

Key Points:

- Limited data and models and disciplinary silos make it difficult to link failures in interdependent infrastructures to social outcomes
- Awareness of infrastructure vulnerabilities needs to be coupled with coordinated action among government, communities, and industries
- We suggest ways to improve understanding of interdependencies and increase stakeholder uptake of relevant information in planning efforts

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From Awareness to Action: Accounting for Infrastructure Interdependencies in Disaster Response and Recovery Planning

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Abstract This paper highlights challenges and open questions pertaining to physical and social infrastructure system interdependencies and their implications for disaster response, recovery, and resilience planning efforts. We describe the importance of understanding interdependencies in disaster contexts and highlight limitations to existing approaches. Suggestions for understanding and addressing interdependencies focus on increasing availability of tools for assessing interdependencies and increasing stakeholder and decisionmaker uptake of infrastructure interdependency-related information in planning efforts.

Plain Language Summary Interdependent physical and social systems offer enormous benefits for daily life because they produce and distribute essential goods and services that are necessary for health, safety, and economic well-being. For instance, the power grid is required for effective functioning of information systems and cell phones, which underpin effective functioning of hospitals, water and sewer systems, traffic lights, and home appliances. In return, communications and information technology is required for effective functioning of the power grid, especially to meet the concurrent demands for reliable energy supply, protection, and automation. In this paper, we describe how failure in interdependent systems can be catastrophic and lead to death and prolonged human suffering. We examine difficulties in linking failures in interdependent systems to measurable social impacts including: limited availability of data and models, disciplinary silos that might stand in the way of different stakeholders, practitioners, and experts working together on this inherently cross-disciplinary problem, and diversity in infrastructure systems, disruptive events, and communities. We suggest that awareness of the vulnerabilities in interdependent infrastructure systems needs to be coupled with coordinated action and collaboration among government agencies, communities, and industries.

1. Introduction

Some of the worst disasters in recent memory are the outcomes of low-probability, high-consequence events that have brought with them failures of interdependent infrastructure systems (Alexander, 2018). By “infrastructure,” we mean not just physical assets (e.g., the power grid, water and wastewater systems, and telecommunications networks) but also social systems that play a key role in human health, safety, and well-being (e.g., government functions, educational programs, parks, and recreation systems). Interdependent infrastructure systems are susceptible to a wide array of shocks (typically abrupt) and stressors (typically slow, with cumulative effects). In addition to natural disasters, shocks can also include premeditated attacks on interdependent infrastructure systems. Stressors can include gradual aging of assets, lack of maintenance due to scarce funds or outmigration of skilled labor, overuse due to population movement or urban expansion that increases demand, a decline in the global or local economy, and a range of environmental changes (e.g., rising sea levels, increasing air temperatures, and greater intensity or frequency of storms). As described in the recent report of the Fourth National Climate Assessment (U.S. Global Change Research Program [USGCRP], 2018), climate-related shocks and stressors can have a direct impact on multiple infrastructure systems (e.g., energy, water, communications, and transport) that interact with and depend on each other and with other systems (e.g., finance and education) that are less directly exposed to climate factors.

This paper aims to highlight and offer recommendations for addressing current knowledge gaps. Specifically, we take stock of approaches, methods, and tools that are currently available to (1) better understand and characterize interdependencies among critical infrastructures and (2) suggest effective ways for

incorporating an understanding of infrastructure interdependencies into disaster response and recovery planning. This paper is not intended to serve as a comprehensive literature review or a systematic assessment of existing tools. Rather, by drawing on the authors' experience in Puerto Rico and other disaster-impacted areas and building on theoretical frameworks and empirical results reported by experts in the field, we seek to highlight leading challenges and identify open questions about how to manage risk in complex, interdependent systems.

2. Example Failures in Interdependent Systems

The consequences of failures that propagate through interdependent systems can be catastrophic (Buldyrev et al., 2010; Vespignani, 2010). Many examples demonstrate how an instigating natural hazard can cause rippling effects across connected infrastructure systems whose failure then results in significant, adverse social impacts. In 2011, for instance, the Tōhoku triple disaster was initiated by an earthquake, which triggered a tsunami, and contributed to the nuclear meltdown at Fukushima, ultimately resulting in 19,000 fatalities (Latcherote et al., 2018). The 1998 Canadian ice storm left 16% of Canadian population without power, caused 45 deaths, and cost the Canadian government \$1.7 billion (Lecomte et al., 1998). The 2010 eruption of Eyjafjallajökull Volcano in Iceland projected so much ash into the atmosphere that flights were grounded across Europe, stranding 8.5 million people and severely affecting commerce (Alexander, 2013). During Hurricane Katrina, initial levee failure, coupled with failure to evacuate and inadequate shelter, contributed to an estimated 1,570 deaths of Louisiana residents and a \$40–50 billion economic loss (Kates et al., 2006). The recovery period after Hurricane Katrina surpassed a decade.

More recently, the severe impacts of serial hurricanes Irma and Maria on Puerto Rico and its 3.4 million inhabitants in 2017 clearly demonstrate challenges of compromised interdependent infrastructure systems. Puerto Rico suffered a complete and extended loss of the power grid, a near-complete loss of cellular communication, a scarcity of drinking water, and impassable roads, resulting in nearly 3,000 deaths and prolonged human suffering (Santos-Burgoa et al., 2018). The poor and vulnerable were disproportionately affected (Zorrilla, 2017). Figure 1 provides a simplified view of how four key infrastructure systems—sometimes called *lifeline functions* or *lifeline systems* (Department of Homeland Security (DHS) Office of Infrastructure Protection; undated)—interacted during and after the 2017 hurricanes in Puerto Rico and the impact that the cascading failures of these lifeline systems had on the population's health and the economy.

Lack of power in Puerto Rico had cascading effects on communications, water, and transportation systems; the resulting effects impacted every sector of the economy and left the island facing profound challenges. Without power, the other lifeline sectors (communications, transportation, and water) and the population's health and economy were negatively impacted. Specifically, people were unable to get health care due to transportation challenges or lack of available facilities. Inadequate sanitation and poor hygiene further resulted in increased risk of illness. Many businesses remained closed due to lack of power, and those that did open suffered from a loss of revenue because transportation challenges prevented customers from accessing the businesses.

Following the hurricanes in Puerto Rico, the DHS National Protection and Programs Directorate, Office of Infrastructure Protection (DHS-IP) conducted regionally focused assessments that highlighted the most difficult interdependencies to manage and efforts taken by industry stakeholders to mitigate potential consequences of their failure (DHS-IP, 2018). *Retrospective* assessments like this one raise awareness of how critical infrastructure systems depend on each other and help improve planning for future disasters. However, work remains to be done to *proactively* link failures in interdependent systems to measurable social impacts. This is especially important given the increasing array of social and physical stresses that people and communities experience, from disasters to economic difficulties to environmental stresses (DHS, 2016; U.S. Army Corps of Engineers, Main Report, 2015).

3. Limitations of Existing Methods for Assessing Physical and Social Infrastructure Interdependencies

Challenges to assessing the social impacts of failures in infrastructure stem from several factors including: limited availability of data and models; disciplinary silos that might stand in the way of different

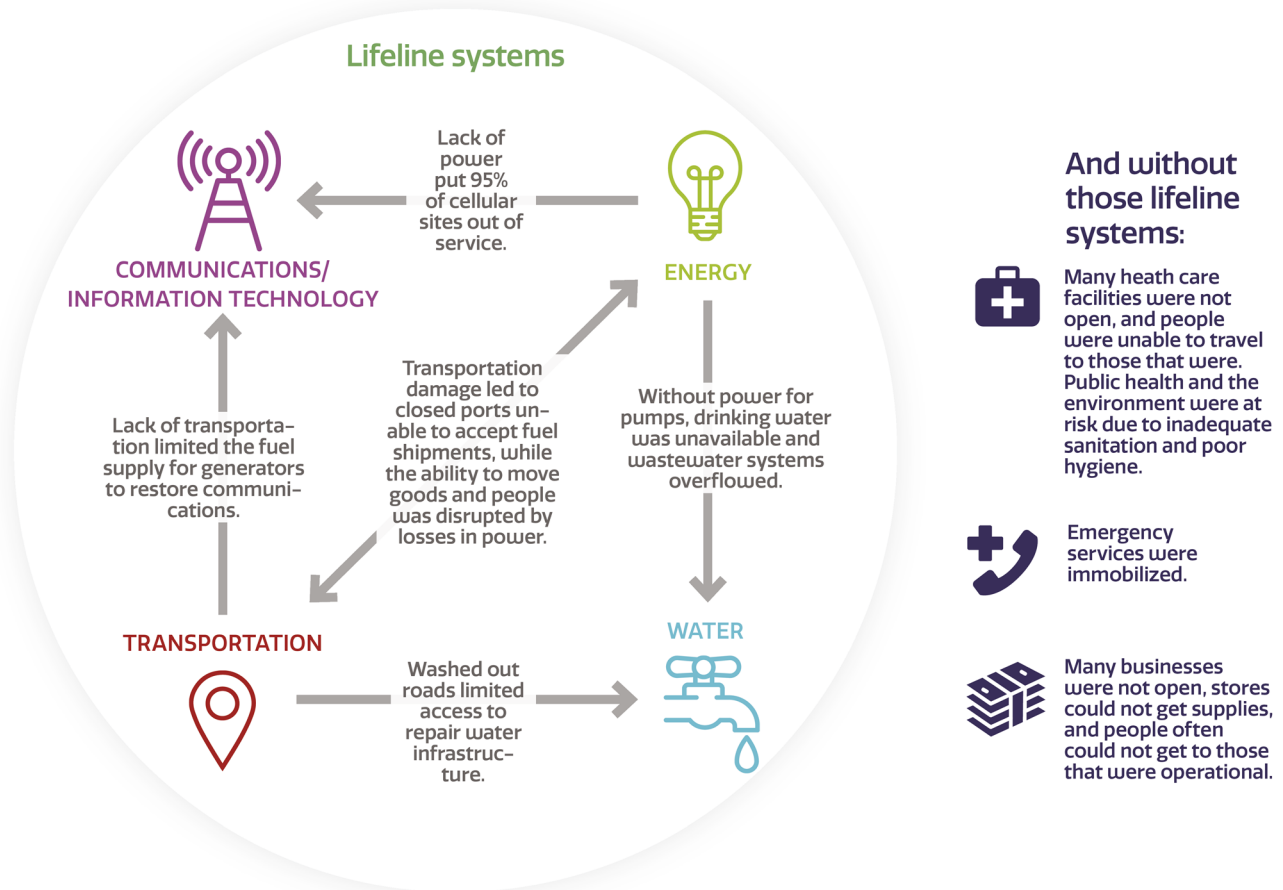


Figure 1. Lack of power had direct implications for communications, water, and transportation systems, and indirect effects on the population's health and economy. Source: RAND created this figure for the government of Puerto Rico under contract to the U.S. Federal Emergency Management Agency. The figure was included in transformation and innovation in the Wake of Devastation: An economic and disaster recovery plan for Puerto Rico, which entered the public domain when published by the government of Puerto Rico 8 August 2018 (Government of Puerto Rico, Central Office for Recovery, 2018).

stakeholders, practitioners, and experts working together on this inherently cross-disciplinary problem; and the undeniable heterogeneity of infrastructure systems, disruptive events, and communities.

Several *analytical* or *computational* approaches have focused on interactions among physical infrastructure systems, particularly the “lifeline” sectors described above but have not typically incorporated social systems. These methodologies include agent-based approaches, system dynamics-based approaches, economic theory-based approaches (input–output-based approaches and computable-general-equilibrium based methods), and network-based approaches (topology-based and flow-based methods), among others (Ouyang, 2014). While some broader attempts at modeling include effects on other critical infrastructure sectors, like finance (Barton et al., 2004), health care (Arboleda et al., 2006; DHS-IP, 2018), and food distribution (DHS-IP, 2018), these are less common.

A second limitation in analytic approaches is a lack of attention to the human impacts of failures within and across physical and social systems. Modeling these impacts would require not just a complete characterization of infrastructure interdependencies (spanning both physical and social systems) but also a translation of system failures into measurable effects on health, safety, and well-being (e.g., in terms of injuries and lives lost or extent of population displacement)—a task that requires engineers, emergency responders, urban planners, sociologists, and others to work together, crossing disciplinary lines (Davidson, 2015; Hamburg, 2019; Meng et al., 2019). These social impacts are often the result of multiple factors (e.g., interaction of pre-existing vulnerabilities with the stress associated with experiencing the disaster), making it difficult to isolate the disaster-specific impacts above and beyond preexisting and changing community-wide conditions. There

is an evolving evidence base that documents the human impacts of disaster (e.g., declining mental health, increasing substance abuse, and worsening chronic conditions) (Cutter et al., 2008; Hobfoll, 1991; Kwok et al., 2017; McFarlane & Williams, 2012; Norris et al., 2002; Tierney, 2006). However, the specific link between disaster-related failures in infrastructure systems and resulting social challenges is less well studied.

Complex systems theory has provided a useful lens to study the links between infrastructure systems and social challenges because it acknowledges the interdependencies within a system and how those interdependencies influence how a system interacts with its broader environment (Coetzee & Van Niekerk, 2016; Fraccascia et al., 2018; Quail et al., 2018). While researchers have discussed the interlocking systems that influence a community's resilience and argued that an integrated resilience approach is needed to enhance resilience, the field of resilience lacks a shared framework or set of metrics to bridge the research across disciplines (e.g., social science, natural science, and economics) and units of analysis (e.g., individuals, families/households, organizations, and systems) (Gillespie-Marthaler et al., 2019; Liu et al., 2017; Long & Bonanno, 2018). This is in part because metrics that capture these complex and dynamic relationships and system adaptations (not just system performance) require new data capture and storage (e.g., machine learning algorithms to capture patterns in "big data" from social media and linked data sets from across multiple systems that require public-private partnerships) (Freeman et al., 2019). Although there are examples of communities moving toward integrated data systems (e.g., NYC Data Integration initiative) and of research institutions mapping a complex adaptive system of systems (e.g., Sandia National Laboratories CASoS Initiative), these examples are more the exception than the norm (Acosta et al., 2017).

A third limitation in analytic approaches is their inability to address the considerable variation in human impacts that depend critically on the scale and scope of the disaster, the heterogeneity of infrastructure systems, and the characteristics of the affected communities (Lindell & Prater, 2003). Additionally, social impacts can take years or decades to materialize requiring models that take into account the lengthy and complex nature of disaster recovery (Gill et al., 2016). These considerations make it difficult (if not impossible) to produce a model that predicts outcomes across contexts and over the lengthy recovery period. For this reason, outcome-oriented modeling efforts and tools tend to focus more broadly on the economic impacts of disasters (Hasan & Foliente, 2015). Common methods for assessing economic impacts include input-output modeling and computable general equilibrium models (Rose, 2004). Some models and tools (e.g., Federal Emergency Management Agency [FEMA's] HAZUS tool) do provide a way to assess or account for noneconomic human impacts resulting specifically from infrastructure failures triggered by disasters but do not account for infrastructure interdependencies in their assessments (Chang, 2003; Hasan & Foliente, 2015).

In contrast to analytical efforts, which are geared toward describing, diagnosing, or predicting problems and prescribing solutions where possible, *empirical approaches* review historical events and so reveal interdependencies as they actually occurred, including frequent or common failure patterns (Ouyang, 2014). Since the empirical approach centers on events that have already occurred, it can offer valuable insight into the relationships between the failures of networked infrastructure systems and the social impacts that result from these failures. These insights could then inform future modeling efforts. But this value is only realized if efforts are taken to carefully trace and document the root causes of adverse social impacts. Further, empirical reviews are often conducted through analysis of documents such as media reports, government assessments, and reports from utilities—such reports are inherently not free of biases (Ouyang, 2014). For example, media reporting biases tend to favor news of interest to their audiences and may not include instances where routine operation was successfully maintained (Van Eeten et al., 2011). Additionally, media reports do not contain proprietary or sensitive information that may be relevant to the cause of the failure. Despite these shortcomings, systematic cataloguing and analysis of the aftermath of disasters can provide useful insights for model development.

4. Limitations of Existing Methods for Incorporating Interdependency Assessments Into Disaster Response and Recovery Planning

Existing methods fall short when it comes to incorporating interdependency assessments into disaster response and recovery planning. Utilizing knowledge of interdependencies in planning is not straightforward for emergency planners and responders; local, state, and federal government officials; or NGOs, all of whom play key roles in the disaster cycle.

Several efforts have aimed to raise awareness of interdependencies. For instance, the Critical Infrastructure Modeling System, from Idaho National Laboratory, was designed as a data visualization system for decision makers to aid in their understanding of interdependencies (Dudenhoeffer et al., 2007). Hasan and Foliente, in their review of ongoing modeling efforts, provided recommended actions for various types of decision makers and suggested the most appropriate method to begin undertaking actions. University College London's Institute for Risk and Disaster Reduction and London Resilience published a guide on the cascading effects of power outages to serve as a reference for emergency planners (Pescaroli et al., 2017).

Unfortunately, simply raising awareness of the vulnerabilities in interdependent critical infrastructure systems and in the communities they serve—and even recommendations for how to remedy these vulnerabilities—is ultimately insufficient to prevent failures and other negative impacts when not coupled with coordinated action. This was vividly demonstrated in the case of Hurricane Katrina, where tabletop exercises held before the storm raised concerns about flooding due to levee failure and evacuating a large population without personal transportation (Leavitt & Kiefer, 2006). Inadequate funding, failed policies, and ineffective intergovernmental communication prevented the problems identified in the exercises from being addressed prior to Katrina. In Puerto Rico, absent or ineffective collaboration among government agencies, communities, industries, and utilities led to unmet needs in the wake of Hurricane Maria. For instance, insufficient coordination between FEMA and local food suppliers may have caused delays in food supply and delivery (DHS-IP, 2018).

The National Institute of Standards and Technology (NIST) Community Resilience Planning Guide for Buildings and Infrastructure Systems is a useful resource that communities can use to set and incorporate resilience goals into various planning activities, including those associated with infrastructure systems (Coetzee & Van Niekerk, 2016). While this NIST guide is not particularly focused on infrastructure *interdependencies* (though Volume II does touch on the topic), the objective and structure of the NIST guide can serve as a template for designing guidance that is more geared toward capturing the specific challenges of accounting for infrastructure interdependencies in disaster response and recovery.

5. Discussion and Open Questions

As discussed in sections 3 and 4, understanding and incorporating knowledge of infrastructure interdependencies are difficult but critical elements of effective disaster response and recovery planning. Comprehensive characterization of how systems and assets depend on each other is necessary to help predict when and why failures might occur so that resources can be distributed appropriately. While sophisticated modeling tools and analytic efforts have elucidated interactions among components of physical infrastructure (especially among lifeline systems), *assessing* interdependencies among social systems and the human impacts of failures poses a challenge.

No less important than improving our understanding of infrastructure interdependencies is improving the rapid uptake of the knowledge and tools by real-world decision makers who work with communities to prepare for and respond to disasters. *Incorporating* physical and social components into planning efforts can be difficult because key factors governing resilience outcomes and options for improving them vary across contexts that span socio-economic, demographic, cultural, historical, and geographical realms. That said, regardless of context, first responders, planners, and community leaders need to be able to share information, in real time, at little cost. One suggestion for improving uptake of data, analytic methods, and knowledge in recovery planning is to employ a collaborative model that promotes information sharing structures among organizations, between organizations and individuals, across multiple levels and branches of government, and the private sector (e.g., through coalitions) (Madrigano et al., 2017). Specifically, the approach encourages building community outreach and engagement skills and develops expertise in translational science among the emergency management and public health workforce responsible for planning (Satterfield et al., 2009; Wells et al., 2013). The Community Tool Box (Center for Community Health and Development), a toolkit utilized by coalition and advocacy groups in the United States, is a good resource in this regard. However, given the increasingly open and exponentially growing data sources for understanding communities, planners may need to also possess the ability to understand “big data” and better reap the benefits of databases containing decision-relevant information (Arribas-Bel, 2014; Miller, 2010).

Several open questions need to be addressed to continue improving awareness of infrastructure interdependencies and increasing uptake of knowledge as it relates to recovering from and rebuilding after disaster events:

1. To what extent (and how) do contextual variables (e.g., preexisting vulnerabilities, legal frameworks, and institutional relationships) affect the value and use of information about infrastructure interdependencies and how they are represented and analyzed?
2. What would motivate or incentivize disaster planners and policy makers to more systematically assess and identify ways to address system interdependencies and prevent future cascading failures from occurring during a disaster?
3. How can system-level dynamics and interactions be modified as the nature of risk exposures, sensitivities, impacts, and resilience changes due to global environmental and demographic trends?
4. What strategic institution building is needed to enhance longitudinal and multifaceted data collection, sharing and modeling tools for the field of hazards and disaster recovery?

The last question highlights a challenge that applies more broadly to disaster response and recovery planning—a lack of appropriate social science research infrastructure for examining trajectories of disasters across time. Predisaster data are no less important than postimpact data for social scientists; without robust baseline data, it is impossible to assess changes in situation, behavior, and beliefs that result from infrastructure failures, regardless of whether they are induced or exacerbated by interdependencies (Parker et al., 2019). Sharing and integrating diverse types of data and modeling tools requires interdisciplinary efforts that are complex and resource intensive. As a result, gaps in knowledge about the cause and consequences of infrastructure interdependencies remain.

The challenges and questions described in this paper need immediate and substantial attention if the disaster research and practice community is to adequately address the changing risks faced by U.S. communities. Mobilizing the necessary resources is a complex undertaking, but nonetheless critical for building resilience.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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