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ORIGINAL PAPER

Application of an extreme winter storm scenario to identify vulnerabilities, mitigation options, and science needs in the Sierra Nevada mountains, USA

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Abstract In the Sierra Nevada mountains (USA), and geographically similar areas across the globe where human development is expanding, extreme winter storm and flood risks are expected to increase with changing climate, heightening the need for communities to assess risks and better prepare for such events. In this case study, we demonstrate a novel approach to examining extreme winter storm and flood risks. We incorporated high-resolution atmospheric–hydrologic modeling of the ARkStorm extreme winter storm scenario with multiple modes of engagement with practitioners, including a series of facilitated discussions and a tabletop emergency management exercise, to develop a regional assessment of extreme storm vulnerabilities, mitigation options, and science needs in the greater Lake Tahoe region of Northern Nevada and California, USA. Through this process, practitioners discussed issues of concern across all phases of the emergency management life cycle, including preparation, response, recovery, and mitigation. Interruption of transportation, communications, and interagency coordination were among the most pressing concerns, and specific approaches for addressing these issues were identified, including prepositioning resources, diversifying communications systems, and improving coordination among state, tribal, and public utility practitioners. Science needs included expanding real-time monitoring capabilities to improve the precision of meteorological models and enhance situational awareness, assessing

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vulnerabilities of critical infrastructure, and conducting cost–benefit analyses to assess opportunities to improve both natural and human-made infrastructure to better withstand extreme storms. Our approach and results can be used to support both land use and emergency planning activities aimed toward increasing community resilience to extreme winter storm hazards in mountainous regions.

Keywords Winter storm hazards · Flood · Emergency preparedness · Emergency management · Scenario · ARkStorm

1 Introduction

1.1 Background

Extreme precipitation events and associated flooding have historically had costly and long-lasting societal and ecological impacts, including risks of human casualties and public health impacts, damage to businesses, transportation networks, and public utilities, disruptions of water supplies, and disturbances of terrestrial and aquatic ecosystems. Over the past 30 years, flood damage costs in the USA alone have averaged eight billion dollars per year (National Oceanic and Atmospheric Administration 2013), and these figures are expected to increase with climate change and with continued population growth and development (Changnon et al. 2000; Choi and Fisher 2003). On the Pacific Coast of the western USA, more than 80 % of all floods have been attributed to atmospheric rivers (ARs) (Ralph et al. 2006; Neiman et al. 2011; Florsheim and Dettinger 2015), which are long corridors of intense water vapor transport that carry warm wet air from the tropics (Fig. 1) and typically make landfall during the winter season in California (Ralph and Dettinger 2012). Analyses of recent climate change projections indicate that the duration of the AR season may increase, with simultaneous increases in temperature, frequency, and magnitude of these events (Dettinger 2011), suggesting increased future risk of extreme winter storm-induced flooding. Indeed, climate change projections suggest a 30–90 % increase in the magnitudes of 50-year flood flows in the Northern and a 50–100 % increase

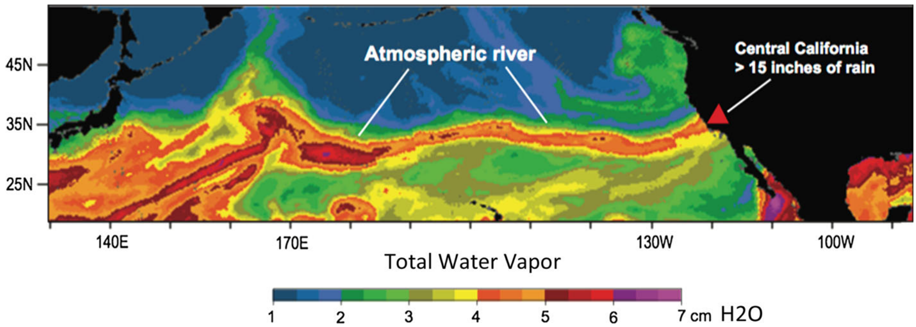

Fig. 1 Total water vapor in the atmosphere on October 13–14, 2009, with an atmospheric river indicated by the *warm-colored band* of moist air extending across the entire North Pacific basin to the central California coast (Ralph and Dettinger 2011)

in the southern Sierra Nevada mountains relative to historical simulations (Das et al. 2011). Projected increases in winter extremes and associated flooding are especially problematic in California and Nevada because the water management infrastructure built during the last century was not designed to accommodate these types of events.

Given these projections, there is a heightened need for communities to prepare for extreme winter storm and associated flood risks. In 2010, the US Geological Survey developed the ARkStorm extreme winter storm event scenario for California to demonstrate and quantify the risks of such an event, to provide better scientific and research focus, and to allow communities to explore and mitigate potential impacts from extreme winter storms using a single, plausible, and specific example as a focal point (Porter et al. 2010). The name “ARkStorm” was coined to describe a large, hypothetical but scientifically plausible AR storm sequence that rivals, but does not exceed, the intense storms of winter 1861–1862. That storm sequence left the Central Valley of California flooded and the state’s economy bankrupt (Dettinger and Ingram 2013). To develop the scenario, climatologists and meteorologists concatenated two historic AR storm sequences from 1969 and 1986 to form a 23-day sequence of intense and prolonged precipitation. The ARkStorm scenario ultimately results in catastrophic flooding in both California and Nevada (Dettinger et al. 2011).

Here, we describe a case study in which we apply a novel blend of qualitative and quantitative methods to evoke discussions and innovative problem solving by informed and trained resource and emergency management practitioners who identified vulnerabilities, mitigation options, and science needs related to extreme flood hazards in the montane and valley areas of Lake Tahoe, Reno, and Carson City, NV. Our objectives are: (1) to demonstrate a novel approach for examining winter storm risks and associated mitigation options that uses scientifically robust atmospheric–hydrologic modeling of the ARkStorm scenario to elicit perspectives from a diversity of regional management practitioners and (2) to report the key vulnerabilities, mitigation options, science needs, and lessons learned. The methods and results from our study are likely to have applicability to many settings in the montane-valley areas of the western USA and similar settings, globally.

1.2 Study area

The Tahoe–Reno–Carson City region addressed here spans approximately 150 km^2, extending eastward from the crest of the central Sierra Nevada Mountains, and including the Lake Tahoe, Truckee River, and Upper Carson River basins, in California and Nevada (Fig. 2). The study area includes parts of eight counties and three tribal jurisdictions. Major population centers are located in Reno and Carson City, and several smaller communities in the Lake Tahoe area serve as major outdoor recreation tourist destinations. The study area extends across a wide range of elevations and precipitation gradients and includes large areas of forest and rangelands and several isolated rural communities. Average 30-year annual precipitation ranges from 10 to 20 cm near the eastern limits of the area to over 250 cm along the crest of the Sierra Nevada (PRISM 2012), where most precipitation falls as snow. Together, this mix of jurisdictions and geography provides opportunities to explore issues associated with flood emergency response coordination across state, county, city, and tribal boundaries and within entire watersheds.

The Truckee River is a critical focal point for flood and emergency management discussions in the study area. In this heavily managed system, municipal and agricultural water supplies (and flood flows) are stored and released at six lakes and reservoirs (including Lake Tahoe) and one major diversion dam (Derby Dam and the Truckee Canal)

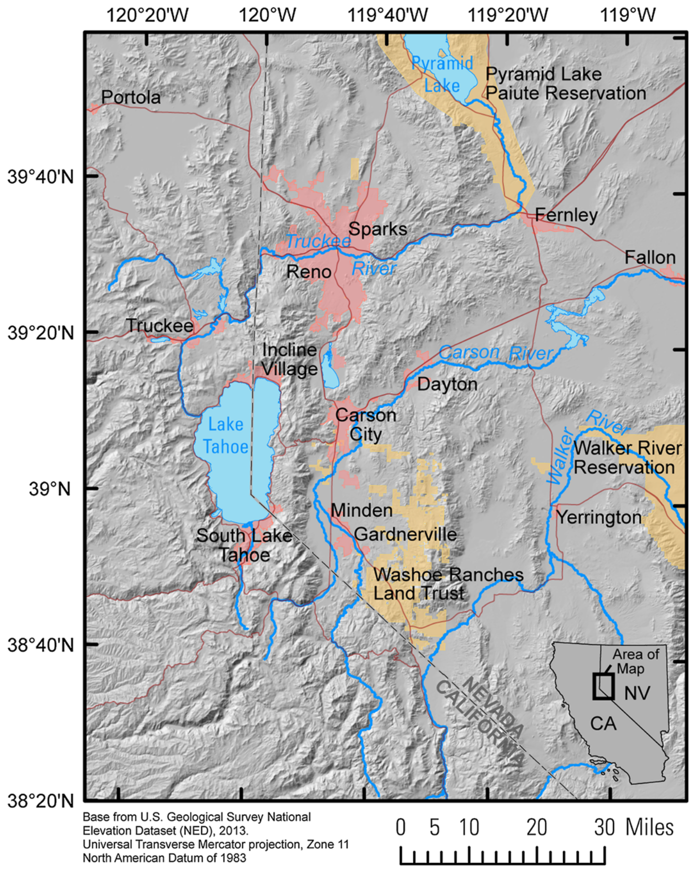

Fig. 2 ARkStorm@Tahoe study area. *Yellow areas* indicate tribal lands and *red areas* indicate urbanized areas

before the river reaches its terminus in Pyramid Lake. Although the majority of the study area is semiarid, and thus relatively little precipitation compared to other climatic regions, several major floods of the Truckee River have occurred over the past century, the majority of which are the direct result of ARs (Fig. 3). One of the most recent and memorable AR-generated winter floods occurred in January 1997, when hundreds of millions of dollars in direct damages occurred in northwestern Nevada during a storm that lasted just 4 days (Rigby et al. 1998). Stark memories of this event by many participants informed and provided context for the ARkStorm discussions and served as an effective point of reference for discussing the ARkStorm scenario, which—in simulations—yielded approximately 1.5–3 times the amount of precipitation and flood flows witnessed in 1997.

2 Approach

Our approach involved first determining, in some temporal and geographic detail, the most likely meteorological and hydrological consequences of the ARkStorm scenario for our study area. These results, in turn, served as a basis for a series of facilitated discussions

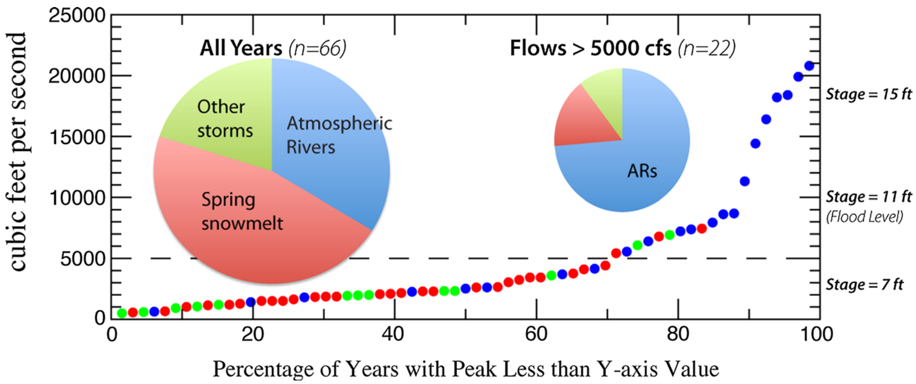

Fig. 3 Sources of annual peak flow occurrences in the Truckee River at Reno, NV gage, 1948–2013. Approximately one-third of all peak flows were caused by atmospheric rivers and nearly three quarters of the highest peak flows [>5000 cubic feet per second (cfs)] were caused by atmospheric rivers (ARs)

with over 300 professionals involved in various aspects of emergency, infrastructure, business, and ecological management to identify and explore vulnerabilities and potential mitigation options. The project culminated in a tabletop emergency response exercise that built upon both the scenario and the issues identified in discussions to focus participants on actions they might take to improve preparedness, response, and recovery. These components (scenario quantification, practitioner discussions, tabletop exercise) are generally included in the Homeland Security Exercise and Evaluation Process (HSEEP; Department of Homeland Security 2013); however, we implemented these components with several enhancements, with the goal of improving emergency response planning and training through the HSEEP process. First, we incorporated both scientifically robust modeling and concerns identified by local practitioners to develop a customized emergency management exercise that is both highly plausible and highly relevant, providing opportunity for practitioners to be better equipped to address the nuances of potential impacts and emergency management issues particular to their community. Second, we included in the practitioner discussions both scientists and managers from a variety of sectors and jurisdictions, many of whom do not typically participate in emergency management exercises at all or who do not typically interact in these activities together. These interactions provided the opportunity to highlight a wide array of management concerns that both emergency managers and scientists can respond to and served to foster communication and collaboration among these groups. Third, unlike more typical emergency management exercises that focus almost exclusively on the response phase of the emergency, we designed our discussions and exercise to cover multiple phases of the emergency management life cycle, including phases of mitigation, preparation, response, and recovery, to provide a more complete picture of winter storm vulnerabilities and options for increasing community resilience to these events.

3 Quantifying the scenario

With the aid of scientists at the Desert Research Institute's California and Nevada Smoke and Air Committee project (CANSAC; http://www.cefa.dri.edu/COFF/cofframe.php), we downscaled the original ARkStorm scenario (Dettinger et al. 2011) to obtain a physically consistent, hourly description of meteorological conditions throughout the study area at a 2-km spatial resolution. We downscaled coarsely resolved (250 km), historical global weather records (NCEP/NCAR Reanalysis fields; Kalnay et al. 1996) to the 2-km resolution to obtain sufficient detail to clearly represent ARkStorm meteorology and impacts in the mountainous terrain and as a basis for describing the temporal and geographic distributions of winds, snowfall, runoff, and flooding, and other meteorologically driven impacts across the region. We accomplished this by simulating the historical storm conditions comprising the scenario using the limited-area Weather Research and Forecasting (WRF; Skamarock et al. 2008) model nested within the global reanalysis-prescribed conditions.

This simulation formed the basis for maps and time series of temperatures, precipitation amounts, and wind directions and speeds that informed the practitioner discussions. The modeled 23-day ARkStorm scenario began with approximately 10 days of heavy precipitation with the snowline hovering mostly around 7500–8000 feet above sea level (Lake Tahoe is at 6200 ft but much of its catchment and the upper watersheds of the Truckee and Carson Rivers are between 7000 and 10,000 ft). Thus, most of the heaviest precipitation fell as snow. A brief lull with little or no precipitation followed, and then another 10 days of heavy precipitation arrived with snow levels reaching above 10,000 ft. Rain drenched the entire catchment during this second wave of storms and fell on the new snowpack that had been deposited by the early storm sequence (Fig. 4). Runoff in this second half of the storm sequence was, as a consequence, rapid and copious. Simulated flood flows rose to roughly 2–3 times of those during Nevada's historical storm of record in 1997.

Collaborators on the project generated streamflow simulations at various locations within the Tahoe Basin and along the Truckee, Carson, and Walker Rivers using the WRF outputs to drive several watershed models of the Tahoe basin and surroundings, using (a) a calibrated version of the GSFLOW model (Markstrom et al. 2008; Huntington and Niswonger 2012; Niswonger et al. 2013); (b) the Lake Tahoe Watershed Model (LTWM) implementation of the LSPC (Loading Simulation Program C++) modeling platform, which in turn evolved from the Stanford Watershed Model (Crawford and Linsley 1966); and (c) the National Weather Service (NWS) California-Nevada River Forecast Center's operational streamflow forecast model (Gijsbers et al. 2009). Use of multiple hydrologic models provided multiple lines of evidence to suggest how streamflows and flooding might play out under ARkStorm conditions, and provided flow estimates at many locations around the study area (no single extant model covered the entire region). Simulated flows and influxes of sediments and nutrients into Lake Tahoe, from the LTWM, were then used

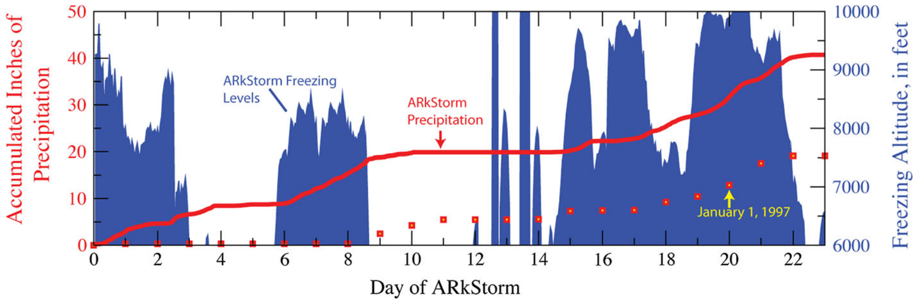

Fig. 4 Accumulated precipitation (*red curve*) at Tahoe City, California during the ARkStorm sequence with accumulated precipitation (*red dots*) during the 1997 AR storm sequence, as a reference. *Blue* (above freezing) and *white* (below freezing) areas indicate altitudes where precipitation falling as rain and snow, respectively, are expected to occur

to as inputs to the Lake Clarity Model (Sahoo et al. 2010) of Lake Tahoe, to evaluate the response of Lake Tahoe chemistry and clarity to the storm, during the storm and in several years thereafter. Broadly speaking, the lake was simulated to suffer some significant clarity impacts (as measured by Secchi disk), amounting to declines of >6 m less visibility in the lake in the year when ARkStorm occurs that might persist as >1 m clarity declines for four or more years afterward (Sahoo and Schladow, unpublished data). Such declines would be a major, if temporary, setback for the heroic efforts to "keep Tahoe blue" that have been underway in the Tahoe basin for decades. Finally, winds from the WRF simulation were used to estimate probable wave heights on Lake Tahoe that, calculated by several means, might reach peaks of some 4 m.

Using information from these various sources, along with long operational experience in the region, the National Weather Service developed and presented a sequence of plausible storm forecasts detailing how they would most likely respond to and report on the storm, for use in a tabletop emergency management exercise. We also compiled spatial datasets of infrastructure, including public utilities, communications, transportation networks, and hazardous materials. We overlaid these with maximum wind gust outputs from the WRF model and plausible flood inundation areas that were identified based on Federal Emergency Management Agency (FEMA) Digital Flood Insurance Rate Maps (DFIRM) 100- and 500-year flood boundaries (Federal Emergency Management Agency 2010), the mapped extent of the 1997 New Year's Flood (Rigby et al. 1998), and locally derived flood maps (California Department of Water Resources 2014).

Together, these various mapping and modeling activities provided a detailed, science-based, and internally consistent depiction of the events that could plausibly occur during and after the ARkStorm sequence. We used this depiction to set the stage for most practitioner discussions and the tabletop exercise. The modeling results also provided a basis for comparing ARkStorm events with the storm and flood conditions of January 1997, a useful mnemonic that made ARkStorm more real and vivid to participants.

4 Practitioner engagement

4.1 Practitioner discussions

We presented the technical products described above at six meetings, each with a different geographic and subject matter focus (Table 1). Holding meetings in different parts of the study area was necessary due to the potential wide variation in important issues and impacts at low versus high elevations as well as the differences related to emergency response resource availability and distribution in urban versus rural areas. This approach also helped to widen participation by eliminating long travel times for participants. In total, over 300 individuals from 138 organizations and agencies participated in one or more of the six meetings. Participants were recruited with the assistance of local leaders in various sectors to maximize attendance and representation from as wide of a variety of sectors and geographies as possible, including those from federal, state, county, tribal, and city governments, non-profit organizations, local businesses, research entities with expertise in emergency management, public utilities, community planning, health and human services, natural resource management, flood management, transportation management, engineering, and commercial business. Although each meeting had representatives from a wide variety of sectors, we targeted recruitment for each meeting to include practitioners with

Table 1 Details of the six ARkStorm@Tahoe practitioner meetings

Focal topic areas	Location	Date	Number of registered attendees	Number of organizations
Public Utilities/Water Supply	Incline Village General Improvement District, Incline Village, NV	September 12, 2013	31	22
Emergency Response/Health and Human Services/ Business Community	Lake Tahoe Visitor's Authority, Stateline, NV	October 11, 2013	63	43
State/Federal Coordination	NV Division of Emergency Management, Carson City, NV	November 12, 2013	68	30
Truckee River Flood Management	Regional Emergency Operations Center, Reno, NV	December 5,2013	138	69
Tribal Impacts	Reno-Sparks Tribal Health Center, Reno, NV	January 13, 2014	40	31
Natural Resource Impacts	Tahoe Regional Planning Agency, Stateline, NV	January 14, 2014	63	39

expertise in the focal topics identified in Table 1. These topics and meeting locations were selected to ensure coverage of issues perceived by the project leads to be the most highly relevant in the study area. In particular, project leads were interested in exploring impacts to tribal communities, mountain communities, water supplies, and other natural resources as these issues had not been explored in previous ARkStorm scenario applications, which largely focused on the built environment (e.g., Hosseinipour et al. 2013).

A short (30 min–1 h) briefing portion of each meeting included an overview of the project goals and objectives, presentation of the meteorology and hydrology of the scenario, the weather forecast timeline, and additional information appropriate to each group. We then facilitated several hours of discussion to identify social and ecological vulnerabilities to extreme winter storms, interdependencies among systems, individuals, and agencies, critical resources and functionalities that have the potential to be compromised, science and information needs, and proactive steps that could help to minimize impacts from this type of event. To get at these issues, our facilitators posed a series of questions (Table 2) intended to stimulate discussion related to participants' ability to continue operations during and following ARkStorm. These discussions identified a wide variety of vulnerabilities, which we organized into eight major topic areas and describe below.

Table 2 Discussion questions posed to participants at ARkStorm@Tahoe practitioner meetings

Who and where are your key staff?	What are your critical functions?	Are your facilities redundant?
Are they prepared?	How long can those functions stop?	Can you function elsewhere?
Who else can perform those key functions?	How else can you perform those functions?	What resources do you need to function elsewhere?
What do they need to function?	Who and what do you need to function?	Can you share space and with whom?
How can you communicate?	Who relies on you to function?	

4.1.1 Transportation networks

In all meetings, disruption of transportation networks was identified as a key vulnerability that presented the most significant challenges for emergency responders. Existing datasets describing areas with high potential for flooding (Federal Emergency Management Agency 2010; CDWR 2014) indicate that over 185 miles of major roads and 70 miles of rail would be inaccessible due to flooding alone. In some parts of the study area, practitioners expressed significant concern about the fact that critical staff often do not live locally in the communities that they serve and their ability to get to their duty stations to respond to the unfolding emergencies would likely be impeded by flooding and snow at river crossings and high mountain passes, respectively.

4.1.2 Communications networks

Discussion routinely revolved around risks of communications disruptions due to weather, terrain, or floods or landslides, as another key vulnerability for all sectors. Practitioners noted that most sectors do not share a common radio platform, and some other systems are of questionable or unknown reliability under ARkStorm scenario conditions. Indeed, GIS analyses revealed that over half of all communications facilities could be impacted by winds or flooding. There were also concerns about how the public would be notified regarding evacuation orders and potential routes and sheltering locations, or if their water supplies became contaminated. With the vibrant tourism industry in the region, another concern was how the large numbers of visitors that may be present would be notified since they do not have permanent addresses or contact information in emergency responder databases. Tribal practitioners from rural areas were concerned about communications, given that the few options they have for communications could be compromised during the storm.

4.1.3 Interagency coordination

Interagency coordination was also routinely a concern among the discussants. Given an ARkStorm event, the consensus of practitioners believed that the state of California would not be able to provide significant emergency management support to Nevada because resources would be stressed in dealing with large storm impacts and disruptions that would be unfolding simultaneously in the rest of California. Indeed, in such an event, many Californians would be evacuating into the study region, adding to the emergency and response requirements there. Coordination with other states will be critical given the expected simultaneous difficulties unfolding in California, but although Nevada and California regularly conduct joint emergency response exercises with each other, they rarely do so with other states.

Beyond issues of interstate coordination, coordination with tribes in the study area is a major concern. Several tribes have only 1–2 emergency response staff and otherwise rely on volunteers and outside resources. Tribal members were concerned about limited emergency response resources and supplies, and voiced a perception that they are often at the end of the line when it comes to assistance and resources. Tribes were also concerned that they are not always explicitly mentioned in mutual aid agreements, although utility operators and state and county emergency responders indicated that they would not hesitate to support tribes, as would be the case for any constituency. Practitioners were also concerned that, in interest of crisis management, law enforcement first responders often bar access to utility workers who need access in order to shut down systems or make repairs that will prevent even worse impacts from developing.

4.1.4 Power and fuel supplies

Electric power outages, coupled with fuel supply limitations for emergency generators, were regularly identified as having the potential to significantly exacerbate storm effects. Many practitioners suggested they have short-term (typically 48- to 72-h) capabilities to work around power outages, but longer-term outages would result in significant cascading impacts. This was a concern for public utilities and hospitals, given energy dependence of essential functions such as supply of water, wastewater transport, medical care, and sheltering. Most public utility managers and hospitals said they have backup generators, but typically only 2–7 days' worth of backup fuel supplies. Because most gas stations require electric power to function, electric power outages would likely lead to fuel supply disruptions in a cascade effect. Many practitioners did not have clear plans for where fuel would be obtained once backup fuel supplies were exhausted (though schools, public transportation or waste management fleets, gas stations, and fire stations were mentioned as possibilities). Similarly, there were no settled plans as to how these "additional" supplies would be managed and prioritized. Once regional fuel supplies were spent, which could occur in less than a week, additional fuel could be brought into airports or military bases if they remain open, but fuel distribution beyond those hubs relies on ground transportation routes that might not be open and on weather conditions fair enough to be conducive to aerial transportation.

4.1.5 Health and human services

Continuity of medical services, sheltering, and care for vulnerable populations were significant concerns. Hospital and healthcare workers indicated that their key concerns were ability of staff to get to work and disruptions of power, fuel, and water supplies. Several medical facilities in the study area are located in 100-year floodplains and would likely need to be evacuated and operations relocated to higher ground in a major flood. Participants identified a need for basic information about where to locate evacuation, shelter, and staging areas, as well as potential routes for transporting staff and supplies to these locations. Significant concerns about how to alert and potentially relocate vulnerable populations, including residents in assisted living or skilled nurse facilities and individuals with special needs (e.g., dialysis units, hearing impaired), were expressed. Maintaining access to prescription medications under emergency conditions is also a concern. The numbers and capacities of medical facilities in tribal areas and in the Tahoe basin are limited, and thus health and human services in these areas may be the most likely to be disrupted. Availability of sufficient shelter space to support tourists and possible large influxes of self-evacuees from California is also a serious concern.

4.1.6 Flood management infrastructure

Several reservoirs along the Truckee River are used to ameliorate flood impacts. However, significant concerns were expressed about the capacity of the dams to withstand inflows as extreme as the ARkStorm scenario. Dam failures would likely result in massive losses of life and property downstream, most of the way to Pyramid Lake at the river's terminus. Storm forecasts provide reservoir managers with lead time to release water to reduce the potential for overtopping of dams and to create storage space to catch (for later release) part of the flood flows in preparation for storms if dams are near capacity. However, releases are limited to maximum outflow capacities depending on dam designs, which may not be sufficient to accommodate rapid inflows or significant wave heights that an ARkStorm would produce. Flood management requires significant coordination and communication between the NWS, the US Bureau of Reclamation, the Army Corps of Engineers, and water masters, and effective flood management is dependent upon rapid and reliable communications between these groups, which may be disrupted during an ARkStorm.

4.1.7 Public flood awareness and preparedness

Practitioners remarked that because floods do not occur as often as is the case in coastal areas, there is less public awareness and preparedness for such events in this region. Thus, practitioners recognized a continuing need for wide-reaching and engaging flood awareness programs for the public. Concerns were also expressed regarding potential public confusion caused by flood inundation maps that are overly complicated, and confusion due to inconsistencies in maps from different times, sources, or methodologies. A particular public awareness difficulty in the region is how to reach the large numbers of tourists and short-term visitors who regularly pass through the area, as well as large numbers of possible self-evacuees from California in an ARkStorm event.

4.1.8 Natural resources

Vulnerabilities of water supplies, wastewater systems, and toxic disposal sites were identified as high-priority concerns at all meetings, but the concerns differed across the study area. In the Tahoe basin, wastewater systems are designed to transport untreated wastewater over long distances using a series of gravity-fed lines and pumping stations and are vulnerable to being overwhelmed by large storm-water flows, particularly in the instance of fuel shortages that may limit the operation of pumping stations. Practitioners below and beyond the Tahoe basin were concerned about the vulnerability of infrastructure, including wastewater treatment plants, feedlots, and industrial sites, in floodplains with the potential to contaminate water sources. For example, tribal members recalled that flood refuse and pollutants from the entire Truckee watershed washed into Pyramid Lake in 1997 and would likely wash in under ARkStorm conditions. Because Pyramid Lake is a terminal lake (no outflows), is home to two endangered fisheries, and is the source of subsistence and revenue for some tribal members, water quality impacts from such contamination could have sustained negative economic consequences.

In the longer-term, land disturbances from an ARkStorm could increase opportunities for spread and establishment of aquatic and terrestrial invasive species. Land- and restoration-project managers felt that recently disturbed areas such as restoration sites, vegetation treatment sites, or recently burned areas would be particularly vulnerable to these invasions. Participants also noted that designs of many infrastructures, such as road culverts and restoration projects, are based on short-duration flood-recurrence intervals. They expressed concerns that current design requirements may not be sufficient given the significant role that prolonged or extreme events (like an ARkStorm) play in the geomorphology of the basin and the likelihood that flooding will become more common and severe under climate change (e.g., Das et al. 2013). They also recognized that they may have to wait until flows subside, snow melts, and soils dry out before they could begin repairs or even begin to assess many of the damages. Finally, they were concerned about ongoing declines in resources for monitoring and emphasized the need for robust and high temporal resolution monitoring to better manage extremes before, during, and after they occur.

4.2 Tabletop emergency management exercise

Following and based on the vulnerabilities identified in the practitioner discussion sessions, we organized a tabletop emergency management exercise with the specific goals of maximizing the interactive dialogue and engagement among different practitioner communities and facilitating discussion of very specific actions that might be taken related to three phases of emergency management, including preparedness, response, and recovery. We used a non-traditional exercise format to facilitate cross-sector discussions at discrete times during the storm event. We structured the tabletop exercise to allow participants to discuss and respond to scenario injects (a plausible news report that might arrive during the course of the scenario; e.g., a sewage pipeline bursts; a hospital is flooded). We assigned participants to small, diverse groups (8–10 individuals) mixed across sectors and Incident Management categories, each comprising a combination of emergency responders, public safety and health officials, natural resource managers, private sector infrastructure owner/operators, tribal members, and other participating organizations. We did this to maximize interactions among individuals from different sectors and to broaden the scope of discussions.

The exercise team presented the scenario events by focusing, in turn, on three "snapshots" during the storm sequence, corresponding to days 8, 18, and 35 of the ARkStorm scenario (Fig. 4). In turn, we encouraged participants to focus on issues related to storm preparedness (Day 8), response (Day 18), and recovery (Day 35). This was a unique approach to tabletop exercises, which more typically focus on a single point in time. At each stage of the storm, we provided participants with weather and flood condition forecast briefings from NWS and maps of predicted flood levels, which included inundation maps and impacts to existing infrastructure. Following a presentation of a stage setter for each phase, participants broke into their respective groups and were facilitated to discuss anticipated impacts, response actions, and potential mitigation measures. Each phase included roughly ten exercise injects, which were designed to focus the participants' discussions on key issues identified in the practitioner meetings.

The tabletop exercise involved approximately 130 participants from over 80 organizations, approximately two-thirds of whom had attended previous practitioner discussions. Different issues and potential actions were discussed in each of the three storm phases (Table 3). During a 1-h Phase One (corresponding to Day 8 of ARkStorm) of the exercise, significant amounts of precipitation had already fallen mostly as snow in the mountains, and participants were informed of a forecast for a potentially large, warm winter storm on the horizon. Activities in this phase focused on preparedness for the potential upcoming storm, and advance preparations for evacuations were identified as a key action by most of the breakout groups. Critical to all of these activities was establishing a Unified Coordination Group to ensure coordination of responses among agencies. In Phase Two (Day 18 of ARkStorm), breakout groups were confronted with record flooding on both the Truckee and

Table 3 Summary of priority issues discussed during the emergency response tabletop exercise

Phase One (Day 8 of ARkStorm) - Priorities during preparedness phase
• Dissemination of information to public
• Advance preparation of shelters and hospitals
• Activation of emergency plans
• Identifying locations of shelters, staging areas, and associated access routes
• Establishing a Unified Coordination Group
Phase Two (Day 18 of ARkStorm) - Priorities during response phase
• Prioritization of existing resources for maintaining roadways, utilities, lifelines, and other critical infrastructure necessary for evacuation and response.
• Coordination of communications within the Incident Command System
• Coordination with dam operators and flood managers
• Maintaining a well-staffed, centralized Joint Information Center
• Continued warnings and communications with the public
Phase Three (Day 35 of ARkStorm) - Approaches to facilitate recovery and enhance resiliency
• Incorporate staging locations identified in the exercise into existing plans and into future training and exercises
• Expand and maintain interagency communications and have assistance agreements in place ahead of event
• Conduct training and exercises to determine how to efficiently manage recovery resources, develop grant proposals, manage volunteer resources, manage temporary housing
• Maintain early and frequent communications with the public, particularly with at-risk, vulnerable, or remote populations
• Engage with private industries that may be able to provide resources for response and recovery
• Engage with policy-makers to garner support for actions deemed necessary by operational staff
• Document damages and elevate public and policy-maker awareness of storm impacts to stimulate flow of recovery resources
• Recognize (and act upon) opportunities to re-establish critical infrastructure and developments so that they are robust to future events.

Carson Rivers. Preservation of life and safety was identified as the primary concern during this phase, and all activities and responses identified were means to this end. During Phase Three (Day 30), participants addressed recovery issues, discussing needs for damage assessments, outreach, and coordination of recovery resources. They also discussed approaches for increasing preparedness for future events, such as establishing formal agreements, conducting trainings, and reducing vulnerabilities through community planning.

The tabletop exercise was designed to confront participants with circumstances related to the concerns that were identified in the practitioner discussions, and thus all of the major issues and priorities discussed in the tabletop exercise (Table 3) had generally been identified previously. Despite this connection, the nature of the discussion during these phases (preparation and response) of the tabletop exercise was quite different from that in the practitioner meetings because they were more squarely focused on near-term actions (immediately before and during the storm), while the practitioner discussions embodied a much longer-term view of concerns and mitigation options (and less-so on immediate actions). For example, while both types of activities discussed critical issues surrounding communications, the practitioner discussions focused more on identifying what infrastructure and modes were or were not available, and the exercise discussion focused on the logistics of setting up incident command and other coordination activities. Thus, with the exception of the recovery discussion, which occurred in both the practitioner meetings and emergency management exercise, different modes of practitioner engagement emphasized different phases of the emergency management life cycle (preparedness–response–

recovery–mitigation), with the emergency management exercise focused more heavily on near-term preparedness and response phases, and practitioner discussions focused more heavily on mitigation and far-term preparedness phases.

5 Practitioner perspectives on vulnerabilities and mitigation options

The practitioner discussions and tabletop exercise identified a wide variety of concerns and options for mitigating the impacts of an ARkStorm. The interruption of transportation routes, breakdown of communications, and inefficiencies in interagency coordination were repeatedly identified as critical concerns, and nearly all of the other concerns identified in both the practitioner meetings and the tabletop exercise could fundamentally be related back to issues in one or more of these areas. For example, staffing and resources for critical functions such as medical care and operation of public utilities have the potential to be cut off with interruption of transportation routes; mitigation of public health risks associated with water contamination is dependent upon ability to communicate among agencies and with the public; and the continuation of critical functions when outside resources are not available is dependent upon the ability of agencies to coordinate efficiently.

Establishing protocols and strategic locations for prepositioning resources such as people, fuel, and other supplies were frequently identified as important mitigation options to address interruptions in transportation (Table 4). Furthermore, diversifying communication modes and technologies to ensure redundancies exist in the system in case of one technology failing was also identified to be important, particularly for reaching out to the many tourists in the region, and for those located in distant rural communities. These concerns and options are consistent with those identified by retrospective case studies (e.g., Holguín-Veras et al. 2007; Boin and ’t Hart 2010; Miao et al. 2013), suggesting that the mitigative actions in these areas have the potential to have the greatest impact. The mixed jurisdictions, isolation of many communities, and varied terrain—including avalanche- and landslide-prone mountain passes and hillsides as well as flood-prone river valleys—in our study area serves to potentially exacerbate many emergency response issues by constraining both transportation and communication options and potentially further isolating distant communities.

A high level of communication and coordination among local agencies was evidenced by the diverse and substantial participation in our study. Despite this, our study highlighted some important weak points in interagency coordination. Such weak points included coordination between tribes and other local government agencies, between public utilities and emergency management agencies, and between states that do not normally call on each other for assistance, but would likely need to during an event such as ARkStorm. Tribal and public utility practitioners, in particular, identified the need to establish formal agreements. In the former case, tribal governments suggested they be explicitly identified in emergency assistance agreements with nontribal governments and institutions. In the latter case, public utility workers expressed the need for law enforcement to establish a credentialing system that would allow them to bypass road closures to carry out their responsibilities. While these formal and explicit agreements are likely to prove useful, their effectiveness may be optimized when coupled with opportunities for individuals among these agencies to cultivate and strengthen interorganizational and interpersonal relationships through regular and/or direct interactions (Holguín-Veras et al. 2007; Boin and ’t Hart 2010; Kapucu et al. 2013).

Table 4 Options identified by practitioners for addressing storm vulnerabilities

Transportation

- Strategically preposition road-clearing equipment to mitigate likely transportation blockages associated with flooding, landslides, and/or avalanches
- Develop memoranda of understanding (MOUs) with private industry, including construction companies, to ensure that resources will be available to assist in providing emergency services and road clearing
- Conduct and make available resource typing assessments or road clearing and maintenance equipment to assess their suitability for rural roads and mountain passes. Resource typing involves categorizing equipment resources according to size, weight, and capabilities to identify in advance where they can be deployed (i.e., relative to road weight limits)
- Preposition staff and other resources needed to conduct critical functions within reach of response facilities/duty stations taking into consideration potential road blockages associated with snow and flooding, and plan to ensure that families of critical staff members are well cared for in the emergency
- Preposition fuel supplies in areas likely to become isolated. Establish recommendations for minimum fuel reserve amounts for different sectors and develop agreements and a prioritization protocol for allocating these reserves.
- Identify and pre-plan options for relocating care facilities, including establishment and staffing of one or more emergency mass-care facilities, to better serve the more vulnerable areas in storm emergencies
- Establish interagency mutual aid agreements and familiarize staff from partnering agencies with operation of systems to maintain operational capabilities in the event transportation corridors are cut off

Communications

- Develop and distribute an assessment of communication technologies used by critical monitoring and response programs. This assessment is needed to determine their vulnerabilities to weather, floods, and landslides, including the potential for networks to be overwhelmed by heavy public use
- Leverage social networking and crowd-sourced information sharing capabilities to enhance situational awareness for emergency responders and the public, especially the visitors who have few other connections to information originating in the area
- Coordinate with, and among, county Amateur Radio Emergency Services to identify alternative communication capabilities for remote areas

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- Tailor public awareness programs to target sectors most at risk or most likely to require critical functions during flood emergencies
- Develop special awareness campaigns and plans to target tourist venues and short-term visitors who may be unfamiliar with the high potential for flooding in these "desert" settings and with potential evacuation routes and locations
- Promote greater public awareness of flood risks to wastewater systems in the Tahoe Basin and provide guidelines for citizens to follow to reduce water consumption--thus reducing pressures on wastewater treatment facilities--during early stages of major storms and floods
- Identify clear lines of authority and communications for shutting down water systems in the event of contamination and consider establishment of pre-determined thresholds and conditions under which these actions would be expected to be taken

Interagency coordination

- Conduct extreme winter storm and flooding emergency response exercises with neighboring states other than California and Nevada
- Develop direct communication links (with backup capabilities) between emergency management agencies in neighboring states
- Engage tribes when developing and updating Emergency Management Assistance Compacts (EMAC)
- Foster additional opportunities for interaction between tribal, county, state, and federal emergency managers to help develop relationships and interactions that facilitate interagency communications and assistance during emergencies
- Develop a credentialing process for critical utilities staffs with county Sheriff's Offices. Include guidelines for information flow and chain of communications to State Highway Patrol and other law enforcement agencies. Create databases of critical personnel from utilities and other organizations who will need access to key infrastructure during emergencies

Infrastructure

- Construct or harden dam spillways, where needed.
- Raise dam heights while maintaining current operational water-storage limits at vulnerable locations
- Invest in infrastructure and technologies that improve, and better integrate, weather and flood-forecasting capabilities to increase lead times for response
- Assess opportunities throughout the study area to upgrade or move sewage lines, pumping stations, and wastewater treatment plants to lessen their vulnerability to flood impacts.
- Upsize and better stabilize culverts, and formulate plans to deploy machinery to regularly maintain them and to protect them in anticipation of, and in the event of, extreme storms.
- Install short-term mitigation measures to stabilize soils and vegetation at sites with known vulnerabilities to flood runoff at the beginning of the winter season

Miao et al. (2013) classified aspects of emergency management and resilience into 'hard' and 'soft' categories. Hard resilience refers to physical and technical aspects of emergency management that create robust and redundant physical systems. Soft resilience refers to aspects of coordination that allow swift, flexible, and agile responses. In our study, practitioners identified mitigation options that fall into both categories. Ideas for increasing hard resilience included moving, improving, or reinforcing various infrastructures, including dams, public utilities, transportation infrastructure, and even enhancing natural infrastructure through floodplain and marsh restoration. Ideas for increasing soft resilience included prepositioning resources, developing plans and agreements, conducting training exercises, and improving coordination and communications. Investments in hard resilience have the potential to save costs over the long term, but they rely on significant initial investments that can be cost-prohibitive, and policy-makers are often unwilling to pay given other priorities. Moreover, faced with a sufficiently extreme event such as ARkStorm, even the most robust infrastructure has potential to become significantly damaged. Thus, increasing hard resilience alone is likely to be ineffective and needs to be coupled with efforts to increase soft resilience (Miao et al. 2013) in the most extreme cases of emergencies.

6 Science needs

The use of the ARkStorm scenario and associated meteorological and hydrologic models provided an opportunity for significant discussion between scientists and emergency management practitioners. As a result, we identified several applied science needs and data gaps related to improving weather forecasting, assessing storm and flood risks, prioritizing mitigation options related to infrastructure improvements, and monitoring (Table 5).

Currently, weather forecast models allow anticipation of ARs 7–10 days in advance (Wick et al. 2013), and reasonable estimates of precipitation amounts can be identified 3–5 days out. Practitioners believed that earlier detection of ARs has the potential to greatly improve emergency response capabilities. Beyond this, the need to better predict freezing elevations was also highlighted, given that freezing elevation strongly influences the extent and severity of flooding. Currently, freezing elevations are highly uncertain even within the 24-h forecast window. Both of these science needs are predicated most immediately on improved monitoring capabilities. In the former case, increased off-shore and ocean monitoring is needed to improve meteorologists understanding of atmospheric dynamics to enable earlier detection of ARs (Ralph et al. 2014; Neiman et al. 2014b). In the latter case, expansion, hardening, and establishment of real-time communications networks for meteorological stations has the potential to both increase situational awareness and provide empirical data to help improve understanding of localized atmospheric dynamics that enable better prediction of freezing altitudes (White et al. 2010; Neiman et al. 2014a).

Science needs related to assessing storm and flood risks included assessment of flood inundation potential, geomorphic hazards, and impacts to water quality. Improved regional flood inundation mapping would allow for more comprehensive flood risk assessments to infrastructure, improved community, and land use planning, and has the potential to facilitate rapid and effective responses during flood emergencies. Current publicly available flood mapping products include FEMA Digital Flood Insurance Rate Maps (DFIRM) 100- and 500-year flood boundaries (Federal Emergency Management Agency 2010) and

Table 5 Science needs identified in ARkStorm@Tahoe practitioner meetings

Storm and Flood Risk Assessments	
Geomorphic hazards	• Develop spatially-explicit information on relative probability of occurrence of avalanches and other geomorphic hazards such as debris flows, mudslides, rockfalls, or landslides
Water quality	• Estimate the relative vulnerability of water supply intakes to sediment loading based on proximity to inputs and potential for sediment transport by winds and water currents
	• Test bioengineering techniques that would help to limit pollutant loading • Assess potential impacts of extreme storms to short- and long-term water quality conditions for sediments and other pollutants • Model shoreline erosion potential that includes effects of wind action on erosion and associated turbidity
Flood inundation mapping	• Develop hydrologic models of extreme events to support development of flood inundation maps to assess flood vulnerabilities of important infrastructure or facilities • Develop sub-watershed resolution flood inundation maps • Develop flood inundation predictions based on streamflow forecasts • Develop a standardized approach to flood mapping to ensure consistency among flood mapping products
Infrastructure Vulnerability	• Assess communication technologies used by critical monitoring and response programs, including the potential for networks to be overwhelmed by extensive public use • Assess critical hospital infrastructure such as heating and cooling systems or diagnostic equipment facilities to flooding and evaluate whether and where such facilities can be moved to better protect them from floodwaters • Assess potential sources of ecological contamination • Assess existing designated staging, emergency shelter, and evacuation locations
Monitoring • Expand and harden real-time meteorological monitoring stations at strategic locations • Leverage existing real time monitoring networks to collect meteorological data to promote situational awareness • Establish a centralized clearinghouse for storing or indexing monitoring data • Establish additional offshore and ocean monitoring to support improved meteorological forecast modeling and response lead times	
Weather and flood forecasting • Develop higher resolution forecast models that more accurately pinpoint freezing elevations and enable better prediction and more lead time to prepare for an ARkStorm-type event • Develop tools and technologies that improve, and better integrate, weather and flood-forecasting capabilities to increase lead times for response	
Cost-Benefit Analyses • Evaluate the relative costs and benefits of using natural infrastructure to protect water sources from pollutant inflows, such as diversion of sewage overflow to retention basins or marshes	

the mapped extent of the 1997 New Year's Flood (Rigby et al. 1998). While these mapping products are accurate and comprehensive within the bounds of their intended use, they do not provide the temporal and spatial resolution required during an emergency response and have the potential to hinder emergency management efforts (e.g., by generating confusion among responders and the public about where evacuations should occur). Additionally, mapping efforts are often limited to jurisdictional boundaries potentially providing incomplete or inconsistent information as flooding occurs between municipalities, counties, or states. Practitioners agreed that the standardization of methods and maps as well as the availability of these mapping products is an important issue to address. Moreover, because multiple drainage basins may affect urban centers within the study area, patterns of inundation are difficult to predict and are subject to variations in precipitation and snow levels within individual subwatersheds, highlighting the need for mapping with greater specificity. An ideal situation described by practitioners was the ability to produce automated inundation maps based on National Weather Service Advanced Hydrologic Prediction Service forecasts. Recently, the USGS, NWS, US Army Corps of Engineers, and FEMA have banded together to develop a new generation of mapping and modeling tools that can provide just such real-time (and forecast) inundation mapping (see, e.g., http://water.usgs.gov/osw/flood_inundation/) that, in turn, could be implemented for key river reaches in the study area to provide just such support information.

Several mitigation actions related to improving infrastructure were identified, including improving natural infrastructure to mitigate flood impacts, improving or moving vulnerable public utilities infrastructure, improving flood resistance of dams and spillways, and raising infrastructure design standards for natural and built infrastructure to withstand larger magnitude flood events. Given both the monetary and ecological costs of these improvements, and recognizing that one mitigation action has the potential to affect the need for others, there was a clear need to prioritize. Prioritization approaches include cost–benefit analyses, effectiveness reviews, multi-criteria analysis, or risk-based prioritization (Sene 2008), but were beyond the scope of the short-term study reported here.

7 Use of the ARkStorm scenario for emergency management planning

Scenario planning and interactive dialogues with managers are increasingly used as an approach to identify management strategies that are robust to the impacts of weather extremes (Algermissen et al. 1972; Steinbrugge et al. 1987; Federal Emergency Management Agency 2004; Scawthorn et al. 2006). Such scenarios and dialogues are also proving to be a useful adjunct to assessments of the standard long-term climate change projections (e.g., Stern et al. 2013; Vermeulen et al. 2013). In this study, use of the ARkStorm scenario helped practitioners to confront and visualize extreme storm impacts and, as evidenced by the variety of vulnerabilities and mitigations listed here, served as a highly effective focus for identifying specific issues and options. Meanwhile, climate change remains an uncertain and often controversial topic in the study area, and our focus on a single, eminently challenging storm event that does not require acceptance of climate change to be a plausible concern provided a less controversial, more immediate opportunity for some very useful emergency preparedness discussions and plans. Climate change is likely to raise the odds of an ARkStorm-like scenario (Dettinger 2011), but climate change is not a prerequisite for such an event. Thus, the ARkStorm scenario and associated practitioner engagement activities such as those described in this study represent an opportunity to integrate climate adaptation and vulnerability reduction into existing emergency response activities and frameworks.

Emergency management exercises serve as a valuable component of emergency preparedness activities (Cottam and Preston 1997; Boin and 't Hart 2010), yet the application of scientifically robust modeling of weather, runoff, and contaminant transports as a basis for operational emergency response training exercises such as the tabletop emergency management exercise implemented here is rare. We identified three primary ways in which the exercise in our study benefitted considerably from the scientifically robust scenario modeling that we undertook. First, greater credibility could be attached a fully fledged scenario, such as ARkStorm. Notably, when the issue at hand is a very large (and admittedly uncommon) level of hazard, there is a risk that participants will be discouraged and feel that they are being asked to address and respond to unrealistic situations. The level of scientific rigor that provided the underpinnings of the ARkStorm discussions and exercise provided the opportunity to dispel such hesitancy and skepticism, and furthermore allowed us to confidently and quantitatively draw real-world parallels between this worse-than-what-had-been-experienced-historically ARkStorm emergency scenario and the most recent and devastating disaster of the same kind (1997) in ways that allowed participants to be much more specific in many of their discussions and concerns than would have been possible in a less detailed and less thoroughly depicted alternative. Second, provision of data associated with the scenario was particularly beneficial to technical partners, as it allowed them to interact with information they might realistically receive and respond to during an extreme storm event. For example, NWS partners commented that the process of developing weather forecasts based on weather data fields generated from the scenario stimulated significant thought related to how they would interpret and report on such information. Third, the wealth of data generated for the scenario provided opportunities for creating tangible, readily visualized focal points for discussion that could be explored in any number of ways in response to the interests and needs of practitioners.

8 Conclusions

In this study, we demonstrate the utility and application of an approach that combines rigorous atmospheric–hydrologic scenario modeling and multiple modes of practitioner engagement to enrich emergency response planning activities and provide insights into community resilience from multiple perspectives. Key to the success of this effort was the active engagement and participation of strong leaders within the emergency management community from the beginning of the project and we suggest this is an essential component in future efforts. These leaders brought practitioners to the table, co-designed meetings and the exercise to help ensure that key issues within their sector were addressed, and will be essential for implementing the mitigation options identified in our study. Our study also highlights the benefits of including practitioners who are not typically involved in emergency management exercises, for example, those from the business community, water and land managers, and the scientific community, in discussions of storm vulnerabilities. In our study, these individuals highlighted new perspectives and issues that are not typically on the radar of the emergency management community, including the potential for and ways of mitigating longer-term ecological impacts. These issues are not typically discussed in the emergency management community, given their primary objectives of saving life and property, yet both short- and long-term ecological impacts (e.g., water contamination) have the potential to greatly hinder recovery efforts. Our study also suggests that multiple modes of practitioner engagement can provide a more holistic view of impacts and issues related to natural disasters to better address all phases of the emergency management life cycle. The approach and results from this study have the potential to address common concerns associated with near-term disaster risk reduction and increased probabilities of winter floods associated with climate change over the longer term (Turnbull et al. 2013). Our methods and results can be used to support both land use and emergency planning activities aimed toward increasing community resilience to extreme winter storm hazards.

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