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The vulnerability of interdependent urban infrastructure systems to climate change: could Phoenix experience a Katrina of extreme heat?

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ABSTRACT

Continued growth in the American Southwest depends on the reliable delivery of services by critical infrastructure systems, including water, power, and transportation. As these systems age, they are increasingly vulnerable to extreme heat events that both increase infrastructure demands and reveal complex interdependencies that amplify stressors. While the traditional analytic approach to preparing for such hazards is risk analysis, the experience of Hurricane Katrina provides a warning of the limitations of risk-based approaches for confronting complexity, and the potential scale and impact that can result from cascading failures under extreme stress. By contrast, this research is the first to apply resilience theory to understanding complex infrastructure interdependencies during an extreme heat event in Phoenix, AZ and the role of sensing, anticipating, adapting, and learning (SAAL) for mitigating catastrophe.

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Introduction

Located within Maricopa County in central Arizona, the Phoenix Metropolitan Area (Phoenix hereafter) contains the City of Phoenix, 26 other municipalities, and three Native American communities. It is one of the largest and fastest growing metropolitan regions in the U.S., with a current population of 4.5 million that is projected to reach almost 8 million by 2050 (Cohen, 2015). To accommodate this growth, Phoenix relies on its infrastructure to provide its residents basic services, like water, energy and transportation. For example, water provision relies on the Central Arizona Project (CAP), a 541 km aqueduct system that pumps 1.9 billion m^3 of Colorado River water to Central Arizona (including Phoenix) through a series of canals and pumping stations. The CAP is the largest end user of electricity in Arizona, requiring 2.8 TWh per year to overcome significant elevation difference – 93% of which is generated by coal, nuclear, and natural gas. The remainder is made up of hydroelectric (5%) and other renewables, including solar (2%) (Bartos & Chester, 2014). Finally, for mobility, Phoenix is an automobile-dependent city. It depends on its growing system of highways and other roads to meet the demands of population growth and urban sprawl, averaging 320 miles of new roadway per year over past six decades (Kimball, 2014). Moreover, transportation fuels are not refined in-state, and are transported hundreds of miles via two pipeline systems, one from California, the other Texas and New Mexico (Clark & Chester, 2016).

Climate and geography play critically important roles in the city's infrastructure needs. Phoenix is dry and hot. It has a desert climate with low annual rainfall (about 20 cm a year) and low relative humidity. Maximum daytime temperatures in the summer months average around 41 °C, with a record high of 50 °C (National Oceanic and Atmospheric Administration, 2016), making Phoenix one of the most vulnerable regions to extreme heat events (EHE) in the United States (Bartos & Chester, 2014; Chow et al., 2012; Grossman-Clarke et al., 2010; Hayden et al., 2011, Meehl & Tebaldi, 2004). From 2006 to 2013, there were 632 heat-associated deaths in Phoenix, AZ averaging 79 deaths a year (Maricopa County Department of Public Health, 2014). In 2016, the death toll increased to 130 heat-associated deaths reported (Maricopa County Department of Public Health, 2016). Moreover, about 3000 heat-related hospitalizations and emergency visits were reported in Arizona for 2015 alone (Arizona Department of Health Services, 2017). As the threshold of human tolerance to rising temperatures are crossed more frequently and for

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longer periods of time, the effort needed to mitigate heat related morbidity and mortality increase. For example, from 2041 to 2070, the frequency of EHE in Phoenix is projected to increase sixfold during the summer (from 0.32 to 1.94 events) and 14-fold each year (from 2.0 to 24.4 events), with an increase in average duration of events from 6.3 to 12.6 days per event (Grossman-Clarke et al., 2010).

Despite existing research on social heat vulnerability (Colley et al., 2012; Harlan et al., 2012; Kuras et al., 2015) as well as the impacts of heat on particular infrastructure systems (Bartos & Chester, 2015; Bartos et al., in press; Bates et al., 2008; Chester et al., 2015; Delpla et al., 2009; Koetse & Rietveld, 2009), there remains a lack of understanding about how *infrastructure* vulnerability to heat can amplify the health impacts of EHEs. Like people, urban infrastructure systems are also vulnerable to EHEs, such that the capacity of built systems to provide services like drinking water, mobility, food, and cooling is diminished in high temperatures. Still, the growing literature on heat vulnerability has yet to describe the dependencies across built systems that can further cascade losses and be detrimental to human health. Systemic interdependencies with common-mode failures like heat are cause for serious concern because analogous extreme event experiences have revealed the potential for cascading catastrophic consequences that both increase damage and slow recovery.

Hurricane Katrina is a valuable model example of interdependent failures that cascade and amplify infrastructure losses and result in significant loss of human life. In 2005, Katrina set in motion a series of unanticipated failures in the critical infrastructure systems of the City of New Orleans and surrounding area. Levee failures resulted in significant disruptions of electric power and widespread contamination of floodwaters by raw sewage, chemical and petroleum leaks, and the leaching of industrial waste sites (Leavitt & Kiefer, 2006). More than 1000 drinking water supply systems and 172 sewage treatment plants in Louisiana, Mississippi, and Alabama were affected. Though not the strongest storm, Katrina was the deadliest and most damaging hurricane to hit the US Gulf Coast since 1928, killing between 1000 and 2000 people and causing over $100 billion in economic losses (Knabb et al., 2005). The high consequence of cascading failures across infrastructure during Katrina, as well as the mounting evidence that critical infrastructure systems are becoming more complex and mutually interdependent (Linkov et al., 2014) exemplifies the urgency for exploring how coupled systems increase vulnerability to extreme events.

While Phoenix is not vulnerable to hurricanes in the same way as coastal cities, the combination of increasing average temperatures (Garfin et al., 2013), more frequent and longer lasting heat waves (Bartos & Chester, 2014), declining water availability (Seager et al., 2013), and more serious wildfires (Westerling, 2016) suggest that the metro region may be vulnerable to the cascading and catastrophic losses from extreme heat that are comparable in scale to Hurricane Katrina. Recent experiences with hurricanes in the U.S. (i.e., Katrina, Sandy, Harvey, Irma, and Maria) have conditioned policy makers and researchers to recognize the devastation that can be associated with severe storms, including how the built environment can amplify impacts. However, understanding how heat could cause impacts at a similar scale is much more challenging. Although the flood losses experienced during Katrina are characteristically different, extreme temperatures may be more deadly and just as pervasive in propagation through connected sectors. Without understanding the multiple points of connection, feedbacks, and feedforward paths that describe the region's complex infrastructure interdependencies, the potential for an unmanaged feedback loop may create conditions that amplify a small disruption originating in one system to cause tragic collapse of critical services in others (Little, 2004; McDaniels et al., 2007; Rinaldi et al., 2001). If such a collapse were to occur because of, or during, an extreme heat event, the consequences for dense urban areas in Phoenix could be devastating. This research is the first to consider this type of scenario, with the goal of informing more adaptive infrastructure management and planning to alleviate impacts and foster resilience.

The interdependencies across infrastructure systems extend far beyond just electricity and water, suggesting that emergency responses to extreme heat, like evacuation to cooler mountain areas, may be infeasible if other critical systems like transport and fuel supply are also damaged. Figure 1 summarizes some of the interactions between changes in the climate and water-energy-transport systems of the Southwest. The sun at the center of the figure symbolizes a warming climate characterized by more frequent extreme heat conditions, which in turn affects multiple processes in ways that potentially compound vulnerabilities for the larger systems. For example, reduced streamflow means less water is available to meet the larger volumes of cooling water required at thermal-electric generating stations (Bartos & Chester, 2015). Moreover, when electricity demand is greatest, so is the risk of interruption to the electricity distribution grid from wildfires that could engulf the sagging transmission lines running through the forested areas that connect remote generating stations to urban areas (Miller et al., 2007). The resulting power outages would impact transportation systems, resulting in loss of

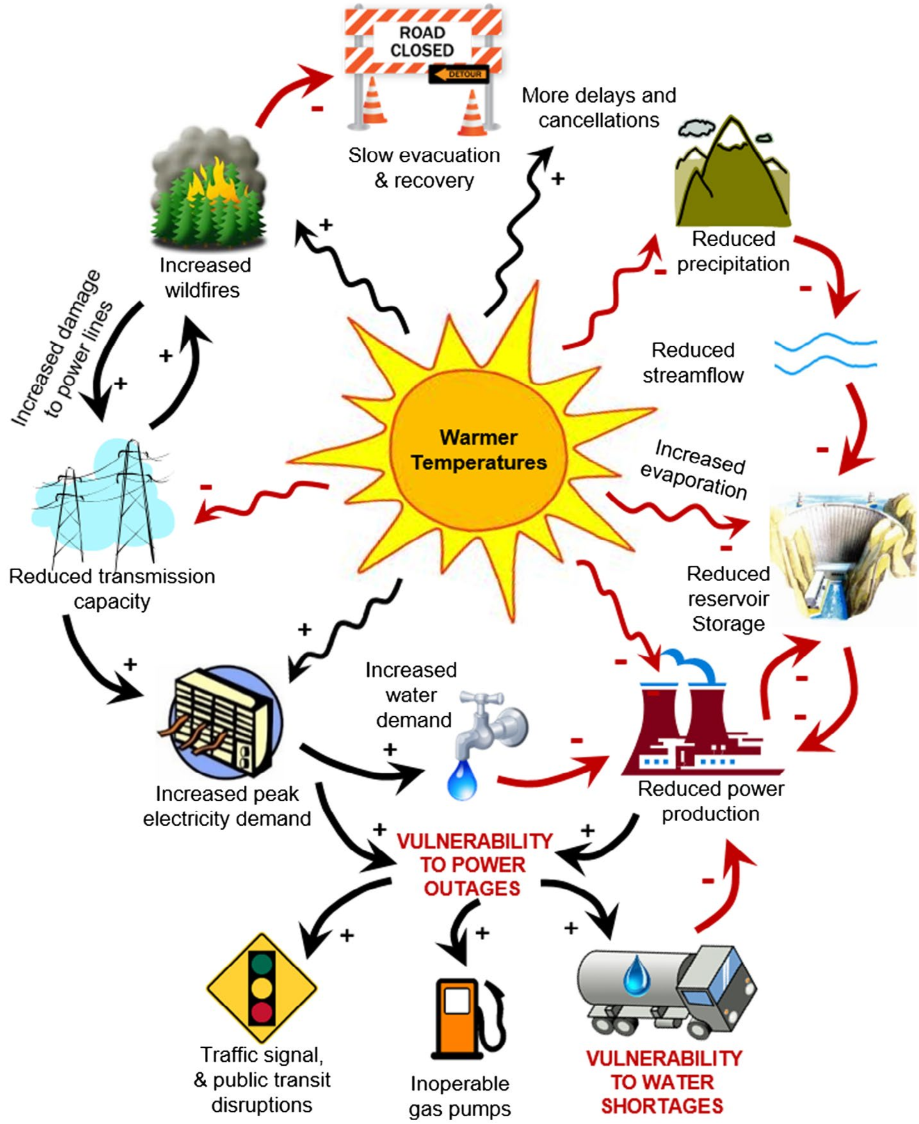

Figure 1. Coupled interactions leading to increased critical infrastructure vulnerability for Southwest cities, including Phoenix, AZ.

traffic signals, roadway closures, reduced road safety, and potentially inhibiting the availability of fuel for evacuation, relocation, or emergency power generation, as well as slow or prevent access to emergency services. Thus, an electrical interruption during an EHE could result in widespread, long-lasting blackouts that put thousands of lives at risk.

Unfortunately, the exact nature of hazards emerging from complex, non-linear, interconnected systems may be impossible to identify using traditional risk-analytic approaches. Even if they could be identified, and their risks quantified, the cost of protecting against all low probability, high consequence EHE scenarios is likely prohibitive. Nevertheless, city and regional managers are not helpless. To address situations that are not amenable to the classic tools of risk management, increasingly policy documents and scholars recommend *resilience* (e.g., Fairbanks et al., 2014; Park et al., 2013, Seager, Clark, et al., 2017).

Whereas risk analysis requires explicit hazard identification, characterization, and mitigation, infrastructure resilience emphasizes building adaptive and recovery capacity in response to *surprise*. At minimum, resilient systems and organizations must be effective at four processes: sensing, anticipating, adapting, and learning (SAAL), described below:

- *Sensing* is the process of building awareness of current state variables. These could include data on weather, technical systems performance, demographics, or available resources. The rapid depletion of groundwater storage in the Colorado River Basin (Castle et al., 2014) and the rising heat wave trends in Phoenix (Habeeb et al., 2015) are examples of sensing related to water scarcity and extreme heat in Phoenix.

- *Anticipating* is the process of building awareness of possible future states. Whereas risk analysis typically requires a probabilistic forecast, anticipation avoids assignment of probabilities to resist the 'fallacy of the unpossible' (Seager, Hollins, et al., 2017) – confusing highly unlikely or unprecedented events with impossibilities. Anticipation is therefore an imaginative, rather than an analytical act. Scenario planning is an example of an effective technique used for anticipating future possible states (Amer et al., 2013).
- *Adapting* is the process of making adjustments. In technical systems, adapting may require changing design variables, moving constraints, rearranging the fundamental relationships between system subcomponents, or ultimately, transforming the entire system through innovation. In governance systems, adapting may require reallocation of decision rights or access to information, or changing patterns and policies of interaction. Adapting to increasing temperatures might involve increasing vegetation and enhancing albedo characteristics to mitigate heat-related morbidity and mortality in urban areas (Stone et al., 2014)
- *Learning* takes place both in automatic control systems, such as in machine learning, and at individual and organizational scales. Learning may improve future sensing, anticipating, and adapting activities based on perspectives of prior catastrophe management successes and failures, and includes education and training. For example, the role of social learning is recognized as a key process for moving towards more adaptive water management practices in the face of climate change (Pahl-Wostl, 2007).

Here, we explore the potential of an extreme heat catastrophe so devastating to the metropolitan area of Phoenix that it would merit comparison to the scale and impact that Katrina had on the City of New Orleans. Because the interdependencies of complex infrastructure systems are unpredictable, we perform this exploration through the lens of resilience via the SAAL processes. For example, in *sensing*, we delineate the coupled events and cascading failures across infrastructure that have historically coincided with EHEs, including: reduced water availability, increased wildfires, and coupled critical infrastructure failures. Together, these past events provide insights for what could happen in the future as heat, drought, and wildfire increasingly threaten critical infrastructure. Based on this evidence, we *anticipate* the potential for a catastrophic scenario that involves a prolonged, widespread power outage in Phoenix during an EHE. Next, methods of *adaptation* or ways to mitigate the impacts of EHEs are discussed. Finally, we briefly describe barriers to *learning* from past events and potential strategies for overcoming them. In doing so, this research has three primary objectives:

(1) Highlight major areas of vulnerability to coupled critical infrastructure systems in the Southwest due to climate change;
(2) Explore how vulnerability in one infrastructure can lead to failures in another, and
(3) Introduce strategies for mitigating vulnerability and impacts of extreme heat on interdependent systems.

We focus on energy, water, and transportation infrastructure because they are community lifeline sectors on which other critical systems depend. Furthermore, we organize these objectives via resilience thinking with the SAAL processes, i.e., this research article itself is a product of SAAL to help future catastrophe management to a Phoenix-based 'Katrina of extreme heat'. This approach informs infrastructure management and planning for building adaptive and recovery capacity in response to unexpected or surprise events resulting from complex, interdependent infrastructure.

Sensing – how does extreme heat affect Phoenix infrastructure systems?

As EHEs become more commonplace and longer lasting, disruptions in energy, water, and transportation systems will be more likely to propagate to other systems (see Figure 1). Because the coupled infrastructure systems that provide critical services (e.g., shelter, water, food) are *complex* and interdependent, predicting the precise nature of the next cascading failure is not possible, even though it is destined to occur (Little, 2004; Perrow, 1999). As with previous catastrophes, risk analytic approaches alone may be inadequate to prepare adaptive response and recovery strategies that ensure infrastructure *resilience* (Hubbard, 2009; Park et al., 2011; Park et al., 2013). Thus, we describe critical interdependencies that are revealed by past failures and near misses to fortify a systems dynamics understanding of infrastructure response to EHE. These critical interdependencies are summarized in Figure 2.

Extreme heat impacts power systems

Peak electricity demand for air conditioning typically spikes during EHEs, increasing the risk of electricity shortages (Bartos et al., in press). High temperatures

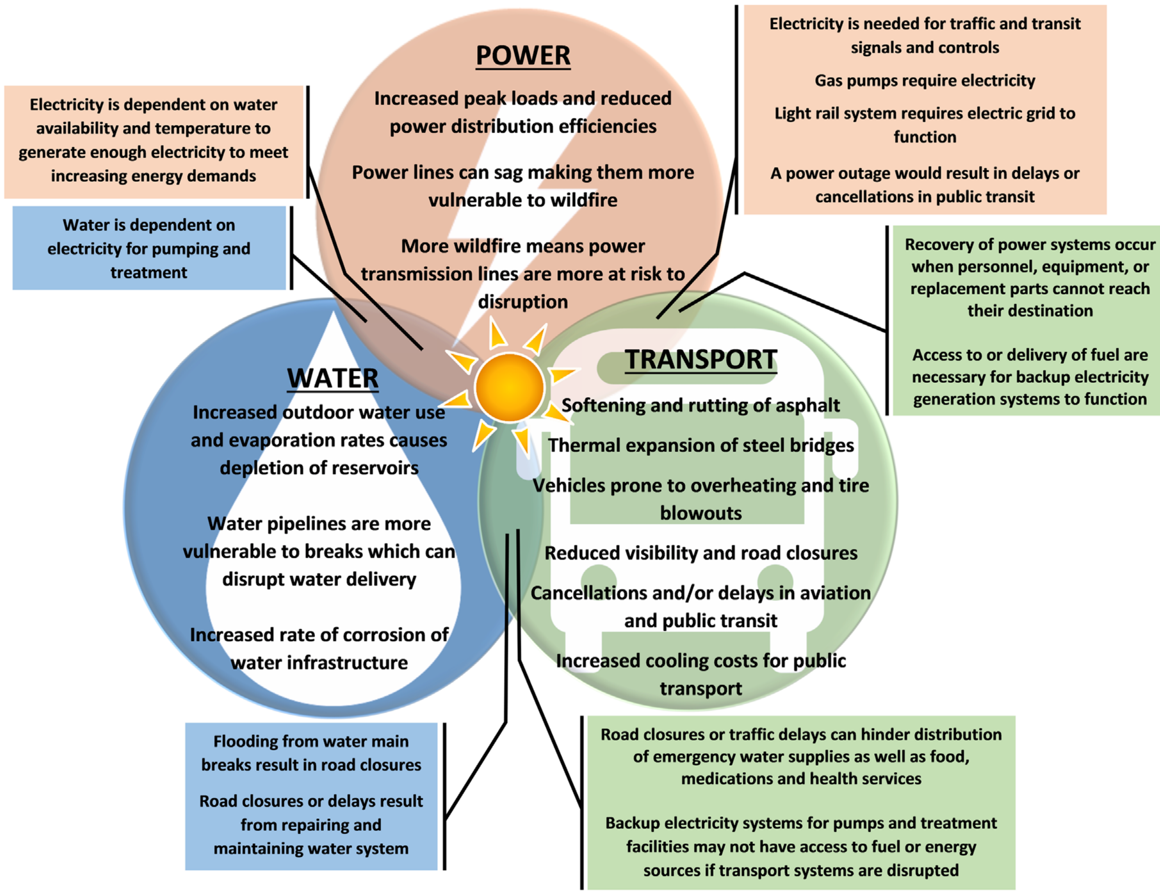

Figure 2. Impacts of EHEs, wildfire and drought conditions on power, water, and transportation infrastructure as well as the dependencies and interdependencies between infrastructure systems.

further reduce available power by increasing generation and transmission losses (Bartos & Chester, 2015; Bartos et al., in press) and power lines in Phoenix already show a significant positive relationship between temperature, energy demand, and unscheduled power outages (Maliszewski et al., 2012). Such disruptions in power can compromise transport, communication, water supply, and fuel supply all of which can lead to adverse socio-economic impacts (Chang, McDaniels, Mikawoz, & Peterson, 2007; Miles et al., 2011; Zimmerman & Restrepo, 2006). A 2011 incident in the City of Mesa (located east of the City of Phoenix) provides an example. When temperatures peaked at 41.7 °C, a transformer fire at a receiving station caused extra strain on the grid, which led to widespread rolling outages as other transformers tripped. The outage impacted more than 100,000 homes, two surface water treatment plants, and approximately 30 traffic intersections across the city. Full power was eventually restored some 11 h later (City of Mesa, 2011).

Moreover, as overall temperatures warm, cooling seasons will also be extended to include late spring and early fall – periods that customarily have reduced generation capacity during seasonal maintenance. For example, in 2011, a utility worker performing routine maintenance near Yuma Arizona caused the loss of a single 500 kilovolt (kV) transmission line that shut off power to San Diego on an unseasonably warm September afternoon when spare capacity was offline for maintenance (Federal Energy and Regulatory Commission and North American Electric Reliability Corporation, 2012). As a result, 2.7 million customers lost power, affecting parts of Arizona, Southern California, and Baja California. All of San Diego lost power, with nearly 1.5 million customers, some for up to 12 h.

Increased temperatures, reduced snowpack, and changing precipitation patterns may also reduce hydropower availability and increase the risk of wildfires (Westerling, 2016), which can both be caused by and directly destroy power distribution structures (Lawrence Berkeley National Laboratory, 2012). For example, in October 2007 power lines damaged by high winds that sparked wildfires that further damaged power lines (CAL FIRE, 2007) causing nearly 80,000 customers to lose power in San Diego for several days and displacing nearly one million residents from their homes (Public Policy Institute of California, 2008). In 2013, wildfires in Yosemite disrupted power and water supplies for San Francisco, over 150 miles away.

Power systems impact water systems

The energy intensive nature of water delivery systems make them vulnerable to electricity disruptions. Arizona's water demand is met by the CAP and other surface water (54%), groundwater (43%), and reclaimed or recycled water (3%) (Sudman & Megdal, 2007), with the contribution from each source varying by municipality. Except for gravity-fed surface water, all sources require electricity for pumping and conveyance. For example, overcoming elevation differences in the CAP canal system requires 2.8 TWh of electricity each year (Bartos & Chester, 2014). Electricity is also needed for groundwater pumping, for the collection, distribution and treatment of reclaimed water, as well as wastewater treatment post-consumption.

During the 2011 San Diego Blackout, areas without gravity-fed water sources experienced problems accessing potable water. Within the City, 13 small areas experienced reduced water pressure. Boil-water advisories was issued in these areas in case of contamination from backflow. Back-up generators at many of the area's pump stations reduced the impacts on water delivery that could have been much more severe. In total, 17 of 166 small water systems in rural San Diego County experienced low water pressure and it took almost two weeks to get these systems running.

The 2011 Mesa power outage reveals limitations in the capacity of the Phoenix water-energy system to maintain critical operations during an electrical power failure. The Val Vista Water Treatment Plant, which has dual power feeds, lost power for only about an hour because it was able to switch to alternative power sources. However, the Brown Road Water Treatment Plant, lost power from the grid for many hours. Backup generators were able to continue pumping water at the plant, but some remote stations lacked full generator back-up. Portable generators had to be brought in to keep water flowing. Despite these efforts, supplies for the Las Sendas reservoir were hindered, and at one point, the reservoir had only 4 to 6 h of water remaining (City of Mesa, 2011).

Power systems impact transportation systems

The loss of electrical power directly influences transportation systems because traffic and/or transit signaling operation and control are lost. During the 2011 San Diego outage, traffic and free-way on-ramp signals were disrupted. As a result, traffic congestion was a major problem for about 3 h after the initial event and signal operations remained unreliable for 2 weeks. Traffic delays were exacerbated in downtown because rail-crossing arms were stuck in the down position to protect rights-of-way for diesel-powered freight and Amtrak locomotives. The electric light rail system was disrupted. Moreover, without electric power for gasoline pumps, fuel supplies for consumers, repair crews, and law enforcement were limited to those fueling stations that were able to operate manually. In a similar fashion, access to natural gas by consumers was also hampered as a result of the outage. Flights in and out of the San Diego International Airport were canceled.

Transportation systems in Phoenix are vulnerable to the same types of electricity disruptions as in San Diego, with at least one additional complication. Because Phoenix is physically located far from the out-of-state refineries that supply fuel, all transportation fuels are supplied through a single pipeline that stretched from California to Texas (Clark & Chester, 2016). This means that if the electric system fails in Phoenix, or anywhere along the supply chain, delivery to gasoline storage facilities may be disrupted. In August 2003, stress corrosion cracking of the fuel pipeline between Tucson and Phoenix caused a shortage in Phoenix that lasted for several days and resulted in fuel hoarding, long lines, price spikes, and frustrated drivers. Moreover, public buses in Phoenix running on natural gas may be vulnerable without electricity to run the compressors and pumping stations that maintain pressure throughout the gas supply system.

The loss of fuel and power to public transportation systems in Phoenix may be especially important to vulnerable populations, given that air-conditioned buses and trains provide ad hoc mobile cooling and improve access to cooling centers. During EHEs, people that depend on public transit will suffer from increased exposure and thus risks of negative heat-health impacts (Fraser & Chester 2017). In particular, the reliability of the Phoenix light rail system may be impacted by power disruptions resulting from future EHEs (Chester et al., 2015) because it has no backup power capacity during electricity failures (Valley Metro, personal communication). With a combined weekday ridership of 220,000 in 2015, a disruption in bus and/or light rail services during an EHE would cause increased heat exposure.

Extreme heat impacts water systems

Heat can also be problematic for water availability, delivery, and reliability. As heat dries the ground, older pipelines can shift, making them more vulnerable to breaks. An increased demand for water on hot days only exacerbates this problem. In the summer of 2011, Houston, TX experienced weeks of above 37.8 °C temperatures that contributed to over 700 water main breaks each day, which is about 3.5 times greater than normal. As more pipes break, the ability of the system to maintain water pressure becomes problematic, which leads to disruptions in water delivery. Higher temperatures can also increase the rate of corrosion for water infrastructure, including both metal (Volk et al., 2000) and plastic pipes (JM Eagle, 2009) that deliver drinking water, and in the concrete pipes that carry sewage (Albin & Kinshella, 2004). In Phoenix, the Water Services Department covers about 700,000 miles of water pipelines over 540 square miles, much of which is over 50 years old and requires newer, stronger pipes to maintain the system (Lane, 2015). In 2014, Phoenix experienced about 850 water-main-breaks or leaks, which is considered to be a normal year for the aging pipeline system (The Republic, 2014).

Water systems impact power systems

When temperatures rise, increases in energy demand for air conditioning means more water is necessary to cool thermoelectric power generators that operate less efficiently in higher temperatures (Bartos & Chester, 2015). Warmer temperatures also increase the demand for outdoor water use, such as irrigating vegetation and filling swimming pools (Guhathakurta & Gober, 2007). Simultaneously, increases in evaporation reduce the water available in water reservoirs. Thus, when temperatures are high and streamflow is low, hydroelectric power production is curtailed (Energy Information Administration, 2016) and thermoelectric power plants may lack the cooling water required for full capacity generation. This is especially problematic for Phoenix because the water intensity of energy in Arizona is about 30% greater than the national average (Bartos & Chester, 2015).

Also, more than a dozen US power plants have been forced to reduce power generation or shutdown units because intake water used for cooling was too hot to provide sufficient cooling, or because water bodies were too already warm to receive discharged cooling water (U.S. Department of Energy, 2013). Examples include the Pilgrim Nuclear Power Station near Cape Cod in 2015 and the Millstone Nuclear Plant in Connecticut in 2012.

Water systems impact transportation systems

The increased risk of water main breaks when temperatures are high results in additional risks to transportation infrastructure. Several cases have made headline news in recent years, including the July 2014 rupture of a pipeline that carries 75,000 gallons of water per minute near the UCLA campus that resulted in the closure of Sunset Boulevard and stranded people and vehicles on campus for hours. An October 2006 failure of a large water main in Phoenix caused extensive flooding that prompted an investigation of large-diameter pre-stressed concrete pipes that identified 43 miles of high-priority pipes requiring inspections and possible rehabilitation (The Republic, 2014). In the past decade several pumping station failures have led to flooding of major Phoenix highways including Interstate 10 (which registered as high as a 984 year return period rainfall) (Kim et al., 2017). Although these transportation disruptions are considered inconvenient rather than catastrophic, if they were to occur at the same time as a power outage or wildfire, they could aggravate the situation by impeding the transport of resources, personnel and possibly prevent evacuation.

Extreme heat impacts transportation systems

Warmer temperatures reduce the life of asphalt roads through pavement softening, traffic-related rutting, and can also stress the steel in bridges through thermal expansion and movement of bridge joints and paved surfaces (Gudipudi et al., 2017; Meyer et al., 2014). Heat can also disrupt vehicle operations because of engine overheating and increased risk of tire blow-outs in heavily loaded vehicles (Demirel, 2012). During EHEs, construction activities and the number of hours that crews can work decreases due to health and safety concerns. And higher temperatures lead to an increased need for refrigerated freight movement, and result in higher transportation costs. Wildfires also poses a risk to travelers and can cause road closures.

EHEs can also affect aviation. Temperature, humidity and field elevation are used to calculate the engine combustion efficiency and the needed runway length for an aircraft to take-off and land. In the extreme (e.g., high altitude airports), aircraft may have to burn fuel or unload weight for safe-takeoff during EHEs, compounding delays and operating restrictions (McGuirk et al., 2008). Grounded airplanes are already a problem. On 29 June 2013, 18 US Airway planes were grounded in Phoenix when temperatures hit 43 °C and exceeded the maximum allowable operating temperature of the planes. Hotter temperatures also mean increased energy loads for cooling aircrafts and passengers while sitting on the runway.

EHEs could negatively impact public light rail systems. Steel rails and overhead power lines expand as the temperatures rise, causing heat kinks or bends in the tracks as well as sagging catenary lines. A system of pulleys and counterweights are used to prevent sagging, but under extreme conditions the counterweights can reach the ground and sagging can be problematic. For example, in Portland OR, light rail speeds are reduced when the temperatures increase past 32.2 °C so that operators have more time to identify heat kinks or buckling along the tracks. Fortunately, Phoenix's light rail is designed for a warmer climate. Its rail ties are set in heat-insulating concrete and its overhead wires are made of steel, which expands less as temperatures increase. Although delays in light rail service due to heat has not been a problem in Phoenix so far, the prospect of more intense EHEs raises the question of whether design standards will accommodate future climate-driven change.

Transportation systems impact water, energy and other resources

When transportation systems are limited or unavailable, access to water, food, health care, and cooling resources can be problematic. The 2009 Kentucky ice storm and resulting power outage serves as an example of this interdependency. During and after the storm, both food and gas distribution was hampered by hazardous road conditions and power outages that disabled fuel pumps. Without access to fuel, residents were prevented from fueling their vehicles to travel to other stores or towns for needed food, water and supplies, which slowed recovery efforts. In the case of a prolonged outage, backup systems depend on the delivery of fuel and the ability to transport mobile generators to critical facilities. Also, depending on the equipment that is damaged, the necessary components and parts to repair the system may need to be shipped from another location and personnel need to be able to travel to perform repairs (Fisher, 2009).

More recent events in Flint MI, where high levels of lead were found in the City's water supply, illustrates the need for transportation of bottled water to residents in the event of emergencies related to substandard water quality. The Phoenix water distribution system is already vulnerable to algae growth during warm summer months, and in the event of a blackout, families that rely on electric stoves will be unable to comply with boil water orders. Already, there are communities in Arizona that receive drinking water exclusively via haul truck. For example, in the town of Sanders, uranium contamination in the water supply exceeds maximum contaminant levels established by the Environmental Protection Agency. Disruptions in transportation could therefore result in loss of emergency water supplies.

Anticipating – what would a Katrina of extreme heat look like?

Although the probability that an EHE in Phoenix will result in a catastrophe on par with the fatalities and damages associated with Hurricane Katrina is small, the evidence provided here suggest that it is *possible*. A good planning principle is to hope for the best but prepare for the worst. However, the worst-case scenario is often difficult to imagine and it is only after a terrible event occurs that we evaluate our emergency response. Backup systems often prevent and/or mitigate cascading impacts, as discussed in many of the examples provided, but not all facilities have backup systems and sometimes backup systems can fail. A report by the Department of Homeland Security (2014) indicates that of the U.S. power and water facilities they assessed, 54% of the electric power substations that depend on external power to function had backup generation capability. Although security purposes require that the report does not identify specific facilities, it does emphasize that a cascading failure is a potential consequence of any incident due to the complex dependencies and interdependencies of critical infrastructure sectors.

A catastrophe scenario would involve an extended power outage in Phoenix during an EHE, causing significant health and economic consequences. With a current population of 4.5 million and forecasts projecting significant increases in EHEs, this type of an event could result in millions of people losing direct access to cooling resources, potable water, and/or transportation resources. Compared to the 2011 San Diego Blackout, a comparable power outage in Phoenix could be much worse, given that temperatures in Phoenix are typically hotter, there is no nearby ocean to provide refuge, and disruptions in the delivery of water are likely to be more serious. If a large wildfire occurred during an EHE, it could contribute to causing a power outage but also make the impacts more severe by reducing air and water quality, causing road closures and/or reduced visibility, and increase demand for water, energy, and transportation resources for fighting the fire. Further, if an evacuation were to occur, a large wildfire could block major evacuation routes to those people trying to escape the heat or find water elsewhere. Water main breaks and limited fuel availability would only exacerbate the situation by hindering transport of emergency supplies and services and complicating evacuation.

Because the average person can survive up to only 48 h without water (or less in extreme heat conditions), an evacuation would be expected for those without access to clean water or air conditioning whenever high temperatures approach or exceed the Phoenix record of 48.9 °C. Experiences prior to major hurricanes illustrate the challenges of evacuating urban areas. During Katrina, the emergency evacuation plan fell apart as roads became clogged with evacuees in private cars, and the buses that were supposed to transport those without cars could not get people out as originally planned (Sullivan, 2005). This resulted in an estimated 150,000 people without means to evacuate the City (Comfort, 2006). Thus, evacuation is particularly problematic for individuals without private transportation and those that cannot access fuel due to the inability to pump fuel at local gas stations.

Even without an EHE, about 80 people die from heat-related impacts and another 8000 are hospitalized for exposure to excessive heat in Arizona annually (Maricopa County Department of Public Health, 2014). Given the large negative health outcomes that have recently been experienced in major developed world cities (including the 700 and 35,000 deaths during the 1995 Chicago and 2003 Europe), a power outage during an EHE in Phoenix could have major consequences (Larsen, 2003; Semenza et al., 1996). Although these events occurred in locations where people are less accustomed to heat than the typical Phoenician, a power outage during an EHE could be deadly to the majority of the population that rely on air conditioning to avoid heat exposure or are otherwise more vulnerable to heat-related illness (Eisenman et al., 2016; Fraser et al., 2016). After Katrina, 103 patients died in nursing facilities due to heat, dehydration, and other ailments (Brunkard et al., 2008). During Irma, eight nursing home residents died in Florida after their air conditioning unit failed, despite being located across the street from a hospital (NBC News, 2017). This is an unfortunate example of the diminished capability of a community or region to provide critical services during extreme events, which can amplify morbidity and mortality impacts beyond populations that are physically exposed to the hazard itself. For Phoenix, the death toll could be higher if the EHE occurred at a time when a large number of tourists were in the area or during the beginning or end of the snow-bird season (Anderson & Bell, 2011), when hundreds of thousands of retirees visit Phoenix to escape the cold Northern US winters and are unaccustomed to the extreme heat conditions of the Southwest.

Phoenix's regional economy is more than double that of pre-Katrina New Orleans (Bureau of Economic Analysis, 2014). Thus, an event that paralyzes Phoenix could potentially cause economic losses even larger than the estimated $100 billion in damages that resulted from Katrina. For comparison, consider that the 13 h power outage effecting 2 million people in San Diego resulted in estimates between $97 and $118 million in productivity losses, government overtime, and loss of perishable food and medicine (National University System Institute for Policy Research, 2011). A 2006 two-week heat wave in California resulted in $5.4 billion in health care costs alone (Natural Resources Defense Council, 2011). A power outage coupled with an EHE in Phoenix has the potential for much larger economic losses, especially considering the relative geographical isolation of the region. For example, Phoenix imports all of its refined transportation fuel (Clark & Chester, 2016) and a significant proportion of its water supply from out-of-state. This could be problematic for transporting aid/resources into the region and could slow overall recovery efforts.

Adapting – options to prevent impacts from extreme heat for Phoenix

While existing literature provides strategies for mitigating heat in urban areas (Jenerette et al., 2011; Kleerekoper et al., 2012; Santamouris, 2014) as well as protecting people from heat (Fraser & Chester, 2016; Chow et al., 2012; Hayden et al., 2011), reducing the impacts of EHEs on *interdependent* infrastructure systems are less studied. Nevertheless, the literature suggests that to become more climate resilient, changes to the design and configuration of critical infrastructure systems are required. This involves revising infrastructure design and operation plans to take future climate scenarios and non-stationary conditions into account, rather than basing design criteria on historical weather events (Gersonius et al., 2013; World Meteorological Organization, 2009). For example, transit system emergency plans should be developed that reroute vehicles and increase services during heat events (Fraser & Chester, 2017). Increasing the adoption of renewable energy sources, such as solar and wind, which are less susceptible to climate change impacts, will decrease the water-intensity of electricity generation as well as reduce green-house gas emissions (Bartos & Chester, 2015). And microgrids with battery storage offer opportunity to protect vulnerable communities from power outages (Jones et al., 2017). Burying power lines would reduce the risk of disruption from heat and wildfire, although might not be appropriate for areas prone to flooding. Other strategies include energy efficiency improvements and smart grid technologies (Bartos et al., in press). Increasing local reserves of fuel and water would also increase the capacity and flexibility of current systems. Developing and implementing plans for the decentralization of energy, water, food, and waste management will reduce the likelihood and impacts of a widespread outage. Thus, key facilities like hospitals and cooling centers should be self-sufficient in terms of critical services. New infrastructure that delivers multiple environmental services while serving basic critical needs should be prioritized (DHS, 2014). Most critically, refuges must exist and be accessible to the most vulnerable groups within the population. Public and private air conditioned spaces, including county sponsored cooling centers and libraries, must be located in places where vulnerable communities exist and the metro region must provide these refuges with the support to handle large numbers of people (Fraser et al., 2016). One strategy is to locate refuge centers in places that house the most vulnerable populations to heat, such as nursing homes and/or hospitals or other medical facilities. If these facilities were built in locations that made them less vulnerable to threats, and if they were self-sufficient in terms of critical services, the need to evacuate would be less likely. However, if evacuation is necessary, protocols should be in place to ensure that the most vulnerable populations are able to do so safely.

Further, infrastructure managers and planners must map and define how their systems interact and can be affected by other systems. Assessing the capacity of back-up systems for power continuity is also critical, especially for critical linkages across systems. In terms of recovery, the discussed system interdependencies suggest that it may not be possible to bring a singular system back online without also bringing interdependent systems online together. All of which will require increased coordination, communication, and general awareness beyond the typical utility and/or departmental boundaries. DHS (2014) suggests that community risk managers develop an Interdependency Operational Plan (IOP) that involves working with critical infrastructure owners and operators to assess interdependencies, assets, alternative means of providing services, and recovery time objectives.

Emergency response and recovery plans must also be developed around system interdependencies. Currently, Arizona's Heat Emergency Response Plan (2016) does not offer a coordinated strategy for a widespread and/or prolonged power outage that disrupts multiple infrastructure systems and/or requires evacuation. Maricopa County has an Emergency Evacuation Plan (2004), but it assumes ideal road conditions, with working traffic signals, and available fuel, and other well-coordinated and proactive strategies. Thus, there is a tendency to assume that critical infrastructure systems will be available to alleviate and mitigate the impacts of extreme heat, when in reality, that is when our critical infrastructure systems are most at risk for failure. There are many physical and institutional responses that could be considered and while a few are mentioned here, a broader suite should be extensively studied to prepare the City.

What the sensing analysis here uniquely offers is the systemic view of key infrastructure vulnerabilities and potential service disruptions, which we think is necessary for effective adaptive infrastructure management. One benefit of this is understanding how we might use infrastructure interdependencies in creative and beneficial ways to help mitigate impacts we anticipate. For example, public buses powered by compressed natural gas could be repurposed as mobile cooling centers during EHEs. We can also rely on transportation infrastructure to deliver other services that we might not have locally, such as water, fuel, and food. Alternatively, communities could utilize sharing economy applications, like Uber, Lyft, and Air B&B, to enable more service sharing opportunities during extreme events, including transportation, shelter, and food/resource distribution (Seager & Clark, 2016). That is, interdependent infrastructure systems may allow us to reroute the delivery of critical services to those in need, even if the physical infrastructure that normally supplies those services fails.

Learning – improving the way we learn from past events

The typical practice in the field of emergency preparedness is a 'lessons-learned' approach to knowledge management, which assumes that learning from experience practice and minimizes avoidable deaths and negative economic and social consequences of disasters (Rostis, 2007). There are many methods currently used for collecting and sharing experiences related to emergency management and disasters, including in-progress reviews, debriefings, and perhaps most popular, after-action reports (AARs). Originally developed by the U.S. Army, AARs are tools for gathering and documenting evaluations of key processes during the response to both real-incidents and fictional exercises. For many U.S. agencies involved with emergency preparedness, AARs are now required.

The Lessons Learned Information Sharing (LLIS) program within the U.S. Federal Emergency Management Agency (FEMA) is an example of an effort to identify themes from a repository of AARs and generalize them to help guide emergency managers and facilitate improvements in resilience and emergency planning. Key themes from trend analysis for community resilience include the need to better integrate input from the whole community and to improve capacity for identifying, protecting and restoring critical services, infrastructure and resources. To address these gaps LLIS recommends community outreach and education/training programs, efforts to build partnerships and maintain communication with the community to improve information sharing, as well as increased evaluation and testing of critical systems and services (LLIS, 2014).

Despite these efforts, evidence suggests that we are not learning effectively from past events, and that many problems that arise in major incidents reoccur. For example, AARs for Hurricane Katrina, the 11 September 2001 attack, Oklahoma City Bombing, and Hurricane Andrew all report issues of communication system failure, problems with command and control structures, and resources that were slow to deploy (Donahue & Tuohy, 2006). Auf der Heide (2006) discusses the common pitfalls seen in the lessons-learned approach itself, commenting that recurring difficulties in responding to disasters are due, in part, to the failure of organizations to produce generalized recommendations that have meaning outside of the context of a specific event. A review of AARs from LLIS by Savoia, Agboola and Biddinger (2012) found that of those reports that included recommendations for improvements, they were often generic in nature without specific guidelines for action or implementation and/or they lacked specific examples or details about the root cause of response challenge. This limits the extraction of common lessons-learned to inform broader planning efforts.

Another limitation is that a typical AAR approach neglects important activities essential for learning. According to the Kolb theory of learning (Kolb, 2014), there are at least four necessary and sometimes overlapping activities required for an effective learning process: (1) abstraction (e.g., theory and modeling), (2) experimentation (i.e., reductionist manipulation of independent variables to discover consequences in a structure, iterative approach to investigation), (3) experience (i.e., immersion in context-rich, inductive sensory experience for the acquisition of tacit knowledge), and (4) reflection (i.e., making meaning). A typical AAR approach strengthens only reflection, leaving other learning activities to chance.

Moreover, AARs require an initiating event (or action), ensuring that the AAR will always be retrospective. This is problematic because hindsight is particularly prone to cognitive biases that may distort historical reconstruction of events (Toft & Reynolds, 2016). In addition, as technologies, the environment, and society change, new hazards and opportunities necessitate *anticipation* wherever the applicability of retrospection is limited.

To overcome these limitations, we argue that AARs should be supplemented by infrastructure simulations. We envision simulating rich case studies of infrastructure failure and management that enable stakeholders to safely experience and reflect upon the consequences of a variety of infrastructure failures before they occur locally. Simulations will allow infrastructure managers and other stakeholders to actively experiment with and experience infrastructure related dilemmas. They will also help improve understanding of infrastructure interdependency and dynamic complexity because simulations allow for repeated actions under different conditions, allow time and to be compressed so that impacts of decisions are not delayed, and enable extreme or even dangerous scenarios to be experienced safely. Ultimately, simulations offer a strategy for fostering a more adaptive approach to infrastructure design and management that benefits from past infrastructure experiences as well as considers longer-term implications of design strategies. The feasibility of simulations for community risk and resilience assessment are provided in the literature, including Cutler, Shields, Tavani, and Zahran (2016) and Ellingwood et al. (2016).

The use of infrastructure simulations for the purpose of learning from past events could be facilitated by a national center or institute for lessons learned, as suggested by Donahue and Tuohy (2006). This institute would develop and oversee the standardization of reporting or AARs, develop simulations of major incidents that exemplify common and reoccurring lessons, as well as help organizations respond to the issues identified. Our updated version of this national center would include a continuously growing database of infrastructure AARS as well as relevant simulations that allow for more effective knowledge transfer from past infrastructure failures. Rather than a reader or spectator of a described event, the simulations would allow stakeholders to play the role of a decision-maker and actually participate in the event as it happens. Through repeated simulation, users will experiment with different strategies and reflect upon the outcomes. We imagine that the simulations, which articulate key relationships revealed through individual case studies, will be used as educational exercises for students as well as a tool for municipalities, businesses, utilities, engineering firms, research institutes, and urban planners to improve infrastructure problem solving across society.

Conclusion

Cities are increasingly vulnerable to extreme events that could disrupt the critical infrastructure systems on which we depend. Whether it is a hurricane in New Orleans or an EHE in the Southwest, critical infrastructure systems are at risk for cascading failure in ways that are unpredictable and surprising due to their complex interdependencies and fragility to extreme conditions. Although sector by sector improvements are necessary, a broader, cross-sector perspective is required to create a more resilient and adaptable infrastructure system overall (Clark et al., in press). Lessons learned from Hurricanes Katrina and other major events that have affected multiple infrastructure systems should serve as learning opportunities for other cities to better prepare for and mitigate the damages of coupled infrastructure failures.

Moreover, the SAAL resilience processes outlined in the introduction and demonstrated throughout this paper is a useful framework for broadening the way organizations, communities, and other stakeholders approach resilience planning to prepare for both predicted and surprise events. The practice of sensing how critical systems are vulnerable to stressors, anticipating how the information from sensing might manifest into possible (not just predictable) future states, taking actions to adapt and adjust current practices to mitigate undesirable future states, and effectively learning and from past successes and failures to improve current practices, are key to creating more resilient infrastructure systems.

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