressed satisfaction in the opportunity to work first-hand with undergraduate students on applied research projects.

DCDC sponsored undergraduate Honors Theses include:

Knox, A. 2010. Peer influence on student water-use practices. Undergraduate Honors Thesis, Biology and Society, School of Life Sciences, Arizona State University. Committee members Ann Kinzig, Margaret Nelson, and Stuart Fisher.

Wingren, E. 2008. Theater of uncertainty: Performance and perception at a science and policy boundary. Undergraduate Honors Thesis, Arizona State University. Committee members John Parker, Beatrice Crona, and Jason Delborne.

Graham, C.J. 2006. Hydroclimatic indexing method for drought monitoring. Fulbright Award-winning Honors Thesis, Department of Geography, Arizona State University.

Graduate Education

A total of 56 graduate students from the School of Life Sciences, School of Geographical Sciences and Urban Planning, School of Sustainability, W.P Carey School of Business, School of Design Innovation, School of Human Evolution and Social Change, the Consortium for Science, Policy & Outcomes, and the departments of History, Political Science, Geology, Psychology, Computer Science, and Communications served as research assistants in DCDC projects. To facilitate greater collaboration among DCDC graduate students, we required participation in a one-credit graduate seminar (Community of Graduate Scholars). The seminar was aimed at sparking cross-disciplinary dialogues and perspectives among graduate students working on sustainability and water issues. One specific goal of the seminar was to organize panel discussions involving researchers from the other DMUU centers. In 2010, the CGS hosted a public panel discussion in April 2010 on Promoting Art/Science Collaborations to Enhance Interdisciplinary Learning. The panel featured a documentary about the interdisciplinary experience of the CGS students who have worked with students from the arts on their projects and a discussion with Julie Anand, Assistant Professor of Photography; Fern Tiger, Principle and Creative Director, FernTiger Associates and Professor of Practice at ASU; and Arnim Wiek, Assistant Professor, School of Sustainability.

DCDC sponsored Dissertations and Theses include:

Kim, W.K. In progress. Understanding open spaces in arid cities. PhD Dissertation. Committee members Elizabeth Wentz (co-chair), Soe Myint (co-chair), Anthony Brazel, and Subhrajit Guhathakurta. Expected defense date September 16, 2011.

Killoren, D. 2011. American Indian water rights in Arizona: From conflict to settlement, 1950-2004. PhD Dissertation defended April 20, 2011. Committee members Dirk Hoerder (chair), Paul Hirt, and Karen Smith.

Hu, Q. 2011. Fostering collaboration through IT tools: An experimental study of public deliberation on water sustainability. PhD Dissertation defended April 19, 2011. Committee members N. Joseph Cayer (co-chair), Zhiyong Lan (co-chair), Erik Johnston, and Ralph Shangraw.

Cutts, B.B., 2010. Multiple information providers and public knowledge of water resources. PhD Dissertation defended April 19, 2010. Committee members Ann Kinzig (chair), Christopher Boone, Dave White, Kelli Larson, and David Schaefer.

Escobar, V. 2009. A scenario based assessment of future groundwater resources for water providers in the Phoenix Active Management Area. Master's Thesis. Committee members: Dan Sarewitz (chair), Jon Fink (co-chair), and Tim Lant

Howard, J. 2008. Water managers' strategies for addressing uncertainty in their use of GIS for decision-making. Master's Thesis, defended April 9, 2008, Arizona State University. Committee members Elizabeth Wentz (chair), Kelli Larson, and Dave White.

Patterson, J. 2008. Spatial forecasting: A case study in single family residential water consumption for Phoenix and Paradise Valley, Arizona. Master's Thesis, defended April 7, 2008, Arizona State University. Committee members Elizabeth Wentz, Patricia Gober, and Subhrajit Guhathakurta.

Tschudi, M. 2006. Spatial allocation of projected population in Maricopa County via an automated workflow. Master's Thesis for Master's of Advanced Studies in Geographic Information Systems (MAS-GIS), School of Geographical Sciences. Arizona State University. July 19, 2006.

Collins, T. 2005. The production of hazard vulnerability: The case of people, forests and fire in Arizona's White Mountains. Ph.D. Dissertation, Department of Geography, Arizona State University. Winner of Gilbert F. White Award of the Hazards Specialty Group of the AAG.

Postdoctoral Fellowships

To date, DCDC has hosted seven postdoctoral fellows:

Darren Ruddell, a recent PhD recipient from the School of Geographical Sciences and Urban Planning, was funded jointly by DCDC and the Central Arizona Phoenix LTER. He worked on vulnerability to heat stress and on the interactions between urban design and energy and water use. He is currently employed as assistant professor in the Department of Geography at the University of Southern California.

Ariane Middel received a PhD in Computer Science from the University of Kaiserslautern, Germany. She collaborated with the climate group on research aimed at understanding the functional relationships between water data and land-cover thermal characteristics. This understanding facilitates the targeting of more effective urban heat island mitigation strategies. She continues as a postdoctoral fellow at DCDC II.

H. Allen Klaiber received a PhD from North Carolina State University. He worked with economist Kerry Smith on methods for evaluating and interpreting measures of the change in residential property value with spatially delineated amenities; developing a new method for measuring the responsiveness of residential water demand to prices; and developing a structural economic model of the role of land-use policy in lowering water demand. He is now an assistant professor in the Department of Agricultural Economics and Rural Sociology at Pennsylvania State University.

Athena Aktipis received a PhD from University of Pennsylvania's Department of Psychology. She worked with the psychologists (Ledlow, Neuberg, Sadalla, and Kenrick). She also collaborated with Dave White and Amber Wutich on an anthropological study of risk pooling behavior and strategies.

Tim Collins, a postdoctoral fellow in 2005–2006 worked with sociologist Bob Bolin on vulnerability issues. He is currently an assistant professor of sociology at The University of Texas at El Paso.

Mohan Seetharam worked on rural and urban vulnerability issues in 2006–2007 and is now employed by Conservation Governances and Policy Asoka Trust for Research on Ecology and Environment in India.

Seung-Jae Lee worked with Patricia Gober, Elizabeth Wentz, and Robert Balling during his tenure at DCDC. He coauthored four research articles (Brazel et al. 2007; Lee et al 2008; Lee and Wentz 2008; Lee et al. 2010) using his expertise in Bayesian Entropy Maximum modeling. Lee is a now a postdoctoral fellow at the National Renewable Energy Laboratory in Golden, Colorado.

Students won prestigious awards in the process of or as an offshoot of their DCDC research:

Brian Pompeii won Honorable Mention at the AAAS meetings in February 2009 for his poster, “Water Privatization and Socially Constructed Scarcity.” He also won the President’s Award for Outstanding Study Paper at the Association of Pacific Coast Geographers meeting in September 2008 for “Mapping Future Water Supplies in Phoenix, Arizona.”

Christopher J. Graham, a 2005 DCDC REU student working with Andrew Ellis, was awarded a Fulbright Fellowship to adapt his work on drought indices in the American Southwest to arid regions in Africa.

References

Brazel, A., P. Gober, S. Lee, S. Grossman-Clarke, J. Zehnder, B. Hedquist and E. Comparri. 2007. Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. *Climate Research* 33(2):171-182.

Lee, S.J., R.C. Balling and P. Gober. 2008. Bayesian Maximum Entropy mapping and the soft data problem in urban climate research. *Annals of the Association of American Geographers* 98(2):309-322.

Lee, S.J. and E. Wentz. 2008. Applying Bayesian Maximum Entropy to extrapolating local-scale water consumption in Maricopa County, Arizona. *Water Resources Research* 44, W01401, doi:10.1029/2007WR006101.

Lee, S.J., E.A. Wentz and P. Gober. 2010. Space-time forecasting using soft geostatistics: A case study in forecasting municipal water demand for Phoenix, Arizona. *Stochastic Environmental Research and Risk Assessment* 24(2):283-295.

IV. Outreach Activities

Water-Climate Briefings

DCDC sponsored four to seven facilitated panel discussions of regional water issues annually. At these events, ASU faculty members and graduate students mixed socially and professionally with local water managers. Presenters were evenly divided among DCDC scientists, outside speakers, and local water stakeholder. Two years ago, we moved from a presentation to a panel format to facilitate dialogue between audience members and panelists. The new format was popular with participants and more consistent with our mandate to provide a space where regional water issues can be openly debated and divergent viewpoints aired.

During the course of funding, we hosted 35 Water Climate Briefings, engaging over 2,500 participants. Briefings included:

2009-2010

September 2, 2009. “Sustainable Water and Energy: Can We Plan for One without Planning for the Other?” Panelists included Kris Mayes (Facilitator), Chairman, Arizona Corporation Commission; Sandy Bahr, Chapter Director, Sierra Club - Grand Canyon Chapter; Robert Lotts, Manager of Water Resources, Arizona Public Service; David McNeil, Environmental Services Administrator, City of Tempe; and Paul Westerhoff, Director, ASU’s School of Sustainable Engineering and the Built Environment. Discussions centered on exploring the impacts of the water-energy nexus on desert cities, particularly in Greater Phoenix. It highlighted the challenges and opportunities decision makers face when developing sustainable solutions.

October 7, 2009. “Water Law and Sustainability.” Panelists included Judith Dworkin, Sacks Tierney, P.A.; William H. Swan, Attorney, Consultant; John B. Weldon, Salmon, Lewis & Weldon, PLC; and Dave White, School of Community Resources and Development, ASU. Discussions centered on the possible impacts of current water laws on the water supply of Arizona and other Western states, and how those impacts will affect the ability of Arizona’s water managers to maintain a sustainable water supply.

December 2, 2009. “Irrigated Agriculture in Arizona: Past, Present and Future in Light of Arizona Water Supplies and Water Management Strategies.” Panelists were Nicholas Kilb, Agricultural Planner, Arizona Department of Water Resources; Chris Udall, Executive Director, The Agri-Business Council of Arizona; and Jim Holway, Joint Venture Director, Sonoran Institute (Facilitator). The panel explored ways of furthering gains in water efficiency for irrigated agriculture while ensuring the economic viability of farming.

January 27, 2010. “Regional Water Governance.” Panelists were Karen Smith, Deputy Director, Arizona Department of Water Resources; Holly Richter, Chair of their Executive Committee of the

Upper San Pedro Partnership and Program Director at The Nature Conservancy; Teresa Makinen, Director, East Valley Water Forum; and Abigail York, Professor, ASU's School of Human Evolution and Social Change (Facilitator). The panel used two regional initiatives—the East Valley Water Forum and the Upper San Pedro Partnership—to showcase the potential for regional governance to ensure sustainable water supply.

February 17, 2010. “Future Scenarios of Agriculture and Water in Central Arizona.” Panelists were Carol Johnson, Head of the Phoenix Planning Department; Arnott Duncan, Duncan Family Farms & Sunfresh Farms, Goodyear; Grady Gammage, Jr., Partner of Gammage & Burnham PLC, Senior Fellow of ASU's Morrison Institute of Public Policy and Sandra Day O'Connor College of Law; John Hetrick, Principal Analyst, Salt River Project; and Rimjhim Aggarwal, Professor, ASU School of Sustainability (Facilitator). The panel commented on three scenarios for the future of agriculture in Central Arizona (Nearly Las Vegas, Urban-Agriculture Partnerships, and Powered by Arizona). These scenarios were developed by students in the School of Sustainability with input from local farmers, water managers, regulators, and planners.

March 1, 2010. “Sustainable Water Reuse in Arizona.” Panelists were Channah Rock, Water Quality Extension Specialist, Soil, Water and Environmental Science Department, The University of Arizona; Chuck Graf, Senior Hydrologist, Arizona Department of Environmental Quality; Chris Hassert, City of Scottsdale, Water Resources, Planning & Engineering Director; and Guy Carpenter, Project Manager, Carollo Engineers, National Director Water Reuse Association (Facilitator). The panel discussion addressed the current and future investments in water reuse, perceptions and attitudes, regulatory and economic challenges, and environmental needs.

September 1, 2010. “Understanding Urban Heat Islands (UHI).” Panelists were Karen Collins, Water Sustainability Analyst, Water Business Development, Salt River Project; Sharon Harlan, Professor, School of Human, Evolution and Social Change, ASU; Steve Rossi, Principal Water Resources Planner, Water Services Department, City of Phoenix; and Darren Ruddell, Postdoc, Decision Center for a Desert City and CAP LTER, ASU (Facilitator). The panel addressed the water, energy, social, and human-comfort challenges presented by Phoenix's intensifying and expanding urban heat island.

2008-2009

October 1, 2008. “Total Water Management.” Trevor Hill, President and CEO of Global Water Resources, spoke on integrated systems, regional planning and the economics of water reclamation. Global water is a management company in Phoenix offering water utilities and management and specializing in the aggregation and consolidation of small and medium size water and wastewater utilities in the Southwest.

November 5, 2008. “Efficacy and Ethics in Decision Making Tools.” DCDC graduate students initiated and organized a DMUU panel-discussion to integrate the DMUU sites. The panel consisted of Nichole Peterson, Center for Research on Environmental Decisions (Columbia University); Dave

White, School of Community Resources and Development (ASU); and Mark Neff, Science Policy Assessment and Research on Climate (University of Colorado). The discussion centered on developing and using decision-support tools in the context of climate change. The goal was to broaden our understanding of decision tools beyond a single approach while increasing communication among DMUU sites and promoting interdisciplinary research.

February 4, 2009. “Participatory Decision Making Under Uncertainty: Facilitating Successful Integration of the Community in the Decision Making Process.” Panelists included Kelli Larson, School of Sustainability, School of Geographical Sciences and Urban Planning; Tim McDaniels, School of Community and Regional Planning, University of British Columbia; and Hallie Eakin, School of Sustainability. The panel sought to advance decision-making efforts by exploring: (1) approaches in participatory decision making, b) determinants of success in participatory decision making, and (3) evaluating the effectiveness and success of decisions.

April 8, 2009. “The Role of Boundary Organizations in the Science-Policy Nexus.” Panelists included Daniel Sarewitz, Consortium for Science, Policy & Outcomes at ASU; David Groves, RAND Corporation; and Genevieve Maricle, Science Policy Assessment and Research on Climate, University of Colorado and Consortium for Science, Policy & Outcomes. The panel explored the conduct of science within boundary organizations and the translation of science into policy, asking: (1) How can boundary organizations reconcile the supply of knowledge by science with the demand for knowledge by policy/society?; (2) How does research created within a boundary organization influence policy decisions?; and (3) Boundary organizations have created boundary objects to support policy making. Which have been effective/not effective?

2007-2008

September 5, 2007. “Groundwater Modeling and Multiple Scenario Analysis in the Prescott Active Management Area.” Daniel Timmons, a recent graduate from Northern Arizona University with a Master of Science degree in Environmental Science and Policy, used a groundwater model and scenario analysis to simulate the effects of continued population growth on groundwater supplies in the Prescott Active Management Area. Tom O’Halloran, Arizona State Senator from District 1, provided commentary and insights.

October 10, 2007. “The American Southwest: Are We Running Dry?” Jim Thebaut, writer, producer, and director, gave a preview of his new documentary film, “Running Dry,” and discussed an upcoming film project, The American Southwest: Are We Running Dry? Thebaut is a member of the International Documentary Association and has written, produced, and directed a series of films dealing with important social issues.

March 5, 2008. “The Colorado River, Climate Warming, and the Perfect Drought.” Glen McDonald, professor of geography at UCLA, used the paleoclimatic record to explore the potential impact of global warming on water in California. Results suggest that the 21st Century may be

fraught with serious and prolonged water-management problems in Southern California and the Southwest.

April 2, 2008. "Challenges and Opportunities for Regional Water Planning: East Valley Water Forum Management Plan." Teresa Makinen, Director of the East Valley Water Forum, and Doug Toy, who is involved in water planning for the City of Chandler, presented the East Valley Water Forum's regional groundwater-management plan and discussed the need for a regional perspective in groundwater management and planning.

April 30, 2008. "Central Arizona Groundwater Replenishment District: Point and Counterpoint Discussion." Robert Anderson, an attorney at Fennemore Craig, and Kathryn Sorensen, Administrative Services Director for the City of Mesa, debated state legislation that allows developers to use the Central Arizona Groundwater Replenishment District to fulfill their requirement for a 100-year assured water supply.

May 16, 2008. "Urban Climate Models and their Applications." Professor Sue Grimmond of Kings College, London spoke on understanding and predicting the impact of cities on climate. The large (and ever-increasing) fraction of the world's population living in cities, and the disproportionate share of resources used by these urban residents, especially in the global North, are key drivers of global environmental change

2006-2007

September 6, 2006. "The Impact of Climate on Water Supply Reliability" was presented by two groups. (1) Katharine L. Jacobs, Executive Director of Arizona Water Institute, and Deputy Director of the NSF Center for Sustainability of Arid Region Hydrology and Riparian Areas at University of Arizona. Project Team: Dr. David Meko, Associate Research Professor, University of Arizona, and Dr. Bonnie Colby Professor for Department of Agricultural, University of Arizona. Students: Laura Lindenmayer and Dustin Garrick. This group discussed enhancing water supply reliability through climate information. (2) Dr. Robert C. Balling, Jr., Professor, School of Geographical Sciences, ASU, and Dr. Andrew W. Ellis, Associate Professor, School of Geographical Sciences, ASU, discussed simulating the potential impacts of regional climate change on water supply from the Salt and Verde watersheds.

October 4, 2006. "Water Implications of the Superstition Vistas Project" was presented by Grady Gammage, Jr., Senior Research Fellow, Morrison Institute for Public Policy. Gammage discussed future water resources for Superstition Vistas and whether or not water will be a constraint on the project.

February 7, 2007. "Inflow and Outflow, Flycatchers and Chubs" was presented by John Keane, Senior Environmental Scientist at SRP, Ruth Valencia, Senior Environmental Scientist at SRP and Charles Paradizick, Senior Ecologist at SRP. The speakers discussed reservoir operations and the endangered species act on the Salt and Verde Rivers.

April 4, 2007. "Water in the Arid West: Moving from Mark Twain to the Realities of Climate Change" was presented by Patricia Mulroy, General Manager, Las Vegas Valley Water District and Southern Nevada Water Authority. Mulroy discussed how relationships between neighbors and neighboring states in the arid west are evolving in response to climate change and reduced flow in the Colorado River basin.

May 2, 2007. "The Next Bucket of Water" was presented by Steve Olson, Executive Director of Arizona Municipal Water Users Association. Olson discussed the current issues in supplying water for Arizona's growth.

2005-2006

September 7, 2005. "Colorado River Law: Key Points of Tension" was presented by William Swan, attorney. Swan provided an overview of the Law of the River and the ongoing litigation and pending legislation affecting Arizona's rights to the water supply.

December 7, 2005. "Salinity Issues in Arizona" was presented by Carol Erwin of the U.S. Bureau of Reclamation. Erwin presented results of the Central Arizona Salinity Study, and discussed implications for the future of the Phoenix region's water supply.

March 1, 2006. "Factors Influencing Water Resources Management" was presented by Elizabeth Wentz, Ph.D. of ASU's Department of Geography and L. Robin Keller, Ph.D. of the Paul Merage School of Business at the University of California, Irvine. Results of DCDC research were presented. Wentz presented results of her work with Gober that identified the determinants of residential water demand in the City of Phoenix. Keller presented findings from a survey conducted with Kirkwood that identified stakeholder values in decisions related to water management.

April 5, 2006. "A New Plan for Operations of the Colorado River Reservoirs: How the Basin States Proposal Was Developed" was presented by Herb Dishlip of Herb Dishlip Consulting. Dishlip discussed the 2006 agreement between the seven basin states on a drought management plan.

May 3, 2006. "Tucson Turnaround & Beyond" was presented by David Modeer, Director of Tucson Water. Modeer discussed water use in Tucson and comparative factors with the Phoenix region.

2004-2005

July 12, 2004. "Water Resource Planning Strategies" presented by the City of Phoenix. This first briefing featured City of Phoenix representatives, who provided in-depth background on their water-resource planning process.

September 1, 2004. "Arizona's Water Management Framework and Current Challenges" presented by the Arizona Department of Water Resources, the City of Mesa, and the City of Peoria.

October 6, 2004. "An Update from the DCDC Climate Science Team" presented by Robert Balling and Joseph Zehnder, who introduced the uncertainties of climatic conditions that impact our region's water supply.

December 1, 2004. "SRP Water Supplies and Growth on the Salt and Verde Watersheds" presented by John Hetrick from the Salt River Project, who detailed impacts on urban Phoenix's water supply from growth on the Salt and Verde Watersheds.

February 9, 2005. "Gila River Indian Community Water Settlement" presented by Ron Lewis, General Counsel for the Gila River Indian Community. Lewis provided background on the history and outcome of federal legislation that settled a decades-old dispute about water allocations to tribal lands in Arizona, including an explanation of historic and future irrigation on the tribal land.

March 2, 2005. "Public Perceptions of Drought in Arizona" presented by the Salt River Project, the City of Phoenix, and The Arizona Republic. These partners presented results of public-attitude surveys and examined how these attitudes impact water decision making.

April 6, 2005. "Managing Arizona's Water" presented by Tim Henley of the Arizona Water Banking Authority, who introduced practices and impacts of water management on the lower basin of the Colorado River.

May 11, 2005. "Water and Climate Research at the University of Arizona: Presentations and Panel Discussion" presented by researchers from the University of Arizona's five water research centers. Directors presented highlights of their research and identified potential opportunities for partnerships between the U of A and ASU.

Workshops

In April 2010, economist Kerry Smith organized a conference, Economic Evaluations of Water/Energy Interactions for Policy, co-sponsored by DCDC and the Center for Environmental Economics and Sustainability Policy (CEESP). The objective was to evaluate the methods used in water management, including integrated river management, water and energy policies, and project evaluation.

In collaboration with the Arizona Water Institute, The University of Arizona, and ASU's Decision Theater, DCDC hosted a series of four workshops in 2009-2010 dealing with climatic uncertainty and climate modeling for scientists and water stakeholders. Topics included: (1) the role of paleo-hydrology for scenario construction and water resource planning; (2) the types of uncertainties that impact on decision-making beyond climate and modeling uncertainty; (3) basics of climate downscaling and hydrological modeling, and (4) preliminary results from The University of Arizona's GCM downscaling and hydrological modeling. The series also included two informational workshops for funding partners. Workshops involved 20 continuing participants and included scientists from ASU

and The University of Arizona and representatives from Arizona cities, Bureau of Reclamation, Salt River Project, Central Arizona Project, and the Arizona Department of Water Resources.

In October 2009, DCDC hosted a collaborative workshop with representatives of the Chinese Research Foundation and the Chinese Academy of Sciences. The visit included a field trip to Grand Canyon National Park, a narrated helicopter tour over the Salt River Basin, and a formal workshop including presentations from DCDC and Chinese scientists. The workshop focused on urban climate adaptation from the perspective of rapidly growing cities in the US and China.

In fall 2006, DCDC collaborated with ASU's Center for Science, Policy and Outcomes (CSPO), an internationally known organization involved in studying the linkages between science and technology and society, to convene a workshop of scientists actively studying water resource management in the Southwest with a goal of identifying the major stressors on the Phoenix metropolitan area water supply. Workshop results were used to help DCDC develop research priorities and to provide regional water managers with information regarding potential vulnerabilities.

DCDC partnered with the Lincoln Institute of Land Policy to host a land-use workshop with eight middle- and high-school teachers on March 1, 2005. Products of this workshop were activities dealing with long-term climate change in Phoenix, a GIS interface that enables students to explore factors related to the UHI, and a thermal-mapping activity.

V. Contributions

Contributions within the Discipline

Systems Dynamics Modeling

WaterSim is an integrated collection of quantitative models that represent water consumption and availability in Central Arizona under scenarios of population growth, climatic uncertainty, individual behavior, and policy choices. WaterSim 4.0 is a spatially explicit model that allows analysis of the spatial distribution of risk from water shortage and experimentation with various cooperative strategies to equalize risk across the urban environment. WaterSim serves as a boundary object that can be used jointly by the scientific community and water managers for meaningful discourse about future water policy.

Boundary Organizations Research

DCDC links geography to the field of science and technology policy generally and to boundary organization research more specifically. Patricia Gober organized two sessions at the 2007 AAG meetings to showcase the application of boundary science in geography. The first session highlighted research that influences energy and environmental policy; the second was a panel discussion confronting the challenges of and opportunities for geographers working in policy-oriented fields. Dave White presented a poster at the 2010 AAAS meeting in San Diego highlighting DCDC boundary organizations research.

Human-Natural Coupled Systems

DCDC produced a critical mass of urban-environmental research that links physical and human geography. Although the discipline of geography includes scientists, social scientists, and humanists, projects that bridge these sub-disciplines are in short supply. DCDC links existing knowledge of climate modeling, water-resource management, and human vulnerability. Gober et al. (2010) published a synthetic article arguing for a new paradigm for water management in the March 2010 issue of the *Annals of the Association of American Geographers*.

Gober, P., C.W. Kirkwood, R.C. Balling, A.W. Ellis and S. Deitrick. 2010. Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm. *Annals of the Association of American Geographers* 100(2):356-372.

Contributions to Other Disciplines

DCDC seeks to break down disciplinary boundaries to solve complex societal problems. As such, our primary goal was always to advance interdisciplinary knowledge. WaterSim provided disciplinary scientists the opportunity to work on interdisciplinary topics, such as water-resource management, decision making under uncertainty, boundary science, policy analysis, climate adaptation, and

vulnerability to risk. A substantial proportion of DCDC research projects involved collaborations of geographers, anthropologists, sociologists, engineers, hydrologists, ecologists, and decision scientists.

Our most successful collaborations occurred in the training programs at various levels. Building interdisciplinary thinking and learning was a major goal in both our Community of Undergraduate Research Scholars (COURS) and our Community of Graduate Scholars (CGS) programs. Students from various DCDC research projects enrolled in formal coursework, attended weekly sessions to exchange information and cooperate on collaborative projects, and participated in a capstone poster session at the end of the year. Interdisciplinary thinking grew from exposure to concepts and approaches defined by a variety of disciplines and integrated to address common problems. The DCDC experience suggests that the newest generation of undergraduate and graduate students are open—indeed eager—to integrate different disciplinary perspectives. They do so by focusing on inherently interdisciplinary problems and collaborating on solutions.

Contributions to Human Resource Development

DCDC provided a framework for training graduate students, nourishing interdisciplinary projects, and contributing to the fields of geography, decision research, vulnerability analysis, and agent-based modeling. We engaged undergraduate students and K-12 teachers, community organizations, government agencies, and the general public. Graduate students were drawn from a wide range of disciplines, including geography, economics, geology, psychology, history, political science, family science, communications, plant biology, and microbiology.

Contributions to Resources for Research and Education

DCDC's setting within a large public institution enhanced its ability to leverage research and outreach programs for educational benefit. A total of 56 graduate students were engaged in DCDC research programs. DCDC is a founding partner and collaborator in the university's Community of Undergraduate Research Scholars (COURS) program. Preparation of the DCDC proposal provided the initial impetus for this innovative program, which integrates undergraduate students into research projects.

Contributions Beyond Science and Engineering

DCDC's mission always included a significant community presence and active participation from the local water-management community. We hosted 35 Water-Climate Briefings; organized and facilitated workshops dealing with climate change, water conservation, and the UHI; and participated in myriad public events ranging from real-estate forums to informal salons and public gatherings. DCDC became an influential forum for public discussion of water problems in Central Arizona. Our Center is the place where science meets policy in search of sustainable solutions to the problems of climate change.

VI. Partner Organizations

Salt River Project: SRP delivers nearly one million acre-feet of water to a service area in central Arizona and operates an extensive water-delivery system that includes reservoirs, wells, canals, and irrigation laterals. SRP provided a wide range of information to DCDC scientists, including hydrological data, public attitude surveys that revealed household perception of drought and responsiveness to conservation messages, reports of water duties (usage rates) associated with different land uses, water delivery data, and irrigation coverage. SRP climatologists and water managers were regular participants at the DCDC Climate-Water Briefings and SRP representatives gave presentations and sparked discussion at Water-Climate Briefings. SRP also partnered with DCDC and University of Arizona's Water Resources Research Center on the first summer workshop for teachers held at DCDC.

City of Phoenix: DCDC collaborated closely with the City of Phoenix's Water Services Department, sharing the results of different but complementary water modeling efforts. In addition, the City provided a useful data set that includes municipal water use by different types of users across census tracts between 1990 and 2009. This data set has served as the basis for numerous DCDC publications. City representatives gave presentations and served as panelists at DCDC events. In year 4, the City of Phoenix and DCDC collaborated on a project that examined the trade-off between water use and temperature feedbacks (combinations of surface land cover fractions ranging from vegetation/water, impervious, vacant land, to areas including buildings) using the LUMPS model. The City of Phoenix contributed financial assistance as well as data.

University of Arizona: DCDC collaborated with three University of Arizona (UA) research centers dedicated partly or wholly to water and climate research. These included the Water Resources Research Center (WRRC), the Climate Assessment for the Southwest (CLIMAS), part of NOAA's RISA programs, and Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA), an NSF-funded hydrology center. These centers shared our interest in climatic and hydrological conditions of the American Southwest and engagement with stakeholders for climate adaptation.

Arizona Water Institute: (now defunct) The Arizona Water Institute was a state-wide initiative to facilitate cross-university research about water resource management. Focus was on developing the Arizona Hydrologic Information System, climate assessment, and the science-policy interface. In collaboration with the Arizona Water Institute, The University of Arizona, and ASU's Decision Theater, DCDC hosted a series of four workshops in 2009-2010 dealing with climatic uncertainty and climate modeling for scientists, and decision making under uncertainty.

Northern Arizona University: (2005-06) DCDC co-sponsored the Arizona Water Summit, held at NAU in August 2005, with the Center for Sustainable Environments. This event brought together the state, local, and tribal water management communities to discuss relevant science and policy issues related to water resource management.

East Valley Water Forum: (2004-05) The East Valley Water Forum consists of tribal, public, and private water agencies in the East Salt River Valley. They shared their groundwater-modeling output that was used to produce visualizations for the Decision Theater. The East Valley Water Forum was a talisman for cooperation among the regional water providers and raised awareness of the need for coordinated groundwater planning.

Arizona Department of Water Resources: A DCDC-sponsored intern worked 20 hours per week at ADWR to retrieve data on the Phoenix area's water budget. The intern also developed metadata about how ADWR created the water budget. ADWR has continued to provide data to support DCDC research projects and meet with DCDC staff as needed.

INTEL: (2004-2005) The DCDC/Intel partnership pursued three areas of mutual interest: (1) sharing expertise and technology through education, training, seminars, and the Decision Theater; (2) working with industrial-sector water users to promote conservation measures and voluntary goals before mandatory water requirements take shape; and (3) researching the policy and technology driving water management.

Lincoln Institute for Land Policy: (2004-05) DCDC partnered with the Lincoln Institute for Land Policy on a land-use workshop that developed three K-12 education modules: (1) long-term climate change in Phoenix, (2) GIS interfaces to explore the urban heat island, and (3) a thermal-mapping activity. DCDC also co-sponsored a policy report: *Watering the Sun Corridor* with Lincoln Institute for Land Policy.

American Indian Policy Center: DCDC, the Morrison Institute for Public Policy, and the American Indian Policy Center collaborated to present the 91st Arizona Town Hall: "Land Use Challenges and Choices for the 21st Century" at the Grand Canyon."

Arizona Town Hall: DCDC and Arizona Town Hall worked together on the "Land Use Challenges and Choices for the 21st Century." Arizona Town Hall is a private, nonprofit civic organization created in 1962 to increase citizens' understanding of the many facets of the state's economic, cultural and social life. Twice each year, the Arizona Town Hall brings together a wide cross-section of approximately 150 prominent Arizona citizens to consider and discuss a topic of major concern to Arizona's future. The 91st Arizona Town Hall included approximately 160 citizens from all corners of the state, political persuasions and occupations who will discuss and develop consensus regarding the land use challenges and choices Arizona faces in the 21st century. When the Town Hall session ends, ASU's background report was combined with the recommendations from the Town Hall into a final report. This final report was widely distributed to Arizona public officials, community and business leaders and many others. "Together," says Condo, "the final report and the work of Town Hall participants will help to effectively guide future challenges and choices about the lands of Arizona."

East Valley Partnership: The Superstition Vistas Area Project is one of the largest expanses of property in the U.S. The land is owned by a single owner, the Arizona Land Trust, and covers 275 square miles of undeveloped land on the eastern edge of the metropolitan Phoenix area. This collaboration will produce scenarios of water, energy, transportation, and economic development policy choices for the development of the Superstition Vistas.

Montgomery & Associates: Montgomery and Associates is a private sector business that is integrally involved in water resource consulting in Arizona and the desert Southwest. They collaborated with DCDC on future scenario planning, simulation modeling, and systems analysis for water resource planning and development of critical emerging needs for these services in the work we do in this country and the other arid regions we serve in Mexico, South America, and the Middle East.

Global Water: Global Water owns and operates private water and wastewater utilities in the greater Phoenix area and presently serves approximately 40,000 connections. Global Water collaborated with DCDC on research and education, and outreach activities by serving on the Stakeholder Advisory Committee; providing and sharing data on water and other resources; offering student internships; providing staff time; and sharing best practices and decision-making tools that advance from your activities.

Sustainable Cities Network: SCN is a regional organization whose community members work together to discuss, solve and overcome everyday sustainability challenges facing cities and the overall region. In partnership with DCDC, SCN had the opportunity to offer valuable municipal staff feedback, access to local resources and research opportunities, and a centralized meeting forum via workshops and network meetings to reach community sustainability practitioners with important DCDC findings. At the same time, SCN and its members benefited from this collaboration by having access to real-time research and scientific knowledge on water and resource related topics aiding municipalities in making more informed water and sustainability decisions.

Maricopa Association of Governments: MAG is composed of the 25 incorporated cities and towns in Maricopa County and the contiguous urbanized area, three Indian communities, Maricopa County, and the Arizona Department of Transportation. MAG collaborated with DCDC research, education, and outreach activities by providing and sharing data; offering student internships where possible; and providing staff time.

Other Collaborators

Center for Science, Policy and Outcomes: DCDC collaborated with ASU's Center for Science, Policy and Outcomes (CSPO), an internationally known organization involved in studying the linkages between science and technology and society. In fall 2006, CSPO convened a workshop scientists and policy makers to identify the major stressors on Phoenix's water supply. Workshop results were used to help DCDC develop research priorities and to provide regional water managers with information regarding potential vulnerabilities. In 2007, CSPO expanded the study to include the entire lower

Colorado River Basin. Working with CSPO allowed DCDC scientist to work closely with and share insights from CSPO's talented team of investigators led by Dan Sarewitz, Dave Guston, and Clark Miller.

Global Institute of Sustainability: DCDC is administered by and closely collaborates with ASU's Global Institute of Sustainability (GIOS). GIOS serves as the bridge to other relevant NSF-sponsored projects, especially the Central Arizona Phoenix Long-Term Ecological Research (CAP LTER) project, the Urban Ecology Integrative Graduate Education and Research Training (IGERT) program, the cross-site Biocomplexity in the Environment project on Agrarian Landscapes in Transition, and the Sustainability Partnership Enterprise.

Decision Theater: Founded simultaneously with DCDC, the Decision Theater at Arizona State University is a learning and decision space in which the latest understanding of complex social, economic, and natural processes and their interactions are visualized. DCDC worked closely with DT to visualize WaterSim and to use it as a tool for public engagement.

Central Arizona – Phoenix Long Term Ecological Research: DCDC and the CAP LTER partnered in the design and implementation of the second round of the Phoenix Area Social Survey (PASS), a survey of 800 randomly selected Phoenix-area households. The survey asked respondents about their knowledge of, attitudes toward, and behaviors about a set of locally-relevant environmental issues, including urban sprawl, air quality, the urban heat island, and water scarcity. Results will allow DCDC researchers to test hypotheses about the interrelationships among environmental knowledge, attitudes and value systems, and ultimate behavior regarding water use and conservation practices. In 2007, DCDC and CAP LTER expanded the PASS project to include GIOS scientists and public sector professionals. A summer 2006 summit bringing together DCDC and LTER scientists developed a research agenda to investigate human and ecological adaptations to future climate change.

University of California, Irvine, Paul Merage School of Business: Decision research at DCDC includes a partnership between L. Robin Keller (University of California, Irvine, Paul Merage School of Business) and ASU faculty. The multi-objective decision analysis work performed in Year 1 was the foundation for developing decision-focused evaluation metrics for use with the models that have been developed within DCDC.

Community of Undergraduate Research Scholars: ASU's Community of Undergraduate Research Scholars (COURS) provided opportunities for undergraduate students enrolled in Barrett, The Honors College to contribute to DCDC research. In 2010, DCDC hosted the fifth annual COURS poster session, highlighting the interdisciplinary work of both undergraduate and graduate students.

Community of Graduate Scholars: This DCDC seminar is modeled on the COURS program. The seminar integrates graduate students into ongoing DCDC research projects, provides an

interdisciplinary environment that enhances cross-disciplinary communication and appreciation for the broader impacts of scientific work, and produces concrete research products

Project Wet: In 2006, DCDC partnered with University of Arizona's Project Wet and the Salt River Project to host the first summer teacher training workshop in 2006, where 30 teachers from K-12 schools in the Phoenix Metropolitan area developed new learning materials based on local environmental issues such as water scarcity, water recycling, and the urban heat island. The new learning materials were based upon DCDC research, data sets, and outreach activities. This successful workshop has been repeated each summer and is always filled to capacity. The fifth Advanced Water Educator's Workshop, with the theme of Water and Agriculture, was held in June 2010.

University of Arizona Maricopa County Cooperative Extension: The Maricopa County Cooperative Extension joined (2007) the collaboration among DCDC and the Salt River Project to host the summer Advanced Water Educator Workshop series.

ASU President's Office: DCDC and other university constituents, under the guidance of the Office of the University President, partnered with the Arizona Republic to create the Metropolitan Phoenix Indicators Project, a set of data presented in an impartial manner to illuminate the current state of the economic, social and cultural life of our region. DCDC continues to provide sustainability indicators for the Project, and arizonaindicators.org has been cited as one of the ten best indicator sites in the nation.

ASU's Morrison Institute for Public Policy: (2008-2010) The Metropolitan Phoenix Indicators Project evolved into the Arizona Indicators, now administered by the Morrison Institute. DCDC continues to contribute data to this project. DCDC collaborated with Morrison on *Watering the Sun Corridor*, an evaluation of future water conditions in the region.

Other ASU research and academic units: DCDC regularly co-sponsored lectures and symposia with other ASU research and academic units. These events brought together individuals from industry and multiple academic disciplines to explore and discuss topics such as robust decision making, historic perspectives of water in societies, visualization in environmental policy, and climate change in human-dominated systems.

Community Partners-Personnel Exchanges

City of Tempe: City of Tempe supplies household-water-use data for DCDC analysis. Under DCDC's auspices and supervision, the Tempe Water Utilities Department sponsored an internship in 2006-07. The student investigated the potential water savings under various landscape water conservation scenarios.

City of Mesa: (2006-07) Under DCDC auspices and supervision, the City of Mesa Utilities Department sponsored an internship for an undergraduate student. The intern worked with a water resource specialists in the Resources Division of the Utilities Department. The intern assisted in research focused on scenario assessment for Mesa's long-term groundwater management plan.

VII. DCDC Participants

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Subramanian Swaminathan, School of Geographical Sciences
Victoria Turner, School of Geographical Sciences and Urban Planning
Margaret White, School of Life Sciences
Lauren Withycombe, School of Sustainability
Yolanda Youngs, School of Geographical Sciences
Sianan Zhang, School of Sustainability
Lilah Zautner, School of Geographical Sciences

Other Grads

Jessica Block, Geology
Hoi Cheung, College of Design
Kade Hutchinson, Geology (Decision Theater)
Steve Swanson, School of Human Evolution and Social Change

Community of Undergraduate Research Scholars (COURS)

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Zach Dorn, School of Sustainability
Laila El-Ashmawy, Civil Engineering
Malaya Fletcher, School of Life Sciences
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Desirae Hoffman, School of Geographical Sciences and Urban Planning
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Eva Wingren, School of Human Evolution and Social Change

Other Undergrads

Lubinka Andonoska, Public Administration
Hillary Butler, School of Life Sciences
Avneet Buttar, Computer Information Systems
Uven Chong, Mechanical Engineering
Laura Hand, Public Administration
Brian Keegan, W.P. Carey School of Business
Andrew Knochel, Urban Planning
Jason Loose, Asian Languages
Santiago Manriquez, Interdisciplinary Studies
Adam McDaniel, Global Institute of Sustainability
Eric Moore, W.P. Carey School of Business, Finance
Caroline Newcombe, Civil Engineering
Mitchell Norgan, Department of Psychology
Annissa Olsen, School of Music
Michelle Rupp, Political Science
Rosanne Servis, English
Manual G. Valenzuela, Education

Community Partners

Nancy Crocker, University of Arizona, Maricopa County Cooperative Extension
Michael Ellegood, Maricopa Flood Control District
Mitchell Haws, Bureau of Reclamation

John Hetrick, Salt River Project
Ray Quay, City of Phoenix
Dallas Reigle, Salt River Project
Kerry Schwartz, University of Arizona, Water Resources Research Center

Organizational Partners and Other Collaborators

American Indian Policy Center (ASU)
Arizona Department of Water Resources
Arizona Town Hall
Arizona Water Institute
ASU President's Office
Center for Science, Policy and Outcomes (ASU)
Central Arizona–Phoenix Long Term Ecological Project [CAP LTER] (ASU)
City of Mesa
City of Phoenix
City of Tempe
Decision Theater (ASU)
East Valley Partnership
East Valley Water Forum
Global Institute of Sustainability (ASU)
Global Water
Intel
Lincoln Institute for Land Policy
Maricopa Association of Governments
Montgomery & Associates
Salt River Project
Sustainable Cities Network (ASU)
University of Arizona (WRRC, CLIMAS, SAHRA, Project Wet)
University of California, Irvine, The Paul Merage School of Business