Framing a new approach to critical infrastructure modelling and extreme events

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Abstract: This paper proposes a new framework to evaluate and improve the resiliency of communities as they face the risk of multiple hazards and cascading infrastructure failure. The central idea is to extend engineering-based fragility models of the effect of extreme events on physical infrastructure and to combine them with regional, economic and social impact models. The modelling framework would support analyses of the sensitivity of a community to varying events, signalling weak links in regional infrastructure systems and subsystems, and suggesting a more efficient allocation of federal, state, and local preparedness resources.

Keywords: infrastructure; extreme events; community; disaster; fragility curves; planning; preparedness.

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1 Introduction

Given the costs of emergency events, natural and technological disasters, and the risks associated with terrorism, there is a clear need for new measurement and evaluative techniques that enable resource allocation decision-making in a more efficient and effective manner. We should have a better understanding of where in the community-wide system is the greatest need for investment to improve overall preparedness, where scarce resources can be most effectively applied, and create the greatest reduction of vulnerability.
Framing a new approach to critical infrastructure modelling

This paper proposes a new framework for addressing critical community infrastructure and extreme events, one that would facilitate the evaluation of the impact of alternative, multiple hazard scenarios and cascading infrastructure failure. The central idea is to extend damage estimates developed by engineering and social impact analyses through disciplinary boundaries such that planners, economists, and other practitioners and community leaders can assess social and community impacts that might result from hazard events. The proposed modelling framework would create the ability to do sensitivity testing for infrastructure systems and subsystems, and enable the testing of alternative investment scenarios to improve resource allocation.

The basic premise of this framework is shown in Figure 1 below. Utilising a system of fragility curves, the impact of a particular extreme event is evaluated up through the community level (top of the schematic in Figure 1).

**Figure 1** Conceptual schematic

Using an interdisciplinary and multi-hazard approach, the framework is designed to create community-wide and systemic measurements of demand, capacity, and preparedness. Modelling community infrastructure is something that has not been done in disaster research with any degree of success. Examples of single system analysis and modelling exist, particularly in the area of seismic events. Those efforts have not been extended to include analysis of a system of infrastructure, including the built environment (transportation, structures, and utilities) and social and economic systems, nor have they been developed for other disaster scenarios.
There are few examples in the literature that develop this type of comprehensive framework, and none that have tested it in practice. There is related research that helps develop the basis for such a framework.

2 Research and concepts

Limited research has been done in which communities are evaluated in a holistic or systemic way with respect to their infrastructure and social/economic systems and extreme event impacts. There are literatures from which one can develop a framework, and those key concepts are reviewed here. We draw on three areas: disaster preparedness (from a community perspective), engineering, and economics.

2.1 Conceptualising 'disaster'

One disaster definition is based on the notion that a disaster is only a ‘disaster’ if the demands created by the event exceed the community’s capacity. Quarantelli calls this an ‘imbalance in the demand-capability ratio in a crisis situation’ (Quarantelli, 1982). The idea of examining formal organisations with respect to extreme stress situations can be traced back to the work of Barton (1969) and Drabek and Haas (1970). Other notable researchers have also considered the framing of a disaster as a crisis state, or social stressor.

Wenger (1978) first articulated that the impact of a disaster agent is not a sufficient enough characteristic to determine a disaster occurrence. Wenger states that “[i]n addition, one must consider the degree of crisis management capability in the community” (Wenger, 1978). Because community resources, commitment to preparedness, and other factors influence the ability to respond to disaster impacts, Wenger goes on to say:

“[I]t is possible that given two different communities, one with extensive crisis management mechanisms and the other with few such resources, disaster agents with similar characteristics may produce a crisis in the latter system, but only an emergency in the former.”

The ‘demands exceeding capabilities’ proposition makes intuitive sense, but it has not been operationalised or empirically tested.

2.2 Modelling community effects

Modelling community or system wide infrastructure capability and resilience with respect to hazards is a difficult task. Two key concepts are important here. The first is the concept of ‘vulnerability,’ which has been more recently argued that since disasters are essentially a socially constructed concept, then too is the idea of social and community vulnerability. In this area, authors have argued that we need a more holistic approach to understanding community vulnerability (and conversely, resiliency) and those traditional approaches to achieving adjustments for potential hazards have been ineffective (Kelly, 1995; McEntire, 2001; Paton and Johnston, 2001; Weichselgartner, 2001). The second concept is the problem of quantifying a complex system in a way that can provide meaningful outputs for application in real world
systems. Researchers have noted the problem of how ratings, with respect to disasters, can have multiple interpretations and be subjective (Lloyd and Wilson, 1997; Nordenson et al., 1999). Others have identified the need to measure, with a scale system, the effects of a disaster on a community, but only conjecture about a general approach (Granot, 1995). A group at the University of Bradford, UK has developed the Bradford Disaster Scale, but apply it using three factors (fatalities, dollar losses, and evacuations) and apply it at the national level (Keller, 1997). In a singular case Menoni et al. (2000), examined the idea of interrelated impacts in a community but focused only on one element of the system, in this case the healthcare system as it is related to seismic vulnerability.

2.3 Community measurement indicators and issues

The validity of indicators to measure social phenomena (De Neufville, 1975), predict urban organisational behaviour (Clark and Wilson, 1994), or identify differences among communities (Colley, 1975; Moberg, 1979; Murphy, 1980), is a source of debate among social scientists. The same can be said about the attempts to conceptualise, measure, or otherwise identify the vulnerability or capacity of a community for extreme events. Quarantelli identifies a number of criteria for evaluating and assessing disaster preparedness and planning (Quarantelli, 1987, 1994). Those criteria in many cases do have measurable outputs. As an example, lifelines such as water or power have definable characteristics of age, redundancy, construction type, and similar factors. Wenger and Drabek note that:

“Community size and the existence of local disaster events are two critical factors that shape local response capability. In general, the greater the size of the community and the more extensive its disaster experience, the more viable is the local response system.” (Wenger and Drabek, 1987)

Primary responsibility for preparedness planning and response is at the local level. In most cases, it is either the municipality/city or county. Ordinance making authority, police power, and general regulatory issues are addressed through city councils. While there are external forces that influence the adoption of some community mitigation actions over others (Mileti, 1980; May et al., 1996), the city/county still has the preponderance of authority for preparedness activity, and for this primary reason is the unit of analysis for our study.

2.4 A gap in standardised, quantitative measurements and analysis

For the large part these ideas have only been qualitatively examined. While methodologically sound case studies in hazards can yield rich results (Yin and Moore, 1985), there is still a need for quantitative approaches that can be empirically applied. More importantly, the model and its application would need to be replicable across communities.

Researchers are calling for just this kind of approach. Lindell and Perry point out

“…future research needs to go beyond cross-sectional assessments of judged probability of an event and its most immediate consequences to multiple operationalisation of constructs…” (Lindell and Perry, 1992)
Rubin’s examination of federal hazard mitigation efforts found that “not many studies have compared the mitigation efforts across two or more program areas” (Rubin, 1996). Here the point is made that there is a need for research and theory development that takes a more ‘all hazards’ approach. Mattingly, when discussing the NFIP, points out that the national mood is “calling for more accountability in the way government spends money and an ever shrinking funding pool resulting from efforts to reduce the deficit” (Mattingly, 1996). But yet there is not reliable means of measuring or linking accountability at the local level to consistently applied cost-benefit or similar analytical tools, in allocating disaster preparedness or recovery funds. Simultaneously, there is a desire for more performance-based evaluations.

2.5 Related efforts in lifeline engineering

Much of the initial hazard mitigation work assessed the vulnerability of the built environment to natural hazards as a component of ‘lifeline engineering’ research. Previous research has worked principally to assess the vulnerability of utility systems due to earthquakes and to evaluate overall system performance.

Some efforts have modelled systems for local communities. For example in one urban community (Louisville, Kentucky) a significant amount of work has already been devoted to assessing utility and lifeline system vulnerability. At the University of Louisville, Cassaro et al. (1993) assessed the vulnerability of the water distribution system in response to a variety of natural hazards including: earthquake (ground motion and liquefaction), high wind (tornados), landslide, temperature and flood. Cassaro et al. developed damage-estimate curves for the critical water system components. This information was then used as a basis for risk and loss estimation analyses.

On a national level, recent work funded by the Multidisciplinary Center for Earthquake Engineering and Research (MCEER) has extended traditional lifeline engineering to include economic impacts of system disruption (Chang et al., 2000). Chang et al. combined Shinozuka et al.’s (1994) water system damage estimate model with economic loss data obtained from the Northridge earthquake in a Monte Carlo simulation model. In this manner, they were able to extrapolate possible damage and loss from a range of earthquakes that may impact the Memphis, Tennessee area (Rose et al., 1997). Similar work for power distribution systems has been performed by Shinozuka et al. (1998).

Cole (1996) has worked to combine all hazards and all utility components to create a disaster preparedness model for the USA. His work attempts to account for the inter-linkage between utilities, businesses, and households to assess vulnerability of individual communities. The vulnerability of the communities are then further combined to determine the vulnerability of regions, and then further combined to assess vulnerability at the national level. In this fashion he attempted to account for the ‘spill-over’ effects of a natural disaster from one community to another.

2.6 The development of ‘fragility curves’

A key concept for this framework, developed primarily for seismic events, is the idea of ‘fragility curves.’ Fragility curves have been developed for numerous scenarios, including: seismic excitation for bridge piers in the USA and Japan (Hwang et al., 2001; Karim and Yamazaki, 2000), water systems (American Lifelines Alliance, 2001),
electrical substations (Anagnos, 1999), tall buildings (Tantala and Deodatis, 2002) and water towers (Mostafa, 1997); fragility of concrete columns subjected to shear (Gardoni et al., 2000); seismic risk assessment for seaports (Pachakis and Kiremidjian, 2004); wind induced loss estimation (Filliben et al., 2002); and seismically retrofitted bridges and transportation networks (Shinozuka, 2001).

Fragility curves can be either empirically or analytically based. Empirical curves can be developed when there is an adequate history of demand; and where there is a database of system damage. For example, the American Lifelines Alliance (2001) developed water system fragility curves based on damage data collected during the San Fernando, Loma Prieta, Northridge and Kobe earthquakes.

In the case where the damage database is sparse or missing entirely, the only recourse is the development of analytical fragility curves. Hwang et al. (2001) developed highway bridge fragility curves synthetically generated earthquakes assumed to occur on the New Madrid fault. In the process they needed to make judgements as to the severity of damage, based on results from their non-linear structural analysis model (SAP, 2000).

To date, fragility curves have been developed for a limited number of ‘demands’, primarily earthquake and wind, and few systems have been analysed: highway bridges, buildings and water supply systems. Consequently, a fundamental part of this model would be to develop fragility curves for multiple demands and multiple systems (for example, power transmission, gas transmission, transportation).

2.7 Regional economic impacts of disasters

Most natural disasters are reoccurring and tend to cluster geographically. At the local level, this means that communities expect occurrences and make arrangements to mitigate human and economic losses. When an extreme weather event occurs, people and businesses modify their behaviour in the aftermath: they clear, clean, and rebuild. Over the years this behaviour becomes part of the structure of the local culture and economy.

Unanticipated disasters are a different story. A strong earthquake in a place with no seismic history would be a catastrophe, since the physical infrastructure would not be built to that higher standard. Construction in the future would be more expensive. Insurance costs would rise. And the place would be considered less attractive to residents and businesses, thus slowing or even reversing the area’s growth.

Human-induced disasters, such as the World Trade Center attack or the Oklahoma City federal building bombing, are more difficult to analyse from an economic point of view. If they are considered to be complete anomalies, then the regional economic impact is only short-term and on net could be positive. Insurance claim money flows in, federal and state grant dollars arrive, new structures are built, and confidence is restored. If the event is considered to be a signal of many future events, then the economic impacts could be severe. Security and insurance costs would escalate, some residents and businesses would flee to other locales, and the area would deteriorate economically.

There is not a large academic literature on the economic impacts of disasters, and the assessments are mixed. A simulation of a major earthquake near Memphis, causing a full electricity disruption, predicted a net loss of regional output of 7% during the recovery period (Shinozuka et al., 1998). Guimaraes et al. (1993) estimated the economic impacts of Hurricane Hugo on the South Carolina coastal area, and found both positive and negative consequences with a neutral net effect on incomes. The construction sector flourished in the aftermath, but there were significant negative effects from the loss of
unreimbursed wealth. Wilson (1998) found that the financial impacts of the 1994 Northridge earthquake were modest and temporary, primarily because of redundancy in the road network. The most recent US disaster, the destruction of the World Trade Center towers, was analysed by economists for the New York Federal Reserve Bank (Bram, 2002). They estimated the lost earnings of those who died to be $7.8 billion, and an additional $3.6–$6.4 billion in lost earnings from displaced workers. Direct property losses were over $20 billion. However, the authors argue that New York’s long-term economic prospects have not necessarily been diminished by the attacks, as the city continues to attract lucrative industries and talented people.

2.8 Transmission of disaster through local industries

A breakdown in physical infrastructure, regardless of the cause, has predictable ripple effects through a local economy. A shutdown in the local ground transportation system, e.g. would effectively halt the economy, as firms could not receive or ship goods and residents could not work, shop or play. The net regional economic impact would be negligible, however, if the shutdown lasted but a few days.

Of more interest here is the case where one or more infrastructure elements were destroyed or compromised for a much longer period. It is difficult to generalise about the local economic consequences, due to the wide variety among US communities in topography, climate, energy systems, industrial concentrations, and exposure. A breach of the water supply available to the Coors brewery could eventually turn Golden, Colorado into a ghost town, as the plant is one of the main employers in this small community. Similarly, a major failure at a water desalination plant and/or electrical generation facility on a Caribbean island would quickly decimate its tourism industry, leading to a steep reduction in jobs, annual income of residents, and tax revenues to pay for schools, roads and other public services. But these examples are more the exception than the rule. Most Americans live and work in larger, more diversified, metropolitan areas. There are usually multiple sources of water, energy, and telecommunications, often linked to other nearby communities who could share resources (albeit at great expense) in the case of disaster.

Assuming a modern physical and socioeconomic environment, how does one analytically evaluate the industrial impacts of an infrastructure disaster? The most common tool used to describe linkages among industries is a regional input–output model (Miller and Blair, 1985; Lahr and Dietzenbacher, 2001; Hewings, 1985). These models have estimates of the production recipes, for up to 500 local industries. They spell out, for example, how much electricity, water, transportation, insurance and raw goods must be purchased from other local and remote industries to produce a million dollars worth of soft drinks, bread, automobiles, or nursing home services. Changes in demand for the output of any sector can be traced through to changes in demand for intermediate goods and services, and to changes in local jobs, income, and retail sales. Regional input–output models have been used for decades as the workhorse tool to evaluate industrial developments for city and state agencies. They have been extended over the years to analyse impacts of energy price shocks, environmental regulations, and interregional demand shocks. They can be adapted and used to evaluate the regional economic impacts of a break in infrastructure to support local production and mobility (Shinozuka et al., 1998).
2.9 Beyond theory: need for practice-based results

The state of the research indicates there is a need to synthesise these economic, social and engineering modes of analysis. Beyond engaging theoretical implications of quantifying community capabilities, there is also a more practical drive for creating standardised measurements of community vulnerability and resilience. The source of this aspect of measurement has emerged from the insurance industry’s need to more accurately capture and identify the risk for specific geographic areas, and then be able to price policies accordingly. This desire, combined with the experiences of the large-scale disasters of the 1990s, has created more discussion regarding the creation of ‘all-peril’ or ‘all-hazards insurance’ first proposed in 1969 by Dacy and Kunreuther (1969) as a risk pooling method.

These needs are reflected in the practical applications of measurement and evaluation systems to communities. There is growing consensus regarding the need for theoretical development that takes a more comprehensive perspective on hazard mitigation and the ability to make meaningful judgements about a community’s progress toward more effective emergency preparedness.

2.10 Trends in US natural hazards policy

The consensus in the USA can be seen in the national dialogue and debate. For example, there has been a rise in the use of terms such as Multi-Hazard Risk Assessment, which the Federal Emergency Management Agency (FEMA) has called its ‘cornerstone of the National Mitigation Strategy’, (FEMA, 1997), or ‘all hazards’ as a concept for risk pricing for insurance portfolios. We have also seen the emergence of the term ‘disaster resistant communities’ to signify a community’s efforts to be more prepared for, and more able to respond to, a disaster event. FEMA’s program to showcase community preparedness, ‘project impact’ (now expired), was intended to show gains that could be made through cross-sector public-private coordination and cooperation in the pre-event, or preparedness phases. Godschalk (2001, 2002) further identifies strategies and approaches to help create, through hazard mitigation, more ‘resilient cities’.

These US national trends, however, have evolved without parallel development in the manner in which success can be measured. We do not have an adequate method for evaluating generic resilience across communities, nor can we compare the relative successes/failures of new federal initiatives that seek as an output increased disaster preparedness, with a goal of disaster damage prevention or reduction.

What do we need to know to do a better modelling job?

These concepts and issues in the current state of research lead to the following questions:

- How can the capacity, vulnerability, and behaviour of critical infrastructure in a community be modelled for analysis?
- How can engineering and socio-economic information be integrated in a framework that improves preparedness and decision-making?
- What is the framework for such a model? How would it be derived? What are the critical inputs and outputs?
3 Developing a framework and approach

The approach described here would combine resources and analytical techniques from a variety of disciplines. The analytical technique envisions a GIS as the basic component that will provide the computing capabilities and data extraction requirements. Within the GIS system, cities or communities are disaggregated into layers or components. The weaknesses of these components (as determined by fragility curves) will be systematically combined to determine the overall community rating in response to extreme events.

As an example, utilities will comprise one of the base analysis levels within the system. However, each primary utility is composed of a conglomerate of buildings, networks and source materials. Each of these will react differently, but may or may not jeopardise the entire system if damaged severely. Enough redundancy may be provided in systems where the loss of one structure is not critical to the overall service capacity. Thus the system is built upon the concept of using fragility curves at the building and network level to assess the potential for and duration of outages for each primary utility.

As utility services are a primary component of the social and economic health of every community, loss of services are immediately felt by other industries. The duration of the outage, however, plays a significant role. Local industry and hospitals may be able to survive short power losses through backup generators, however, outages in excess of several hours or days will begin to severely impact performance and capacity. When industry, hospitals, and other essential facilities are unable to meet service demands, the community residents are severely impacted. Not only are they affected by the same utility service interruption, but they must also endure service interruptions to other key community components. This loss of service has a significant economic effect on the larger community.

Different regions of a city may respond differently to extreme events or be better prepared. Thus, the GIS is a critical component of the overall system as it will allow for spatial variability throughout the community. As an example, some communities may be less vulnerable to flooding due to higher elevations. However, it may be that the flooding limits access to the community and thus they are at an increased risk of fire hazard and other emergency vehicle response. Or, the water distribution system within one community may be cast-iron pipe, but PVC pipe in an adjacent community. The number of anticipated pipe breaks in response to an earthquake event would thus be very different.

The system can then be used to identify areas within a city that are more or less vulnerable to a catastrophic event. Disaggregation techniques can then be used to ‘work the system backwards’ to identify cost effective improvements. In this fashion, hazard preparedness funds can be better allocated to improve community performance.

4 Fragility curves and probabilistic methodology

The basic tool for describing the vulnerability of an element is the fragility curve. Fragility curves give the conditional probability that a ‘demand’ on an element will produce ‘damage’ corresponding to pre-determined states. The fragility curve technique utilises HAZUS methodology (Shinozuka et al., 1998).
Here, both ‘demand’ and ‘damage’ is used in a generic sense – demand could be an earthquake, flood, tornado, hurricane, blast, or other event. The HAZUS methodology specifies four damage states: slight, moderate, severe, and complete. These are the damage states used in the methodology proposed here. See Figure 2, below for an example in which fragility curves have been developed for a bridge.

Figure 2  Bridge fragility curve after Hwang et al. 2001 (damage vs. acceleration)

A fragility curve is a mathematical expression that relates the conditional probability of reaching or exceeding a particular damage state, given a particular level of a demand or hazard. Part of the research need is to develop the set of demands, and their levels. These demands would include, but not necessarily be limited to flood, earthquake, fire and terrorist attack. Categories of damage states would also need better definition. HAZUS specifies four damage states: slight, moderate, severe, and complete. This will be the basis for the damage states in this research, but the states may be expanded or modified, as appropriate.

The fragility curves incorporate both uncertainty and randomness. This is attributed to the type of hazard, its characteristics, and chances of occurring, and also to the performance of each individual component to each level of the hazard.

Fragility curves can be either empirically or analytically based. Empirical curves can be developed when there is a history of demand and for which there exists an adequate database of system damage (e.g., flooding). In the case where the damage database is sparse or missing entirely, the only recourse is to develop analytical fragility curves using Monte-Carlo simulation. The three-dimensional matrix shown in Figure 3 below is a representation of community infrastructure interrelationships. The interrelationship is between systems, characteristics and events. In principle, additional interrelationships may exist, but here only three are shown. Further, only a limited number of systems, characteristics and events are shown for the example. In a real community, there would be many more of these elements.
Figure 3  The infrastructure relationships and fragility curves

Each cell of the matrix holds a fragility relationship. In Figure 3, the particular fragility relationship is shown for a water supply system of a given age, experiencing an earthquake event. By collapsing this three-dimensional matrix along the characteristic axis, a two-dimensional matrix of system/events relationships may be obtained. The fragility relationship in the cells of this matrix are for the system/event pair where the effects of all system characteristics have been considered. ‘Collapse’ along the characteristic axis requires that the fragility relationships for all system characteristics be appropriately combined.

The second part of the figure shows the fragility relationship for a water supply system subjected to an earthquake event, where the effects of age, redundancy, capacity and resiliency have been considered. Further collapse of the relationships is possible. For example, the two-dimensional matrix may be collapsed along the system axis to produce fragility relationships for the community for a flood, tornado, earthquake or terrorist attack.
4.1 Working through the model

Once the individual fragility curves have been developed, the information within them must be integrated to provide fragility information for the entire system. This requires a suitable model of links and nodes for the entire system. Thus, the first step in developing a fragility curve for the community system is to identify the entire system in a network diagram, consisting of the various infrastructure elements and their dependencies. Similar to a PERT network, activity precedence illustrating different situations must be represented. (i.e., ‘A’ must happen before either B or C can happen, both A and B must happen before C can happen, etc.) If needed, severity rankings would also need to be assigned. This is an assessment of the seriousness of the effect of a particular node’s failure to the next node (component, subsystem).

The methodologies employed in risk assessment (Wang and Roush, 2000; Henley and Kumamoto, 1991; Betteley et al., 1994) can be used to build fragility curves from the basic subsystems up to the entire community system. To use risk assessment terminology, ‘fault’ is used to represent a particular damage state, and ‘hazard’ is used to represent a particular demand and its level.

In complex multi-component systems, the possibilities of a fault or the different ways in which a fault of the system can occur, create complex systems. Risk analysis techniques would be employed for use in the framework: Fault tree analysis (FTA), event tree analysis (ETA), and cause–consequence analysis. Each can be used for identifying different potential fault modes and their consequences.

Fault tree analysis is a technique that uses a deductive approach in determining how a specific system fault was caused by individual or lower level component faults. The fault tree analysis used here will include quantitative evaluation of the probabilities of the various hazardous events and system component faults, eventually leading to the calculation of the probability of the specified system fault. This fault tree analysis can be used to identify weak links in the system. FTA is a systematic approach in evaluating faults by first hypothesising potential high-level faults and then identifying the primary and secondary causes, down to the lowest component level, that could bring about the high-level fault.

Event tree analysis is an inductive risk assessment technique. Given a particular hazard, the initial component faults can have a wide spectrum of results, ranging from inconsequential to catastrophic. This analysis begins with a ‘what if,’ an initiating event or hazard, and then follows paths of the different possible sequences of events resulting from failure or success of the various system components. After the sequences are defined, quantitative probabilities can be found for them.

Cause–consequence analysis is a combination of fault tree analysis and event tree analysis. Taken in their natural sequence of occurrence, fault trees are used to show causes, and event trees are used to show consequences.

In general, the analysis of trees involves Boolean algebra, set theory, and probabilistic laws of set operations and conditional probabilities. Fault tree analysis includes a quantitative evaluation of the probabilities of the various damage states for subsystems, that will eventually lead to the calculation of the probability of the top event – a damage state for the community system. To accomplish this, fault tree diagrams will be developed to show the decomposition of the damage state of the community system in terms of unions and/or intersections of the damage states of lower systems.
The sequences that can lead to the top event are represented by ‘or’ and ‘and’ gates. The ‘or’ gate represents a union, and the ‘and’ gate represents an intersection.

Event tree analysis examines the progression (consequences) of a hazard beginning with the effects on the basis components or subsystems and building up to the effect on the community system. By developing an event tree, the analysis begins with an initiating hazard, and follows each of the possible sequences of events that result from the damage state of each subsystem component. The hazard scenario develops at discrete stages; at each stage there are a number of subsequent events that may occur. The links between the events form the branches of the tree. After the sequences are defined, the probability of each system outcome is found by multiplying the probabilities of the branches leading to that outcome. These probabilities will come from the fragility curves.

When simulation is used to generate the fragility curves, the first step will be to evaluate each basic subsystem separately, for the different levels of the various demands, using a Monte-Carlo simulation. Then for each simulation, results for each individual subsystem will be combined into a system performance at the next level of the tree, leading to an overall system performance.

5 Analysis for social and economic impacts

One of the unique components of this framework is the transition from engineering-based analyses to an overall assessment of social and economic impact on a community in response to an extreme event. Fragility curves are used as a means to estimate building or system performance. This data is then propagated up through multiple model levels and transitioned from estimated damage, to loss of service, to reduced operating capacity, and finally to community impact. Figure 4 shows the dependency of each model level on multiple variables from preceding levels. Figure 5 shows a simplified progression of the analyses necessary to propagate fragility curve information to economic and society impact assessment.

Propagating the fragility data through a community is accomplished by first estimating the extent of damage of each subcomponent of a utility system in response to an extreme event. With an understanding of anticipated subcomponent damage, the utility level components can use the data to estimate the amount of time they may be out of service. Outage length estimates will vary spatially throughout a community due to varying quality of system components. The outage length estimate is subsequently used to assess the affect on the health and welfare level due to loss of key utility services. Hospitals and other key components may be able to operate for short periods of time without a loss in capacity; however, extended utility outages would greatly affect their operations capacity. Similar components that affect the health and welfare level also affect the regional economy level. Not only are key industries dependent upon the base utilities, they are also dependent on an able workforce and other community issues. Finally, the community resiliency level is comprised of data from the previous levels. This level assesses an overall impact to a community due to utility outages, loss of public services, and reduced economic capacity.
Figure 4  Interactions between multiple data sources

- **Sub Component Level**: Frailty curves for each hazard event and utility system.
- **Utility Level**: Outage Curves based on estimated damage.
- **Health and Welfare Level**: Reduced capacity based on outage lengths.
- **Regional Economy Level (industry)**: Reduced capacity based on outage lengths.
- **Community Resiliency Level**: Impact estimate based on limiting resources.

Figure 5  Propagation from hazard event to economic and social impact
5.1 Taking it to the street: applying the framework to a test community

In order to test the framework and evaluate its validity, it would need a direct application to a test community. There are several issues that should be considered before doing so, including: GIS data availability; community cooperation (especially in the form of infrastructure provider participation); hazard data and probabilistic estimates of recurrence; and historic data on losses and impacts from prior disasters or extreme events. In the USA there are many communities that would fit the needed profile. Until a large-scale application could be done, it would be helpful if researchers could develop and apply the sub-components of this framework in order to further the ability to do more comprehensive evaluations of community-wide systems.

5.2 What gains might be expected from this approach?

The type of research, whether at the subcomponent level of the model or if it was attempted in a larger test case, would produce a variety of results that would be greatly beneficial to the hazard preparedness community. First, and most importantly, the framework produces a model that expresses the interrelations and multiple dependencies of key community components with respect to multiple hazards. The model is based on the concept of using fragility curves at the sub-base level to estimate response at higher levels within the community. By propagating the estimated damage from the fragility curves at the sub-base level, through the system to the economic response level, an overall community resiliency factor can be determined. Initially, the model can be populated with representative data from a US metropolitan community. Future research would be able to populate the model with different community data, enabling the comparison of resiliency factors among communities.

Second, the model will identify areas within a community that are more at risk due to a specific event. Similar to the idea of disaggregation in earthquake engineering, events or areas that dominate the risk analyses can be identified. With this information, communities can identify their most critical catastrophic event and begin to reduce the associated risks.

Third, ‘shadow pricing’ or optimisation techniques can be used within the model. In this fashion, specific fragility curves can be modified to simulate investing additional community resources into specific areas. The resulting changes to the community resiliency factor can be used as an indicator of the benefits of the allocated funds. The shadow pricing or optimisation techniques can be used to identify the projects or fund allocations that will most significantly improve the community resiliency factor.

6 Conclusion

As communities struggle to deal with extreme events and the risk of such events, researchers must find new and creative ways to model the impacts of these events. A newer paradigm of cross-disciplinary efforts is evolving in the research community. This proposed framework described here is one of many such efforts that will emerge. Research is continually needed to find the optimal framework to model community preparedness and resiliency, thus ensuring that the funds spent to strengthen a community have the greatest effect.
References

American Lifelines Alliance (2001) Seismic Fragility Formulations for Water Systems, April, ASCE.


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