PREPARING FOR HIGH-CONSEQUENCE, LOW-PROBABILITY EVENTS

HEAT, WATER & ENERGY IN THE SOUTHWEST

WORKSHOP REPORT

SEPTEMBER 28-29, 2015

ZACK GUIDO

PREPARING FOR HIGH CONSEQUENCE, LOW PROBABILITY EVENTS:

HEAT, WATER & ENERGY IN THE SOUTHWEST

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EXECUTIVE SUMMARY

Projections for the U.S. Southwest of longer, more severe heat waves and droughts, along with decreased surface water reliability, means an increased risk of constrained water resources in the region. Episodes of extreme summer heat can also disrupt energy production and transmission, leading to impact cascades potentially affecting millions of people in Southwest cities. These impacts have ramifications for public health and safety, transportation, and food supply. While much effort has focused on exploring the risks of projected climate change on individual economic and resource management sectors, there has been relatively little emphasis on examining the interactions of multi-sector vulnerabilities and emergency management at the intersections of extreme heat, water, and energy.

To identify risks, vulnerabilities, and knowledge gaps, and to prioritize research and management needs, a workshop, *Preparing for High Consequence, Low Probability Events: Heat, Water & Energy in the Southwest*, was held at the University of Arizona (Tucson, AZ) on September 28-29, 2015. Participants included regional researchers and resource managers with expertise in water, energy, climate, natural hazards, and emergency management.

This report outlines challenges and provides background on the topic, including analysis of case studies and conceptual diagrams created prior to and during the workshop. In addition, we discuss major themes that emerged during the workshop, and key research, management, and policy needs identified by participants.

Challenges

Higher temperatures projected for the Southwest over the current century will increase demand for both water and energy, especially during periods of peak load. Increasing temperatures have already changed the character of drought in the region, by increasing evapotranspiration and snowpack sublimation and decreasing soil moisture. These conditions lead to more rapid snowmelt runoff and decreased streamflow. Moreover, recent research suggests there are increased chances of a megadrought episode rivaling or exceeding the megadroughts that are well documented in the paleoclimate record. Extreme weather events, such as heat waves, which often occur amid extreme drought episodes, have already caused disruptions to energy production and transmission in some parts of the United States.

The water and energy sectors are tightly linked. Thermoelectric power plants use and consume vast amounts of water for cooling; conversely, large amounts of energy are required to pump and convey water hundreds of miles, especially in the Southwest. If stressed beyond a threshold, impacts to water and energy can generate cascades of impacts that affect public health and safety and have ramifications for emergency management.

Cascading Effects

Workshop participants investigated multiple recent case studies, including the 2011 San Diego blackout, the 2011 Texas drought, and the 2003 blackout in the northeastern U.S. Through a complex water energy system that intersects with social, technological, environmental, and political factors, these extreme events generated effects that cascaded through electric power generation, transmission, and water treatment and distribution systems. Workshop participants identified the key factors that characterized the primary connections within these case studies. They generated a knowledge-map of important impact cascades spawned by the plausible combination of drought and heat waves leading to diminished water supply and power outages—a low-probability combination of events, but one of high consequence if it occurred. We termed this combination a "high-low event."

Important themes identified during these discussions included the following:

- *Boundary issues:* Cascading effects transcend disciplinary, sectoral, and jurisdictional boundaries; thus planning and response efforts will increasingly need to move towards greater transboundary and multi-sector coordination.
- *Timescale issues:* The non-stationarity of climate changes, including the increasing trend in average and extreme temperatures, induces erratic background conditions that underlie acute natural hazard episodes, such as heat waves, and amplifies the frequency and risk of these acute events. Resource managers, utility planners, and emergency managers will need to reconcile the non-stationarity at the intersection of these chronic (e.g., drought) and acute (e.g., extreme heat) hazard triggers.
- *Metrics issues:* Risk-reduction interventions for high-low events need to be evaluated for their efficacy at both long and short timescales. The definition of long-term success must be refined as it applies to complex disasters with cascading impacts.

Research Needs

To answer questions about new knowledge needed to improve decision making for high-low events, participants identified the following high-priority research needs:

- Improved understanding of the roles of centralized (federal and state) and decentralized (local, community, and household) systems of monitoring and response to high-low events, and evaluation of their effectiveness.
- Improved understanding of the preparedness measures and multi-sector planning needed to address the increased risk from the intersection of slowly evolving trends in physical factors and acute, or threshold exceedance-based, short-term events.
- Critical examination of how institutions and individuals learn from high-low events. Important lessons learned during crises are often forgotten, unless institutions are in place to capture them.
- Improved post-event evaluation and analysis to learn why some areas are able to avoid impacts.
- Identification and evaluation of physical, institutional, and social resilience indicators of adaptive capacity.

Key Conclusions and Recommendations

Two workshop sessions focused on managing cascading impacts and identifying policy instruments associated with high-low events. Discussions about key management and policy issues raised concerns about capturing, retaining, and learning from the lessons of managing in the context of high-low events. The following are key conclusions and recommendations from workshop participants:

- Participants repeatedly stressed the importance of developing institutions with sufficient authority and capacity to manage across sectors and jurisdictions, capture important lessons, reinforce them, and keep them in the collective memory of organizations and leadership. They noted that high-low events provide windows of opportunity for managers and planners to learn and use gained knowledge to plan for future events—in other words, "never let a crisis go to waste."
- Effective learning requires comprehensive post-event evaluation, which relies on a foundation of good data and monitoring.
- Strong connections and open lines of communication across sectors, jurisdictions, and scales of governance are essential if disaster preparedness planning is to be effective in dealing with high-low events. Affected sectors and jurisdictions may be remote or indirectly linked to the epicenter of a high-low trigger (e.g., power outage), but may be impacted as much as or more severely than the epicenter. *Alignment of management and policy* across boundaries is fundamental for success in dealing effectively with high-low cascading events.
- Anticipatory planning, such as multi-scenario planning and visioning exercises, is an essential means of helping resource, utility, and emergency managers plan and prepare effectively for high-low events. It can facilitate better understanding of the possible chains of events within this system and could help mitigate costs associated with response-oriented approaches.
- Policies must bridge short- (e.g., months to years) and long-term (e.g., multiple years to multiple decades) planning. A key policy challenge is keeping short-term and long-term resources in balance so the resource reserve is not squandered by an emphasis on short-term needs.

INTRODUCTION

The Southwest U.S. is particularly vulnerable to the impacts of extreme heat and drought, given future projections of higher summer temperatures[1] and longer and more severe heat waves and droughts (Gershunov et al., 2013). Higher temperatures will increase energy demand, especially during periods of peak load, and decreased water supply can lead to water shortages and can further strain energy production through low reservoir levels. Extreme weather events, such as heat waves, which often occur amid extreme drought episodes, have caused significant recent disruptions to energy production and transmission in some parts of the United States.

High-consequence events related to weather and climate not only directly impact water and energy in the Southwest, but can also cascade into impacts on activities and sectors such as emergency management, public health, and transportation. As the population increases in this area—which already teeters in some locations on the edge of being habitable for those without access to cooling resources, especially in summer—these impacts can be increasingly damaging and far reaching. We refer to the intersection of high-consequence, low-probability events characterized by cascading impacts as "high-low events."

[1] 3.5°F in 2021-2050, 5.5°F in 2041-2070, and 9°F in 2070-2099, compared to 1971-2000, based on a set of CMIP3 outputs from fifteen GCMs and downscaled projection data sets (Cayan et al. 2013, p. 106).

The complexity of interactions requires consideration of the complete system, in order to adequately assess risks, determine knowledge gaps, and prioritize research agendas to fill these gaps. To this end, more than 30 water, energy, climate, and emergency management experts from the western United States met at the University of Arizona to better understand how to prepare for disasters stemming from extreme drought and heat, such as power outages and water shortages (see Appendix A for a list of participants).

Talks by prestigious researchers in their fields outlined challenges, including changing water availability, energy-water tradeoffs, and how existing disaster paradigms have failed. Case studies of drought in Texas and a power outage in San Diego illustrated the nature of cascading impacts and set the stage for enlightening discussions. Some of these discussions revolved around a conceptual model illustrating the heat-water-energy nexus. Participants identified possible cascading impacts of extreme heat and drought episodes, potentially under-recognized vulnerabilities that might result from cascading events within the system, and some of the mechanisms that amplify risk. Further discussions illuminated management and policy challenges, such as questions of funding and responsibility, and research and monitoring needs (see Appendix B for a full agenda).


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CHALLENGES

Key Messages

- With higher temperatures projected for the Southwest, the risk of a megadrought occurring this century increases and more precipitation will fall as rain rather than snow, quickening snowmelt.
- Water and energy are tightly connected. Thermoelectric power plants require large amounts of water for cooling and, conversely, energy is required to pump and convey water.
- In order to manage cascading impacts of water and power disruptions, as well as extreme weather events related to a changing climate, the emergency management field will require a partial paradigm shift that emphasizes flexibility over standardization and recognizes that disasters are influenced by long-term trends and chronic conditions such as drought.

Exposure to Climate Risk

Much of the Southwest has been in drought for at least the past decade, and paleoclimate records tell us that the current drought pales in comparison to prehistoric droughts, some of which lasted for many decades and were more severe than what the region is currently experiencing. The longest megadrought now known to have occurred in the Colorado River and Rio Grande headwaters lasted 50 years, with only one year of non-drought conditions (Routson et. al., 2011). With expected higher temperatures, the risk of a megadrought occurring this century increases dramatically to over 80 percent (Cook et al., 2015).
The influence of higher temperatures in the region has already changed the character of drought. Evaporation of surface water and water from plants and soils occurs more readily in a warmer atmosphere, as does sublimation—the transformation of water directly from solid to gas state—from snow. With increasing temperatures, more precipitation will fall as rain rather than snow, and rain on snow quickens snowmelt, all of which decreases streamflows. A recent study predicts that warming alone will decrease Colorado River streamflows by 6.5 percent +/- 3.5 percent per degree Celsius (Vano et al., 2014). Recent studies connect the increasing risk of regional megadrought with projected water shortages and power outages (Frumhoff et al., 2015).

Another risk to the energy sector related to weather is lightning strikes, which are predicted to increase 12 +/- 5 percent per degree C in the contiguous U.S. (Romps et al., 2014). Taking into account projections of future warming, this equates to a 50 percent increase in lightning strikes over this century. Beyond the direct impact of lightning strikes, they can also indirectly affect power supply by igniting wildfires, which have the added potential of affecting the watershed and water supply. From 1987 to 2003, the area of wildfires in the western U.S. was more than five times larger than during 1970–1986, primarily due to lightning-ignited wildfires and the impacts of increased temperatures and earlier spring snowmelt. As temperatures and evapotranspiration increase, projections indicate that the area of forest burned will increase substantially: by 380 percent in the mountains of Arizona and New Mexico and 656 percent in the southern Rocky Mountains for a 1.8 degree Fahrenheit (1 degree C) increase in temperature (Fleishman et al., 2013).

Energy and Water Systems

Water and energy are tightly connected: water is needed to create energy and energy is needed to supply water. Thermoelectric power plants, which produce 90 percent of the country's energy, use (take in and release) or consume (take in and recirculate) large amounts of water, depending on the type of plant. Sometimes the returned water can be much hotter than when it enters the plant, threatening and damaging downstream ecosystems; a hotter future climate will only make these impacts worse by increasing the temperature of the returned water. Concentrated solar and nuclear power consume even more water—at least twice that of coal-fired plants.

Even though less than 2 percent of water is consumed for electricity in the Southwest (less than half of the rest of the country, which uses about 5 percent), every percent of water is critical given the over-allocation of supplies on rivers in the region, such as the Colorado, and the increasing likelihood of lower water resource reliability. Climate change will increase the amount of water needed for energy; by 2050, about 3 percent more water will be needed to provide energy for air conditioning and evaporative cooling in Arizona and New Mexico.

While the energy sector in the region consumes a small percentage of water, a large amount of energy is required for water. More than 20 percent of the electricity supply in the Southwest is used to pump and convey water. The Central Arizona Project (CAP) canal, which carries water 336 miles from the Colorado River to central and southern Arizona, is the highest user of electricity in the state of Arizona. This energy is financially costly and represents large amounts of greenhouse gas emissions.

Conception of the Problem: Cascades, Hazards, and Disasters

Power and water are our most critical infrastructure systems. Water is essential for public health and power. Power is a lifeline system, central to banking, telecommunications, health, water supply, transportation, and other critical infrastructure. Without these necessities, cascades of effects can occur. A 2003 power outage in the northeastern U.S. and Canada led to the shutdown of mass transit and airports, traffic and pedestrian congestion from loss of traffic signals, $7.8 billion in economic losses, and many more impacts.

Cascading effects from power outages can also include economic and reputational losses for power companies. The public has very high expectations of electric utilities, including both the need for continuous uninterrupted service and the need for rapid restoration of disrupted services. The failure of electric utilities to perform adequately can lead to "outage outrage," which has a range of negative political, economic, and reputational effects, including "recreancy," in which the public loses faith in public institutions such as power and water utilities.

Managing cascading impacts of water and power disruptions, as well as extreme weather events related to a changing climate, may require a different way of thinking about emergency management. The definition of a disaster is an event that temporarily overwhelms the ability of a community to respond. It is something that happens to us, has a clear beginning and end, and a clear spatial domain. Some extreme events occurring today, however, do not necessarily have such clear temporal and spatial boundaries. It is difficult, for example, to define a start and end date for drought or spatial boundaries of an extreme heat episode. In addition, the goal of disaster response is to return the community to "normal," but how do we define what is normal? With climate change, projections show a new normal (Milly et al., 2008). In the prevailing view of disasters, all events share a canonical life cycle of preparation, response, recovery, mitigation, and (again) preparation. Does this conceptual cycle help us prepare for cascading impacts? Does it help us prepare for chronic events, such as drought?

Participants of the workshop in the emergency management field suggested that a partial paradigm shift in the current view of emergency management may be necessary in order to prepare for and respond to extreme events under a changed climate. A one-size-fits-all approach that assumes stationarity of climate will no longer work in a changing world. A more useful approach, according to workshop participants, is an integrated emergency management perspective, centered on community change, in which emergency managers act as community change agents. An all-hazards approach, one that plans for every possibility, is another option, but is this umbrella big enough to fit the "new" type of hazard associated with a changing climate? What is certain, however, is that emergency management must now:

- emphasize flexibility over standardization;
- reconsider the phases of a disaster;
- consider that all disasters are "glocal"—that is, they are affected by global and hemispheric climate and weather patterns, as well as global supply chains, and that they may affect national or global supply chains, electricity transmission networks, and so on, and;
- adopt the view that disasters are influenced by long-term trends (e.g., in temperature) and chronic conditions such as drought, and thus conceptualizing disasters as discrete events may hinder preparedness efforts.

CASCADING EFFECTS

Key Messages

- Strategic planning and scenario development can play a role in helping multiple agencies think about how impacts are shared across their respective networks.
- The impact of acute events vs. chronic underlying conditions that amplify disaster, and how we plan for and manage these different types of events, was a key theme of the workshop. Are different plans required to address short-term acute disaster events compared to longer-term chronic conditions?
- Cascading effects transcend disciplinary/jurisdictional boundaries; planning and response efforts have to move in this direction as well.

An emphasis on the cascading effects within a system requires a holistic approach to disaster management. This holistic focus extends beyond acute events that are frequently designated as disasters to include underlying social and environmental conditions that affect the outcomes of acute events, where any number of possible cascades could result from a given acute event that amplifies underlying or pre-existing vulnerabilities. A specific chain of events may be a low-probability occurrence, but numerous different low-probability cascades *could occur*, each of which reflect the vulnerabilities that accumulate within a given social or technological system. These vulnerabilities may be minor when taken in isolation or may represent major tipping points that trigger a drastic change within the system. It is important to document and understand the interconnected effect of singular but related events and how they might combine to cause more catastrophic or disastrous outcomes than any isolated event might cause. A key goal of this workshop was to better characterize the connections within the system that reflect this accumulated vulnerability in order to begin thinking about how to plan for and mitigate these types of high-low events with cascading impacts, focusing on the holistic approach to disaster management mentioned above.

Case Studies

Prior to the workshop, we investigated three case study examples—the 2011 San Diego blackout, the 2011 Texas drought, and the 2003 blackout in the northeastern U.S.—all of which demonstrated effects that cascaded through a complex system, as it relates to water and electrical systems. These examples also illustrate the intersection of social, technological, environmental, and political factors, and provide examples of discrete events acting as precipitating conditions that layer onto existing systems, influenced by existing social and environmental vulnerabilities.

SAN DIEGO, 2011

The Southern California blackout in 2011 started when transmission was interrupted due to human error. This resulted in the largest blackout in the state's history and also affected

Baja California Norte, Mexico, and parts of Arizona (FERC/NERC, 2012; County of San Diego, 2011). This blackout caused cascading effects whose impacts extended outside of the energy sector, including the shutdown of San Diego's wastewater treatment plant, public health mandates to boil water, spillage of raw sewage on local beaches, airport closure, and other public health issues.

A seemingly simple human error led to a number of cascades within the system that extended downstream as a number of social systems were affected, as well as upstream as the cause of the outage was investigated, including early fears about a terrorist attack on the electrical grid. The San Diego outage illustrated how relatively small triggers can lead to larger effects within a linked system, and how these effects cascade and intensify as larger and larger areas are affected. The outage also highlighted the amplifying effects an outage can have on vulnerable populations contained within these areas.

TEXAS, 2011
As opposed to an acute event like in San Diego, the effects of vulnerabilities in the Texas case study accumulated during a multi-year drought that set the stage for a more serious water shortage. Below-normal precipitation and above-normal temperatures resulted in extreme drought conditions in the state in 2011. These conditions led to water shortages, reduced water quality, and power outages in some areas (power plants require sufficient water for cooling the power generating system for both the thermoelectric and hydroelectric power systems), as well as restrictions on agricultural water usage (affecting crop yields and profits, and even infrastructure concerns, such as cracking asphalt and road surfaces or threats to integrity of water mains and piping systems via subsidence). This case study demonstrated how chronic conditions such as drought can result in cascading impacts that lead to power outages and other acute problems and illustrates how the heat, water, and energy sectors are interlinked.

NORTHEAST U.S., 2003
In a blackout in the northeastern U.S. in 2003, trees are believed to have short-circuited a part of a transmission line in Cuyahoga County, Ohio. Extreme heat then overloaded the line that resulted in a blackout that affected eight eastern U.S. states and Ontario, Canada (U.S./Canada POTF, 2004). Moreover, the alarm system failed, amplifying the event. Fifty million people were affected and there was an estimated $7.8 billion in losses. Subways stopped, flights were delayed, water systems shut down, and lack of air conditioning led to public health issues on hot summer days. Again, this case study illustrates the connections between heat, water, and energy. In this case, effects of an initial event in the energy sector were amplified by extreme heat and cascaded to issues in the water sector.

Scenario Diagrams

As part of a pre-workshop planning exercise, we sought to better understand these connections using visualizations tied to a specific example. We created a diagram of the connections between climate, water, and energy supply (Appendix C), as well as specific diagrams for two of the case studies (Appendices D—E). These specific examples helped us think through what types of cascades could occur in a given system and helped us plan for our activities in the workshop to further discuss other connections that *could* occur rather than simply diagnose events that had occurred.

As part of this process, we identified the key factors that characterized the primary connections within these case studies, and created a simplified conceptual diagram that illustrates the important relationships and cascades/intersections we planned to focus on during the workshop (Figure 1). We provided this

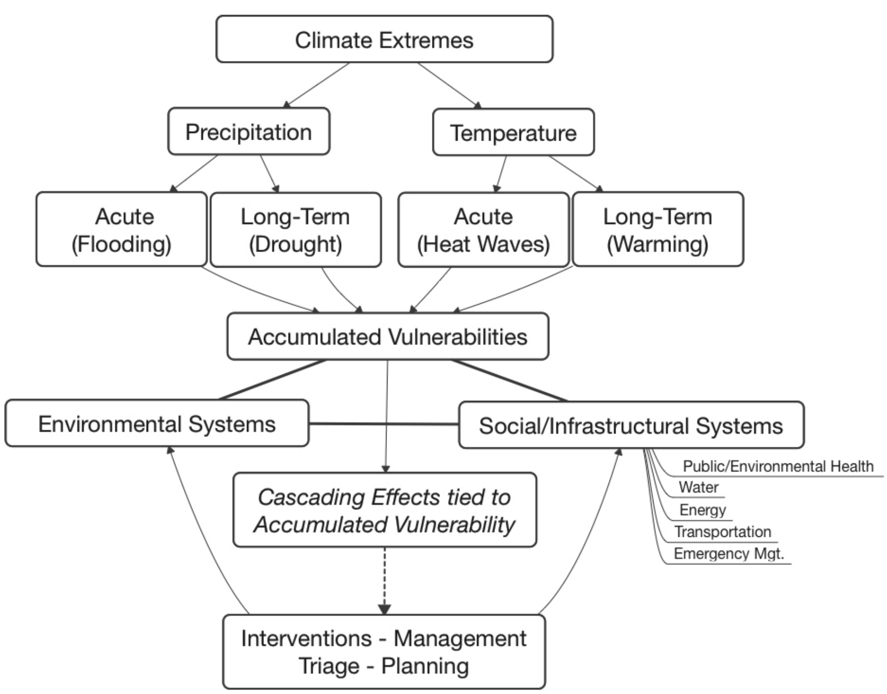


Figure 1: Conceptual diagram presented prior to the workshop, illustrating climate, vulnerabilities, and system relationships.

conceptual diagram to participants in advance of the workshop, along with background information on a number of events that were characterized by a series of cascading effects.

We used this diagram at the workshop as a starting point for sessions designed to elicit further discussion and exploration of cascading effects, focused on the connections within the system, as well as the pathways that move through these systems. We focused on abstract discussion of the model framework of how cascades occur (for a general sense of the types of connections that are important), as well as the specific examples of known cascades that have (or could) occur, in order to document known pathways within systems. We aimed to document the components of this diagram at three stages: 1) the factors that contribute to a given event that may culminate in a series of cascading effects; 2) the social and infrastructural systems that were designed and implemented either in anticipation of, or in response to, a given set of planning criteria; and 3) more generally, the vulnerability and resilience of a given system that either contribute to the risk of cascading events or help prevent their occurrence.

This process led to a number of fruitful discussions that we captured by modifying the diagram in real time. As participants pushed our discussion forward, we incorporated their comments, feedback, and information into the model diagram. In the first session, *Conceptual Model of the Heat-Water-Energy System and Links to Emergency Management*, we updated the diagram, based on group discussion, by adding issues that would be pertinent to a better understanding of the key points of failure or rupture within the energy-water-climate system (Figures 2 and 3).

These diagrams capture the main points from two key discussions that took place in the conceptual model-focused section of the workshop. In the first diagram (Figure 2), we see the main components that participants identified as key areas of concern when defining possible cascading effects, as well as specific examples of how cascades could (or have) occur(red). This included issues related to a stable and clean/safe water supply, public health and human safety, air and water quality more generally, transportation, and infrastructure concerns. In particular, this exercise highlights that many possible cascading effects are well understood as an accumulation of smaller events. These smaller events, when taken individually, are generally manageable and plans already in place are adequate to address the specific bounded needs of these individual events. This discussion also highlighted the potential disruptive impact a set of concurrent or cascading events can have, as jurisdictional boundaries are blurred, and that cumulative effects of a series of events can pose management challenges that are not easily solved by focusing on bounded definitions of the problems at hand.

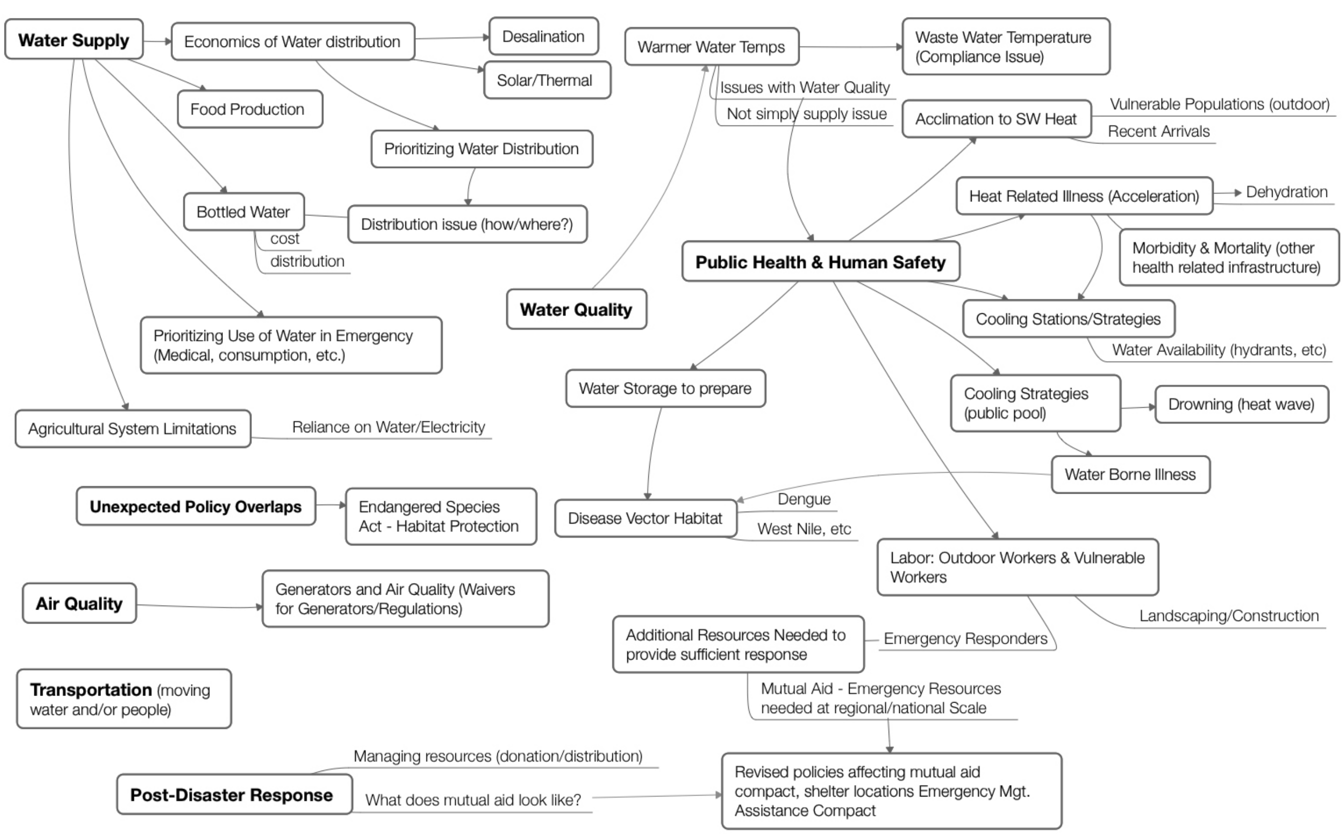


Figure 2: A portion of the diagram created in real time during participant discussion.

In the second half of this session, participants moved on to discuss management challenges that would complicate any planning efforts targeted at these issues (Figure 3). This discussion reflected the complex nature of managing cascading events, and served to reiterate the point that there exists a diverse set of challenges associated with developing planning and response strategies that adequately anticipate events and their associated complications/challenges. Participant examples highlighted that cumulative effects from a particular cascade can overwhelm the response capacity across a number of systems, a situation not unlike the San Diego blackout, in which a small event led to larger and larger impacts, with somewhat catastrophic effects. Participants also emphasized the distributed nature of components or steps of any given series in a cascading event. Participants asserted that when the causes and effects of a cascade are decentralized and do not hew to the boundaries of a single agency or jurisdiction, planning and response strategies are similarly hard to define. This makes for increased difficulty in identifying points of intervention and complicates response and management efforts, especially when the effects span multiple scales of governance.

Some specific concerns and questions participants identified in the second half of the session included:

- How to design plans for sub-populations in the area, especially those that are more vulnerable? Is there a one-size-fits-all plan that will encompass the needs of marginalized or vulnerable populations, or are special plans necessary to adequately prepare for disproportionate effects?
- How to determine the efficacy of interventions and a better understanding of how to define long-term success of a given program (vs. short-term success)? A sub-question within this discussion was how to ensure the long-term sustainability of successful programs.
- How do plans change depending on the timescale of the disaster, and are different plans required to address short-term acute disaster events compared to longer-term chronic conditions? This represents an ongoing discussion with scholars of disaster, namely the impact of acute events vs. chronic underlying conditions that amplify disaster, with the general consensus in the room being focused on the intersection of these two time scales.
- The necessity of defining the nature of the particular cascading effect—is this an issue where a singular event caused a (likely unforeseen) chain of events, or the cumulative effect of a number of small events, which contribute to the larger context?
- What are the social and economic consequences of this event? Who will be most affected and how will affected regions/communities pay for recovery? Are insurance or federal resources available or required to implement recovery plans? What social services might be interrupted during these events that will have cascading effects on the populations that depend on these services?

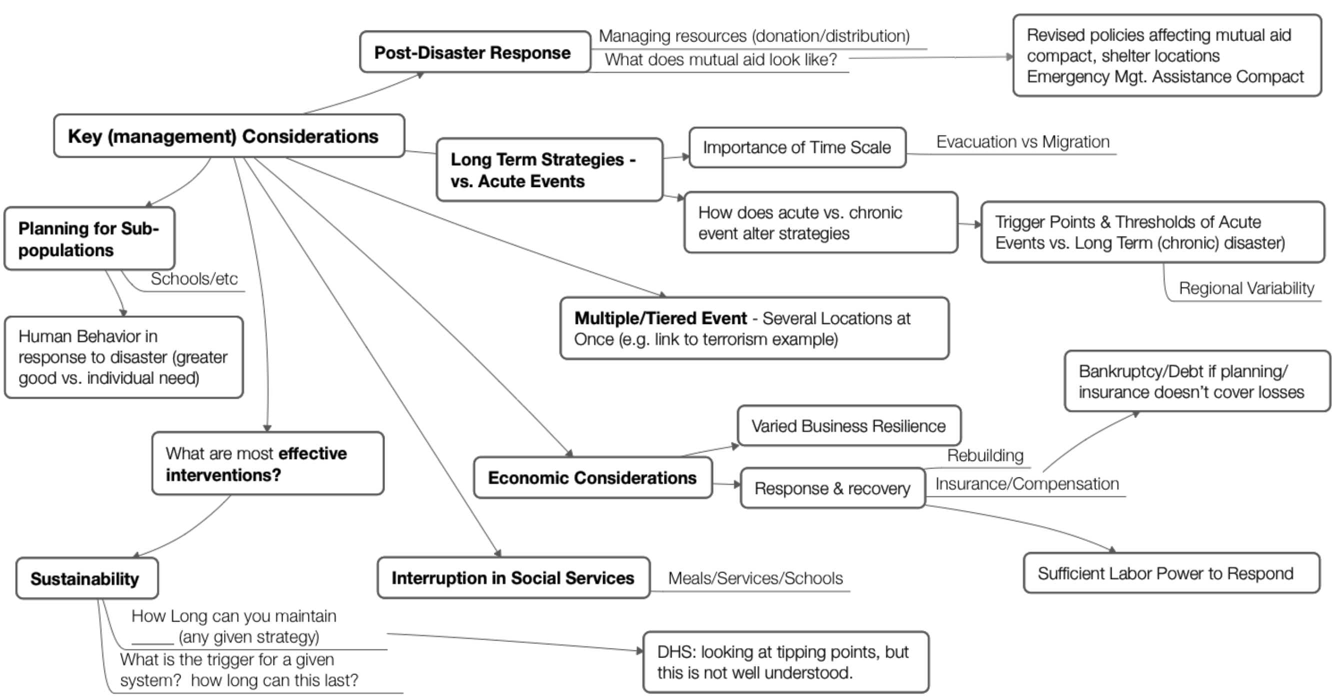


Figure 3: A portion of the diagram created in real time during participant discussion.

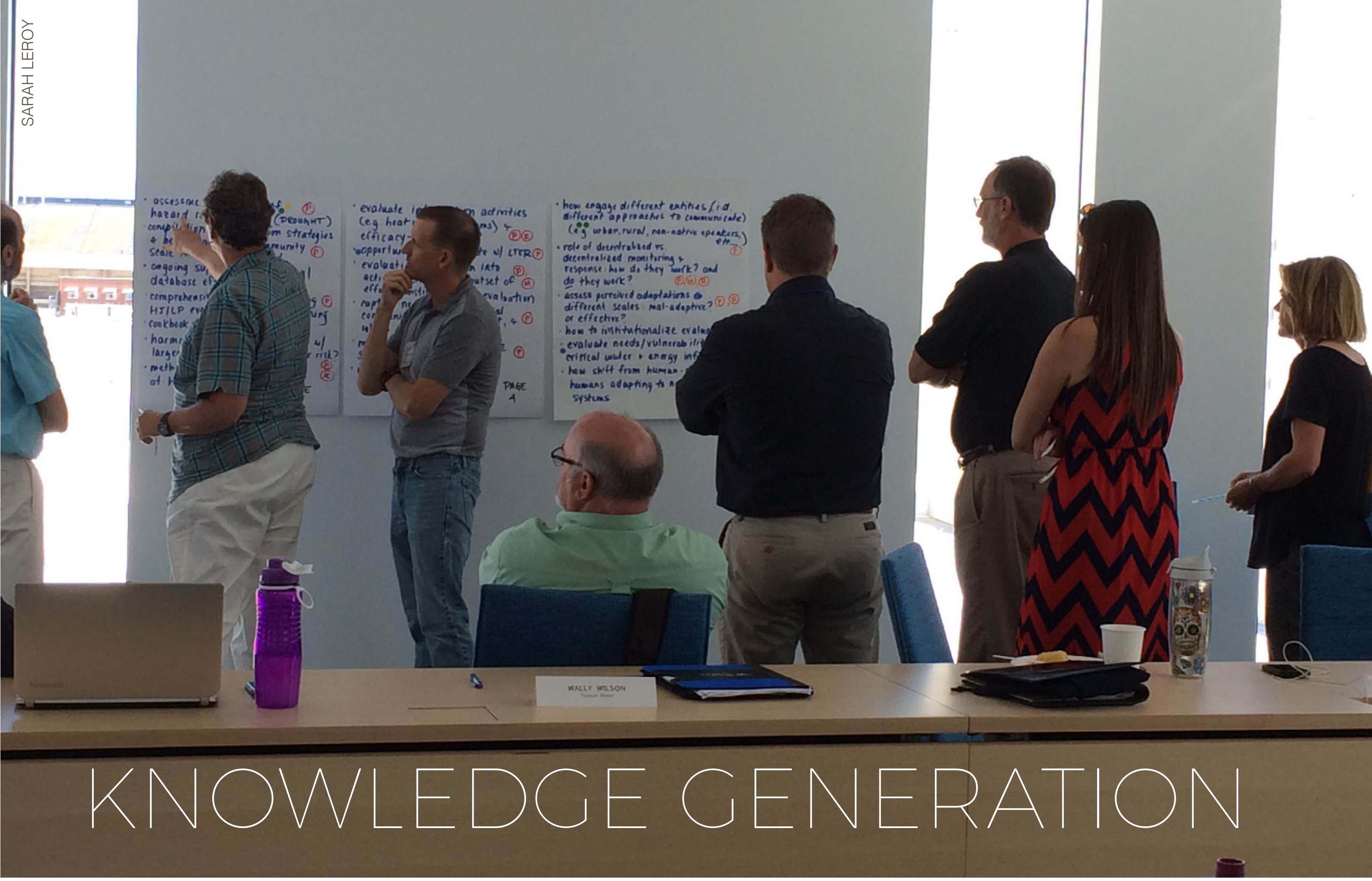
In a subsequent session, *Managing Cascading Impacts*, we expanded on these themes and led participants on a guided discussion to work through a number of key questions that were raised in the workshop. These questions progressed through various stages of thinking. Initial discussion focused on the question, Who is involved in management? Participants discussed the wide range of public and private entities that might be involved in management, and talked through specific examples of how this mix of management had been deployed, using examples from their own agencies and regions. The question of "who is involved" also returned us to the ongoing theme, as this question of "who" is embedded within the larger question of "crisis management vs. long-term adaptation" (as one participant described the dichotomy). This divide emphasizes different perspectives on managing cascades, ranging from grappling with an acute crisis to addressing the underlying conditions that might exacerbate the impacts of a given disaster. In addition to conversations about these "official" planning and response strategies, this discussion also brought to light the presence of "unofficial" or community response networks. These may have formed organically in response to a given event, or may be planned in advance and associated with other social support (such as regional charities, NGOs, or other community support networks). Finally, participants identified researchers (and university researchers specifically), as playing a role through their analysis of these events, as well as their participation in some of these networks.

After thinking through the "who" of management, participants moved on to a discussion of timing, and more specifically about how the timescale (acute vs. chronic conditions) affects planning. What are the challenges associated with thinking through acute events vs. underlying conditions? This in turn precipitated discussion on which agencies are tasked with responding to acute disasters (fire management and response), compared to those that are oriented towards underlying conditions (drought management and planning). Participants emphasized that even in the most well-defined examples, there was blurring between jurisdictional boundaries, and it was hard to specifically attach any given event, circumstance, or context to a single management agency. Yet, it was pointed out that many disaster declarations are specifically bounded, which can complicate response and recovery.

This discussion of challenges (along with "who" is involved in management) drove us toward a key discussion point in the session, when a participant posed the question, Do we have the institutions in place to manage these cascading effects? In other words, is the current organizational structure oriented in such a way that it can adequately respond to cascading effects that span spatial and temporal boundaries, not to mention scales of governance? Most participants involved in the discussion seemed to think that we did have the institutions in place to manage most cascading events, but that the institutional orientation was not well situated to address the underlying conditions—longer-term chronic disaster issues.

This discussion highlighted two key points: the difficulty in planning for an event that hasn't happened yet and the difficulty in planning for (and responding to) an event that has a complex origin and multiple moving parts. Participants highlighted the need to justify the cost of management plans, and that vague, nebulous, or poorly defined components of a larger system or disaster were hard to justify further work on, since they were not associated with a specific or discrete event/disaster.

This led participants into a two-pronged discussion. The first discussion focused on emergent planning efforts (including strategic or scenario planning exercises) that encourage collaboration and sharing across networks and scales of governance. This emphasized the role that strategic planning and scenario development could play in helping multiple agencies think about how impacts were shared across their respective networks, and what an integrated and holistic management plan might look like. The second prong was a follow-up discussion that emphasized the conditions for successful collaboration that participants had observed within their own management activities. At a foundational level, there was emphasis on three key issues: 1) a collaborative context (willingness to share and work together); 2) empowered individuals who could make change and planning happen within their management context; and 3) a precipitating event (that spurred further action and planning). Even though the precipitating event, often in the form of a disaster, helped spur action, this motivation can also be employed to help address long-term issues as well. In fact, one of the discussion points in this session emphasized that some of the most successful collaborations were able to move past simple triage management of a given disaster event to long-term planning that begins to address underlying conditions as well as the specific impacts of disaster.



SARAH LEROY

KNOWLEDGE GENERATION

Key Messages

- The most important research, policy, and management need identified by participants is understanding the roles of centralized and decentralized systems of monitoring and response to high-low events. Do these systems work? How do they work?
- Slowly evolving trends, such as long-term temperature trends and drought, increase the possibility of acute high-low events. What changes in planning are required to address the challenges associated with managing and preparing for the increased risk brought on by the combination of slowly evolving trends in physical factors and acute or threshold/exceedance-based short-term episodes?
- Participants noted a key emerging research issue—that critical lessons learned during crises are often forgotten, unless institutional mechanisms are in place to capture them—and posed the key question, What does it take for organizations to learn after disasters?

In this section, we articulate research needs expressed by workshop participants, with an emphasis on knowledge generation—identifying what new knowledge is needed to improve decision making with respect to high-low climate-generated disasters. We assess knowledge that is already well established, needs for new fundamental science, research needs to inform management and solutions to key management problems, and emerging issues to address existing or anticipated challenges.

We classify research needs gleaned from discussions in the following ways:

- Emphasis area: climate, water, energy, emergency management
- Strategic area: planning, management, research
- Intersections: where emphasis areas intersect, and where participants identified emerging issues

What We Know

CLIMATE

- Temperature. Plenary speaker Dr. Jonathan Overpeck presented evidence from CMIP5 temperature projections (RCP 8.5) (IPCC WG I, 2013), showing that higher future temperatures are projected for the western U.S. Ensemble average CMIP5 precipitation projections (RCP 8.5) lack certainty for the future of the Upper Colorado River Basin and Upper Rio Grande Basin; temperature projections, however, are more consistent.
- Paleoclimate drought reconstruction. Given the large range of CMIP precipitation projections for the region and the

consistency of recent paleoclimate drought, precipitation, and streamflow reconstructions, there is at least moderate confidence that the CMIP models underestimate future drought severity and duration (Ault et al., 2014; Cook et al., 2015; Meko et al., 2007).
- Hadley Cell. Based on the first principles of atmospheric physics, plus observational evidence, it is a reasonable assumption that Hadley Cell circulation is becoming, and will continue to become, more vigorous and expanded in a warming world (IPCC WG I, 2013; Walsh et al., 2014). A more vigorous and expanded Hadley Cell circulation would enhance drying in parts of the Southwest.
- Influence of temperature on Colorado River Basin hydrology. Based on modeling studies and observations, a 1 degree C temperature increase results in a 6.5 percent +/- 3.5 percent decline in Colorado River streamflow (Vano et al., 2014).

EMERGENCY MANAGEMENT
- Disaster management is often tied to singular or acute events based on both the nature of these events (a singular occurrence) and the policies that are in place to respond (e.g., insurance claims, federal emergency response, state and local response) (NRC, 2012).
- There has been a gradual shift in thinking regarding disasters to better capture, document, and understand the underlying conditions that serve as the context within which they take place. This increasingly holistic understanding focuses on the network of related effects or the possible chains of events that amplify the effects of disaster.[2]
- Lack of jurisdictional authority or overlap makes holistic strategic response to disaster difficult, as questions of funding, responsibility, and authority are more difficult to determine when the event in question spans obvious spatial, temporal, and jurisdictional boundaries.

WATER-ENERGY NEXUS
- Water-cooled thermoelectric power plants withdraw vast amounts of water from nearby freshwater resources such as rivers, lakes, and aquifers, contributing to water supply stress in some areas. In 2008 in the Southwest U.S., power plants withdrew an average of 125 to 190 million gallons of groundwater each day (Averyt et al., 2011).
- Population growth and climate change will increase the amount of water needed for power generation; by 2050, about 3 percent more water will be needed to provide cooling in Arizona and New Mexico.
- A large amount of energy is also required for water. Plenary speaker Dr. Kristen Averyt explained that greater than 20 percent of the electricity supply in the Southwest is used to pump and convey water.

[2] Hurricane Katrina in 2005 was not the first (or even the most recent) disaster in which this social/environmental/technological intersection was brought to the forefront, but it was one of the first in a heavily mediated (as in mass media) environment, which meant these connections (and the failures within a chain of events) were rendered more visible than past events.

Fundamental Science Research Needs

During the course of the workshop, we documented science research needs and associated uncertainties. The key issues raised by participants, including plenary speakers, include the following:

CLIMATE
- Improved climate modeling to project:
  - Northern Hemisphere storm tracks (current status: low confidence) (based on IPCC WG I, 2013)
  - Western U.S. precipitation (current status: low confidence) (based on IPCC WG I, 2013)
    - Special focus: Upper Colorado River Basin high-elevation precipitation
  - Drought risk (current status: moderate confidence in trends, but magnitude underestimated) (based on Ault et al., 2014; Cayan et al., 2013; Cook et al., 2015; Routson et al., 2011)
  - North American monsoon precipitation (current status: low confidence) (based on IPCC WG I, 2013; Carrillo et al., in review)
  - Climate variability (current status: low-moderate confidence) (based on Cayan et al., 2013; IPCC WG I, 2013; Walsh et al., 2014)
  - The changing character of drought—a combination of temperature, precipitation, and variability (current status: low-moderate confidence) (based on Cayan et al., 2013; Reclamation, 2011; Llewellyn and Vaddey, 2013)

WATER
- Improved estimates of water demand
- Improved projections of water resources
- Influence of temperature on soil moisture and absorption of precipitation (Texas reservoir example)

Research, Data, Information and Knowledge Needed to Inform Management and Solutions

To gauge key data, research, information, and knowledge needs form high-low events, and to inform management, operations, and policies leading to solutions (such as reduced risk and reduced vulnerability), workshop participants brainstormed and prioritized these needs in a dedicated session. Appendix F lists participants' suggestions and highlights the priority recommendations for three foci: planning, management, and research. In some cases, recommendations could not be easily categorized; thus, the table lists recommendations in multiple places. Based on a simple count of participant responses, the following were the highest priority recommendations:

1. Understanding the roles of centralized and decentralized systems of monitoring and response to high-low events. Do these systems work? How do they work?
2. Understanding and developing a framework for explicitly integrating high-low events into scenario planning. This recommendation originated from observations that many scenario-planning exercises lead to strategies that tend to stay close to existing plans, focus on known experiences, and be risk averse since they tend to rely on general consensus and be based on least common denominator preparations (i.e., the lowest cost or easiest to implement strategies that

might not be the most effective or creative, but have general support amongst a larger number of people).

   a. In addition, participants noted a mismatch between scenario planning, which emphasizes multiple future paths and embraces uncertainty, and policy instruments, which tend to require yes/no triggers and decisions.

3. Critical examination of whether and how institutions and individuals learn from high-low events. Do they change behavior? If so, what factors foster changes of behavior that improve high-low event preparedness and response management outcomes and/or lead to increased resilience?
4. Critical assessment of the quality of hazard response plans, with a special emphasis on drought plans. This includes assessment of content and how often the plans are updated.
5. Identification and evaluation of system triggers that lead to exceedance of adaptive capacity and adverse impacts. Triggers can include factors such as physical indicators (e.g., climate and water availability factors), institutional factors, preparedness and response coordination, social vulnerabilities and/or social network resilience factors, and others.
6. Improved understanding and assessment of the diffusion of innovations within various systems related to high-low event preparedness and response. How do innovations move through these systems? How can the resource and emergency management communities best propagate and maintain adoption and retention of innovations?

In addition, the following management needs areas were deemed noteworthy:

- Mechanisms for improved information sharing, including:
  - Effective means for cross-sector and cross-agency communication of strategies and key lessons
  - Efficacy of social media and other kinds of messaging in disaster response, including the development of testbeds and demonstration projects
  - Efficacy of engagement and communication strategies for different entities and communities (e.g., urban, rural, tribal, non-English-speaking communities)
- Social network analysis (SNA), including both quantitative (structural) and qualitative analyses, in order to determine gaps and holes in existing networks and to design improved communication efforts with hard-to-reach demographic groups. Planning methods and processes for dealing with deep uncertainty, such as high-low event cascades, including robust decision-making methods
- Evaluation of strategies and actions in preparation for and response to high-low events, including:
  - Efficacy of intervention activities such as heat early warning systems
  - Assessment of adaptations at multiple scales… does scale affect effectiveness? What instances of adaptations at one scale lead to maladaptation at another scale?
  - Combined and coordinated evaluation of vulnerabilities of critical water and energy infrastructure
- Collaborative approaches, including:
  - Ongoing forums for water and energy professionals to improve coordination, understanding of institutional cultures, and effectiveness for dealing with high-low events
  - Incentivizing researcher-practitioner collaborations (e.g., increased support for, or expectation of, such collaborative activities in the tenure review process)

Emerging Issues

During the workshop, the organizing team noted potential areas of interest and further investigation, and following the workshop the team reviewed responses and notes for emerging research issues. The following are the key emerging areas identified by the team:

- *How do we resolve emerging high-low event management and preparedness challenges from increased risk brought on by the combination of slowly evolving trends in physical factors and acute or threshold/exceedance-based short-term episodes?* Long-term temperatures are projected to increase (an evolving trend), elevating the likelihood of severe and sustained drought and decreasing water supply reliability. The combination of these effects will also increase the possibility of acute high-low events. Thus, what changes in planning are required to develop effective interventions? There are clear lines of responsibility for acute events, such as severe storms or floods, but no single lead agency is in charge of the added risk from long-term trends. Participants identified this area as an important direction in which researchers and practitioners can work together to understand temporal intersections between prediction, planning, and management, in order to reduce societal risk, even as exposure to risk (e.g., heat waves, lower water supply reliability, etc.) increases.
- *What cross-sector governance, coordination, and communication structures are needed to improve preparedness and reduce vulnerabilities to high-low events? How can we best coordinate multiple levels of disaster planning and response in anticipation of high-low events?* While state and national-level coordination is essential, citizen- and neighborhood-level monitoring, knowledge, and social networks play key roles—but too little is known about those networks, their intrinsic preparedness, and their adaptability. *Possibilistic* thinking—planning and preparation for plausible, even if low probability, events—was recommended to maximize preparedness, reduce risk, and reduce the costs associated with disasters. Yet, little is known about (a) how to propagate possibilistic thinking, (b) the costs of implementing possibilistic approaches, and (c) the pitfalls of possibilistic approaches (e.g., false alarms, over-building, resource drain, political fallout, etc.).
- *What does it take for organizations to learn after disasters?* This issue has long roots in the disciplines of natural hazard and disaster management. Nevertheless, the question still has great relevance and poignancy for the semiarid western U.S., which has been assaulted repeatedly by drought episodes, power outages, heat waves, floods, and dust storms that sometimes trigger impact cascades. Participants noted that critical lessons learned during crises are often forgotten,

unless institutional mechanisms are in place to capture them. For example, it took a second severe drought in less than a decade for Colorado to set up institutions to tackle simultaneous intersecting impacts (e.g., low water supply and multiple fire outbreaks), and to establish routine pre-crisis planning and preparedness for multiple impacts. In contrast, in the 1990s, earthquake-prone Los Angeles successfully mobilized public funding to reduce risks from future quakes by learning from an earlier Mexico City earthquake.

- *To what degree can we apply lessons learned from the earthquake, for example, to impact cascades triggered by climate and weather? Do these lessons translate across scales of governance? Across sectors?* Social or institutional memory can play an important role in transmission and persistence of learning from a given disaster. The accumulated experience within a particular location can improve subsequent responses to similar events, and these lessons learned can also be communicated to other locales that might be designing emergency response plans for similar types or categories of disaster events. Additionally, as ongoing research continues to demonstrate the role that social and economic disparities play in the experience of disaster, regardless of type, this may push different governing actors to focus on general vulnerability in addition to the specific chains of events that might lead to a particular disaster. Another key point related to sharing across networks and scales of governance is to recognize any barriers in place that prevent or limit sharing within/across these networks.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MANAGEMENT AND POLICY CHALLENGES:

Learning from High-Low Events

Key Messages

- Strong connections and open lines of communication across sectors, jurisdictions, and scales of governance are essential if disaster preparedness planning is to be effective in dealing with high-low events.
- Anticipatory planning was identified as an essential means of helping resource, utility, and emergency managers plan and prepare effectively for high-low events. It can facilitate better understanding of the possible chains of events within this system and could help mitigate costs associated with lack of planning for cascading effects. Building social and institutional memory that draws on past experiences is a key part of anticipatory planning.
- Social learning is essential for capitalizing on the management and policy insights needed to address high-low events. Participatory and anticipatory planning can be used together, allowing for greater ability to manage events effectively and to act decisively, and can help bridge the intersection of short- (event) and long-term (trend) drivers of change. The long-term perspective must be dominant; otherwise, crisis management is reactive rather than proactive, and therefore less effective and more costly.

Workshop sessions on *Identifying and Managing Cascading Impacts and Interventions, Policy Instruments, and Costs* fed subsequent discussions about key management and policy issues and the kind of learning needed to improve response to high-low disasters. These discussions were stimulated by a participant question, Do institutions and individuals learn from high-low events? In subsequent discussions, participants further asked: Does learning result in behavioral change? What factors influence institutional and individual learning from [high-low] events? Do emergency managers look at crises as learning opportunities, or is learning capacity lacking or constrained by other priorities? How does emergency management planning need to change in anticipation of climate change? Can institutions learn from the experience of others (e.g., from an event that occurred in another locale), or does learning only occur in response to disasters that directly affect an individual, community, or organization?

Plenary session talks, case studies, and subsequent discussions provided strong evidence of significant human contributions to high-low disasters that result in cascading impacts to water and energy systems, while acknowledging the role of external triggers such as climate and weather. Examples drew on the emergency response in the Gulf Coast during and following Hurricane Katrina in 2005, cascading impacts during the 2003 Northeast power outage, and health care system vulnerabilities exposed in Houston from Hurricane Allison in 2001. Even well-intentioned anticipatory measures, such as the expansion of emergency generator capacity in New York City's Langone Hospital preceding Superstorm Sandy in 2012, were thwarted by a failure to consider other impactful low-probability risks; in this case, the extensive flooding that accompanied the storm incapacitated the new generators that had been installed in the hospital basement. Many of our discussions were predicated on the central roles that human behavior and social institutions can play in disasters in the context and circumstances that lead up to an event, as well as the response and recovery efforts that are enacted during and after. This understanding laid the foundation for discussions on how to learn from a crisis, whether it is experienced directly or vicariously.

Discussions ranged from acute-event emergency management concerns to chronic, long-term planning concerns that increase risk, such as those experienced in water resources management during drought.

Several key themes and needs emerged across the topics of management, policy, and learning, including:

- The need for improved connections across management sectors, levels of government, and jurisdictions (including transboundary)
- The need to bridge acute and chronic phenomena, and the short- and long-term timescales associated with them
- Anticipatory planning as a means to bridge timescales and improve preparedness for complex, high-low cascading events
- The unique windows of opportunity for learning and policy change created when crises occur
- The need to develop institutions sufficiently flexible to foster connectivity, engage in anticipatory planning, and document lessons learned from high-low events
- The importance of post-event evaluation and gap analysis

Collectively these themes, which are explored in greater depth below, link management, policy, and learning necessary to improve preparedness and response to high-low events.

Management

Participants pointed out that strong connections across sectors (e.g., public health, the environmental community, and water planning) or across scales of governance (e.g., federal, regional watershed, and local or volunteer) improve chances that disaster preparedness planning will be effective. Without these connections, communication and learning are impeded. Because many complex, cascading issues cross boundaries such as watersheds, open lines of communication across jurisdictions are essential. Also, *aligning management and policy* across boundaries is fundamental for success in dealing effectively with high-low cascading events. For example, in the 2011 San Diego power outage, lack of consideration of operations of facilities in extended networks or contingencies affecting neighboring systems (including systems across state and international boundaries), and lack of consideration of multiple contingency losses all contributed to the high magnitude and extent of the impacts of the outage (FERC-NERC, 2012). In contrast, when the U.S. and Mexico work bilaterally toward solutions of Southwest groundwater resource issues in international watersheds through data sharing and improved information flows, ongoing social learning can lead to more systematic incorporation of new information and science-based approaches into planning on both sides of the border (Wilder et al., 2010).

Anticipatory planning such as strategic planning for multiple scenarios of the future (Schwartz, 1991; Peterson et al., 2003; Mahmoud et al., 2011; Holway et al., 2012; Rowland et al., 2014) was identified as an essential and promising avenue for helping resource, utility, and emergency managers plan and prepare effectively for high-low events. Currently, these events are primarily handled by specific networks and protocols that focus on short-term event preparedness and emergency response planning. Participants noted that responsibility for planning, as well as jurisdictional authority, was difficult to establish for conditions like long-term trends in temperature and precipitation that were not well characterized by a specific event (e.g., an ongoing drought). This makes it more difficult to anticipate and manage short-term, acute events within the context of long-term "non-events."

Participants noted that gap analysis and comprehensive evaluation of capacities (and lack thereof) are key elements in effective short- and long-term planning, management, and learning. They observed that critical evaluation is seldom funded to an extent commensurate with the learning needed to reduce costs associated with future disasters. This comes as no surprise, as emergency management and disaster response are targeted at specific bounded events, but participant comments pointed towards a view of these events that extended beyond their specific bounds.

One participant noted the role of leadership in effective management and pointed out emerging leaders—those who get their jobs done efficiently and become champions of a particular management strategy or approach through their own initiative and interest—are especially effective in helping prepare for potential crises.

Policy

The theme of connections, connectivity, and communication among sectors and across boundaries, was noted as an important policy issue. Participants mentioned, for example, that whereas water managers make decisions to ensure that supplies are available, they do not decide on the best uses or allocations of water, which is the domain of policymakers, elected officials, and voters. Making connections between sectors such as land and water management allows for policy innovation to simultaneously address water supply and use. The city of Chandler, Arizona, was noted for having implemented a policy for base-level allocation of water for growth based on community-identified economic and quality-of-life goals. In this case, cross-sectoral connections (water and land use) facilitated the identification of values that could motivate and compel voter and decision-maker acceptance of policy innovation. One participant suggested that economics and job creation are topics that can motivate adoption of policy innovations; prioritizing these values in discussions of disaster and adaptation planning could effectively bridge learning, policy, and management because they are issues that elected officials care about. While water resource planning is often not on the policy agenda of elected officials, efforts to contextualize the connection between water resources, economics, and job creation could improve the chances of catalyzing policy innovations that might include consideration of high-low type events. Participants noted that in recent years the private sector has more actively acknowledged the connection of disaster and extreme-event preparedness and economics. This spurs policy innovation. Early adopters of preparedness planning in business, because of their perceived credibility by elected officials, could catalyze policy change. One example is the way in which private sector water users such as Coca-Cola have become engaged in climate change and water sustainability planning.

Participants also acknowledged the importance of planning, noting that more than 90 percent of disaster costs are related to recovery, and that dollars invested in disaster preparedness often return four to seven times the return of dollars invested in disaster relief (Multihazard Mitigation Council, 2005; Associated Press, 2013; Weiss and Weidman, 2013). Anticipatory planning, with an emphasis on holistic linkages across multiple systems, will facilitate better understanding of the possible chains of events within this system and could help mitigate costs associated with lack of planning for cascading effects; multiple scenario planning is one example of anticipatory planning. Crises often provide significant opportunities for learning and updating policy and management options, providing strong motivation for policymakers to adopt scenario planning. Further discussion about anticipatory planning and policy focused on the role of the private sector. Growing use of scenarios in the private sector and in multi-sector community advisory groups may encourage elected officials to adopt anticipatory planning for high-low events, as advisory groups incorporate broad support and the private sector is frequently perceived as a credible test bed for management practice and innovation.

An example from a multi-sector community effort is the "branded worst-case scenario" used by USGS (e.g., Porter et al., 2011), in which multiple agencies in multiple jurisdictions unite to change operational policy and to bridge short- and long-term thinking in an anticipatory way. In California, USGS has led teams of emergency managers, planners, and scientists in using scenarios to plan for events related to atmospheric rivers, which have delivered historic floods in California and are projected to occur more frequently in the future (Hoerling et al., 2013). USGS uses specific, codeveloped, branded worst-case scenarios of atmospheric river storms that are somewhat larger or more frequent than the historic storm of record (Dettinger et al., 2012). It is conducting further research on atmospheric rivers and their potential economic and public health impacts in a variety of locations (e.g., Plumlee et al., 2015). Workshop participants noted that more research is needed to evaluate the efficacy of this approach. One key aspect of the use of branded scenarios is that they combine the credibility of federal science with the legitimacy of government (e.g., through city, county, and state emergency management).

A key policy need identified by workshop participants pertains to disaster insurance. Actuarial tables presume that events are discrete, not overlapping, in contrast to the complex, cascading, high-impact events experienced in recent decades and discussed in the workshop. Moreover, autocorrelation, due to the upward trend in average annual temperature, raises the prospect of recurrent or protracted drought—increasing the likelihood of overlapping acute events such as sharp water supply decreases concomitant with heat waves and power outages.

Participants also suggested that multi-institutional policies and agreements are needed to manage the local effects of complex disasters. They noted that, while most states currently have sufficient organizational capacity, they lack the institutional arrangements to manage complex, cascading events in the context of long-term trends. For example, to address the anticipated public health effects of protracted and severe heat waves (short-term time frame), in coordination with bolstering urban resilience (long-term time frame), anticipatory planning institutions would need to involve urban planners, architects, public health officials, building experts, hospitality industry representatives, and parks and recreation government staff, among others. As another example, connections (and disconnections) between sectors such as forestry and water resources become more apparent and critical during and following acute events such as stand-replacing fires, which occur during long-term drought and result in post-fire flooding and debris flows. Planning for effective solutions to this issue requires an entity with authority and responsibility for coordinated action; yet, in practice, changes in policy and operational actions occur through the actions of individual organizations in shared governance of the problem (e.g., Denver, Colorado's Forests to Faucets[3] initiative, or the Northern Arizona Forest Fund[4]). These observations reflect a growing awareness of the role of legitimate extra-governmental institutions, which develop and leverage social capital to address governance of common pool resources (e.g., Ostrom, 1990).

Similarly, policies must bridge short-term (e.g., months to years) and long-term planning time frames (e.g., multiple years to multiple decades). A key policy challenge is keeping short-term and long-term resources in balance so the resource reserve is not squandered by an emphasis on short-term needs. This may

[3] Forests to Faucets is a partnership between the USDA-Forest Service and Denver Water. The goal of the initiative is to improve watershed health and protect water quality in watersheds critical to Denver Water's water resources supplies.

[4] The Northern Arizona Forest Fund is a partnership between the Salt River Project (the major water supplier to the Phoenix, Arizona metropolitan area) and the National Forest Foundation. The partnership aims to fund and implement forest restoration projects, with the dual goals of improving forest ecosystem health in watershed headwaters regions and protecting water quality values for downstream urban water users.

require policy changes to ensure that a resource is not further strained or overstretched, precipitating another crisis. Several arid communities have water policies in place to conserve water resources. However, these resource conservation efforts—one tool used to reduce drought risk—could be undermined by short-term economic pressures to promote growth, unless a fundamental shift in thinking and policy is adopted.

Flexible regulations can foster effective management of acute events such as water allocation during drought episodes. It was noted that more policy flexibility is needed during crisis situations in some management sectors. An example is the relaxation of air quality requirements during acute wildfires, which can permeate urban areas with particulate matter that causes exceedance of air quality thresholds, even when emissions from pollution point sources, such as automobiles and industries, are within requirements. In addition, resource needs must keep up with policy change. For example, although FEMA now requires inclusion of climate change planning in state hazard plans, there is a lack of state agency capacity to adequately connect short- and long-term planning and management.

Learning

Social learning is essential for capitalizing on the management and policy insights needed to address high-low events. Workshop participants noted the role of anticipatory planning as a vehicle for cross-sector learning to bridge acute and chronic problems, short- and long-term timescales, and multiple levels of governance. Social learning can be built into planning processes, especially when the planning engagement is sustained (Pahl-Wostl, 2009). Workshop participants noted that crises can provide a learning opportunity for planners and policymakers. To ensure learning, one workshop participant recommended a participatory and anticipatory approach, which allows for greater ability to manage events effectively and to act decisively. Public participation is essential for establishing both a legitimate process and the foundation for a learning community (e.g., Ostrom, 1990; NRC, 2006; 2012; Pahl-Wostl, 2009). When combined with an anticipatory approach, participatory planning creates conditions for greater public acceptance of preparedness measures and a base of support for elected officials to appropriate funds for such measures. Similarly, participants suggested that visioning exercises are useful because they foster thinking about those who are making decisions 30 years hence. Consequently, anticipatory planning can help bridge the intersection of short- (event) and long-term (trend) drivers of change and promote the learning necessary to develop institutions for capturing lessons from high-low events. To mainstream "possibilistic" thinking—i.e., thinking about complex cascades during extreme events instead of the most probable scenarios—anticipatory planning methods such as gaming and scenario planning exercises are key. Moreover, participants suggested that the long-term perspective must be dominant; otherwise, crisis management is reactive rather than proactive, and therefore less effective and more costly (e.g., NRC, 2006; United Nations, 2010).

Effective learning requires comprehensive post-event evaluation, which relies on a foundation of good data and monitoring. The Maricopa Flood Control District (in central Arizona) was cited as an example in which only locations damaged in severe flood events have been examined; much could be learned from evaluating why severe damage *didn't* happen in other areas. Gap analysis and comprehensive evaluation of capacities and, importantly, *lack* of capacities, were considered essential to effective short- and long-term planning, management, and learning.

Participants repeatedly stressed that high-low events provide windows of opportunity for learning by managers and planners. The Western Electricity Coordinating Council's (WECC) scenario planning initiative, for example, was aided by the San Diego outage, which spurred WECC and partners to more adequately evaluate the nexus between water and energy and identify strategic choices that needed to be made to ensure grid reliability in a hotter world. Yet, participants noted a tendency for climate change planning processes to avoid conversations about the real worst cases, often because planners rely on projections of the central tendencies of future climate parameters. They suggested that worst-case evaluation spurs learning by focusing on complex trade-offs, requiring participants to articulate and acknowledge uncertainties, and integrating the perspectives of a wide range of participants—including the operations of neighboring systems and small, but potentially cascading, elements and interactions in the system (e.g., San Diego 2011 power outage; FERC-NERC, 2012).

Finally, the discussion stressed the importance of institutions in capturing important lessons, reinforcing them, and keeping them in the collective memory of organizations and leadership. Building social and institutional memory that draws on past experiences is a key part of anticipatory planning, but given the nature of many of these high-impact (and low-probability) events, incorporating lessons learned from outside sources was also a key source of improving planning and response. Los Angeles was able to improve its resilience to earthquakes by learning from the 1985 Mexico City earthquake, which demonstrated the severe damage that could happen without adequate planning and regulations. Following that disaster, the city of Los Angeles was able to break an impasse on earthquake-proof construction regulation revisions.

In contrast, as discussed earlier, it took multiple acute crises or near crises for Denver to learn to adequately prepare for drought. Severe drought there in 2002 stimulated water resource planning and conservation by individuals (see, for example, Kenney et al., 2004), but recognition of the connection of multiple interacting components of impacts from that drought (such as wildfire and water quality issues) over subsequent years and implementation in drought preparedness planning was slow. Another severe drought in 2012, which strained water resources and contributed to severe fires in Fort Collins and Colorado Springs, captured sufficient interest to initiate collaborative scenario planning that led to new approaches to plan for and manage the multiple intersecting impacts of drought. Denver Water, a leader in regional water and scenario planning, has doubled its public affairs division in response to a need for dealing with intersecting drought issues.

AUSTIN WATER

DISCUSSION

Characterization of the Problem

We tend to characterize disasters as discrete events. Even poorly defined events are described as specific "instances." However, we need look no further than our case study examples—the San Diego blackout and the Texas drought—both of which are named as discrete events, to see that many disasters are actually a messy assemblage of events, interlinked impacts, and effects. This pushes us to think more broadly about the nature of disaster and the chains of impacts that make up these complex episodes leading to what we have called high-low events. It also challenges us to consider and better understand the conditions that set the context for how these events are experienced, often disproportionately across sub-populations, and how impacts extend from these acute events, with different timescales and intensities depending on who and what is affected. This is particularly the case when spatially extensive climate factors such as extreme heat and extended drought serve as common triggers for impacts across multiple sectors, including energy and water. In the hypothetical case that we examined, with a chronic onset factor (drought) slowly affecting water resources and an acute onset factor (an extreme heat wave) rapidly affecting electricity demand, it is clear that the unfolding disaster is made neither of discrete events nor discrete impacts.

Social science research has shown that key factors affecting response to disasters include the degree and quality of disaster preparedness, as well as the scope, severity, and speed of onset of the precipitating disaster trigger (NRC, 2006). Emergency management focuses on four phases in disaster events, including preparedness, response, recovery, and mitigation, embedded in a prevailing view that disasters have clear-cut beginnings and ends, they are bounded temporally and geographically, and the goals of response and recovery are to restore things to normal (G. Webb presentation, this workshop, September 28, 2015). Workshop participants noted new features for consideration, such as the impact chain reactions and cascading effects associated with high-low events (Figures 2 and 3) and the widespread and cross-jurisdictional and cross-sectoral impacts associated with high-low events. Consequently, workshop participants came to the conclusion that a one-size-fits-all approach to emergency management will not be as effective as a flexible approach that acknowledges complexity, impact linkages, and messiness. A flexible approach allows for assessment of vulnerabilities and risks across multiple time horizons, anticipatory approaches that focus on worst cases, and the ability to better incorporate emerging local interventions, which are often based on local knowledge and social networks.

Responsibility and Authority

Issues of responsibility are also related to issues of jurisdiction. At a pragmatic level, it is useful to know which individual, agency, or government entity is responsible for mitigating the impacts of a given disaster or for planning for subsequent events. As discussed previously, cascading events spread this responsibility across multiple groups (e.g., personal responsibility, private insurance, or federal emergency management), and responsibility may shift based on different timescales of ongoing events (e.g., short-term acute disaster response vs. planning and recovery targeted at underlying conditions that amplify the effects of disaster). Anticipatory planning need not propose a solution for every possible outcome, or attach responsibility to every possible chain of events, but it should incorporate an understanding of the way these events link and span across jurisdictional and temporal scales so as to not resort to simplistic planning or reactionary responses that isolate components of the system without considering their place within the larger chain of events.

The issue of responsibility is also complicated by the emergence of personal responsibility narratives within state and federal emergency response planning. On one hand, individuals, households, and communities are encouraged to learn what they need to do to be prepared (or "be ready"—ready.gov) for relevant potential events in their area or community. In most cases, community preparedness and awareness will do no harm and will likely help in the event of a disaster. On the other hand, many of these events, especially large-scale cascading events, will quickly surpass any community-based response capacity. As long as cultivating community-based preparedness is seen as a supplement and not a replacement to larger state and federal efforts, it should only improve community resilience. Further research as to what this small-scale preparedness planning would look like and how well it works would be instrumental in ongoing response planning and may help shape future policy if these types of efforts are shown to improve community resilience and response capacity.

Funding

Funding is also linked to issues of responsibility, beyond abstract notions of who is in charge, as planning efforts are relatively expensive and disaster recovery can involve monumental costs. Issues, such as mandatory vs. optional insurance, distribution of recovery funds (and if there are any restrictions on where they can be used, or what they can be used for), and the locus of financial reasonability (e.g., who pays for recovery efforts—individuals, insurance, state or federal programs, etc.) will dramatically affect the post-disaster recovery landscape. Changes to policy can shift from a subsidized model of disaster recovery to an actuarially oriented framework, which can drastically alter recovery costs.


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CONCLUSIONS AND RECOMMENDATIONS

Learning

Social learning is essential for capitalizing on the management and policy insights needed to address high-low events. Effective management practice and policy implementation to prepare for and respond to the potential consequences of high-low events would be enhanced by institutions that can capture lessons learned from previous disasters from learning communities designed to strengthen knowledge exchange between multiple entities. Development of these institutions should focus on integration across disciplines, risk management sectors, levels of governance, jurisdictional boundaries, and systems (e.g., environmental, economic, social). The institutions should also ensure connections between research and management communities concerned with both the short-term (acute) and long-term (chronic) factors that combine to create risks associated with high-low events. Retrospective evaluation and gap analysis is central in solidifying learning from high-low events. Social network analysis can help determine gaps and holes in existing networks and to design improved communication efforts with hard-to-reach demographic groups and across sectors affected by high-low events. Further research is needed to evaluate the quality and effectiveness of hazard mitigation plans and to develop standards that apply across jurisdictions and regions to address the great disparity in the quality of review.

Dealing with Boundaries: Integration and Collaboration

A key aspect of drought-heat-water-energy high-low cascading impact disasters is that they cross many boundaries, including jurisdictions, sectors, areas of disciplinary expertise, and timescales. Integration across disciplines, systems, and sectors can help increase understanding and improve preparedness and response. Strong connections and open lines of communication across sectors, jurisdictions, and scales of governance are essential if disaster preparedness planning is to be effective in dealing with high-low events. Affected sectors and jurisdictions may be remote or indirectly linked to the epicenter of a high-low trigger (e.g., power outage), but may be impacted as much as or more severely than the epicenter. Thus, alignment of management and policy across boundaries is fundamental for success in dealing effectively with high-low cascading events. Moreover, multi-sector, multi-jurisdictional participatory and anticipatory planning approaches will help to develop capacity to bridge timescales (short or acute and long-term or chronic) and increase the effectiveness of coordination and management of high-low events.

Implications for the Water Sector

Non-stationary changes in background climate conditions, along with increasing recognition of the way that systems intersect and impacts cascade through a complex institutional and jurisdictional landscape, suggest that research is needed to address emerging issues that intersect directly or indirectly with water management. High-low events, as described in this report, have ramifications not only for the water and energy management sectors, but for emergency management, public health, and food safety and distribution. Continued collaborative, multi-sector work to envision, anticipate, and plan for future scenarios is recommended in order to mitigate some effects of cascading high-low events, generate *possibilistic* thinking regarding the plausible intersection of multiple extremes in contrast to likely averages, and ensure graceful rather than catastrophic failure when resources and time are insufficient to build infrastructure to emerging standards.

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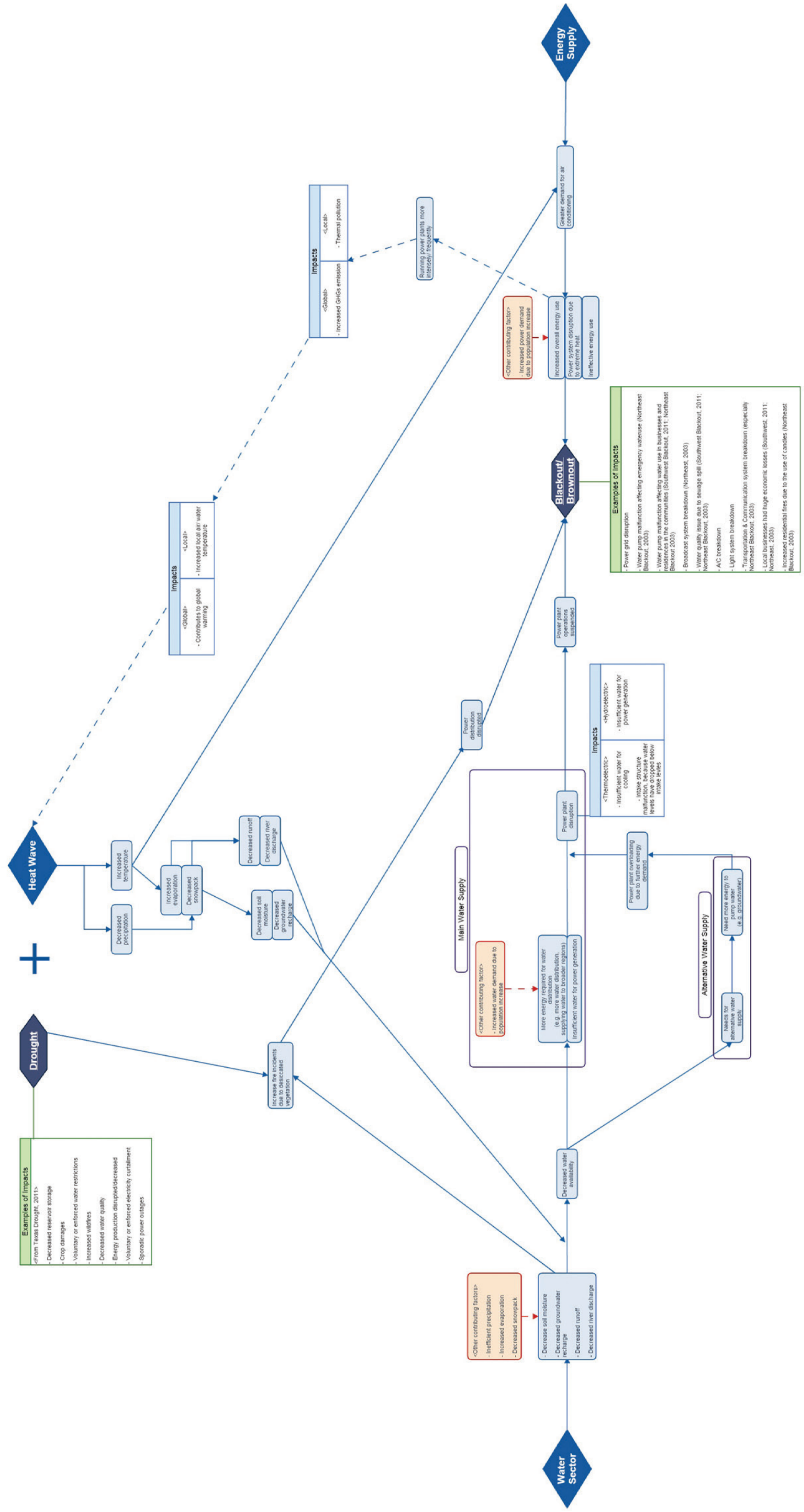
Appendix A: List of workshop participants.

First Name	Last Name	Organization
Kristen	Averyt	Cooperative Institute for Research in Environmental Sciences (CIRES)
Mary	Black	University of Arizona
Keely	Brooks	Southern Nevada Water Authority
Sandra	Espinoza	Arizona Department of Emergency and Military Affairs (AZDEMA)
Charlie	Ester	Salt River Project
Leslie	Ethen	City of Tucson
Dan	Ferguson	University of Arizona
Gregg	Garfin	University of Arizona
Kerrie	Geil	University of Arizona
Jim	Holway	Central Arizona Water Conservation District
David	Hondula	Arizona State University
Michelle	Huckabee	Texas Division of Emergency Management
Kathy	Jacobs	University of Arizona
Laurna	Kaatz	Denver Water
Lisa	LaRocque	City of Las Cruces
Ronald	Lane	San Diego County
Sarah	LeRoy	University of Arizona
Ben	McMahan	University of Arizona
Jonathan	Overpeck	University of Arizona
Ray	Quay	Arizona State University
Antoinette	Reyes	City of Las Cruces
Bokjin	Roh	University of Arizona
Chris	Scott	University of Arizona
Daryl	Slusher	Austin Water Utility
Robert	Summerfield	City of Las Vegas
Darren	Sversvold	City of Phoenix
Vince	Tidwell	Sandia National Laboratories
Kathleen	Tierney	University of Colorado Natural Hazards Center
Susan	Walker	New Mexico Department of Homeland Security & Emergency Management
Gary	Webb	University of North Texas
Olga	Wihelmi	University Corporation for Atmospheric Research (UCAR)
Wally	Wilson	Tucson Water
Byron	Woertz	Western Electricity Coordinating Council

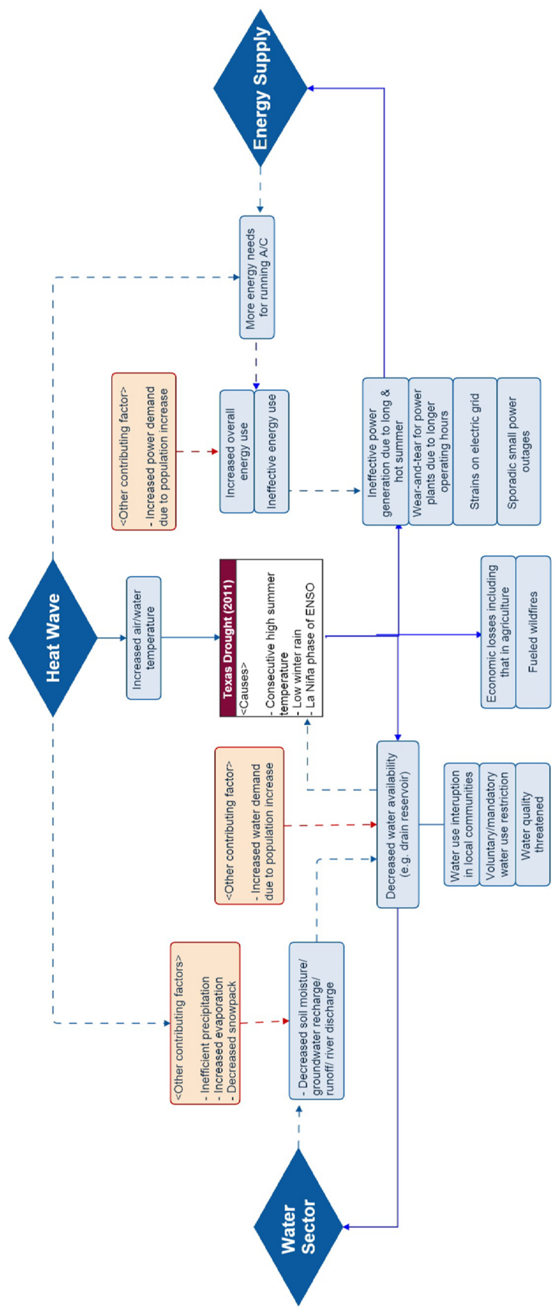
Appendix B: Workshop Agenda

Monday, September 28, 2015	
8:00-8:30	Registration, Breakfast (provided)
8:30-9:15	Welcome, Overview, Introductions
9:15-10:45	Stage-setting Talks (15 min. each) and Discussion
	Heat-Energy-Water-Emergency Management Overview (Kathleen Tierney, Univ. of Colorado Natural Hazards Center)
	Extreme Heat & Drought (Jonathan Overpeck, Univ. of Arizona)
	Heat-Water-Energy Nexus (Kristen Averyt, NOAA-CIRES, Univ. of Colorado)
	Disaster and Emergency Management (Gary Webb, Univ. of North Texas)
10:45-11:00	Break
11:00-11:30	Texas 2011 Case Study (Daryl Slusher, Austin Water Utility)
11:30-12:00	San Diego 2011 Case Study (Ronald Lane, San Diego County)
12:00-12:30	Discussion
12:30-1:30	Lunch (provided)
1:30-3:00	Group Discussion: Conceptual Model of the Heat-Water-Energy System and Links to Emergency Management
3:00-3:15	Break
3:15-4:45	Group Discussion: Managing Cascading Impacts
4:45-5:30	Discussion, General Questions, Review Agenda for Day 2
7:00	GROUP DINNER

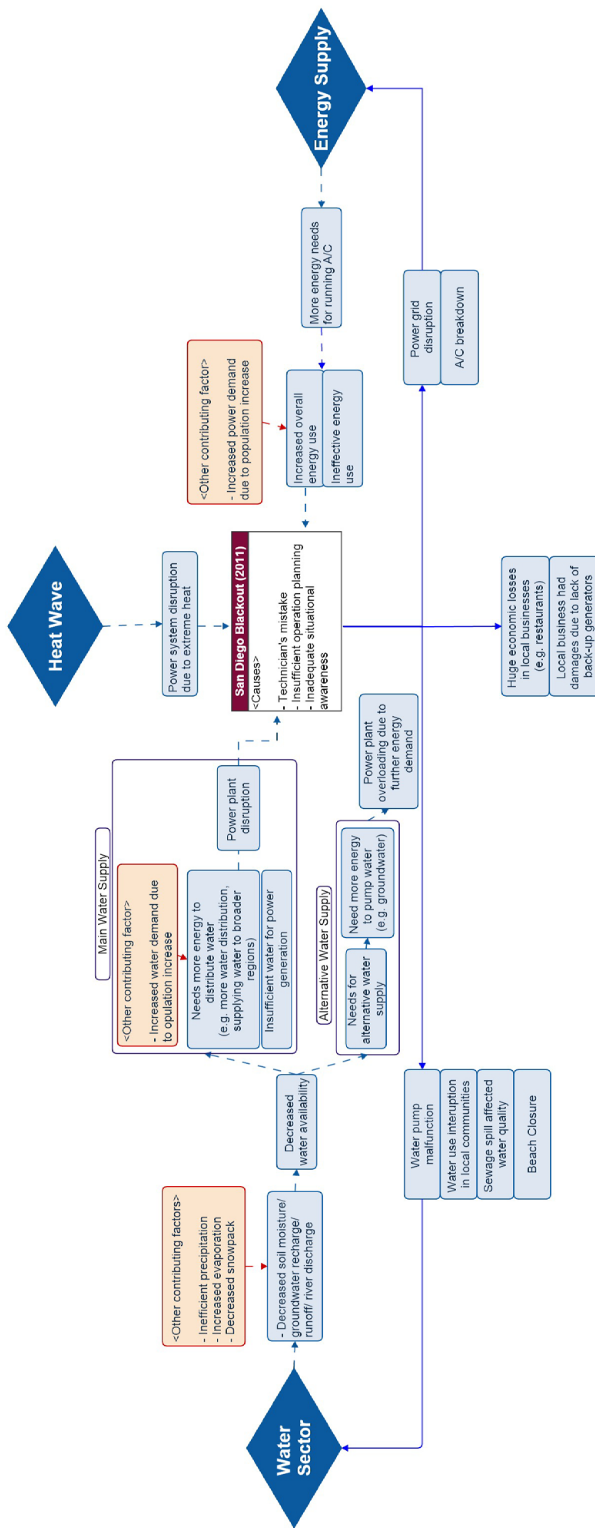
Tuesday, September 29, 2015	
8:30-9:00	Recap of Day 1, Breakfast (provided)
9:00-10:30	Group Discussion: Interventions, Policy Instruments, and Costs
10:30-10:45	Break
10:45-12:15	Small Group Discussions: Pre-, During-, and Post-Outage – Knowledge, Research and Management Needs
12:15-1:00	Lunch (provided)
1:00-1:45	Prioritizing Needs
1:45-2:00	Wrap-up and Next Steps
2:00	ADJOURN



Appendix C: Diagram showing the connections between climate, water, and energy supply.



Appendix D: Diagram showing the connections between heat, water, and energy sectors during the 2011 Texas drought.



Appendix E: Diagram showing the connections between heat, water, and energy sectors during the 2011 San Diego blackout.

Appendix F: Science and outreach needs, in order of priority (highest to lowest), determined by participant votes. Needs in red were voted to be highest priority by participants.

Planning	Management	Research
Role of decentralized vs. centralized monitoring and response: how do they work? And do they work?	Role of decentralized vs. centralized monitoring and response: how do they work? And do they work?	Role of decentralized vs. centralized monitoring and response: how do they work? And do they work?
Comprehensive look at integrating high-impact/low-probability events into scenario planning	Triggers that result in impacts and exceedance of adaptive capacity	Do institutions/individuals learn from events? Do they change behavior?
Assessment of quality of hazard response plans (esp. drought)	How to engage millennials	Evaluate intervention activities (e.g., heat warning systems) and efficacy—do they work?
Institutional and public knowledge development; stakeholder workshops to identify and develop community planning opportunities	Triggers and thresholds at community and regional scales	Evaluate communication networks (social network analysis) in hard to reach demographics
Future: diffusion of innovation? How does it move through the system? How can we perpetuate it?	Monitoring temperature/heat trajectories (indicator development)	“Slow response” grants; how to cope with lingering conditions (e.g., drought)
How to engage different entities (identify different approaches to communicate, e.g., urban, rural, non-native speakers, etc.)	Key indicators to track vulnerabilities	Efficacy of social media in disaster response; opportunities and risks
Methods for seeding action at household scale	Identify multiple methods of messaging and map to targets; possible testbeds and demonstration projects	Identify multiple methods of messaging and map to targets; possible testbeds and demonstration projects
Robust decision making under deep uncertainty	Catalog and project water demands	Evaluate spatial and temporal response options for energy and water
Mechanism for information sharing, e.g., communication strategies, lessons learned	Assess perceived adaptations at different scales: Maladaptive? Or effective?	Evaluation integration into actions/activities at outset of effort; institutionalize evaluation
Evaluate needs/vulnerabilities of critical water and energy infrastructure	Indoor exposures and vulnerabilities, e.g., thermal tolerance	Harmonize individual actions with larger response: opportunity or risk?
Get energy and water people together in ongoing forum to develop long-term relationships—only then can they understand how to work together	Institutional network analysis	Tribal communities and resilience
Evaluate communication networks (social network analysis) in hard to reach demographics	Adaptive capacity at institutional and community scales	
How to engage millennials	Heat-related mortality data	
How to integrate (mainstream) climate change across an organization AND a network of organizations		
Incentivize research/practitioner collaborative endeavors		
Evaluate intervention activities (e.g., heat warning systems) and efficacy—do they work?		
Triggers and thresholds at community and regional scales		
Pathways and circumstances that lead to exposure of vulnerable communities		
Ongoing support for cataloging/database efforts		

Appendix F: *(continued)*.

Planning	**Management**	**Research**
Capture needs and engage rural communities; who needs what, and what's being done		
How to institutionalize evaluation		
How to shift from human-driven change to humans adapting to natural systems		
Identify lingering questions from previous research to be pursued (e.g., Electric Power Research Institute, Association of Municipal Water Authorities); bridge the gap between research and "peer-review" publications		
Behavior during emergencies, risk perception		
Social connections and relation to exposure		
Opportunities to integrate with Long-Term Ecological Research facilities		
Mechanisms to engage private sector; needs ad opportunities		
Efficacy of social media in disaster response; opportunities and risks		
Identify multiple methods of messaging and map to targets; possible testbeds and demonstration projects		
Catalog and project water demands		
Institutional network analysis		
Tribal communities and resilience		
Compilation of adaptation strategies and best practices at community scale that can be shared		
Cookbook of questions		
Harmonize individual actions with larger response: opportunity or risk?		
Evaluation integration into actions/activities at outset of effort; institutionalize evaluation		
Assess perceived adaptations at different scales: mal-adaptive? Or effective?		
Evaluate spatial and temporal response options for energy and water		
Understanding connections and possible avenues for help		
New institutional configurations: will they meet long-term challenges?