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Disaster Prevention and Resilience

Review

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The role of social institutions in community resilience following extreme natural hazard events

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Abstract
Social institutions such as hospitals and schools are among the main pillars of community stability. A drop in the functionality of hospitals and schools is likely to have short-term and long-term effects on a community, including a reduction in medical interventions, an increase in unschooled children, and population outmigration in search of essential social services. However, comprehensive community resilience models that consider the role played by social institutions in community stability following natural disasters are scarce at the present time. This paper provides a literature review and critical appraisal of previous studies on the resilience of hospital and school systems and their impact on community well-being. The review encompasses existing resilience models for single hospitals and schools, their role when connected with other hospitals and schools in a network, their reliance on each other as interdependent systems, and their role in community resilience and stability. Different mitigation strategies and policies to enhance hospital and school systems' resilience after extreme natural hazards are also summarized. The paper concludes with a series of recommendations to improve current models for social institutions, enhance the connection between existing hospital and school resilience models and community resilience frameworks, and develop social stability indices that policymakers can use in preparing and mitigating future extreme events.

Keywords: Community resilience, hazard, hospitals, public health and welfare, risk mitigation, schools

INTRODUCTION

The intensity and frequency of natural hazards have been on the rise due to urban growth and a changing climate[1]. Severe or extreme natural hazards can cause significant damage to the physical infrastructure of communities and result in substantial socio-economic consequences. In the year 2021 alone, the earthquake in Haiti caused 2,248 death, super typhoon Rai in the Philippines killed 375, and floods and landslides in China killed at least 302[2]. The direct economic cost worldwide due to natural disasters in 2021 reached $343 Billion in U.S. dollars[3], while this cost in the United States exceeded $145 Billion in the same year[4]. The ability of communities to withstand and recover from natural disasters has been the focus of many national and international organizations, and decision-makers have adopted numerous different strategic plans and policies to quantify and enhance community resilience[5,6]. For instance, the National Institute of Standards and Technology (NIST) has provided a community resilience planning guide for buildings and infrastructure[7,8], and has been funding an effort to develop a computational platform (IN-CORE) led by the Center of Risk-Based Community Resilience, which can be used to evaluate community resilience[9]. Similarly, the U.S. Environmental Protection Agency (EPA) has introduced different tools to improve the community's resilience to different disasters[10], which are based on resilience screening indices such as those introduced by Summer *et al.*[11-13]. Recently, the Federal Emergency Management Agency (FEMA) introduced a Resilience Analysis and Planning Tool (RAPT)[14] to assess potential challenges to community resilience in the US. Natural hazard events impact social institutions within communities and not only cause damage to their facilities but also disrupt the essential services they provide. The catastrophic impacts resulting from a shortage of healthcare and educational services[15-19] have motivated guidelines and studies to provide extensive retrofitting and mitigation strategies to enhance the safety of existing and new hospital and school buildings[20-23]. Other studies pertaining to healthcare systems have established a basis for assessing the functionality of hospitals following earthquake events[24-26], modeling the surge capacity of hospitals[27], developing real-time hospital bed tracking/monitoring systems[28], and modeling the interaction between hospitals as a network[29]. Previous studies of educational systems following extreme events are more limited and have focused on measuring the performance of schools during normal operating conditions[30,31] or during and after earthquakes[32-34]. One study introduced a model that could be used to predict school functionality after extreme natural disasters[35]. Interdependencies between hospitals and schools have been investigated using empirical approaches[36] and agent-based modeling[37]. However, these studies stopped short of investigating the impact of the different social institutions on the community's overall resilience.

Community resilience is defined by its ability to prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions[5,7]. Social institutions can encompass healthcare, education, community services organizations, and religious and cultural organizations[38]. However, the essential roles that hospitals and schools play after natural disasters in most communities place them at the forefront of services to be recovered after natural disasters. The resilience of these social institutions can be defined as their ability to bounce back after an event and provide a level of service similar to that prior to an event[37]. The resilience of a hospital, the healthcare system's main component, can be defined as its ability to withstand, absorb, and respond to disasters while maintaining critical functions before recovering to its original state[39]. Healthcare system resilience can be described as the ability of a network of connected hospitals to absorb any sudden surge in demand[40]. Similarly, the educational system's resilience can be measured as the ability of schools to absorb and/or manage disaster effects and return to the previous function using available resources[35,41]. Different indicators have been proposed to measure the resilience of social institutions based on the services they provide, such as staffed hospital beds and waiting time for the healthcare system[29], school seats, and education quality for the education system[35]. These indicators were then integrated into a more holistic community resilience index[36,42].

This paper introduces a multi-disciplinary appraisal of the literature on the resilience of social institutions through a review of current studies on the resilience of hospitals and schools. First, the importance of hospitals and schools in ensuring resilient communities is summarized. Next, a literature review of functionality, recovery, and resilience models for social institutions and the developed tools and metrics are reviewed. The paper concludes with a discussion of critical gaps and research needs to enable and improve social institutions' resilience assessment and assurance.

BETTER HEALTHCARE AND EDUCATION FOR RESILIENT COMMUNITY

Previous disaster events have highlighted the vulnerability of hospitals and schools[43-45]. For example, the 1989 Loma Prieta earthquake in California damaged two hospitals[46] and severely damaged three schools[47]. The 1995 Kobe earthquake in Japan damaged approximately 4,500 educational facilities[21]. The 2008 Sichuan earthquake in China caused the collapse of many hospitals and more than 10,000 schools[48,49]. Other natural disasters, such as the 2018 Camp Fire in Paradise, CA, destroyed the only hospital in Paradise and severely damaged buildings at three schools out of the 13 schools[50]. Hurricane Katrina in New Orleans severely impacted 11 hospitals[51] and completely damaged 110 out of 126 public schools[52]. During the 2011 Tohoku Tsunami in Japan, more than 300 hospitals experienced building damage, and 6,284 public schools[53] were damaged. The total number of people who have been injured due to natural disasters worldwide between 2003 and 2019 and the distribution of natural disaster-related injuries are shown in Figure 1A.

Disaster events can also indirectly impact hospitals and schools by increasing the demand on hospitals and forcing school closure[37]. For instance, major earthquakes such as Loma Prieta, Kobe, and Sichuan resulted in 2,435, 35,000, and 370,000 injuries, respectively[47,48,56]. This surge in the number of injuries in a short time period can increase the demand on hospitals immensely[46], reducing their ability to provide essential medical services to all patients and/or significantly reducing the quality of the services provided. On the other hand, damage to the community housing can cause death and injuries to school staff and students[48], which can significantly reduce staff availability, increase chronic absenteeism of students, and force schools to close, which disrupts the education process[19]. Significant disasters can also increase post-traumatic stress for hospital and school staff and impact schoolchildren's perceptions of safety, security, and normalcy[57]. Natural disasters and bad weather are responsible, on average, for about 93% of the yearly unplanned school closures in the US[58]. The total number of school closure days due to natural disasters in California between 2003 and 2019 is displayed in Figure 1B.

Maintaining the functionality of hospitals and schools after disasters is vital, not only because of the essential services they provide to the community but also because they are often used as emergency operation centers for communities after disasters[59]. Hospitals also help protect and preserve patient records and ensure medical services for low-income, underserved, and uninsured populations. Schools are commonly used as temporary shelters[60] and community recovery centers[22]. Furthermore, they are critical for the recovery of the community as they provide a sense of normalcy, routine, and belonging for not only school children but also families[61,62]. Recent studies have shown that exposure to disasters can have catastrophic impacts on school children's developmental and behavioral resilience[63-65]. In addition, stress resulting from exposure to disastrous events can cause substantial deterioration in their mental health over time[61].

Healthcare systems

The proper functioning of healthcare systems hinges on the availability of various elements, including personnel (e.g., physicians, nurses, administrative staff, and volunteers), hospital buildings (e.g., inpatient

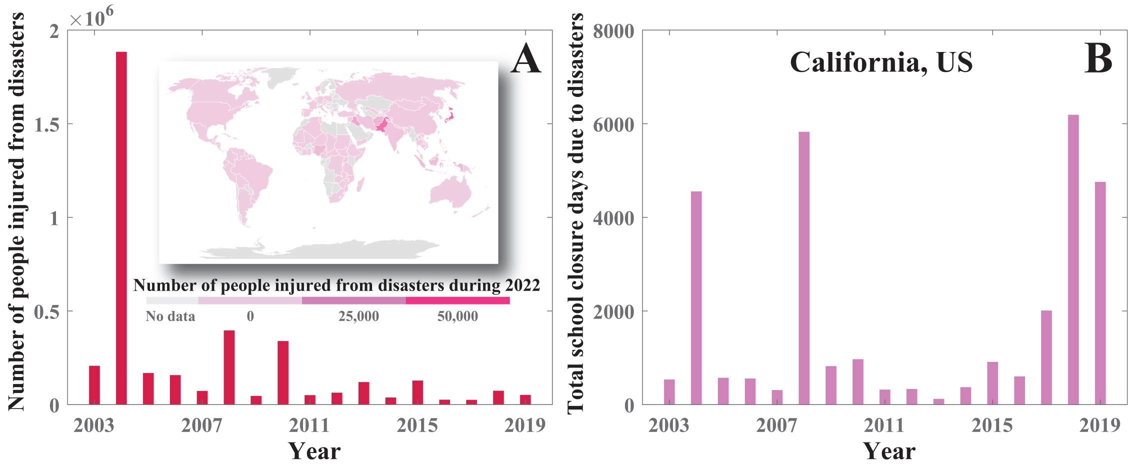

Figure 1. Impact of natural disasters on healthcare and educational systems: (A) The yearly total number of disasters-related casualties in the world, showing the spatial distribution of the casualties per country for the year 2022[54]; and (B) the yearly total number of school closure days in California, US[55].

and emergency rooms, surgical units, and intensive care units), and supplies (e.g., medical supplies, surgical supplies, food supplies, and other supplies). Hospitals face many challenges resulting from natural disasters. These challenges can be classified into two major classes: (a) challenges related to the reduction in hospital capacity[50]; and (b) challenges related to an increase in demand for hospital services[66]. Hospitals utilize different sets of mitigation strategies to tackle these challenges. These strategies are typically listed in each hospital's emergency plan, developed to identify the most critical hazards for each hospital and how best to respond to those hazards[67]. These strategies are based on lessons learned from previous events, training and exercises, and emergency program reviews[68].

The capacity of hospitals can be reduced after disasters due to staff casualty[69], damage to hospital buildings[70], and distribution of supplies[71]. Because healthcare facilities are highly dependent on other community buildings and infrastructure[36], a reduction in the capacity of hospitals can result from (a) indirect impacts such as staff outmigration due to damage to their housing; (b) delay in ambulance response due to road damage[72]; and (c) delay in response due to water or power outages[16]. To improve the performance of the hospitals and maintain their capability to provide medical services to the highest number of patients in disasters, hospitals apply different mitigation strategies before, during, and after disasters. Hospitals focus on surge capacity, which allows them to have adequate staff, space, and supplies to provide sufficient medical services to meet the immediate needs of an influx of patients following different extreme events[73]. This surge capacity is one of the most important components of hospital and the local health departments preparedness and emergency planning to overcome the sudden increase in patient surges after natural or man-made hazards[74]. Hospital utilization rates are carefully monitored to ensure their ability to provide immediate surge capacity[28]. Based on modern standards, hospitals are designed to withstand higher levels of natural disasters and retain functionality following such events compared to other community buildings[75]. To ensure the continuation of hospitals' main services after disasters, hospitals are provided with backup systems to temporarily replace utilities such as water, power, telecommunication, wastewater, and drinking water[71], which are recommended by FEMA 577[76] to maintain the hospital for at least four days after disasters. However, only a limited number of hospitals in the US are provided with redundant sources of essential utility services.

Hospitals can utilize different approaches to maintain their medical services during and after disasters while avoiding being overwhelmed with patients. These approaches include using reverse triage, where non-acute patients are discharged early from hospitals[77], or applying various types of patient triage, where most of the resources are directed to save the highest number of patients[78,79]. Hospital staff can reduce patients' mean length of stay[72,73] and the patient treatment time. Hospitals can reduce their demand by transferring the additional demand to other facilities. Even though patient transfer usually is efficient, mutual agreements between hospitals are needed to transfer medical records to facilitate patient treatment[71]. Hospitals can expand their capacity by using backup spaces and/or utilizing non-acute facilities. To overcome the staff shortage, hospitals can borrow staff from other hospitals through voluntary or structured processes and/or voluntarily assign additional work hours for the existing staff to cover any staff shortage. Applying these strategies can impact patient outcomes and, in some cases, increase healthcare disparities among segments of the population, some of which may be more vulnerable than others[80]. Therefore, they need to be well-managed and are supposed to be limited to the patient surge time after disasters. While these mitigation strategies are critical to enhancing the functionality and resilience of healthcare facilities, they may not be sufficient in all cases. Many healthcare facilities damaged during previous natural hazard events were forced to reduce their capacity and evacuate their patients.

Educational systems

Various elements are critical for providing adequate educational services to children. These elements include personnel (e.g., teachers, administrations, volunteers, and regulators), school buildings (e.g., classrooms, laboratories, and athletic facilities), and supplies (e.g., instructional supplies, administrative supplies, and janitorial-engineering supplies). School buildings play a major role in providing education services; damage due to natural disasters may significantly diminish these services and may force many schools to close. Consequently, student learning can be delayed[81], and families can be forced to either do homeschooling or out-migrate to educate their children. Schools apply different strategies to mitigate the impacts of disasters on education services. While school districts centrally manage public schools' strategies, private schools' decisions are made independently. Approximately 90% of students in the US are enrolled in public schools[82]. Therefore, ensuring the continuation of public schools after disasters can be prioritized by public policy.

The impact on schools during and following extreme events includes damage to their structural systems, non-structural components and finishes, and contents[83,84]. In addition, disasters might lead to the outmigration of school staff as an indirect consequence of damage to their housing and/or reduction in essential community services[85]. School bus transportation services can be disturbed after disasters because of damage to the transportation network and school buses and a shortage of bus drivers[85]. Schools depend on community utilities to provide them with water, power, wastewater, and telecommunication services. These utilities can be disturbed after disasters, which can hinder the school's operation. Food, educational materials, and other supplies can also be damaged during disasters[35]. Resupplying schools can be challenging due to damage to the transportation network and supply shortages due to supply chain disturbance that can result from the disaster. To ensure the continuation of educational services at public schools after disasters, school districts apply different mitigation strategies and policies that ensure student and staff safety during disasters and ensure expeditious recovery of educational services. Different guidelines have been introduced to enhance the performance of schools during natural hazards, such as FEMA P-1000[43], which provides operational guidance to help schools to prepare and properly respond, recover, and mitigate future natural hazards. Other guidelines have been focused on school safety during terrorist attacks and shootings[84]. Different programs have been developed to assist developing countries during crises to restore and continue education services[86,87]. While these mitigation strategies are critical to enhancing the functionality and resilience of schools, they have proven insufficient, and many schools are still suffering a major drop in their functionality after major natural hazard events[88].

A safe and rapid resumption of school services is vital for ensuring a stable community support system for children, particularly because schools offer important programs and resources such as meals and counselors[89]. In addition, the role played by the classroom environment and school staff to help students emotionally recover from disasters and traumatic events is critical to relieving their stress[90]. Therefore, school districts commonly work with community decision-makers to facilitate the recovery of school buildings using local, state, and federal funds. Different agencies in the US support school recovery after disasters, such as the FEMA's Public Assistance program[91] and the Department of Education's Immediate Aid to Restart School Operations (Restart) program[92]. Allocation of sufficient repair resources to restore school buildings is essential for the quick recovery of schools after disasters, contributing significantly to the community's overall resilience and stability. Reopening damaged schools after disasters is a complicated process, where the school districts, school administrators, building departments, police and fire departments, and community leaders contribute to the decision-making process to ensure the safety of the students and staff[85]. To reduce the impact of disasters on school children and minimize the reduction in student performance, school administrations typically work with families to find alternatives to continue their children's education, including homeschooling[93], remote learning, or hybrid learning techniques[94]. Even though these approaches are helpful, recent studies have shown that they negatively impact student learning progress[81].

In addition to their role in education, schools can also be used as recovery coordination centers, temporary community shelters, and centers for community disaster relief[43,60,95]. However, using schools as shelters or community centers needs to be limited to school breaks. A recent study investigated the functionality of schools as community shelters, considering the time at which the disaster occurs, space availability within the school facility, and safety provided by the school building[35].

Collective importance of hospitals and schools

US healthcare spending represented 19.7% of the nation's gross domestic product in 2020[96], and more than 10% of the US population is admitted to hospitals annually[97]. On the other hand, expenditures for K-12 public schools in the US denoted 6.1% of the nation's gross domestic product in 2020[98] and provided educational services for about 49.4 million students[99]. Therefore, the services provided by healthcare and educational facilities are essential to many US residents. Hospitals and schools are considered hubs of a healthy community, offering services that improve residents' health, welfare, and economic mobility[100], especially after hazards. For instance, maintaining good health and quality education are among the United Nations' sustainable development goals in 2030[101] and *UNICEF*'s New Strategic Plan[102]. The National Institute for Standards and Technology (*NIST*) included them as essential institutions for providing social services and stability within a community[8].

Hospitals and schools impact each other and the community's resilience and stability of a community following a natural disaster[37]. In a previous study, an interdependency value between different infrastructures was assigned, including hospitals and schools, based on the type of failure and importance factor that represents one infrastructure's significance to others' functionality[36]. That study indicated that the total loss of healthcare system functionality might lead to a 30% reduction in education functionality. In comparison, a complete loss of educational functionality may cause a 60% decline in the healthcare system functionality. In a more recent study[37], an agent-based model was used to simulate interdependencies between healthcare and educational networks more accurately through a representation of the different components governing their behavior, including hospitals, schools, school districts, patients, hospital staff, students and school staff, as well as supporting infrastructure. The interdependency of each facility, either hospital or school, is a function of the spatial relation of the facilities as well as the level of connectivity between the users and staff of the hospitals and schools. In contrast to Ref.[28], the more recent study revealed a higher degree of interdependency between hospitals and schools: a complete loss of healthcare network functionality was shown to reduce the education functionality by 47%, while a complete loss of education functionality was shown to decrease healthcare functionality by 43%. The importance of schools and hospitals to public welfare was also emphasized by defining a social services stability index developed by Hassan and Mahmoud[37] to measure the influence of hospitals and school services on the stability of the community's residents. However, additional studies are needed to measure the social stability of communities following disasters. Additionally, more investigations into the role played by hospitals and schools in community resilience are essential to fully understand their contribution to reducing population outmigration and other socio-economic consequences.

Initiatives for resilient hospitals and schools

Enhancing the resilience of social institutions within communities is at the forefront of many recent initiatives by international, federal, and state agencies. Reducing the direct and indirect losses resulting from disastrous hazard events and ensuring the continuation of the services provided by these institutions are now among communities' main resilience goals[7,8]. This section discusses the different initiatives introduced to enhance the resistance of hospitals and schools to natural disasters. The main goal of these initiatives is to support the functionality, recovery, and resilience of the hospitals and schools after major events, orchestrated by either governments in a centralized approach or communities themselves in a decentralized manner.

Different mitigation strategies have been proposed to reduce damage to hospitals caused by extreme natural hazards, which can significantly enhance the performance of their structural and non-structural systems and contents significantly. For instance, the World Health Organization introduced a seismic assessment methodology for hospitals in developing countries and presented examples of mitigation for vulnerable non-structural components[103]. Another study focused on reducing the effects of future earthquakes in the US[104], where the observations and lessons learned from previous seismic events provided practical seismic preparedness guidance for hospitals and presented retrofit solutions for structural systems and non-structural components. FEMA introduced a guideline[105] to reduce the risks of non-structural component damage in a typical hospital during earthquakes, which includes installation and upgrades for building utility systems, architectural elements, furniture, and contents. FEMA also provided guidelines for improving the resilience of healthcare facilities to power outages, highlighting the importance of standby power generators in maintaining the function of healthcare facilities[106]. Turning to staffing requirements, the Centers for Disease Control and Prevention (CDC) has provided strategies to mitigate the shortage of hospital staff during a pandemic[107]. Other organizations also provide disaster preparedness plans for their healthcare facilities to mitigate the impact of natural disasters such as hurricanes[43]. The Administration for Strategic Planning and Response (ASPR)[108] developed a Hospital Preparedness Program to provide leadership and funding for healthcare systems to plan, prepare, and respond to emergencies and disasters. This program can help healthcare systems to save lives through the development of agreements between hospitals during disasters which can assist in transferring patients and resources among them[108]. To assist with hospital building resilience, the Department of Health and Human Services provided the Sustainable and Climate Resilient Health Care Facilities Toolkit[109], which contains guidance, tools, and resource that highlight emerging best practices for developing sustainable and climate-resilient health care facilities.

Various national plans, including extensive retrofitting strategies for existing schools, also have been introduced to reduce the vulnerability of schools to natural disasters[20,43]. FEMA P-1000 has introduced effective strategies to enhance school safety during natural disasters, including earthquakes, tornados, hurricanes, floods, tsunamis, and windstorms, which can be used by school administrators and staff for *K-12* school facilities and by emergency managers[43]. Readiness and Emergency Management of Schools Centers (*REMS*), which is funded by the US Department of Education, introduced recommendations and strategies for schools and school districts to mitigate the impacts of disasters[110]. Federal and state governments provide resources for schools and school districts to properly manage natural disasters and emergency hazards[43,110]. Internationally, USAID provided an initiative to ensure the continuation of education services during natural disasters[87]. Different initiatives were also proposed to enhance the mental health of school staff and students. Recently, the US Department of Health and Human Services (HSS) introduced project *AWARE* to promote sustainable infrastructure for school-based mental health programs and services. This project utilizes mental health-related awareness and resilience activities to ensure students' accessibility to effective behavioral health services[111]. The Resilience of Schools and Educators (RISE) initiative is developed to provide guidance, practices, and strategies to enhance a school's social-emotional development and support staff and students subjected to traumatic stress[112]. Other initiatives were produced to address student mental health needs and reduce stress resulting from the pandemic[113].

MODELING RESILIENCE OF SOCIAL INSTITUTIONS

Disruptions resulting from extreme natural hazard events can cause direct damage to social institutions and their supporting infrastructure, leading to a drop in their functionality[35,37]. The resilience of the social institutions can be analytically quantified as the area underneath the functionality curve, as shown in Figure 2. However, measuring the change in the functionality over time requires modeling the hazard intensity distribution, damage to different infrastructure components caused by the relevant hazard parameters, losses resulting from this damage, decrease in functionality associated with the losses, and restoration of functionality during the recovery process[114]. While many researchers have modeled hazards, damage, and losses related to social institutions[83,105,115-132], relatively few have investigated their functionality, recovery, and resilience[29,35,37,133]. Examples of resilience definitions for the healthcare and educational systems are listed in Table 1.

Community resources must be properly allocated to repair damaged physical infrastructure and restore social institutions' functionality. The resource allocation is based on priorities, which are established by the community leaders and are unique to the community. Restoration time can be divided into two distinct stages: (a) the assessment and planning stage; and (b) the recovery stage, as shown in Figure 2. The assessment and planning stage extends from the time when the damaging event occurs to the time when the repair process initiates. It includes various sub-stages: damage inspection, engineering mobilization, reviewing/redesigning, financing and bidding, contractor mobilization, and permitting and procurement[146]. The recovery process starts at the end of the assessment and planning stage and ends when the target level of functionality is attained (full functionality or a percentage of the full functionality). To understand the resilience of social institutions that provide public services, such as hospitals and schools, the quantity and quality of the services need to be defined. In addition, the demand for these services, the interaction between the service providers, and the interdependency between the social institutions' facilities and the community infrastructure need to be quantified. The decision-making process and its impact on the facility's recovery trajectory should also be included. In this section, we summarize recent studies that address the resilience of social institutions with a focus on hospitals and schools while highlighting the major gaps and research needs.

Table 1. Resilience definition of the healthcare and educational systems

Healthcare system	Bruneau *et al.*[134]	The ability of acute care facilities to recover quickly after a shock
	European Commission[135]	The ability of the healthcare system to effectively adapt to changing environments and tackle major challenges using limited resources
	WHO[136]	The ability of the healthcare system to anticipate, respond to, cope with, recover from, and adapt to climate-related shocks and stress to provide sustained improvements in population health despite an unstable climate
	Kruk *et al.*[137]	The capacity of health actors, institutions, and populations to prepare for and effectively respond to crises, maintain core functions when crises hit, and, informed by lessons learned during the crisis, reorganize if conditions require it
	Blanchet *et al.*[138]	The healthcare system's capacity to adapt, absorb and transform when exposed to a shock such as a pandemic, natural disaster, armed conflict, or financial crisis and still retain the same control over its structure and functions
	Abimbola and Topp[139]	The adaptability of the healthcare system in the context of robustness
	Hassan and Mahmoud[29]	The ability of hospitals to provide services during and after a sudden increase in patient numbers from natural disasters
Education system	Benavrd[140]	A set of qualities or protective mechanisms that give rise to successful adaptation despite the presence of high-risk factors during the course of development
	Handmer *et al.*[141]	The rigidity and inadequacy of present institutional responses to global environmental change
	UNICEF[142]	The ability of children, communities, and systems to anticipate, prevent, withstand, adapt to, and recover from stresses and shocks
	Peacock *et al.*[143]	The ability of social systems, such as schools, to resist or absorb the impacts of natural hazards, recover from those impacts, and reduce future vulnerabilities through adaptive strategies
	Tong *et al.*[144]	The efforts of the education system to absorb, manage and recover from the impacts of disasters using its own resources
	Shiwaku *et al.*[145]	The capacity of institutions and systems to restart school activities after disasters
	Hassan *et al.*[35]	The ability of a school to provide the desired level of educational services after disasters

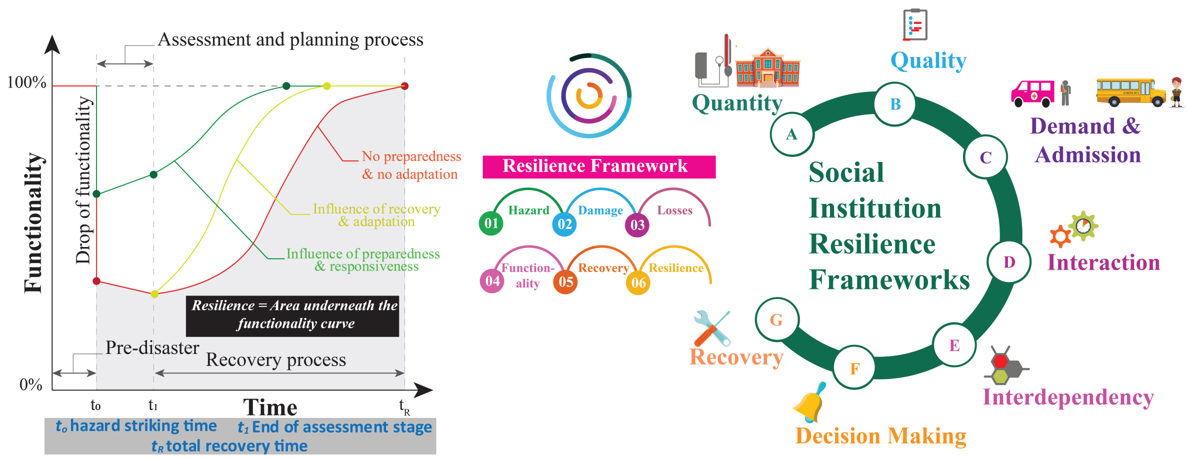

Figure 2. Resilience framework showing the different stages of functionality and the required components to estimate the resilience of healthcare and educational systems.

Healthcare systems

Healthcare functionality is commonly measured as a combination of the quantity and quality of medical services that are provided[29,133,147]. Hospital capacity can be used as an index for quantity functionality[28], while quality can be estimated based on patient outcomes[148,149]. Hospital capacity measured by the number of staffed beds requires trained personnel such as physicians, nurses, and supporting staff, qualified space, and sufficient supplies[16,133]. Hospital capacity can be impacted by direct damage from extreme natural hazard events, such as earthquakes, tornadoes, and floods. Previous studies investigated damage to hospitals due to previous events such as earthquakes[115-118] and other natural hazards[119-121]. Damage probabilities (fragilities) for hospitals, which are required for estimating the expected damage to the hospital facilities, given a hazard intensity, were also estimated for their structural systems[122-125], non-structural components and building contents[126-128]. A community's functional infrastructure is also essential to achieve the full functionality of healthcare systems. For example, a reduction in transportation network functionality may lead to delays in the responses of ambulances[150,151]. Similarly, a decrease in water or power may disrupt hospital functionality[29]. Natural disasters can also impact hospital staff because staff themselves can be among the casualties of the disaster, their homes can be damaged, and their ability to work can be limited when their families are indirectly affected[37]. The quality of healthcare services can be identified using multiple dimensions[148,149], among them: patient waiting time in the emergency department before being seen by a physician[133,152] and the time spent by a physician to provide healthcare services to the patients[29]. A recent study estimated the hospitals' functionality as a function of the availability of municipal water, power, telecommunication, and wastewater[133]. Other studies highlighted the impact of transportation network damage on healthcare systems after earthquakes[29,150,151]. A drop in hospital functionality can also be defined as the losses to different hospital departments while considering the possibility of redistribution of services among the departments[16].

Patient demand and hospital surge capacity are other components impacting the functionality of healthcare facilities after extreme events. Different models have been developed to estimate the demand for healthcare facilities: empirical models[153], gravity-based accessibility model[154], floating catchment area[155], and Huff-based model[156]. Most of these models estimate the number of patients at each healthcare facility and the demographic distributions of the patients admitted to each facility efficiently. However, these models are static and cannot capture the disruption resulting from disasters that impact the demand (number of patients), supply (number of beds available at each facility), and the accessibility of the healthcare facility to patients (transportation network). A Markov decision process with limited inputs, such as mean travel times and congestion levels, was employed to compare the impacts on patient survival rates of two proposed heuristic policies used for allocating ambulances and hospitals to patients after disasters[157], which highlights the rule of aftermath communications on increasing the patient survival rate. More recently, a dynamic patient-driven model was developed to address the aforementioned shortcomings of existing models[29]. This model considers the role played by patients, healthcare facilities, and the connection between the patient and facility for patient accessibility and distribution. Other studies have identified the main factors influencing patient distribution after mass casualty incidents[158]. In addition to better managing patient distribution, it is critical for hospitals to be able to expand their capacity to provide care for an increased volume of patients through their surge capacity. Surge capacities are typically designed based on possible disaster scenarios involving mass casualties, and different studies have investigated the role of surge capacity as a successful mitigation strategy for hospitals[159-162]. Even though components of surge capacity are well defined, previously published research revealed a variation in its conceptualization, terms, definitions, and applications, which restrains the development of standardized models, measurements, or metrics that are useful to inform policies covering different disaster situations[163].

The aforementioned models and approaches for modeling overall healthcare system functionality can be classified based on the methodology they utilize in conceptual frameworks[164]: empirical methods based on surveys[15], fault-tree-based models[16,122,133], state tree-based methods[165], discrete event simulation models[66], Leontief based models[166], and dynamic models[151]. These methods have been used to investigate the impact of different disasters on hospitals and healthcare systems, including seismic events, wildfires[50,167], climate events[168-176], and other disasters[72,177-185]. Other studies have focused on patient flow within healthcare systems after disasters, which provides hospitals with an estimated operational and response capacity that can significantly enhance their resilience[186]. Existing patient flow models within a healthcare facility can be classified based on their main purpose into queueing models[187] and simulation models[186]. Queueing models describe hospitals as service centers and patients as customers. The patients might be in the queue when the hospitals reach their capacity. Simulation models have been built using various approaches, such as system dynamics approaches[188], agent-based models[189], and discrete-event simulation models[190]. However, their applications have been limited to small-scale hospitals and departments. Furthermore, many studies have modeled decisions made within healthcare systems that impact their recovery and resilience. For instance, Mahmoud and Hassan[191] provided guidelines and recommendations to achieve rapid recovery of hospitalization services following an earthquake. Achour and Price[192] introduced a review of the resilience strategies of healthcare facilities, covering research papers, governmental and non-governmental reports, code and guidance documents, and databases. Wachs *et al*. investigated resilience skills in the emergency department, focusing on case studies in two emergency departments: one in Brazil and the other in the US[193]. Even though combining the models that simulate the patient flow in each hospital with the large-scale healthcare system resilience models can enhance the current healthcare system models, especially in estimating the healthcare system utilization, it is yet to be achieved.

Educational systems

The functionality of the educational services provided by *K-12* schools commonly has been measured using: (a) the service availability[194]; and (b) the quality of the education providers[30]. Previous case studies[35] have shown that school functionality immediately after disasters depends on service availability. In contrast, the quality of the providers in the long term can have more impact on the total education functionality. The educational providers for the *K-12* schools include institutions or individuals who provide students with access to education services and/or work with students in connection with the education services and include school, school district, teacher, and school administration. The availability of education services is commonly measured using the number of school seats available to children of school age, which requires qualified staff, suitable space, and sufficient supplies and services[35]. These seats can be reduced as a consequence of the direct damage resulting from extreme events, which not only impact the school buildings but also limit their access to utility services such as water and power. To reduce the damage and vulnerability of schools to extreme events, previous studies investigated the seismic risk to structural systems[83], non-structural components and systems[105,130,131], and building contents[129]. The Federal Emergency Management Agency (*FEMA*) has provided design guidelines to enhance the safety of school facilities in earthquake, flood, and high wind events[132]. The quality of educational services can also be impacted when education institutions are forced to replace their staff with less qualified individuals or when the staff is physically or psychologically impacted by the disaster. Extreme events can also force staff, teachers, or administrators to out-migrate from the community if their homes are severely damaged during an event, resulting in a reduction in the number of well-qualified personnel to be hired[35]. However, schools also need the services provided by other community infrastructures, such as transportation, water, and power, to be fully functional. A recent study by Hassan *et al*. investigated the impact of earthquake disasters on public school networks, in which school dependency on the community's different physical, social, and economic components was considered[35]. In this study, quantity functionality was measured by the number of school seats available, while quality was assessed as a combination of the quality of the teacher, classroom, and school. Other matrices were also used to measure the quality of the education services provided to school students, such as educational attainment[195] and student outcomes[196]. Schools also monitor their student outcomes using test-based measures and/or self-reported[197]. Another essential measure of school functionality after major disasters is chronic student absenteeism[198], which may be the result of school closure, population dislocation, stress, and trauma. Chronic student absenteeism is a common resilience measure for educational services[35]. There is a need for a unified and comprehensive resilience index that represents the performance of schools after disasters and facilitates the comparison of the resilience of schools in different communities subjected to different hazards.

Other factors impacting the functionality of educational facilities after disasters are student enrollment and transfer and the roles played by school administrators in the decision-making process[199,200]. While the enrollment and transfer processes are well-defined and are managed by the school's administration and school district during normal operating conditions[201], the disruption caused by extreme hazard events can impact these processes. For instance, following major disruptive events, schools may employ different mitigation strategies such as transferring students if their school is damaged, increasing class capacity to close the gap resulting from the shortage in space or staff, or reducing or suspending the school transportation service due to damage to roads or damage to buses[132,202]. Previous studies[30,31] have investigated different tools that can be used to measure the performance of schools during normal operating conditions. However, these studies did not provide a simulation model that could predict school performance after extreme natural events. The recent study by Hassan *et al*., which introduced a framework to model the school system's performance after earthquake events, considered the role played by school administrators and the school district in maintaining school operations[35]. However, models that quantify school functionality and resilience following natural disasters are yet to be developed.

Different approaches have been utilized to model educational functionality, including success tree analysis[35] and agent-based modeling[37]. While success tree analysis is a simple method to apply, it cannot independently capture the detailed decisions made on the individual level. The impact of the individual's decisions on the school's performance can be modeled efficiently using more complex models such as agent-based modeling. While these studies focused on the public schools in the US, which are centrally managed by the school districts, the resilience of the other educational systems has yet to be investigated. Most existing studies and guidelines on the resilience of educational systems subjected to natural disasters are focused on conceptual frameworks, with the main objective of continuing school operations and ensuring positive student outcomes. For instance, UNESCO introduced Education for Resilience resource kits that provide practical tools, strategies, and guidelines on addressing safety, resilience, and social cohesion in educational planning[203]. FEMA presented a Programmatic Environmental Assessment procedure for schools in Puerto Rico that focused on recovery decisions that enhance the resilience of the schools after natural disasters[204]. School reopening after an earthquake is one of the main decisions made by school administrators and the school district[85]; however, this decision also involves different agents such as buildings, police and fire departments, the office of public safety, and community leaders. Generally, schools can be partially reopened using backup space and backup systems or may stay closed until buildings are fully functional[85,205]. Schools can also support other learning approaches after disasters, such as homeschooling and virtual learning[206]. The school administration is also responsible for appointing staff to replace staff impacted during or after the earthquake, subject to the funds available for these appointments[188], and can also temporarily transfer staff to solve the staff shortage problem. The school administration is also responsible for managing the supplies and repair resources and transferring them between the schools to bridge the gap in any supply shortage and to achieve their recovery objectives[207]. Further investigation into the impact of different school decisions and mitigation strategies on community resilience is needed.

POTENTIAL PATH FORWARD

Despite the large number of studies reported in the literature that primarily focus on the damage, functionality, recovery, and resilience of healthcare and educational facilities, among other social institutions, there are still significant gaps in knowledge that need future investigations. In addition, practical guidelines and recommendations to ensure safety and guarantee the continuation of the services provided by these facilities must be updated to reflect current challenges. These knowledge gaps and needs, along with recommendations for decision-makers at hospitals and schools, are summarized below in three themes associated with future research directions.

Healthcare systems

While most of the existing studies in the area of the resilience of healthcare systems focus on single hospital facilities, there is a lack of studies addressing healthcare as a system. Connecting the models capturing patient flow within the healthcare facility (small-scale) to the healthcare system model (large-scale) is critical to properly simulate the impact of disaster-related disruptions to the community's healthcare system on patient admission and discharge processes. Existing surge capacity modeling and planning need to be significantly enhanced so that a hospital's surge capacity can be designed to meet community needs and resilience goals. Additionally, the role played by primary care providers and non-acute facilities to reduce the demand on hospitals during disasters must include properly estimating the patient demand distribution. Including the impacts of disasters on a hospital's regular non-acute demand can be significant to accurately estimate the hospital demand, which can significantly be reduced as a consequence of canceling or rescheduling appointments and procedures, reducing the functionality of the transportation network, and shortage of staff. Addressing the potential increase of healthcare inequality during and after disasters is important to ensure the community's social stability. Decision support tools that can simulate the impact of different decisions on the functionality and resilience of healthcare facilities after disasters are essential for mitigation and planning.

Different mitigation strategies can be applied to enhance the resilience of healthcare facilities following natural hazard events, including alternative staff, regular training for the staff to increase their preparedness for disasters, and mutual-aid agreements with other hospitals. Hospitals in which utility backup systems and backup spaces are available can significantly reduce the impact of disasters on their functionality. In addition, securing alternative providers for the main services that hospitals require and relying on multiple suppliers is pivotal to their functionality. Shortages of hospital supplies after natural disasters can lead to catastrophic consequences. Therefore, receiving the required supplies on time is vital for maintaining an acceptable level of functionality. This can be achieved by including redundant supplies and enhancing the performance of healthcare supply chains performance. Organizing the healthcare service between hospitals and other healthcare facilities, especially after extreme events, is fundamental to ensuring that most patients receive appropriate service and reducing mortality rates. Therefore, protocols that ensure full cooperation between healthcare facilities within a community, especially during and after disasters, need to be developed as a priority by public health managers. Allocation of repair resources among healthcare facilities and other infrastructure requires careful planning to ensure a balance between the social and economic stability of the communities. Sustaining patient satisfaction and monitoring patient outcomes is the key to maintaining resilient and socially stable communities. Ensuring both equity and adequacy of the healthcare services provided by hospitals during disasters is essential to reducing healthcare inequality. Therefore, building platforms that connect patients and hospitals that not only enhance patients' accessibility and transfer but also address healthcare inequality through patient feedback can significantly improve social justice during disasters. While the healthcare facilities in the US are currently independently managed, it is recommended for regulators such as the Centers for Medicare and Medicaid (CMS) to ensure the preparedness and adequacy of the healthcare facilities in each community to withstand different disasters as a system.

Educational systems

Even though a continuation of educational services is critical for communities, there is a lack of studies addressing the functionality and resilience of schools after disasters. Most existing studies have investigated the physical behavior of school buildings subjected to earthquakes. More research is needed to understand the performance of schools during other natural disasters. Moreover, modeling the interaction between different public and private schools in the community is essential to understanding the resilience of the education system and the expected role played by this interaction in enhancing the availability of school seats for all schoolchildren after disasters. Currently, only one study models the functionality, recovery, and resilience of schools as an education system subjected to earthquake hazards[35]; however, simulation models that mimic the impact of other natural disasters on educational systems are needed. These models will help develop decision support tools that can be used by school administration to plan properly for different disasters. Different modeling approaches can be utilized to study the resilience of educational services, such as agent-based and dynamic models, which require extensive data collection from different case studies to construct and validate these models. These models also need to include the role played by community physical, social, and economic components in the functionality and recovery of schools. Furthermore, connecting existing social models that focus on the developmental and behavioral impacts of natural disasters on children with models that investigate school's physical components can enhance our understanding of the resilience of education systems. School emergency plans that address different natural disasters and provide guidelines for maintaining functionality and accelerating recovery are recommended to be developed for each school and school district.

Different mitigation strategies can be applied to enhance the resilience of education facilities following natural hazard events, including utilizing volunteer staff, appointing qualified teachers, and transferring staff between schools. Schools require essential utilities and appropriate space to provide educational services to their students. Utilizing backup systems and spaces at schools subjected to high risks of disasters can allow them to overcome the disruption to these components. Managing school supplies after the disasters and ensuring the availability of their main supplies by, for example, transferring supplies between schools and finding alternative supplies are important to school functionality. The role played by school administrators and school districts is critical in managing student enrollment, staff and supplies transfer, managing the repair process of the damaged schools, and finding alternatives for the damaged and impacted components that are important for educational functionality. School administrators must be well-trained and well-prepared for disasters. Distributing repair resources among schools requires careful investigation to ensure equality in educational services distribution. Monitoring and enhancing student outcomes, especially after disastrous events, is the key to maintaining resilient and socially stable communities. Enhancing the school staff and students' mental health and providing proper resources to support families after disasters are essential steps toward strengthening the community's social stability and resilience.

Integration of healthcare and educational services within a community

Even though hospitals and schools are vital for the short-term and long-term functioning of the communities, their contribution to overall community resilience has yet to be investigated in sufficient detail to develop risk-informed public policies for post-disaster community planning and management. The dependency of hospitals and schools on other infrastructure systems has been examined, and their impact on these infrastructures needs more investigation. For instance, coupling resilience models for social institutions with resilience models for housing and infrastructures is yet to be achieved. Coupling these models can also simulate the impacts of decisions made for one system on the others, which can also allow for interdependency assessment between social institutions and other community lifelines. Decisions made by communities before, during, and after disasters are critical for the resilience of healthcare and educational systems; however, models that simulate these decisions do not exist. Optimizing the allocation of repair resources during recovery time is an essential step toward achieving resilient communities. Decision tools that support the allocation of scarce resources for all sectors within the community do not exist. The role played by other community lifelines, such as transportation, water, and power, in delaying or accelerating the repair process of social institutions is a critical component in modeling recovery that has not been fully quantified. Comprehensive measures that quantify the social stability of the community, which combines the performance and quality of different social institutions and depend on easily measured quantities, are needed for communities to verify if they meet their resilience goals.

The stability of different social services, such as healthcare and education, can significantly enhance community resilience and reduce population outmigration. Communities can increase the social stability of their populations and restore normalcy after disasters by ensuring a quick recovery of hospitals and schools. Even though the needs of everyone for the services provided by these institutions are different, most community individuals, certainly those who are financially able, may out-migrate because of the lack of these services. Thus, the continuation of healthcare and educational services following extreme natural hazard events is one of the most important resilience goals for virtually all communities. To achieve this goal, communities must allocate sufficient repair resources for impacted hospitals and schools, provide them with volunteers to close the gap in staff shortages, and support them with the supplies needed. Communities can also indirectly support hospitals and schools by providing temporary housing for their staff, facilitating staff attendance at work, and prioritizing the delivery of medical and educational supplies to these essential public institutions.

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Authors' contributions

Conception and design, or analysis and interpretation of the data; drafting the article or revising it critically for important intellectual content; approval of the final version: Hassan EM, Mahmoud H, Ellingwood B

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Conflicts of Interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

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