Smart technologies and systems can improve disaster monitoring and threat assessment to strengthen cities' ability to predict and prepare for disaster impacts.

The Promise of Smart and Resilient Cities

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The need to equip cities with smart infrastructure systems that make them more sustainable, more prosperous, more resilient, and more equitable is a critical challenge of this generation. Rapid and often unplanned urbanization, the impacts of climate change, and aging infrastructure combine to increase the frequency and severity of impacts from natural disasters such as hurricanes, landslides, and floods.

According to the United Nations, approximately 55 percent of the world's population lives in cities, and this number is expected to increase to 60 percent by 2030 and 85 percent by 2100 (Gu et al. 2015). Cities need to find new and creative solutions to survive, adapt, and thrive. Smart technologies can enhance urban disaster resilience by significantly improving preparedness and the capacity to quickly recover from the impacts of natural hazards.

The Need for Resilience in Cities

More than half of the world's cities with a population of over 300,000 are at high risk of exposure to at least one natural disaster (Gu et al. 2015).

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Most losses associated with natural disasters occur near known hazards such as floodplains, hurricane-prone areas, and earthquake fault zones, but the impacts are felt disproportionately by cities. The 2010 Haiti earthquake (figure 1), which occurred in the densely populated city of Port-au-Prince, resulted in an estimated 230,000 deaths (DesRoches et al. 2011). In the United States, New Orleans, New York, and Houston were hard hit by Hurricanes Katrina (2005), Sandy (2012), and Harvey (2017).

The very features that make cities desirable places to live—population concentration, physical infrastructure, and, often, location near water—also put them at high risk of significant impacts from natural hazards. And these risks are increasing, because of urban growth and complexity as well as uncertainty associated with climate change.

The concept of resilience has been explored in numerous fields, from medicine and psychology to materials science and economics. In this paper we use the following definition: "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NRC 2012, p. 16).

The impacts of numerous recent natural disasters show that inadequate infrastructure systems make it increasingly difficult for cities to respond to severe weather events. In the face of these and other natural events, cities across the country recognize the importance of replacing aging water, power, telecommunication, and transportation systems with smarter, more effective and efficient systems.

Urban Systems: Physical, Environmental, Social

Cities are centers of population with interacting and interdependent physical, environmental, and social systems. Physical systems include extensive infrastructure networks for water, storm water, and sewage; roadways, bridges, tunnels, and other elements of transportation; electricity, gas, and other types of power generation; wireless, Wi-Fi, and wireline communications; and the commercial, residential, and industrial built environment. This short list of urban physical systems indicates the complexity with which they must interact, interdepend, and integrate to provide necessary services.

Environmental systems include ground-level, botanical systems such as forests, wetlands, mangroves, and farms; the water systems of streams, rivers, lakes, and oceans; animal systems such as insects, mammals, fish, birds, and other creatures; and climate—air temperature, humidity, pollutants, pollen count, and the like. These different systems are directly linked to a city's resilience and their preservation is an important component of urban resilience strategies.

Finally, cities are social systems. Their citizens live, work, commute, and seek leisure using the physical infrastructure systems, and they depend on the natural systems for food, fresh water, and clean air. Cities cannot thrive without the people in them, and people cannot thrive without well-functioning, resilient physical systems and healthy, abundant environmental systems.

FIGURE 1 (left) The Haitian National Palace after the 2010 earthquake, which killed over 230,000 people and is considered one of the deadliest natural disasters in the Western Hemisphere. Photo by Reginald DesRoches. (right) Homes near Addicks Reservoir, west of Houston, after Hurricane Harvey, the costliest natural disaster in the United States in 2017. Photo by Philip Bedient used with permission.

System Interconnectivity

Until recently human systems and their interactions with physical and environmental systems lacked interconnectivity. Now, driven by the demands of rapid urbanization, increasing broadband connectivity/availability, and the reduced cost of sensors, many cities are investing in smart technologies and systems that establish interconnectivity within and between social, physical, and environmental systems.

Interconnectivity enables new forms of interaction between humans and urban physical systems, such as digital delivery of services, real-time feedback on traffic and transportation system performance, and smart homes that can use machine learning techniques to adapt to occupant needs. It is also making it possible to introduce sensor infrastructure in natural systems to develop a real-time understanding of important changes in environmental systems.

Strengthening the robustness of smart technologies and systems, and optimizing interactions within and across social, physical, and environmental systems, will make cities more efficient, more sustainable, more equitable, and, ultimately, more resilient. Investment in and deployment of sensor-connected technologies and systems to create smart cities can benefit all four phases of disaster management: mitigation, preparedness, response, and recovery.

Smart Cities and the Resilience Imperative

There is no formal standardized definition of a smart city, but it involves deploying technologies and systems to interconnect citizens and improve services with the goal of enhancing urban system efficiency.

A report by the International Telecommunication Union (2014, p. 4) defines a smart city as "an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects." And a report by the UN Commission on Science and Technology for Development (2016) sets out principles for the design and development of smart cities, spanning buildings, mobility, energy, water, waste management, health, and digital layers.

Notably absent from these definitions is the impact of smart systems and technologies on urban resilience. Most cities are characterized by sprawl, rapid urbanization, poorly planned and managed development, inadequate and fragile infrastructure, and degraded ecosystems, all of which contribute to low resilience and poor capability to cope in disasters. Unfortunately, data suggest that disasters may be increasing in frequency and severity, and their impacts are taking a devastating toll on many cities.

Because a well-functioning city depends on the integration, interdependent functioning, and interactive capabilities of complicated infrastructure systems and services, strengthening their functioning will increase resilience and improve disaster management. Timely emergency communications, for example, are critical, but current systems fall short in terms of crisis detection, alerts, and assistance (NASEM 2017).

Developing Smart Resilience

Smart technologies and systems can be used to create a smart "digital twin" city for monitoring, assessment, prediction, and, ultimately, adaptation across systems (Mohammadi and Taylor 2017) to improve disaster resilience.

Creation of a smart "digital twin" city enables monitoring, assessment, prediction, and adaptation across systems.

The rapid expansion of existing cities and the creation of entirely new cities (e.g., Masdar in the United Arab Emirates [www.masdar.ae] and Xiongan in China; Phillips 2017) offer the opportunity to make cities disaster resilient by design. Urban planning can substantially improve communities' preparedness and capacity to recover by using sensors in physical and environmental systems to diagnose, predict, and adapt. In addition, smart growth strategies such as flexible land use policies, targeted public investment, and community engagement in decision making can help communities recover more quickly from a disaster, rebuild according to a shared community vision, and be better prepared for a future event.

For cities and urban regions, the concept of resilience moves away from traditional risk assessment, which generally looks at specific hazards, to encompass a range of possible disruptive events. The focus is on enhancing system performance in the face of multiple hazards rather than preventing or mitigating losses due to a specific event. Resilience planning requires a systems-level approach, based on the notion that cities are "systems of systems," that combines a city's physical aspects with considerations of human behavior in the context of economic, physical, and social disruption.

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The Multidisciplinary Center for Earthquake Engineering Research developed a framework that defines resilient systems and communities as having the following interconnected properties (Bruneau et al. 2003):

- *Robustness:* The ability to withstand a given level of stress or demand without degradation or loss of function
- *Redundancy:* The extent to which elements and components of a system are substitutable to satisfy functional requirements in the event of a disruption
- *Resourcefulness:* Allocation of the appropriate budget and capacity to establish priorities and mobilize resources after an extreme event
- *Rapidity:* The ability to meet priorities and achieve goals in a timely manner in order to limit losses.

Smart Robustness

In the context of resilience, robustness reflects the ability of physical, social, and environmental systems to withstand significant degradation from disasters. Physical infrastructure systems that are designed to modern code, are retrofitted, or use advanced materials and design concepts, including sensors and "green" methods, tend to be more robust.

Advances in sensor technologies and wireless communications have led to the development and application of monitoring systems to assess the real-time condition of infrastructure, from buried pipelines to dams, bridges, and power and telecommunication systems (Lynch and Loh 2006). Such monitoring systems are useful for tracking the behavior of structures during forced vibration or natural exciting (e.g., wind, live loading). They can also provide information to help cities (1) determine whether changes are needed in the material and/or geometric properties of a structural system, including changes to the system connectivity, and (2), more broadly, make both real-time decisions about infrastructure safety and long-term investment decisions. Sensor-connected infrastructure systems are critical in identifying potential vulnerabilities before catastrophic failure and enhancing infrastructure robustness.

Robustness also requires the security of financial and other transactions. Blockchain is a new smart technology that increases the reliability and transparency of transactions. It can ensure the security of transactions both during and after disasters, when restoring normal daily life—including the ability to make routine purchases and pay bills—is critical to a well-functioning city.

The robustness of an urban environmental system can be improved by passive solutions such as "green" water retention in coastal cities (e.g., Buffalo Bayou Park in Houston). These can be coupled with active smart solutions that integrate sensors to monitor the performance and danger levels of hurricanes and floods, such as the rain gauge sensors in the Houston area bayous that were pivotal in providing flood warning during and after Hurricane Harvey, whose impacts could have been even worse.[1]

Smart Redundancy

Redundancy refers to the extent to which alternatives can fulfill the functions of disrupted systems. For physical systems, alternative transportation routes or backup electricity can provide system redundancy.

Electricity is necessary for many of a city's essential physical system services, such as water, power, communications, and public transportation. These functions are particularly critical in the minutes, days, and weeks after a natural disaster.

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[1] A county flood warning system is posted online through the interactive mapping tools of the Harris County Flood Control District (https://www.hcfcd.org/interactive-mapping-tools/harris-county-flood-warning-system/).

Electrical power networks have become large and highly complex technical systems, geographically distributed, and with varying degrees of connectivity, often requiring constant real-time operation to manage supply and varying demand. Natural disasters can cause damage to a wide geographic area of an electricity system, leading to outages that can last several weeks. For example, over 8 million people along the East Coast were without power after Superstorm Sandy, and many homes and businesses did not return to normal operations for weeks. The cascading effects of power outages on critical systems have been shown to exacerbate the impacts of natural disasters (González et al. 2017; Wu and Dueñas-Osorio 2013).

Smart grid technologies can improve the resilience of cities by shortening the length of power outages and thus significantly reducing the scale and severity of disaster impacts. For example, microgrids can automatically detach from the greater grid and continue to deliver power to affected customers. This also enables utilities to deploy resources to damaged areas of the grid to make repairs and restore service. Smart grid technologies thus provide redundancy and reconfigurability.

Cities also are investing in green infrastructure for redundant systems. For example, alternatives to large storm water drainage projects, such as water retention parks, meet environmental needs while providing a place for storm water to collect during severe flooding. Atlanta's Historic Fourth Ward Park (www.h4wpc.org/) was completed in 2011 at a cost of $15 million less than the traditional storm water tunnel system. Designed to capture storm water runoff in an area of the city historically plagued by flooding, it "increases the sewer capacity, reduces the burden on aging city infrastructure, and minimizes downstream flooding and property damage."[2] It is credited with averting substantial flooding in Atlanta during Hurricane Irma when 3½" of rain fell over a short period of time—the park captured storm water from a 350-acre area of the city (Sears 2017).

For the urban social system, redundancy can be enabled through smartphone sharing applications, such as Lyft or Uber for ride sharing, Waze or Google Maps for traffic routing, and Airbnb for accommodations. Traffic routing applications crowd-sense information from users about roadway obstructions and delays and can provide realistic estimates of travel times. In times of significant traffic perturbations, such as evacuations, these applications identify lesser-known and less-trafficked alternatives. Ride and accommodation sharing applications post information about open seats in a vehicle and rooms in a home. When Hurricane Irma struck in September 2017, Airbnb launched a disaster response program in Florida that enabled providers to offer free rooms to displaced citizens, and Uber capped fares in South Florida, offering hundreds of thousands of dollars in free rides to communities in need (Griswold 2017).

[2] The park's features are described at https://beltline.org/parks/historic-fourth-ward-park/.

FIGURE 2 A smart mobile sensor used to assess the integrity of a bridge. Photo by Yang Wang used with permission.

Smart Resourcefulness

Resourcefulness reflects the availability of supplies, repair crews, and other resources to restore functionality to damaged systems. The 2010 Haiti earthquake and Hurricane Irma (2017) in Puerto Rico are clear examples of how lack of resources, supplies, and personnel can severely hamper the ability to recover from a disaster (DesRoches et al. 2011).

Advances in robotics, cyberphysical systems, and artificial intelligence support resourcefulness through the development of mobile sensors that can be used after a disaster to determine the safety of buildings, bridges, and other infrastructure. A network of such sensors can autonomously or semiautonomously move sensors around a structure to assess it at various locations (Zhu et al. 2010). Small crawling or flying robots (figure 2) have shown great promise for infrastructure inspection, particularly on remote sections of a bridge (Wang et al. 2017).

Smart resourcefulness has recently emerged in the social system during natural disasters, leading to fundamental changes in postdisaster response. During and

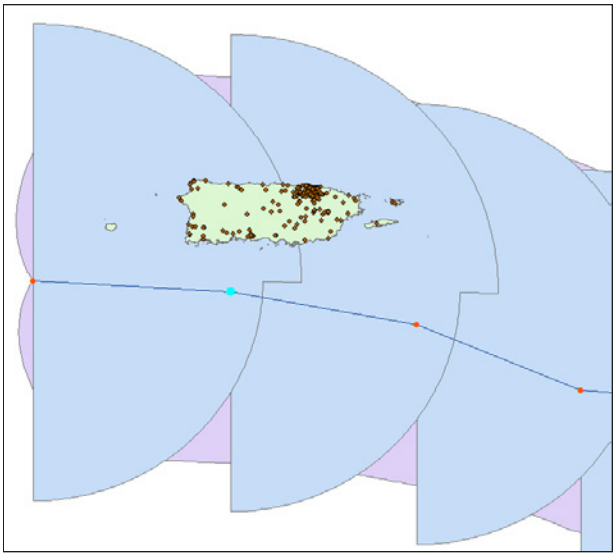

FIGURE 3 Image of 622 geotagged microblog postings in Puerto Rico during Tropical Storm Erica on August 28, 2015, with clustered postings in San Juan on the northeastern coast. The blue line south of the island is the storm's centerline, and the blue and red dots denote the tracking area using GIS data from the National Hurricane Center.

immediately after Hurricane Harvey, emergency lines in Houston were jammed and citizens in need of help were not able to reach emergency responders. Some users turned to geotagged social media microblogs on platforms such as Twitter to indicate the nature of their emergency and their location. Figure 3 illustrates geotagged social media postings during Tropical Storm Erica in August 2015 in Puerto Rico. This information provides first responders with an alternate channel to locate citizens in crisis. Other applications and methods are under development to use social media postings to assist first responders (e.g., Wang and Taylor 2015, 2018a).

Cities do not typically have the land space to support the scale of farming required to meet residents' daily food consumption needs, but a number of cities are including urban farming approaches in their smart resilience plans. The vulnerability of cities to sudden food shortages after a natural disaster was exposed in New York after Superstorm Sandy, when the city experienced persistent power outages, lack of fuel, and closed tunnels, all of which challenged food supplies (Mahanta 2013). High-tech urban farming companies can automate many aspects of the growing and harvesting process, and they can grow fruits and vegetables in vertical stacks indoors with no soil and as much as 95 percent less water compared to traditional farming (Marks 2014). In addition to the sustainability aspect of locally harvested food, if food supply lines are disrupted the availability of food nearby may be critical to survival.

Smart Rapidity

Rapidity concerns the ability to quickly restore system functions.

Crowd-sensing applications are accelerating the ability to assess natural disasters through physical, social, and environmental systems (Conrado et al. 2016). The US Geological Survey maintains a "Did You Feel It" website[3] that allows citizens to indicate the degree to which they feel an earthquake, and the data have been shown to correlate with actual earthquake-induced ground motion (Atkinson and Wald 2007). Applications are being extended to recognize sentiment of social media microblog postings, with a significant spatiotemporal correlation between the sentiment level of urban residents and earthquake intensity (Wang and Taylor 2018b). Such applications provide first responders with near real-time information about emergent crises to more rapidly deploy emergency services to areas of need in a city.

Social media data are also being used to enable rapid assessments of danger over large areas in physical urban infrastructure, serving as a new and critical resource for rapid attention and recovery in natural disasters (Kryvasheyeu et al. 2016).

Conclusions

The integration of smart technologies and systems with a city's physical, environmental, and social systems can enhance efficiency, sustainability, and disaster resilience by improving robustness, redundancy, resourcefulness, and rapidity. Emergency response and hazard mitigation officials also need to be involved in smart city planning efforts.

Smart technologies and systems can improve disaster monitoring and risk assessment, thereby strengthening cities' ability to predict and prepare for disaster impacts. They can also enhance the ability to respond to citizen concerns, monitor infrastructure and environments in crisis, and address associated safety issues. Finally, they can support the uninterrupted use or rapid restoration of critical services.

[3] https://earthquake.usgs.gov/data/dyfi/

The promise of smart and resilient cities will be fulfilled only when cities broaden their strategic plans to incorporate smart technology and system implementation in order to increase the robustness, redundancy, resourcefulness, and rapidity of their disaster planning, response, and recovery.

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