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Improving Healthcare Supply Chain Resilience During Extreme Weather Events

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Abstract

Damage to coastal and inland communities in the United States from extreme weather events has increased dramatically in recent years and the decade of the 2010s was particularly harsh. These violent storms damage civil infrastructure systems, such as transportation, power, water and sewer, and communications, resulting in many people losing access to healthcare services. These breakdowns in the healthcare supply chain can be relatively minor, e.g., a pharmacy closed for a few hours, or life-threatening, e.g., when dialysis or radiation treatment for cancer is unavailable for days or weeks. In 2017, more than 1,500 deaths were attributed to delayed or interrupted healthcare in Puerto Rico following Hurricane Maria. This paper describes how damage to civil infrastructure from an extreme weather event can disrupt the delivery of critical healthcare services, how such disruptions impact those in need of services, and offer suggestions for improving the resilience of the healthcare supply chain.

Keywords: critical infrastructure, civic infrastructure, infrastructure systems, resilience, healthcare, supply chain, extreme weather, climate change, computer modeling

Background

In the aftermath of the 9/11 attacks, field research conducted in New York City by the Department of Industrial and Systems Engineering at Rensselaer Polytechnic Institute initiated a decades-long effort to develop the theoretical and conceptual basis underlying the failure and restoration of interdependent infrastructures and translate this work into decision-support tools that were readily accessible to the practitioner community. One of the outcomes of this effort was CRISIS, a

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computer-aided, decision-support model that maps the services provided by civil infrastructure to the performance of social infrastructure systems and optimizes the scheduled repair of damaged civil infrastructure based on stakeholder-determined priorities for the restoration of social infrastructure services that depend on the damaged civil systems (Loggins et al. 2019). During the development and testing of the model, it became apparent that the healthcare supply chain (and the people that depended on it) was particularly vulnerable to damage of civil infrastructures caused by extreme weather events, such as hurricanes.

This vulnerability typically manifests in the "last mile" in the delivery of healthcare goods and services: the actual provider-consumer interface. Pharmaceuticals and medical supplies are usually obtained at commercial pharmacies and services such as dialysis and oncological radiation treatment are usually obtained at outpatient centers that may or may not be associated with a hospital. The facilities that provide these services must be functional (i.e., not physically damaged and have supporting operative infrastructure, such as power, water supply, and communications) and accessible by both patients and healthcare personnel. This is a critical point. An otherwise fully functional facility that cannot be reached by patients or healthcare personnel due to road closures or other transportation disruptions provides no service. Understanding this interdependency between civil infrastructure and the social infrastructure of healthcare delivery is critical to maintaining the delivery of vital services during an extreme event such as a hurricane. This paper describes how damage to civil infrastructure from an extreme weather event can disrupt the delivery of critical healthcare services, how such disruptions impact those in need of services, and offer suggestions for improving the resilience of the healthcare supply chain.

Hurricanes and Their Impacts

Damage to coastal and inland communities in the United States from extreme weather events has increased dramatically in recent years; Superstorm Sandy in 2012 was the second costliest storm in US history, but was only a harbinger of what the decade was to bring. Hurricanes Matthew in 2016, Harvey, Irma, and Maria in 2017, and Florence and Michael in 2018 heavily impacted Texas, Florida, North and South Carolina, and Puerto Rico. Hurricanes Matthew, Harvey, and Florence dropped unprecedented amounts of rain on Texas and the Carolinas,[1] while Maria and Michael devastated Puerto Rico and northwestern Florida, respectively. These disasters have far-reaching effects on communities, including direct damage to homes, businesses, and government facilities; damage to civil infrastructure such as power, transportation, water and sewer service, and communications; and dis-

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[1] Hurricane Matthew dropped as much as 16.9 inches of rain in South Carolina and 18.95 in North Carolina. During Hurricane Florence, nearly three feet fell in Elizabethtown, North Carolina, Over 60 inches of rain was recorded in Nederland, Texas during Hurricane Harvey.

ruption in the delivery of social infrastructure services (Steinberg, Santella, and Zoli 2011).

Civil and Social Infrastructure in Modern Society

Conceptually, civil infrastructure systems can be considered to be networks of nodes and arcs with commodities (e.g., electric power, water, food, drugs) flowing from node to node along paths in the network. The arcs are the paths along which services flow between the nodes, such as roadways, power lines, or pipes. Nodes are where the commodity is produced or consumed or both. For example, in addition to being a supply node for water, a pumping station is also a demand point for both water and power. If a node does not receive all the services it requires, its service is degraded, ultimately to the point where it no longer functions. (If the electrical or water supply of the pumping station is disrupted, it cannot function.)

The services provided by civil infrastructure systems are needed to support almost every type of societal action. Simply stated, we cannot live the way we do without infrastructure; more accurately, we cannot live without the social infrastructure services it enables. The delivery of public safety, education, healthcare, and critical commercial services are all made possible by civil infrastructure. Table 1 summarizes the differing characteristics of civil and social infrastructure.

Table 1. Characteristics of civil versus social infrastructure systems

Civil Infrastructure (transportation, power, water, sewer, communications)	**Social Infrastructures** (public safety, critical commercial services, healthcare services)
Physical networks, normal operations have little need for human interaction	Services are provided by people, supported by physical structures
Services are autonomous and needed continuously	Services are requested on a discrete, as-needed basis and people are part of the system
Services move from supply to demand	Services can either move from supply to demand (e.g., police, fire) or move from supply to distribution points (e.g., pharmaceuticals, food)
Damage is to the network itself and has little or no effect on demand for services	Damage is to the facilities that support the system and can have a redistributive effect on demand levels for services
A disruption in services at an interdependent node can result in customers not receiving services	A disruption can result in customers not receiving services, in increases in demand for services, or in an increase in the cost to provide services

When civil infrastructure is damaged during an extreme weather event, critical social infrastructure, such as healthcare, public safety, and commercial services, is also disrupted. Breakdowns in the healthcare supply chain can be relatively minor, e.g., a pharmacy can be closed for a few hours, or life threatening to those needing continuous care, e.g., when dialysis or radiation treatment is unavailable for days or weeks. For example, during Hurricane Harvey in 2017, in eighteen counties in the Houston area, fewer than 75 percent of pharmacies were open (Hamm 2017) and more than 60 dialysis clinics operated by Fresenius Kidney Care in Houston and Corpus Christie were closed for some period of time (Loeper 2018). In Puerto Rico following Hurricane Maria, more than 1,500 deaths were attributed to delayed or interrupted healthcare (NEJM 2018). Murakami et al. (2015) find that "Patients with ESRD (end stage renal disease) on dialysis live in a complex socio-medical situation and are dependent on technology and infrastructure, such as transportation, electricity, and water, to sustain their lives. Interruptions of this infrastructure by natural disasters can result in devastating outcomes." Similar impacts have been noted for all of the major storms mentioned previously (see, for example, Grew et al. 2013; Lempert and Kopp 2013; Sharpe and Clennon 2019; Travia et al. 2019).

In addition to direct physical damage, these systems are also vulnerable to damage and disruption from the interdependencies that exist between the various systems and services and that can be quite complex (Rinaldi, Peerenboom, and Kelly 2001). Two examples illustrate this point. During Hurricane Matthew in 2016, the Southeastern Regional Medical Center in Lumberton, North Carolina was able to provide electrical power by means of emergency generators, but pumping stations for municipal water and waste water external to the hospital were flooded and unable to function. As a result, hospital operations were disrupted despite the availability of electric power. During Superstorm Sandy in 2012, although some service stations were fully operational, road closures resulted in tanker trucks not being able to resupply the stations after their pre-event supplies were depleted. Additionally, power and telecommunication failures at well-stocked filling stations made credit and debit card transactions impossible and limited purchases to cash or informal credit transactions. In system terms, hospitals and service stations are not stand-alone entities, but delivery points for healthcare and fuel and are dependent on other systems in order to be fully functional.

Implications for Healthcare

As previously noted, the focus of this paper is on the provider-consumer interface: the "last mile" in the delivery of healthcare goods and services. Because of the size and complexity of the healthcare delivery system, the discussion uses just two sectors as exemplars: prescription drugs and outpatient critical care services for kidney disease and cancer.

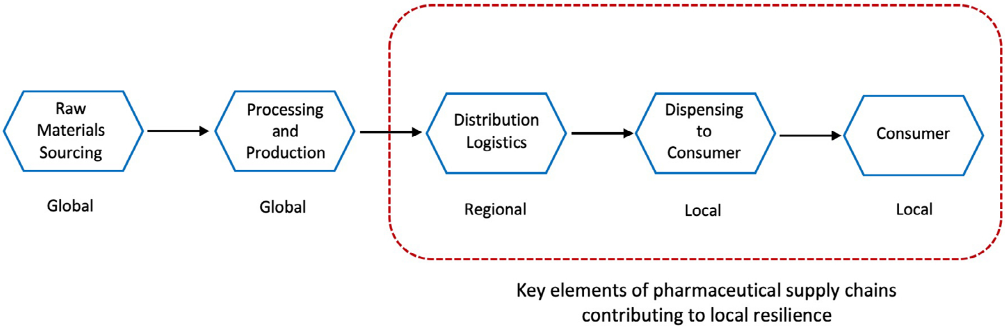

Figure 1. The Pharmaceutical Supply Chain

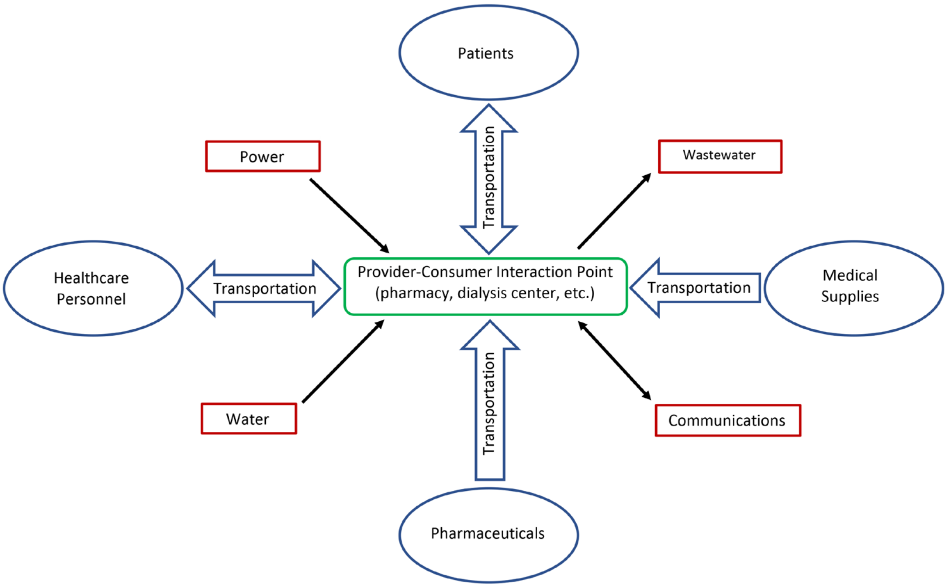

Figure 2. Schematic Model of Healthcare Service Delivery

Pharmaceuticals are typically obtained at commercial pharmacies and in 2015–2016, 45.8 percent of the U.S. population used one or more prescription drugs; the percentage climbed to 85 percent for those over the age of 60 (Martin et al. 2019). Pharmacies are also at the end of a just-in-time supply chain that stretches from the global sourcing of raw materials and manufacture to local retail sales or mail order delivery. Restocking from regional distribution centers occurs on a daily basis and often more frequently (See Figure 1).

More than 700,000 people in the US have end stage renal disease (ESRD) and the number of those with ESRD increases by about 20,000 cases each year (United States Renal Data System 2019). At the end of 2015, almost one-half million patients were receiving kidney dialysis treatment and, of these, 90 percent travel to dialysis facilities for their treatment (National Academies 2019a). About

650,000 patients annually receive chemotherapy at outpatient oncology clinics (CDC 2019) and Man et al. (2018) find that "Natural disasters cause substantial interruption to the provision of oncology care."

Figure 2 is a schematic that illustrates how the facilities that provide these services are dependent on their enabling civil infrastructures and how they must also be accessible by patients, service providers, and drug suppliers. An otherwise fully operational facility that cannot be reached by patients, healthcare personnel, or drug distributors due to road closures or other transportation disruptions provides no service.

Risk and the Delivery of Healthcare Services

Effective risk management can lead directly to enhanced resilience of healthcare delivery. Traditionally, the response to threats from various hazards has been to identify a "design basis event" such as a "100-year storm" that connotes the worst that is believed likely to occur given what is known from past experience. Short of abandoning the threatened area, efforts are then made either to prevent the event from occurring (not currently possible for extreme storm events) or designing systems (i.e., buildings, infrastructure, institutions) that are sufficiently robust to withstand its effects. Although it is compelling to believe that designing for some maximum probable event fully addresses the risk issue, history is littered with accounts of protective technologies that supposedly could not fail in theory but that failed spectacularly in practice. For example, the "unsinkable" Titanic and the "impregnable" Maginot Line are now metaphors for failure. Climate change and sea-level rise will further complicate planning for extreme weather events, as the past becomes a less and less reliable guide to the future because of the non-stationarity of the historical record[2] and brings more and more uncertainty into what we think we know about how the natural world behaves. Because of this uncertainty, risk-based scenario planning may be a more prudent approach than design-based thinking.

Risk can be thought of as the product of the probability (P) of a *hazard* occurring, the *exposure* (E) of the population or place to the hazard, and their *vulnerability* (V) to these effects, or R = P x E x V. Exposure refers to the presence of people, services, infrastructure, or other assets in places that could be adversely affected by extreme weather events. If people, critical services, and assets were not located in potentially dangerous settings, the risk would be negligible. Vulnerability refers to the likelihood that people, critical services, and assets will be adversely impacted by an extreme event should it occur. Exposure is a necessary,

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[2] Stationarity assumes that the statistical properties of climate extremes will be similar to those of the past. Non-stationarity assumes that they will vary substantially. This has the troubling result of "50-year" storm events occurring far more frequently and makes the supposed 50-year floodplain boundary a somewhat meaningless delimiter.

but not sufficient, element of the risk equation, because it is possible to be exposed but not vulnerable. For example, a strongly constructed and elevated beachfront home could be exposed to the high winds and storm surge of a hurricane but still survive their impacts. To be at risk from an extreme event, it is necessary to be both exposed and vulnerable.

Although not a precise mathematical formulation, the simple equation presented above has surprising explanatory power for effective risk management. For example, during a hurricane, the risk of losing access to dialysis services is far greater for people living in low-lying coastal areas than for those at higher elevations, because coastal populations are more exposed to lowland flooding and storm surge and vulnerable to transportation disruptions caused by that flooding. Even though the rich and poor may experience the same event, their risk differs markedly because the poor are far more exposed and vulnerable to the hazard's impacts. They tend to live in areas more prone to flooding, have fewer resources available to reinforce their homes or evacuate prior to the event, and often have less access to private vehicles in which to travel to obtain services; further, low-income neighborhoods are not typically the highest priority for the restoration of damaged infrastructure. A recent report by the National Academies (2019b) on urban flooding in the US included reports from workshops held in Baltimore, Houston, Chicago, and Phoenix, all of which noted the disparate impacts of flooding in these cities on low-income communities. The report notes, "This observation is supported by decades of research, which demonstrates that impacts from flooding tend to fall disproportionately on the most vulnerable and resource-constrained members of society ..."

Returning to the risk equation, the risk from a hurricane can theoretically be reduced by reducing one or more of the three factors that contribute to it: i.e., the occurrence of the hazard (P), the exposure (E) of people and places to the effects of the storm, and their vulnerability (V) to those effects. This translates into three sequential actions: avoid the hazard if possible, withstand its effects, and recover from its impacts.

Avoid the Hazard

At this time, extreme weather events cannot be prevented. The only practical way to avoid them is not to be there when one occurs. In the case of coastal and riverine areas, for example, building residences and critical service facilities outside possible inundation zones is perhaps the wisest choice, although certainly not a short-term option for the many people already living in flood-prone areas. However, as a longer term strategy, better identification and delineation of floodways and flood-prone areas, including the recognition of non-stationarity, and the implementation of appropriate land use planning and regulatory tools would lead to development patterns where less of the population, building stock, and supporting infrastructure would be at risk. New facilities and infrastructure would also benefit from this approach; as facilities age and major reconstruction becomes warranted, consideration must be given to relocating those facilities that could be moved to elevations above expected flood levels.

Withstand its Effects

Although it may prove too costly in the near term to reduce *exposure* by relocating existing development and infrastructure to safer ground, flood-protection works, such as levees and floodwalls, can be employed to reduce *vulnerability*, i.e., structures can be elevated and infrastructure systems made more robust. Building and design codes to improve hazard resistance have proven their effectiveness through countless major events, and designing and building for known hazards is an area for which the engineering community is well prepared. This also includes identifying roads and bridges that are subject to flooding and washout and taking the appropriate steps to reduce the likelihood of this occurring. There is little here that is not known: the operative question is whether there are sufficient resources, political will, and regulatory oversight to ensure that risk-appropriate designs, materials, and practices are employed.

Recover from its Impacts

Despite the best efforts to identify, avoid, and design and prepare for extreme weather events, they will continue to occur. How societies respond to and recover from these events depend, in large measure, on the degree to which they invest in planning, building, and funding the basic building blocks of a resilient society. This includes the identification of critical infrastructure and services, the locations of vulnerable populations and critical healthcare personnel, and the critical linkages between civil and social infrastructure systems. The prioritization for repair and restoration of damaged infrastructure systems should be informed by the relative vulnerabilities of those affected.

The Role of Computer Modeling

As noted at the beginning of this paper, the authors' interest in the civil infrastructure/healthcare nexus grew out of efforts to model the repair of damaged civil systems based on community-determined priorities for the restoration of social infrastructure services. The model shown in Figure 3 simulates the damage-disruption-recovery cycle for civil and social infrastructure and can be applied directly to healthcare services during an extreme weather event. A hypothetical storm can be chosen, infrastructure damage simulated, disruptions determined, and varying priorities assigned for the restoration of the damaged civil systems. CLARC , an artificial community of 500,000 residents was specifically developed to serve as a test bed for alternative restoration strategies and can be used to evaluate these alternatives (Little et al. 2019; Ni et al. 2019). The authors are currently in the process of enhancing the realism of CLARC by adding a complement of outpatient critical care facilities along with more socio-demographic data so that assumptions regarding changes in exposure, vulnerability, and restoration priorities can be tested and evaluated.

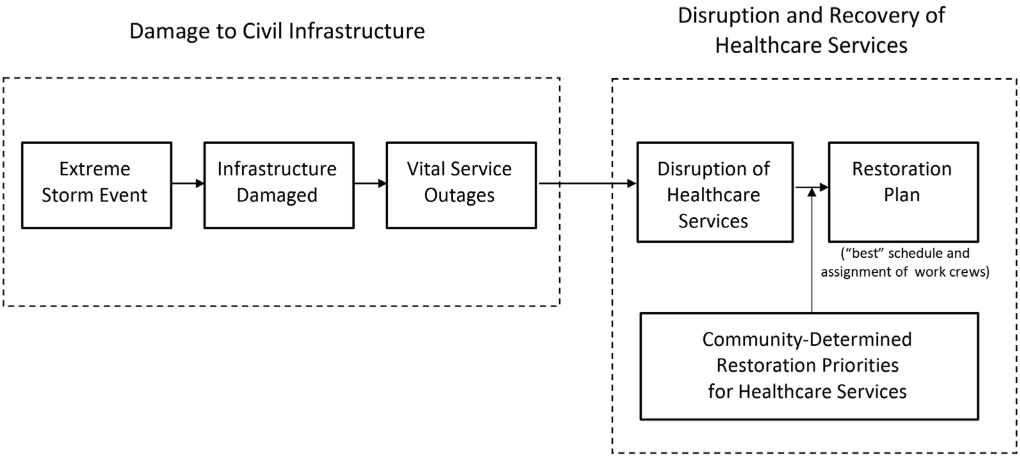

Figure 3. The Damage-Disruption-Recovery Cycle for
Civil Infrastructure and Healthcare Services

By their nature, extreme events are rare and unpredictable and if not unique, nearly so. As a result, it is difficult to develop and curate the institutional knowledge necessary to grasp the multiplicity of possible paths over which an event could unfold and respond optimally. One objective of the modeling effort is to provide a tool that can demonstrate how better collaboration during the restoration of critical infrastructure services can lead to significant improvements in the overall resilience of a community. Managers of critical services, emergency managers and responders, and community representatives can make use computer-aided decision-support tools to understand that joint, informed decisions can result in better overall outcomes than if the multiple actors involved just attempt to maximize their own organizational objectives.

Simulation modeling can enhance the understanding of a wide range of public and private officials and managers regarding the interdependencies that exist among infrastructure systems, the dependence of critical healthcare services on civil infrastructure, and the implications of alternative preparedness and response strategies on overall community resilience. With online capability, the model can network a full complement of public and private users at multiple sites in evaluating multiple scenarios with the ability to alter several parameters in a short space of time so that response capability to a wide range of possible events can be determined and many different (and sometimes novel) approaches to actual response and restoration procedures can be evaluated. This virtual planning approach could supplement existing "boots on the ground" exercises at much lower cost in time and money. Forearmed with such knowledge, communities would be far better prepared to face the growing challenge of maintaining access to critical healthcare services during extreme weather events.

Conclusions

This paper has attempted to integrate findings from two separate, but related, aspects of disaster research: the physical impacts of extreme storm events on civil infrastructure systems and the impacts of such extreme events on the delivery of healthcare services. We know a great deal about how infrastructure is damaged during hurricanes. At the same time, there are innumerable summaries of lessons learned by the medical community from past events. What has not been studied as extensively are the interdependent relationships between civil infrastructure and the healthcare supply chain and how changes on the infrastructure side could improve healthcare delivery. One of the reasons for this is that civil infrastructure is owned and operated by a mix of public and private sector organizations that may have vastly different cultures and organizational structures with each organization having its own set of goals for the restoration of service to its customers. They focus on their own operations far more than on how they fit into a bigger picture (Comfort 2002; Leavitt and Kiefer 2006; McGuire and Schneck 2010). Statewide emergency management organizations coordinate disaster response as best they can, but effective joint action by government and private service providers to prioritize response actions for community benefit cannot be assumed; such cooperation is discretionary, not legally mandated. During Hurricane Harvey, Fresenius Kidney Care acted on its own volition to ensure continuity of service at its clinics by pre-staging (and providing security for) generators, fuel, and potable water and took extraordinary measures to locate and transport patients in critical need of dialysis (Loeper 2018). Although such heroics are certainly laudable, we might wish to ask whether relying wholly on the private sector in these matters best serves society as a whole. Developing a better understanding of how all stakeholders can work to improve the resilience of the infrastructure/healthcare interface would be a good place to start.

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