Sustainability **2015**, *7*, 14761-14784; doi:10.3390/su71114761

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Decision-Making under Uncertainty for Water Sustainability and Urban Climate Change Adaptation

Kelli L. Larson [1,3,*], Dave D. White [2], Patricia Gober [3] and Amber Wutich [4]

[1] School of Sustainability, Arizona State University, Tempe, AZ 85287, USA

[2] School of Community Resources and Development, Arizona State University, Tempe, AZ 85287, USA; E-Mail: Dave.White@asu.edu

[3] School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ 85287, USA; E-Mail: gober@asu.edu

[4] School of Human Evolution and Social Change, Arizona State University, Tempe, AZ 85287, USA; E-Mail: Amber.Wutich@asu.edu

* Author to whom correspondence should be addressed; E-Mail: Kelli.Larson@asu.edu; Tel.: +1-480-727-3603.

Academic Editor: Tan Yigitcanlar

Received: 3 September 2015 / Accepted: 28 October 2015 / Published: 4 November 2015

Abstract: Complexities and uncertainties surrounding urbanization and climate change complicate water resource sustainability. Although research has examined various aspects of complex water systems, including uncertainties, relatively few attempts have been made to synthesize research findings in particular contexts. We fill this gap by examining the complexities, uncertainties, and decision processes for water sustainability and urban adaptation to climate change in the case study region of Phoenix, Arizona. In doing so, we integrate over a decade of research conducted by Arizona State University's Decision Center for a Desert City (DCDC). DCDC is a boundary organization that conducts research in collaboration with policy makers, with the goal of informing decision-making under uncertainty. Our results highlight: the counterintuitive, non-linear, and competing relationships in human–environment dynamics; the myriad uncertainties in climatic, scientific, political, and other domains of knowledge and practice; and, the social learning that has occurred across science and policy spheres. Finally, we reflect on how our interdisciplinary research and boundary organization has evolved over time to enhance adaptive and sustainable governance in the face of complex system dynamics.

Keywords: sustainability science; water resources; climate change; boundary organizations; social learning; adaptive governance

1. Introduction

The degree to which people have altered land and water resources, climate and hydrologic dynamics, biodiversity, and biogeochemical cycles in recent decades is unprecedented in human history [1]. Some scholars argue that periods of abrupt change in the nature of these systems are likely to increase in frequency, duration, and magnitude and, in the process, strain the capacity of ecosystems to remain in desired states [2]. In their influential *Science* article, Milly *et al.* proclaimed that stationarity is dead, meaning that we can no longer expect natural systems to operate within a known and predictable envelope of variability derived from historical records [3]. Human-induced environmental changes are so significant that the 20th century and onward have been dubbed the Anthropocene, a new geological epoch marked by the indelible signature of human influence [4]. Complexities, coupled with momentous uncertainties, characterize decision and policy making in the Anthropocene.

The complexity of interactions between human and natural systems is not fully understood by scientists or decision makers [5,6]. As demonstrated herein, complexities in coupled human-natural systems manifest in the form of interdependencies and feedbacks, non-linear dynamics and thresholds, time lags and legacies, and tradeoffs and unintended consequences [7]. Although complexities have been theoretically explored by particular disciplines (e.g., social or ecological sciences), far less research has empirically examined these dynamics in real-world contexts using mixed methods and interdisciplinary approaches [7,8]. Thus, empirical, place-based research on complex sustainability challenges is needed to consider what works in practice as well as theory [9].

This paper contributes to the literature on decision-making under uncertainty in complex systems by synthesizing more than a decade of place-based, interdisciplinary, social and biophysical research focused on water sustainability and climate change adaptation in metropolitan Phoenix, Arizona. The arid study site in the southwestern U.S. is highly relevant for research on climate and water dynamics due to rapid regional growth and expected climate changes that foreshadow the likelihood of a warmer, drier future [10]. It also represents the rapid growth and land-use transitions that characterize much of the developing world. Lastly, the study region is the focus of the Decision Center for a Desert City (DCDC), a boundary organization that helps connect the science and policy spheres so that the research and knowledge produced regarding urban water management and climate adaptation can advance both science and decision-making.

Synthesizing key findings across hundreds of studies conducted by DCDC, our goal is to derive strategic insights from a large body of relatively long-term work that has yet to be considered in a comprehensive manner. We also reflect on the degree to which this research has informed policy and decision-making and fulfilled the functions of a boundary organization designed to link knowledge and action for sustainability. Major highlights include: the complex, uneven, and multifaceted dynamics in human–environmental relations, including difficult tradeoffs and cross-sector interactions that must be addressed in pursuit of urban sustainability; the array of uncertainties identified beyond climatic and

scientific uncertainty, and the multifaceted strategies that could collectively be pursued for anticipating and adapting to change under uncertainties; and, the potential and challenges for science-policy collaborations to enhance social and institutional learning and society's ability to cope with urban environmental change and associated risks.

2. Theoretical Backdrop

2.1. Complexity

Complexity arises from multifarious conditions and dynamic processes that involve interactions across environmental (e.g., land, water) and human (e.g., society, economy, technology) sub-systems. Society depends on and interacts with the environment (e.g., ecosystems, natural resources) in ways that affect human health, the economy, national security, and social justice [11,12]. Interactions across sub-systems result in reciprocal relationships that can spur positive or negative feedbacks. Negative loops are self-adjusting processes, and positive loops are self-reinforcing processes that magnify the effects of an initial disturbance.

Interactions among coupled human–environment systems give rise to tradeoffs and thresholds, both of which are critical to decision-making. Tradeoffs challenge governance because of the inevitability of making choices that present conflicting outcomes; since the pursuit of one outcome can lead to the deterioration of another, positive gains in one arena may lead to negative impacts in another. Often these situations arise because of simplistic assumptions or narrow viewpoints that ignore multifarious system interactions and outcomes [13]. Further, this array of complexities gives rise to unintended consequences—situations in which particular plans or actions lead to unforeseen impacts. Conflicting social values affect tradeoffs, since people sometimes disagree on what objectives or outcomes are necessary or desirable [14]. The context of a place also affects tradeoffs, since the conditions in one community or ecosystem partly determine local problems and goals.

Societal values and local context also influence thresholds, which emerge from non-linear relationships or trends. The result is so-called "tipping points", which are conditions under which change occurs abruptly [7]. Thresholds are critical to decision-making, since they can mark potentially irreversible changes or points at which a system experiences a significant change or impact. Moreover, the exact nature of interactions between various conditions or processes can identify thresholds as the point at which two or more outcomes can be maximized. In this way, anticipating and managing thresholds is one way to address tradeoffs—that is, by making compromises among conflicting objectives.

Complexities in human–environment systems also occur given multi-scalar and temporal dynamics that confound decision-making for sustainability. Multiple scales of action—from individual and local to national and international levels—complicate sustainable governance, since conditions and decisions at one scale can affect those at another scale. The coupling of human scales of decision-making with biophysical scales (e.g., watersheds or ecosystems) further presents challenges to coordinating governance in ways that map onto both social and environmental system dynamics. Regarding temporal dynamics, legacy effects complicate the mitigation and management of environmental changes, as the trajectories set by historic conditions in social and environmental sub-systems lead to a situation in which past decisions affect current conditions and practices [7,15]. Time lags can also stem from long-standing

institutional norms and inertia in decision-making, or from delayed biophysical responses to certain events or changes [16].

Altogether, the complexities inherent in human–environment systems present uncertainties and challenges for decision-making. With knowledge of sub-system interactions, tradeoffs and thresholds, as well as spatial and temporal dynamics, planners and policy makers can anticipate and manage these dynamics in order to reduce vulnerability to risks as well as negative feedbacks and unintended consequences. As demonstrated in this paper, research on decision-making under uncertainty in Arizona has advanced knowledge of complex human–environment interactions while highlighting tradeoffs and thresholds, examining alternative future scenarios, and demonstrating a range of scientific and other uncertainties.

2.2. Uncertainties in Decision-Making

The complexities involved with human–environment systems have contributed to the challenges of utilizing scientific understanding for decision-making insights, a situation Sarewitz so eloquently described in his article "How science makes environmental controversies worse" [17]. The products of science for mitigating and adapting to climate change, in particular, have increased attention in the geosciences community to the issue of uncertainty—how to quantify it, reduce it, and communicate its relevance to decision makers [18–21]. An underlying assumption is that the large uncertainties associated with climate systems, data, and modeling (e.g., parameters, assumptions, and alternative ways to represent physical systems) have impeded the capacity of decision makers to translate expanding knowledge about the climate system into adaptive actions.

Uncertainty quantification is seen as a strategy to produce risk-based assessments, and thus, to facilitate informed decision-making. Trenberth (2010) has warned, however, that greater knowledge about climate system—with respect to important relationships and feedbacks and the use of empirical data to initialize system conditions—may have the paradoxical effect of increasing, not decreasing, uncertainty for certain system parameters and dynamics, which is problematic for decision makers [22]. One resulting recommendation is less emphasis on top-down climate-impact assessments and more emphasis on place-based vulnerability assessments and sensitivity analyses [23]. The value of this approach resides in reducing the vulnerability in current resource systems, irrespective of uncertainties about the future climate.

Uncertainties, however, manifest and are interpreted in diverse ways in scientific and political discourse [24]. In the scientific discourse, uncertainty is typically described in quantitative terms and defined as either ontological, derived from inherent variability occurring with system processes; or epistemic, resulting from limited understanding about a system [25,26]. In other words, "Uncertainty reflects our incomplete and imperfect characterization of current conditions relevant to an environmental problem, and our incomplete and imperfect knowledge of the future consequences of these conditions" [17]. Many scientists have become frustrated by the way uncertainty is treated in policy-making processes and consider political decision-making irrational [27]. From the perspective of decision-making, however, uncertainty is defined not only in scientific but also in political terms and is created from divergent understandings of systems and their dynamics, different values and priorities, and relationships between diverse actors and perceptions.

Further, a basic principle from decision science research is that "people dislike uncertainty" and as a result people will pay a premium for certain outcomes, can be insensitive to differences in probabilities of outcomes, and can be sensitive to ambiguities in the way choices are presented [28]. To address these challenges, scholars have begun to view uncertainty in comprehensive terms; rather than something only to be described, reduced, and communicated, uncertainty is seen as an inevitable characteristic of today's complex environmental systems that are in constant states of change, reacting to new information and new stressors [2,13,29]. This view of uncertainty is a "paradigm changer" for environmental governance, as it is no longer assumed possible to reduce uncertainty entirely and control system function with traditional management strategies and technological fixes. Researchers, thus, have looked to new strategies for conceptualizing, managing, and describing uncertainty in both scientific and policy-making discourse [8].

In the Arizona case we explore, uncertainties span the realms of science and data as well as those of human behavior, politics, and institutions that govern decision-making. Research on decision-making under uncertainty illuminates the various ways in which complexities can manifest in knowledge systems and how those might be addressed in pursuit of urban and water resource sustainability.

2.3. Managing Uncertainties

In dealing with complexities and uncertainties, adaptive approaches involving foresight and flexibility and cross-system insights are needed for sustainability science and governance [30]. Adaptive management implies increasing the capacity of a system (e.g., a community water system) to adapt and respond to, or to cope with, stressors and changes [2,8]. Adaptive capacity is a necessary condition for water management's transition from the traditional "prediction and control" regime to one that encompasses "management as learning". In an adaptive system, new knowledge leads to new management strategies, which in turn require continuing assessment and deeper understanding of system dynamics.

With attention to proactive measures to avert risks, Guston makes a useful distinction between precaution and anticipation. While precaution entails acting to avoid predicted but uncertain hazards, anticipation involves building capacity to deal with unpredictable and unanticipated risks [31]. The latter stands in stark contrast to the dominant "predict and plan" paradigm that represents the long-standing paradigm in water resources management [30].

Managing uncertainty also includes a meaningful role for stakeholders in formal decision processes. Collaborations between scientists and decision makers (e.g., planners, managers, policy makers) are central to addressing uncertainties and applying sustainability research to real-world decision-making [12]. Science and technology policy scholars have advocated the concept of boundary organizations—and the associated "work" they undertake—as a means of linking scientific knowledge and action for sustainability [32]. Boundary organizations are social and institutional arrangements designed to "help stabilize the boundary between science and politics" [33]. As such, they facilitate social networks while being accountable to both scientific and political institutions. One example of a boundary organization is a university-based, policy-facing research center.

Since boundary organizations are responsive to the needs of scientists and decision makers, they provide a useful framework for the cooperative production of knowledge for decision-making under multiple uncertainties [33]. One form of interaction involves the cooperative development of boundary

"objects", which may include maps, datasets, models, and other material forms that facilitate communication. As with the DCDC's WaterSim model, boundary objects can include computerized decision-support tools that can help facilitate communication across groups.

As initially described [33], boundary organizations facilitate communications across the science and policymaking spheres, thereby potentially contributing to the application of knowledge to action. As a forum for science-policy collaborations, boundary organizations frame and define the scale of problems, mediate data and knowledge exchange, and capitalize on the advantages of collaborative partnerships [34]. A primary goal of boundary organizations and the cooperative activities they undertake is to facilitate the use of science and research in decision-making by providing mechanisms for communicating and interacting across these distinctive societal realms.

Research has demonstrated that the degree to which scientific and technical knowledge is successfully applied to decision-making depends on three criteria: salience, credibility, and legitimacy. Here, salience reflects the relevance of the knowledge to decision-making, credibility embodies the degree to which knowledge and actors are viewed as valid and reliable, and legitimacy represents fairness and respectfulness [35]. Research has shown boundary research that successfully meets these criteria is determined by the level of: joint participation by multiple scientific disciplines and stakeholders, accountability to scientific and policy concerns, and production of boundary objects [36,37]. Two-way, iterative engagement between producers and users of scientific information is also key to building trust and better understanding the needs of policy and what scientists can provide to assist policy making [38].

Boundary research conducted in Arizona, and reviewed as a part of this analysis, has revealed a number of challenges and opportunities for water resource decision-making in the face of complexities and uncertainties in system dynamics. After describing the context of our case study, we expand upon research on decision-making under uncertainty that has reflexively analyzed boundary interactions, the social network, and associated outcomes.

3. Context: The Decision Center for a Desert City

The research insights presented in the next section come from a review of research produced through the Decision Center for a Desert City (DCDC), which has been funded by the National Science Foundation since 2004 as a part of the Decision-making under Uncertainty (DMUU) program within the Division of Social and Economic Sciences. The mission of DCDC is to conduct fundamental research and provide guidance on decision-making under uncertainty for urban water sustainability and climate change adaptation. Consistent with its goals, DCDC was designed to implement the conceptual principles of a boundary organization to span science and policy arenas.

DCDC's mission at its inception was to enhance knowledge of water resource decision-making under climatic uncertainty. As research progressed over the first round of funding (2004–2009), it became imperative to consider other sources of uncertainty (*i.e.*, beyond climate science) and to expand the focus to urban environmental adaptation and sustainability for the second round of funding (2010–2015). The change in focus reflects the evolution of research towards a broader conceptualization of uncertainties and an evolving realization that uncertainties sometime arise through scientific research on complex systems [22]. Additionally, acknowledging the urban focus of the project, it became increasingly

apparent that broader system dynamics (such as interactions and tradeoffs across the water-land-energy sectors) must be considered for urban sustainability as a whole [39,40].

As research topics and investigators have expanded over time, so too have the methods of analysis employed. The range of disciplinary approaches has included physical sciences such as climatology and hydrology as well as social sciences including psychology, economics, anthropology, and policy analysis. Geospatial methods for interpolating water data and classifying land cover at fine scales have also been used to refine data accuracies. Experimental and participatory studies were also added into the mix by scholars ranging from psychologists to sustainability scientists. Although our intent is not to detail methods of analyses, some specific tools (e.g., geospatial techniques) are highlighted as they relate to core themes in our research, (e.g., how to reduce data uncertainties). The DCDC's main boundary object is WaterSim, which is a dynamic water simulation model designed to examine and anticipate the impact of stressors (e.g., drought, climate change, and growth) and certain policy levers (e.g., water transfers and reductions in per-capita demands) on water supplies and demands in the region [41,42].

In this paper, our goal is to provide insights based on more than a decade of research conducted by DCDC investigators and collaborators [43]. These insights are presented in the following section, which focuses on complexities, uncertainties, and adaptive governance in urban water systems. Later, in the discussion section, we point to the decision-making implications of DCDC's research. We also reflect on how the DCDC research agenda has changed and adapted over time to address different research problems as well as the needs and interests of stakeholders. These lessons could serve other research centers around the world, especially those operating as boundary organizations or as collaborative endeavors between researchers and decision makers.

This synthesis effort is not intended as an exhaustive review of findings, but rather as an overview of major contributions that have arisen over more than a decade of research. Building upon the literature, we detail how our place-based research has advanced knowledge as well as strategies for dealing with complexity and uncertainty through adaptive approaches. While most DCDC research has been centered on the desert study region of metropolitan Phoenix, some studies—leveraged with additional resources from other grants and projects—have been comparative in nature [40,44]. For example, we focus in particular in this analysis on how a National Oceanographic and Atmospheric Administration (NOAA) sponsored study of arid Phoenix, Arizona and humid Portland, Oregon has expanded knowledge through comparative analysis of land-water-climate dynamics and how they play out across these rather different biomes.

4. Synthetic Insights

4.1. Complex System Dynamics

One significant line of DCDC research has focused on the urban heat island (UHI) effect, which in its basic form involves increases in nighttime temperatures due to features of the built environment (e.g., concrete, asphalt) that retain and emit heat [45]. The urban heat island epitomizes the complex and dynamic nature of social and biophysical systems, including the potential for unintended consequences and feedbacks, inherent tradeoffs between water conservation and heat mitigation, and non-linear dynamics that create thresholds that inform decision-making. The major focal point is land cover patterns and their effects on water demands, microclimates, and other factors. The NOAA-funded comparative

research across Phoenix, AZ and Portland, OR demonstrates that these dynamics play out in distinctive climate regions, although as explained below, the implications for decision tradeoffs vary due to their respective arid and humid settings [40]. Altogether, this research points to landscape designs and planning as a key lever in managing landscapes in ways that address tradeoffs.

In Phoenix and elsewhere, lawns contribute significantly to water demands and thus present an opportunity for residential water conservation [46]. Water conservation can be achieved through greater indoor efficiencies and by shifting from turf grass and irrigated vegetation to native, desert and drought-tolerant plants. Water savings outdoors may, however, have unintended impacts, specifically in terms of exacerbating the UHI effect, which in turn increases water demands [47,48]. This dynamic represents a positive feedback loop, since water shortages trigger conservation, which in turn exacerbates heat, thereby increasing demands and worsening water scarcity.

Climatologists have documented the physical aspects of the UHI and its relationship to the rapid build-up of urbanizing Phoenix. Summer nighttime low temperatures have increased by up to 6 °C on hot summer nights over the past five decades [49]. Interdisciplinary research followed, asking the "why" and "so-what" questions. For example, strong spatial effects were found on the order to 2 to 4 °C across weather stations in the region. The cumulative build-up of homes around weather stations resulted in an increase of 1.4 °C for every new 1000 homes built. Linking urban heating to water consumption, another study found that increasing the daily low temperatures by 1 °F is associated with an average monthly increase in water use of 1098 L (290 gallons) for a typical single-family housing unit [47]. These findings raised the question: How much water would it take to mitigate UHI effects, and is it feasible to use more outdoor water to cool the urban environment?

Subsequent research uncovered critical thresholds for decision-making. One study found a non-linear relationship between vegetative cover (*i.e.*, grass and trees) and cooling efficiency (the rate at which increasing water use delivers temperature reduction) [39]. In other words, beyond a certain amount of grass (around 30%; Figure 1), adding water provides no additional cooling benefits to the urban environment. This finding is important since it suggests a point at which the tradeoff between water conservation and heat mitigation could be balanced through landscape designs.

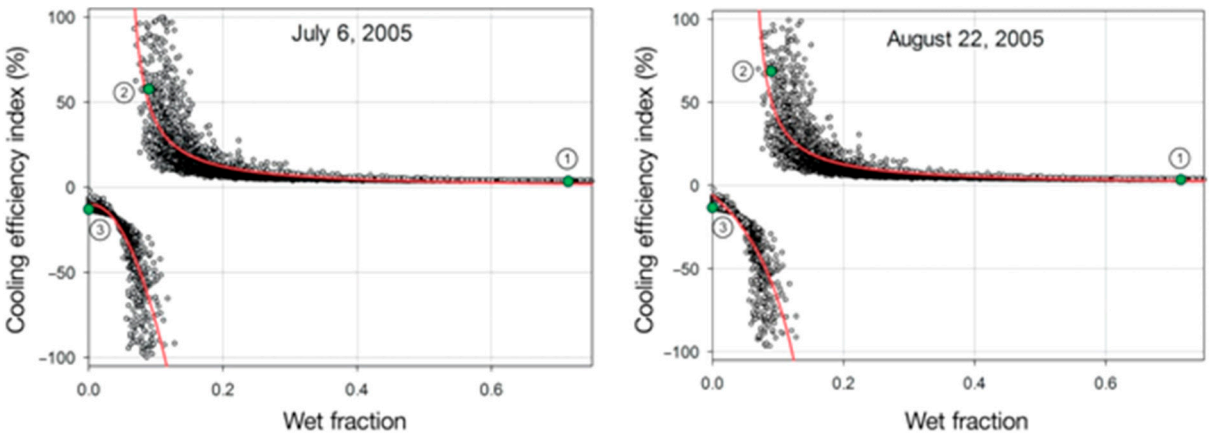

Figure 1. Cooling Efficiency Index for the Various Local Climate Zones (LCZ) for two summer days in 2005; LCZ 1: mesic open-set low-rise; LCZ 2: dry open-set low-rise; LCZ 3: bare concrete [48].

Later efforts to confirm this effect [41,42,50] found a similar phenomenon in Portland. In quantifying the relationship between outdoor water use and urban temperatures, this line of research tackled the inherent tradeoffs between urban water conservation and temperature amelioration by asking questions about how urban buildings and landscapes could be more effectively designed to balance the goals of water conservation and temperature amelioration. Are there strategies where co-benefits could be achieved? In later simulations of climate change conditions and manipulations in the built environment, it was determined that a higher density built environment might achieve both water conservation and UHI mitigation [50]. The fact that the varying urban designs had a more substantial impact on urban temperatures than varying climate change scenarios suggests that there are opportunities for cities to take proactive measures to alter landscapes, regardless of the climate change impact on city surfaces.

Comparative case studies have also revealed the importance of place-based studies in understanding the context for these trade-offs. Whereas hot, arid regions such as Phoenix must prioritize water conservation *versus* heat mitigation as a dominant tradeoff, Portland's seasonal climate trends result in an additional tradeoff between water conservation in the arid summers and stormwater management in the rainy winters [40]. Since a dominant goal in Portland has been stormwater, planting vegetation to slow and retain water flows may ultimately come at the expense of high water demands for outdoor irrigation in the summer. This is especially true given significant investments in green infrastructure in recent years, coupled with future expectations for warmer summers that would require additional irrigation to maintain such vegetative landscapes in the arid season [50]. Ironically, then, Portland may be more sensitive to changes in climate because a much larger proportion of urban surfaces are covered with trees, grasses, and shrubs.

This research on landscape designs and the urban heat island has revealed a number of complexities that underscore the need to anticipate unintended consequences, tradeoffs, non-linear relationships, and other system dynamics. The next section now details the array of uncertainties involved in understanding and managing complex human–environment interactions.

4.2. Inevitable Uncertainties in Decision-Making

More than a decade of research in the Phoenix region has identified an array of uncertainties that challenge decision-making, including but not limited to global and regional climate change projections and potential effects on water and urban sustainability. As demonstrated in this section, uncertainties arise not only from unpredictable biophysical changes in the environment, but also from inadequate data or information as well as uneven cause-and-effect relationships that potentially vary across populations and places.

Research has helped to illuminate the effects of climate variability on water supplies and demands in Phoenix, while also highlighting the uncertainty in such predictions given a non-stationary future. With respect to supplies, scientists attempted to detail the range of likely future climate conditions in the Colorado River Basin and upstream watersheds of the Salt and Verde Rivers (two of Phoenix's three major source regions for water supply) by downscaling global climate model-scenarios combinations to assess their possible effects on local water supplies. A water-budget model for the Salt and Verde River watersheds of central Arizona examined how twenty climate model-emission scenario combinations (*i.e.*, as identified by the Intergovernmental Panel on Climate Change) might affect temperatures,

precipitation, and surface runoff for 2050 [51]. All twenty scenarios predicted at least a 2 °C rise in temperatures. Three-fourths (16 scenarios) predicted a decline in surface water runoff. Precipitation was far more variable across scenarios, with about one-third (6 scenarios) indicating an increase in precipitation. For all models, the range of runoff scenarios spanned 50%–127% of historic flows, with an average reduction of 77% (Figure 2). With the scenarios updated by the 4th IPCC assessment, the band of uncertainty widened to 19%–123% of historical flows [52].

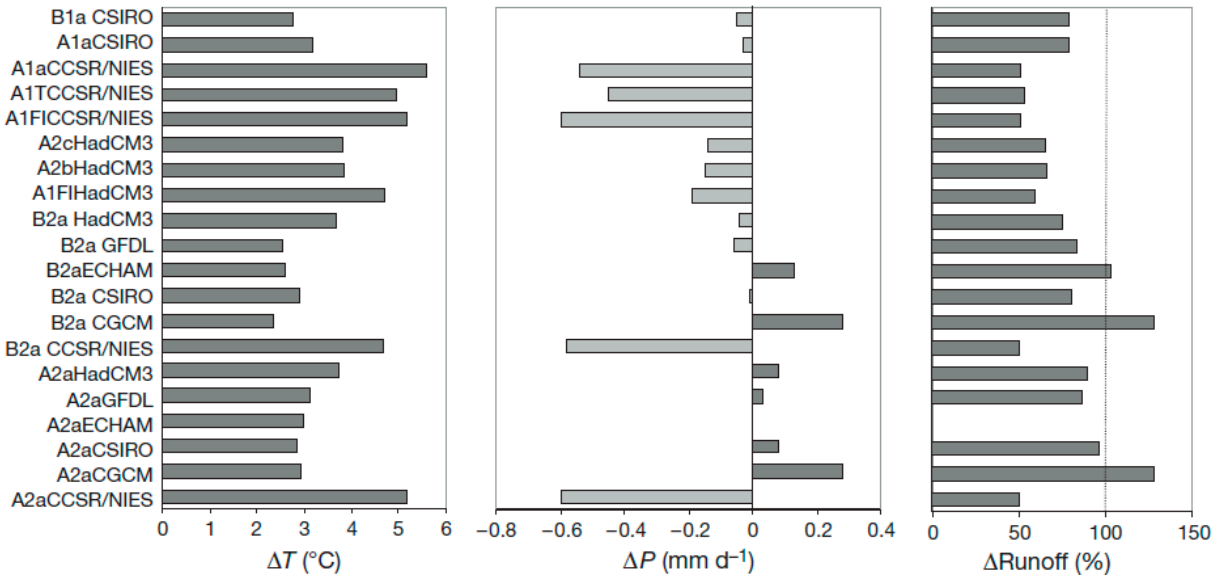

Figure 2. Twenty model-scenario combinations predicting change in temperature (ΔT), precipitation (ΔP), and runoff (% of historical levels) for 2050 [51].

In addition to water supply uncertainties, water demand studies raise similar doubts about how climatic and other factors contribute to patterns of consumption. Annual water use rates have been shown to increase with warmer temperatures and drought conditions and to decrease in response to precipitation [53,54]. However, correlation coefficients (around 0.5–0.6) were lower than anticipated. The lack of influence of climatic conditions on water demands is at least partly explained by uncertain management behaviors, wherein residents do not always change their irrigation schedules to reflect seasonality or current weather conditions.

The influence of climate on demands is complicated further by the fact that the effects are not uniform across space [46,55]. For instance, one-third of neighborhoods (defined as census tracts) in Phoenix did not respond at all to climatic conditions, perhaps because they already use low amounts of water outdoors [56]. This was particularly true for areas with Latino residents and large families. Yet atmospheric conditions explain up to 72 percent of demands in other neighborhoods, especially those with relatively high-income residents who have access to large lots, lawns, and pools. Another study found spatial effects in the way water use responded to the usual determinants of water demand: size of household, presence of swimming pool, lot size, and presence of landscaping that requires a moist environment. The implication was that neighborhoods responded differently perhaps because of physical factors (e.g., neighborhoods with pools were more affected by the UHI) or social and behavioral factors (e.g., green lawns were a form of social status in some areas but more xeric vegetation was socially valued in others) [46].

Overall, these differentiated findings cast uncertainties about the implications of one-size-fits all strategy for reducing water consumption while underscoring the need for place-based, neighborhood approaches.

Beyond climate, factors such as land use/cover patterns influence water demands while also presenting data uncertainties and scientific tools for coping with them. One significant uncertainty involves the lack of accuracy in classifying landscape characteristics based on aerial imagery. Advances in remote sensing can address those uncertainties by improving classification schemes with object-based methods that are superior to traditional per-pixel classifiers [57,58]. The power of this method resides largely in considering the context of an area (object) through a classification process that considers more than what is going on in a single pixel. In the study by Myint *et al.*, the highest accuracy for land cover classifications was for object-based methods (90%), as compared to maximum likelihood (68%) and discriminant analysis (63%) methods.

Additional geospatial techniques have been developed to address uncertainties by improving data reliability through advanced interpolation methods. Geospatial analyses have demonstrated how soft data that captures uncertainties can be used with Bayesian Maximum Entropy (BME) to improve downscaling of neighborhood-level water demand data [59,60]. In part by integrating error projections, BME methods were shown to be up to 44% more accurate than other methods (e.g., traditional kriging) that do not estimate such uncertainty [61]. Urban heat island data were also improved by extrapolating missing data, with the BME methods proving to be up to 13%–35% more accurate than traditional approaches [59]. Another technique—called the space-time interpolation environment (STIE)—was developed to analyze rich spatial and temporal datasets (e.g., from aerial imagery and weather stations) [61,62]. This process involves spatial and temporal interpolation, since both contextual factors are key. Calibration methods also involve placing constraints on behaviors depending on the nature of the phenomena. Overall, these methods together proved to be 85% more accurate in predicting land cover than either technique used alone.

In addition to technical uncertainties, research in the Phoenix area has revealed social complexities and uncertainties concerning behavioral, political, and institutional processes. Behavioral uncertainties stem from assorted complexities, contradictions, and counterintuitive decisions and actions concerning water and other natural resources. Although people express substantial concerns about drought and water conservation, they tend not to act on those concerns [63], instead choosing other priorities for managing their landscapes (e.g., beautiful landscapes, traditional lawns, yards that are neat and easy to maintain) [64,65]. DCDC research has actually found the opposite relationship one might expect concerning environmental values (as measured by the New Ecological Paradigm, or NEP scale) and water consumption. That is, people with stronger environmental (biocentric) values water their yards more often than those with relatively anthropocentric values [65]. One explanation for this counterintuitive finding is that people who are environmentally minded tend to enjoy being outdoors, and as a result, they may manage their yard more intensively than others. Another finding counter to a commonly held belief, which posits that newcomers to arid Phoenix are responsible for the grass-dominated landscapes across the region—in actuality, empirically, residents who live longer in the area prefer non-native lawns that require irrigation relative to new residents [66–68]. This result has been explained as a legacy of the "oasis mentality", which has long pervaded the region and has left long-term residents accustomed to lush, green landscapes that stand apart from the desert ecosystem in which the metropolitan region resides.

Inconsistent findings across studies also raise uncertainties about human–environment relationships, specifically between environmental values or attitudes and landscaping and water-use practices. While one study reported an insignificant relationship between concerns about water resources and landscape preferences [63], still others found contradictory patterns using the New Ecological Paradigm scale [69]. For example, one Phoenix-area study found that ecological worldviews did not affect preferences for desert or xeric landscapes; however, they were negatively associated with preferences for mesic (grass) landscapes, such that residents with anthropocentric mindsets tend to prefer lawns [66–68]. Another study reported similar findings in that anthropocentrism was associated with preferences for mixed "oasis" landscapes with a mix of grass and rock groundcover. Yet another study found that residents with relatively pro-ecological worldviews placed less priority on irrigating landscapes and more on protecting wildlife through water allocations compared to those with relatively weak ecological worldviews [67].

Other uncertainties arise from political factors, for example, such that a lack of leadership or inadequate social support for certain policies renders certain strategies unlikely [70]. A key example is resistance to increasing the price of water and to imposing restrictions on residential water use among water managers and other planning professionals [71]. Even compared to residents, policy makers have exhibited greater opposition to these strategies, which reflects conservative practices among water managers who have been shown to dislike regulating their customers [16,71]. This largely reflects a lack of political will to pursue or implement regulations and higher prices for water as demand management strategies.

In interview-based studies, water managers explicitly identified a number of institutional uncertainties of concern: legal changes involving the listing of endangered species; the procedures and expectations for complying with such programs; and, the unknowns concerning the legal status of Native American water rights claims [72,73]. The adjudication of water rights that are still ongoing for some Native tribes in the region casts doubt on resource allocations into the future. In the next section, we explore further the decision processes involved with science–policy interactions and adaptation to climate change, among other dynamics involved with decision-making under uncertainties.

4.3. Boundary Organizations and Adaptive Management

Complexities and uncertainties necessitate innovative, flexible, and adaptive approaches to water resource governance and urban sustainability. Through our research on the social and institutional dynamics between scientific and decision-making communities, we have learned lessons about stakeholders' perspectives and needs while enhancing the production of credible, salient, and legitimate research. As detailed in this section, tensions across the science–policy boundaries have been illuminated while DCDC—as a boundary organization—has built trust, relationships, and knowledge-action networks. Meanwhile, research has shown how different informational contexts—physical, social, and technological—affect people's thoughts, actions, and decision-making for water resource management and urban sustainability.

Our research identified boundary objects and activities most valued by both researchers and practitioners who are working in the Phoenix region: research results of relevance to stakeholders such as water providers and managers (e.g., City of Phoenix, Salt River Project, and the U.S. Bureau of Reclamation); regular meetings, briefings, and collaborative workshops that provide time for networking;

educational outreach through internships and other events, such as workshops for K-12 teachers; and, the use of models, graphics, scenarios, and visualizations such as the WaterSim model [74,75]. Convening at a neutral, apolitical place is critical for facilitating dialogue, trust, and relationship-building, as are formal tools such as data-sharing agreements.

Following the initial establishment of the center, researchers conducted a formal social network analysis to characterize the participants and their linkages in DCDC's boundary research and related collaborations [74]. The communication network was described as one large group and nine smaller groups that were less connected to the main group. At the time, the network was moderately interdisciplinary; the group included geographers, ecologists, economists, and planners and policy analysts; but little interaction occurred between physical and social scientists. The physical scientists—who early on focused on climate research and modeling and visualization (through WaterSim)—were more connected within the main network as well as to the policy community. In terms of impacts, the social network analysis revealed a positive influence of DCDC interactions on knowledge utilization among policymakers [76,77]. Direct interactions between researchers and policy-making professionals have increased the use of information produced through DCDC activities, as did indirect communications about DCDC research within the policy community alone. The centrality of actors in the network had no effect on how knowledge is utilized, although the policy professionals with greater connections to DCDC also tended to talk more with their policy peers about research.

Tensions can arise from different professional pressures across the science and policy spheres, including those focused on basic science *versus* applied science, as well as on the slow pace of research in contrast to near-term decision needs [72,78,79]. Professional orientations and pressures—for example, toward autonomous research within the academic world and the consultancy needs in the policy community—also create challenges to the production of knowledge that is useful for both realms [78]. Opposing pressures also exist within the realm of science based on the degree to which research is disciplinary or interdisciplinary, particularly since the major funding agencies and universities (including Arizona State University) have recently been pushing integrated research while academics themselves still face the imperative to contribute to their fields of specialization.

Additional challenges emerge when research and scientists are not seen as credible, salient, and legitimate. In early stages of project development, Phoenix-based studies have found that stakeholders perceived the WaterSim model to be limited by a lack of: comprehensive hydrologic data (*i.e.*, the latest information from tree ring studies); certain strategies and stakeholder views (e.g., water pricing as well as environmental organizations and Native Americans); and, municipal-scale information of relevance to town water providers [72]. Water managers were particularly concerned with the lack of saliency in early versions of this water model, whereas they were most positive about its legitimacy (Figure 3) in addressing major water threats such as drought. The ability to reflect on and adapt to these concerns has ultimately improved the model and its acceptance among decision makers (e.g., water managers and elected officials). As seen in Figure 3, technical consultants and data analysts were initially more negative about WaterSim compared to policy makers, perhaps due to the relatively scientific or technical nature of their positions.

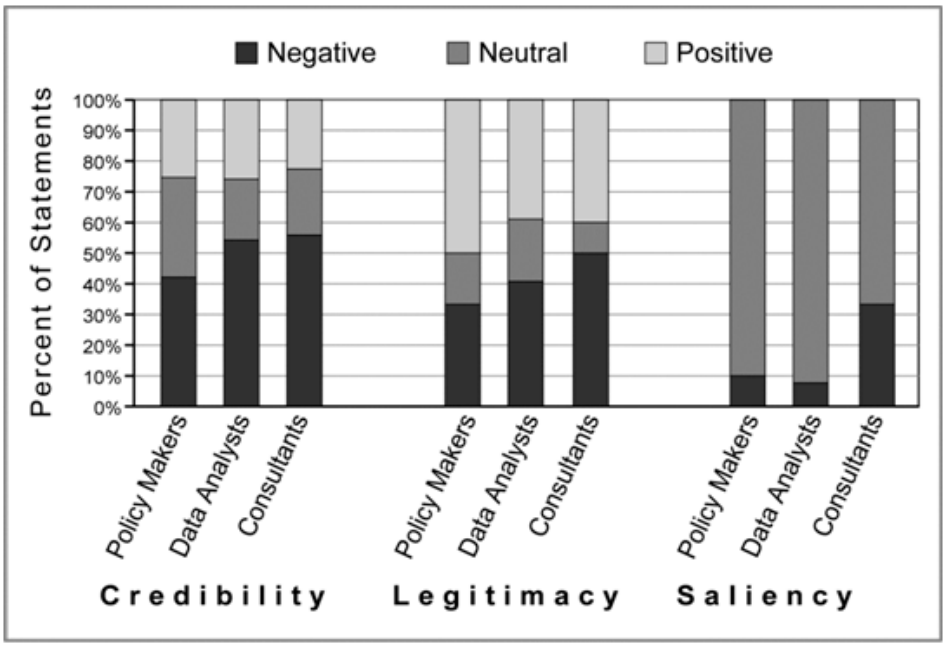

Figure 3. Perceived credibility, legitimacy and saliency of WaterSim model among diverse resource managers [73].

We have also demonstrated empirically that collaborative processes that facilitate social learning and the co-production of knowledge can overcome concerns about the credibility, saliency, and legitimacy of research and related objects (e.g., water models). Boundary organization studies have identified a number of ways this can be done. First, perceived credibility and legitimacy can be enhanced as individuals' concerns are heard and collective decisions are made to improve the research and information [80]. Second, opportunities for privately or confidentially expressing opinions can be important, since group settings can inhibit the sharing of controversial viewpoints [81]. Third, communal computer displays have been found to enhance cooperative decision-making compared to the use of personal displays [82]. As a whole, studies in the Phoenix region have shown that both the social and technological context of deliberative situations matters.

In related research, water managers in Phoenix noted that water models and graphical outputs could be useful for communicating with elected officials and reducing political uncertainties, specifically by building the scientific rationality and credibility for policy decisions [24]. Quasi-experimental research has shown that visual modeling output is particularly useful for centering discussions on specific *problems* and *solutions*. However, visual information is not as useful in achieving common ground on the *causes* of certain problems—especially if perceptions are grounded in value-based ideologies, which tend to be relatively resistant to change [83]. Immersive 3D visual environments, moreover, were found to be more effective for developing common grounds on innovative solution strategies compared to traditional 2D presentations [84]. Overall, research in Phoenix has found that using models as boundary objects can foster mutual understanding while narrowing attention to particular problems or solutions [82,83].

5. Discussion

More than a decade of place-based and use-inspired research on decision-making under uncertainty in complex systems has produced three strategic insights. First, empirical research on complexities and uncertainty is essential to support decision-making in the Anthropocene. Second, novel decision-support tools are needed to assist decision-making under high or increasing uncertainty. Third, empirical research and decision-support tools are improved by boundary organizations that enhance social networks and bridge scientists and policymakers. In this section, we briefly discuss each of these strategic insights and how they apply to our case and others. We then explain how decision makers have engaged with DCDC research and how the information we produced has affected governance.

First, our review demonstrates how empirical research on complexity and uncertainty, building upon theoretical foundations, can contribute to our understanding of coupled human–environment systems. Research in Phoenix, Arizona illustrates the importance of understanding sub-system interactions, tradeoffs and thresholds, as well as spatial and temporal dynamics, for decision-making under uncertainty. Without understanding these relationships, policy, planning, and management decisions for water and climate adaptation are made in isolation from one another—without full consideration of the tradeoffs between sectors. This is primarily because of the complexity of each isolated sub-system, which makes understanding the interconnections *between* sub-systems difficult to identify let alone assess in an integrated manner. Despite this challenge, our research demonstrates that knowledge of the linkages, synergies, and conflicts of these nexus areas is needed to provide evidence-based decision-making for policies in each sector that are most likely to produce positive effects in the other sectors. The results underscore the limitations of planning initiatives focused on single objectives since singular actions tend to result in negative feedbacks and unintended consequences.

Second, our review found that, consistent with some recent scholarship [22], uncertainties in some complex human–environment interactions are increasing rather than decreasing as new knowledge develops about system properties and dynamics. This challenges conventional approaches to risk assessment and management. The uncertainties involved with predicting the future, coupled with the sometimes-widening envelopes of projections in climate change research, call for examining possible alternative scenarios as a primary planning strategy for sustainability. One promising approach for incorporating complexity, uncertainty, and variability into environmental modeling and decision-making, developed by DCDC researchers, is anticipatory modeling with advanced scenario analysis [42]. Geospatial techniques also offer tools for reducing uncertainties, especially those (such as object-oriented methods) aimed at classifying land-use and land-cover patterns at fine scales that reflect the heterogeneity of cities. Such techniques—including the incorporation of "soft data" and space-time interpolation methods—can also offer refined information in the face of data limitations, including the lack of access to household water demand data. Finally, more attention on social and political uncertainties is needed, although those challenges may be a bit harder to anticipate and manage due to the sometimes unpredictable nature of human behavior and politics. Nevertheless, new decision-support tools, such as scenario and envisioning methods [85], can help in addressing these challenges.

Third, our research demonstrates the important impacts of science–policy interactions on decision-making and knowledge utilization. In Phoenix, Arizona, knowledge-action networks have been organized in ways that enhance the efficacy of boundary organizations that bridge scientists and

policymakers. Although challenges stem from different professional needs, goals, and pressures, communications within and across scientist and policymaker groups have been essential for ensuring that knowledge produced through DCDC has been considered in decision-making. Boundary studies have also increased the saliency, credibility, and legitimacy of boundary objects such as WaterSim to decision makers, for example, through: increasing the relevance of the model by downscaling from the regional (metro-area) level to the local (municipal) level at which water utilities tend to operate; helping to establish trust in the model by incorporating the best available data and a wide range of plausible scenarios; and expanding the policy levers embodied in the model to include both supply-side and demand-side alternatives. Our experiences highlight the need for iterative interactions between boundary activities, research studies, and decision-making processes that enable the boundary organizations and the scientists and policymakers that support such organizations to learn, grow, and evolve.

Lastly, since one aim of the DCDC is to advance knowledge in support of decision-making under uncertainty, we reflect on the benefits of our research, education, and partnership activities to stakeholders. In our assessment, the areas with the most direct ties to decision-making have involved efforts focused on the various factors affecting urban water demands: social and institutional factors (e.g., environmental values, attitudes and behaviors; household characteristics; pricing; conservation education and policies; water governance regimes); weather and climatic factors (e.g., drought; climate change impacts on temperature, precipitation and runoff); urban form and dynamics (e.g., urbanization and land use/land cover change; agricultural transitions); and myriad strategies for anticipating climate impacts on water supply (e.g., scenario planning). Our view is that this work, most all of it conducted in cooperation with stakeholders, has influenced the ways in which agencies plan for future water sustainability.

Communications with water managers help demonstrate the DCDC's impact. For instance, one high-level water resource policy professional has said (in personal communication), "For me personally (our relationship with DCDC) has given me a better context for decisions in uncertainty and forced me to think about climate risks more critically". According to the manager of one large utility in the Phoenix area: "The Decision Center for Desert Cities (DCDC) has contributed greatly to discussions involving water supply resiliency by creating forums in which people from a wide variety of backgrounds can exchange information and ideas about how water can be managed in an environment of scarcity". A planner at the same utility was more specific about how DCDC have affected decision-making in Arizona.

> "The research and workshops associated with the center have served at least two critical roles for those involved in water planning. One is to operate as an 'honest broker' clearing house for data and concepts related to water supplies and demands in a time of technological and climate change when different agencies, professions and academic disciplines inevitably have their own perspectives and priorities. An example of this would be the water demand workshop that DCDC initiated along with partners like the Water Research Foundation and a number of western utilities. Another role is to make people understand through scenario analysis that although predicting the future with great precision is difficult, organizations can benefit greatly by preparing for a variety of likely outcomes—especially when something as important as water is involved. These activities have influenced how we prepare water resource and water/wastewater infrastructure plans".

Ultimately, it is difficult—though not impossible—to track the impact of scientific research and partnerships on specific decisions and policies. The challenge comes in part because there is often no clear or linear causal chain of evidence that links specific knowledge produced to specific decisions made. Rather, environmental policy making occurs within a cycle affected by knowledge and information, power and interests, public opinion, budget surpluses and deficits, crises and opportunities—an estuary more than a river. Major polices take years to develop and implement. Furthermore, real-word decision makers operate within specific institutional and procedural contexts and can be hesitant to specify which specific input led to a decision; rather they cite their own leadership or professional judgment after considering and integrating the various inputs. As we consider the impact of this research on decision-making under uncertainty in Phoenix, Arizona, we carefully watch the actions and policies that are being considered and developed now to ensure a secure and sustainable future for the region.

These integrated research, education, and outreach activities have contributed to scientific understanding, trained a diverse group of scholars, and informed policy- and decision-making processes, especially at the city and regional scale. The region's sustainability, however, remains uncertain. The Phoenix region, like other metropolitan areas that depend upon the Colorado River, continues to grapple with long-term drought, climate-change impacts, population growth, and complex social, institutional, and economic dynamics. In part because of these dynamics, transformational change remains difficult. What is needed are innovative approaches to understanding, simulating, and evaluating tradeoffs in complex urban systems; anticipating plausible and desirable futures; and developing and testing transition strategies toward urban water sustainability in the Phoenix region, the Colorado River Basin, and beyond.

In the face of challenges, we argue that not only incremental but also *transformational solutions* are needed to transition toward urban water sustainability. It is time we shift our focus from *adaptation to transformation.* Distinguishing transformation from adaptation, Charles Redman [86] notes that, while adaptation implies incremental changes to build adaptive capacity in response to a shock, transformation involves major, potentially fundamental reorganization of social–ecological systems in response to major threats such as severe climate change. While transformational efforts may involve substantial societal risks and uncertain outcomes, there is growing evidence that, in the case of water sustainability in the Colorado River Basin, innovations and risks are increasingly warranted given the seriousness of social, economic, and environmental pressures. Transformational means addressing problems in a manner that shifts how water is governed in cities, such that water is extracted, distributed, used, and recharged in ways that generate sufficient and equitable benefits without compromising the long-term viability and integrity of supporting hydrologic and environmental systems [86,87]. Here, we consider that transitions to sustainable water systems include not only the conventional priorities of acceptable quality and sufficient quantity but also the transformational approaches that lead to an equitable provision of water resources for society and ecosystems now and in the future [87].

6. Conclusions

This review from the Decision Center for a Desert City illustrates that place-based and stakeholder-engaged research in Phoenix, Arizona has advanced knowledge and decisions about urban water sustainability and climate change adaptation. In particular, research in Phoenix, Arizona has done much to clarify our

understanding of complex system dynamics and boundary management techniques—and to highlight an emerging agenda for how to further develop information that is urgently needed to support sustainability. To this end, social science knowledge about how transformational change occurs in complex social-ecological systems is essential given the challenges associated with uncertainties in the scientific data as well as behavioral and political realms. Innovative approaches are also needed to understand, simulate, and evaluate outcomes and tradeoffs in urban systems; anticipate plausible and desirable futures; and develop and test transition strategies toward urban water sustainability.

Based on this research—and the strategies and insights it has yielded to date—we have identified several important areas for future research, education, and engagement efforts around decision-making under uncertainty in complex human–environment systems. First, new initiatives should place greater emphasis on active management of boundaries—including theoretical and methodological integration across scientific disciplines as well as between science and decision-making communities. The ontological, epistemological, and methodological pluralism present in inter- and trans-disciplinary sustainability science requires active deliberation and negotiation of fundamental assumptions about knowledge systems and the relationships between knowledge and action. Second, there is a need for more research that is not only *place-based* but also *comparative* (e.g., cross-site, cross-ecosystem, cross-cultural) to advance sustainability science. Such research will be essential in identifying both context-specific and generalizable patterns and relationships. Third, we should increase our focus on understanding and informing sustainability transitions in ways that are anticipatory, adaptive, and responsive to stakeholder needs and interests.

Acknowledgments

This material is based upon work supported by the National Science Foundation (NSF) under Grant No. SES-0345945, DMUU: Decision Center for a Desert City: The Science and Policy of Climate Uncertainty; Grant No. SES-0951366, DMUU: Decision Center for a Desert City II: Urban Climate Adaptation; and Grant No. SES-1462086, DMUU: DCDC III: Transformational Solutions for Urban Water Sustainability Transitions in the Colorado River Basin. Additional support was provided by NSF grant BCS-1026865: Central-Arizona Phoenix Long-Term Ecological Research. Any opinions, findings and conclusions or recommendation expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation (NSF). We also acknowledge and thank Sally Wittlinger and Danielle Chipman for assistance with graphics and formatting.

Author Contributions

Kelli Larson wrote the first draft of the paper and led the integration of revisions and edits from her co-authors. Dave White contributed by editing the paper as well as refining parts, especially concerning boundary organizations, uncertainty in decision-making, and the introductory and concluding sections of the paper. Pat Gober assisted primarily with revising and improving the sections on climate research, complex system dynamics, and uncertainties in decision-making. Amber Wutich assisted with final editing and finalizing the discussion and conclusion sections.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Vitousek, P.M.; Mooney, H.A.; Lubchenco, J.; Melillo, J.M. Human domination of Earth's ecosystems. *Science* **1997**, *277*, 494–499.
2. Folke, C.; Hahn, T.; Olsson, P.; Norberg, J. Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.* **2005**, *30*, 441–473.
3. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. Stationarity is dead: Whither water management? *Science* **2008**, *319*, 573–574.
4. Crutzen, P.J. Geology of mankind. *Nature* **2002**, *415*, 23.
5. Clark, W.C. Sustainability science: A room of its own. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 1737–1738
6. Liu, J.; Dietz, T.; Carpenter, S.R.; Folke, C.; Alberti, M.; Redman, C.L.; Schneider, S.H.; Ostrom, E.; Pell, A.N.; Lubchenco, J. Coupled human and natural systems. *J. Hum. Environ.* **2007**, *36*, 639–649.
7. Liu, J.; Dietz, T.; Carpenter, S.R.; Alberti, M.; Folke, C.; Moran, E.; Pell, A.N.; Deadman, P.; Kratz, T.; Lubchenco, J. Complexity of coupled human and natural systems. *Science* **2007**, *317*, 1513–1516.
8. Pahl-Wostl, C. The implications of complexity for integrated resources management. *Environ. Model. Softw.* **2007**, *22*, 561–569.
9. Brunner, R.D. Adaptive governance as a reform strategy. *Policy Sci.* **2010**, *43*, 301–341.
10. MacDonald, G.M. Water, climate change, and sustainability in the southwest. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 21256–21262.
11. Leichenko, R. Climate change and urban resilience. *Curr. Opin. Environ. Sustain.* **2011**, *3*, 164–168.
12. Lubchenco, J. Entering the century of the environment: A new social contract for science. *Science* **1998**, *279*, 491–497.
13. Pahl-Wostl, C. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Glob. Environ. Chang.* **2009**, *19*, 354–365.
14. Adger, W.N. Vulnerability. *Glob. Environ. Chang.* **2006**, *16*, 268–281.
15. Haberl, H.; Winiwarter, V.; Andersson, K.; Ayres, R.U.; Boone, C.; Castillo, A.; Cunfer, G.; Fischer-Kowalski, M.; Freudenburg, W.R.; Furman, E. From LTER to LTSER: Conceptualizing the socioeconomic dimension of long-term socioecological research. *Ecol. Soc.* **2006**, *11*, Article 13.
16. Lach, D.; Ingram, H.; Rayner, S. Maintaining the status quo: How institutional norms and practices create conservative water organizations. *Tex. Law Rev.* **2004**, *83*, 2027–2053.
17. Sarewitz, D. How science makes environmental controversies worse. *Environ. Sci. Policy* **2004**, *7*, 385–403.
18. Katz, R.W.; Craigmile, P.F.; Guttorp, P.; Haran, M.; Sansó, B.; Stein, M.L. Uncertainty analysis in climate change assessments. *Nat. Clim. Chang.* **2013**, *3*, 769–771.
19. Reilly, J.M.; Stone, P.H.; Forest, C.E.; Webster, M.D.; Jacoby, H.D.; Prinn, R.G. Uncertainty and Climate Change Assessments. *Science* **2001**, *293*, 430–433.

20. Wilby, R. When and where might climate change be detectable in UK river flows? *Geophys. Res. Lett.* **2006**, doi:10.1029/2006GL027552.
21. Wilby, R.L. Uncertainty in water resource model parameters used for climate change impact assessment. *Hydrol. Process.* **2005**, *19*, 3201–3219.
22. Trenberth, K. More knowledge, less certainty. *Nat. Rep. Clim. Chang.* **2010**, doi:10.1038/climate.2010.06.
23. Wilby, R.L.; Dessai, S. Robust adaptation to climate change. *Weather* **2010**, *65*, 180–185.
24. White, D.D.; Wutich, A.; Larson, K.L.; Lant, T. Water management decision makers' evaluations of uncertainty in a decision support system: The case of WaterSim in the Decision Theater. *J. Environ. Plan. Manag.* **2015**, *58*, 616–630.
25. Walker, W.E.; Harremoes, P.; Rotmans, J.; van der Sluijs, J.; van Asselt, M.; Janssen, P.; von Krauss, M.P.K. Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integr. Assess.* **2003**, *4*, 5–17
26. Van Asselt, M.B.; Rotmans, J. Uncertainty in integrated assessment modelling. *Clim. Chang.* **2002**, *54*, 75–105.
27. Garvin, T. Analytical paradigms: The epistemological distances between scientists, policy makers, and the public. *Risk Anal.* **2001**, *21*, 443–456.
28. Fischhoff, B. Nonpersuasive communication about matters of great urgency: Climate change. *Environ. Sci. Technol.* **2007**, *41*, 7204–7208.
29. Lempert, R.J. *Shaping the Next one Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*; The RAND Pardee Center: Santa Monica, CA, USA, 2003.
30. Quay, R. Anticipatory governance. *J. Am. Plan. Assoc.* **2010**, *76*, 496–511.
31. Guston, D.H. Innovation policy: Not just a jumbo shrimp. *Nature* **2008**, *454*, 940–941.
32. Clark, W.C.; Tomich, T.P.; Noordwijk, M.V.; Guston, D.; Delia, C.; Dickson, N.M.; McNie, E. Boundary work for sustainable development: Natural resource management at the consultative group on International agricultural research (CGIAR*). Proc. Natl. Acad. Sci. USA* **2011**, doi:10.1073/pnas.0900231108.
33. Guston, D.H. Stabilizing the boundary between US politics and science: The role of the Office of Technology Transfer as a boundary organization. *Soc. Stud. Sci.* **1999**, *29*, 87–111.
34. Cash, D.W. "In order to aid in diffusing useful and practical information": Agricultural extension and boundary organizations. *Sci. Technol. Hum. Values* **2001**, *26*, 431–453.
35. Cash, D.W.; Clark, W.C.; Alcock, F.; Dickson, N.M.; Eckley, N.; Guston, D.H.; Jäger, J.; Mitchell, R.B. Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 8086–8091.
36. Fujimura, J.H. Crafting science: Standardized packages, boundary objects, and "translation". In *Science as Practice and Culture*; Pickering, A., Ed.; The University of Chicago Press: Chicago, IL, USA, 1992; pp. 168–211
37. Star, S.L.; Griesemer, J.R. Institutional ecology, translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–1939. *Soc. Stud. Sci.* **1989**, *19*, 387–420.
38. Dilling, L.; Lemos, M.C. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Glob. Environ. Chang.* **2011**, *21*, 680–689.

39. Gober, P.; Kirkwood, C.W. Vulnerability assessment of climate-induced water shortage in Phoenix. *Proc. Natl. Acad. Sci. USA* **2010**, doi:10.1073/pnas.0911113107.
40. Larson, K.L.; Polsky, C.; Gober, P.; Chang, H.; Shandas, V. Vulnerability of water systems to the effects of climate change and urbanization: A comparison of Phoenix, Arizona and Portland, Oregon (USA). *Environ. Manag.* **2013**, 52, 179–195.
41. Sampson, D.A.; Escobar, V.; Tschudi, M.K.; Lant, T.; Gober, P. A provider-based water planning and management model—WaterSim 4.0—For the Phoenix Metropolitan Area. *J. Environ. Manag.* **2011**, *92*, 2596–2610
42. Gober, P.; White, D.D.; Quay, R.; Sampson, D.A.; Kirkwood, C.W. Socio-hydrology modelling for an uncertain future, with examples from the USA and Canada. *Geol. Soc. Lond. Spec. Publ.* **2014**, doi:10.1144/SP408.2.
43. Larson, K.L.; White, D.C.; Gober, P.; Kirkwood, C.W.; Smith, V.K.; Nelson, M.C.; Redman, C.L.; Wittlinger, S.K. *Advancing Science in Support of Water Policy and Urban Climate Change Adaptation at Arizona State University's Decision Center for a Desert City: A Synthesis of Interdisciplinary Research on Climate, Water, and Decision-making Under Uncertainty*; Decision Center for a Desert City, Arizona State University: Tempe, AZ, USA, 2013.
44. Middel, A.; Brazel, A.J.; Gober, P.; Myint, S.W.; Chang, H.; Duh, J.D. Land cover, climate, and the summer surface energy balance in Phoenix, AZ, and Portland, OR. *Int. J. Climatol.* **2012**, *32*, 2020–2032.
45. Chow, W.T.L.; Brennan, D.; Brazel, A.J. Urban heat island research in Phoenix, Arizona: Theoretical contributions and policy applications. *Bull. Am. Meteorol. Soc.* **2012**, *93*, 517–530.
46. Wentz, E.A.; Gober, P. Determinants of small-area water consumption for the city of Phoenix, Arizona. *Water Resour. Manag.* **2007**, *21*, 1849–1863.
47. Guhathakurta, S.; Gober, P. The impact of the Phoenix urban heat island on residential water use. *J. Am. Plan. Assoc.* **2007**, *73*, 317–329
48. Middel, A.; Brazel, A.J.; Kaplan, S.; Myint, S.W. Daytime cooling efficiency and diurnal energy balance in Phoenix, Arizona, USA. *Clim. Res.* **2012**, *54*, 21–34.
49. Brazel, A.; Gober, P.; Lee, S.J.; Grossman-Clarke, S.; Zehnder, J.; Hedquist, B.; Comparri, E. Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. *Clim. Res.* **2007**, *33*, 171–182.
50. Gober, P.; Middel, A.; Brazel, A.; Myint, S.; Chang, H.; Duh, J.; House-Peters, L. Tradeoffs between water conservation and temperature amelioration in Phoenix and Portland: Implications for urban sustainability. *Urban Geogr.* **2012**, *33*, 1030–1054.
51. Ellis, A.W.; Hawkins, T.W.; Balling, R.C., Jr.; Gober, P. Estimating future runoff levels for a semi-arid fluvial system in central Arizona, USA. *Clim. Res.* **2008**, *35*, 227–239.
52. Gober, P.; Kirkwood, C.W.; Balling, R.C., Jr; Ellis, A.W.; Deitrick, S. Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm. *Ann. Assoc. Am. Geogr.* **2010**, *100*, 356–372.
53. Balling, R.C., Jr.; Gober, P. Climate variability and residential water use in the city of Phoenix, Arizona. *J. Appl. Meteorol. Climatol.* **2007**, *46*, 1130–1137.

54. Gober, P.; Quay, R. Harnessing urban water demand: The challenges ahead. In *Handbook on Urbanization and Global Environmental Change*; Seto, K.C., Solecki, W., Eds.; Routledge: London, UK, 2015; in press.
55. Balling, R.C., Jr.; Cubaque, H.C. Estimating future residential water consumption in Phoenix, Arizona based on simulated changes in climate. *Phys. Geogr.* **2009**, *30*, 308–323.
56. Balling, R.C., Jr.; Gober, P.; Jones, N. Sensitivity of residential water consumption to variations in climate: An intraurban analysis of Phoenix, Arizona. *Water Resour. Res.* **2008**, doi:10.1029/2007WR006722.
57. Middel, A.; Brazel, A.; Hagen, B.; Myint, S. Land cover modification scenarios and their effects on daytime heating in the inner core residential neighborhoods of Phoenix, Arizona. *J. Urban Technol.* **2011**, *18*, 61–79.
58. Myint, S.W.; Gober, P.; Brazel, A.; Grossman-Clarke, S.; Weng, Q. Per-pixel *vs.* object-based classification of urban land cover extraction using high spatial resolution imagery. *Remote Sens. Environ.* **2011**, *115*, 1145–1161.
59. Lee, S.J.; Balling, R., Jr.; Gober, P. Bayesian Maximum Entropy mapping and the soft data problem in urban climate research. *Ann. Assoc. Am. Geogr.* **2008**, *98*, 309–322.
60. Lee, S.J.; Wentz, E.A. Applying Bayesian Maximum Entropy to extrapolating local-scale water consumption in Maricopa County, Arizona. *Water Resour. Res.* **2008**, doi:10.1029/2007WR006101.
61. Lee, S.J.; Wentz, E.A.; Gober, P. Space-time forecasting using soft geostatistics: A case study in forecasting municipal water demand for Phoenix, Arizona. *Stoch. Environ. Res. Risk Assess.* **2010**, *24*, 283–295.
62. Wentz, E.A.; Peuquet, D.J.; Anderson, S. An ensemble approach to space-time interpolation. *Int. J. Geogr. Inf. Sci.* **2010**, *24*, 1309–1325.
63. Larsen, L.; Harlan, S.L. Desert dreamscapes: Residential landscape preference and behavior. *Landsc. Urban Plan.* **2006**, *78*, 85–100.
64. Larson, K.L.; Brumand, J. Paradoxes in landscape management and water conservation: Examining neighborhood norms and institutional forces. *Cities Environ. (CATE)* **2014**, *7*, 2–24.
65. Larson, K.L.; Cook, E.; Strawhacker, C.; Hall, S.J. The Influence of diverse values, ecological structure, and geographic context on residents' multifaceted landscaping decisions. *Hum. Ecol.* **2010**, *38*, 747–761.
66. Larson, K.L.; Casagrande, D.; Harlan, S.L.; Yabiku, S.T. Residents' yard choices and rationales in a desert city: Social priorities, ecological impacts, and decision tradeoffs. *Environ. Manag.* **2009**, *44*, 921–937
67. Sadalla, E.; Berlin, A.; Neel, R.; Ledlow, S. Priorities in residential water use: A trade-off analysis. *Environ. Behav.* **2014**, *46*, 303–328.
68. Yabiku, S.; Casagrande, D.G.; Farley-Metzger, E. Preferences for landscape choice in a southwestern desert city. *Environ. Behav.* **2008**, *40*, 382–400.
69. Dunlap, R.E.; van Liere, K.D.; Mertig, A.G.; Jones, R.E. Measuring Endorsement of the New Ecological Paradigm: A Revised NEP Scale. *J. Soc. Issues* **2000**, *56*, 425–442.
70. Hirt, P.; Gustafson, A.; Larson, K.L. The mirage in the Valley of the Sun. *Environ. Hist.* **2008**, *13*, 482–514.

71. Larson, K.L.; Gustafson, A.; Hirt, P. Insatiable thirst and a finite supply: An assessment of municipal water-conservation policy in greater Phoenix, Arizona, 1980–2007. *J. Policy Hist.* **2009**, *21*, 107–137.
72. White, D.D.; Corley, E.A.; White, M.S. Water managers' perceptions of the science-policy interface in Phoenix, Arizona: Implications for an emerging boundary organization. *Soc. Natl. Resour.* **2008**, *21*, 230–243.
73. White, D.D.; Wutich, A.; Larson, K.L.; Gober, P.; Lant, T.; Senneville, C. Credibility, salience, and legitimacy of boundary objects: Water managers' assessment of a simulation model in an immersive decision theater. *Sci. Public Policy* **2010**, *37*, 219–232.
74. Crona, B.; Parker, J. *All Things to All People: An Assessment of DCDC as a Boundary Organization*; Arizona State University: Tempe, AZ, USA, 2008.
75. Gober, P.; Larson, K.L.; Quay, R.; Polsky, C.; Chang, H.; Shandas, V. Why land planners and water managers don't talk to one another and why they should! *Soc. Natl. Resour.* **2013**, *26*, 356–364.
76. Crona, B.I.; Parker, J.N. Network determinants of knowledge utilization: Preliminary lessons from a boundary organization. *Sci. Commun.* **2011**, *33*, 448–471.
77. Crona, B.I.; Parker, J.N. Learning in Support of Governance: Theories, Methods, and a Framework to Assess How Bridging Organizations Contribute to Adaptive Resource Governance. *Ecol. Soc.* **2012**, doi:10.5751/ES-04534-170132.
78. Parker, J.; Crona, B. On being all things to all people: Boundary organizations and the contemporary research university. *Soc. Stud. Sci.* **2012**, *42*, 262–289.
79. Quay, R.; Larson, K.L.; White, D.D. Enhancing water sustainability through university–policy collaborations: Experiences and lessons from researchers and decision-makers. *Water Resour. IMPACT* **2013**, *15*, 17–19.
80. Cutts, B.B.; White, D.D.; Kinzig, A.P. Participatory geographic information systems for the co-production of science and policy in an emerging boundary organization. *Environ. Sci. Policy* **2011**, *14*, 977–985.
81. Wutich, A.; Lant, T.; White, D.D.; Larson, K.L.; Gartin, M. Comparing focus group and individual responses on sensitive topics: A study of water decision makers in a desert city. *Field Methods* **2010**, *22*, 88–110.
82. Hu, Q.; Johnston, E.; Hemphill, L. Fostering cooperative community behavior with IT tools: The influence of a designed deliberative space on efforts to address collective challenges. *J. Community Inform.* **2013**, *9*, 1–47.
83. Larson, K.L.; Edsall, R.M. The impact of visual information on perceptions of water resource problems and management alternatives. *J. Environ. Plan. Manag.* **2010**, *53*, 335–352.
84. Edsall, R.M.; Larson, K.L. Effectiveness of a semi-immersive virtual environment in understanding human environment interactions. *Cartogr. Geogr. Inf. Sci.* **2009**, *36*, 367–384.
85. Wiek, A.; Withycombe, L.; Redman, C.L. Key competencies in sustainability—A reference framework for academic program development. *Sustain. Sci.* **2011**, *6*, 203–218.
86. Redman, C.L. Should sustainability and resilience be combined or remain distinct pursuits? *Ecol. Soc.* **2014**, doi:10.5751/ES-06390-190237.

87. Wiek, A.; Larson, K.L. Water, people, and sustainability—A systems framework for analyzing and assessing water governance regimes. *Water Resour. Manag.* **2012**, *26*, 3153–3171.