THESIS

THE CONNECTIVITY BETWEEN DAMAGE TO PHYSICAL INFRASTRUCTURE AND SOCIAL SCIENCE: A NEW FIELD STUDY PROTOCOL CONCEPT

Submitted by

Todd Clapp

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2016

Master's Committee:

Advisor: John van de Lindt

Hussam Mahmoud
Lori Peek
Therese McAllister

ABSTRACT

THE CONNECTIVITY BETWEEN DAMAGE TO PHYSICAL INFRASTRUCTURE AND SOCIAL SCIENCE: A NEW FIELD STUDY PROTOCOL CONCEPT

The primary objective of this thesis is to introduce a field study methodology that will be calibrated over the next several years to enable researchers to collect data in the field that can be used to better understand and quantify community resilience. Specifically, a key objective is to provide a mechanism to link damage to the physical infrastructure to social and economic dimensions of a community in a measurable way. Although there have been several past attempts at creating a common post-disaster field study protocol, none of them have attempted to quantify community resilience in a quantitative manner that can be used for risk and resilience analysis. The methodology explained in this thesis is unique because it discusses potential metrics that can be used to quantify community resilience and describes methods of quantifying these metrics using field data. These metrics come from a combination of disciplines including engineering, sociology, and economics. This work combines a literature review of past field study protocols with perceived data requirements in order to outline a field study methodology that can be used for disasters (primarily natural; not anthropogenic) of any type including tornados, hurricanes, flood, tsunamis, wildland-urban interface (WUI) fires, and earthquakes. Algorithms were derived that include the ability to process raw field study data in order to create probabilistic models of resilience metrics (i.e., fragility functions). These algorithms were then demonstrated using existing field data related to population dislocation caused by Hurricane Andrew. Finally, a community resilience field study was conducted five years into the recovery process in order to investigate and model the long term effects of the May 22, 2011 tornado that occurred in Joplin, MO. The planning and execution of this study is described and the data that was gathered is used to provide an illustrative example of the interconnectivity between the physical damage and socio-economic consequences.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the efforts of my advisor, John van de Lindt and thesis committee members, Lori Peek, Hussam Mahmoud, and Therese McAllister, who provided advising, direction, and review. It was also greatly influenced by the ideas and experiences of many members of the NIST Center for Risk-Based Community Resilience Planning, including Jennifer Tobin-Gurley at Colorado State University and Walter Peacock and Nathanael Rosenheim at Texas A&M University. This study was sponsored by the National Institute of Standards and Technology (NIST) through cooperative agreement 70NANB15H044 to Colorado State University. That support is gratefully acknowledged. The views and opinions expressed in this thesis do not necessarily represent those of NIST or the Department of Commerce.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Background

This thesis describes a field study methodology that has the objective of linking the socio-economic dimensions of a community with the physical effects on a community's infrastructure that are caused by a natural hazard. The NIST Center for Risk-Based Community Resilience Planning is a NIST Center of Excellence (CoE), which is headquartered at Colorado State University (CSU) with nine partnering universities across the U.S. This five-year project is focused on developing a computational environment called Interdependent Networked Community Resilience Modeling Environment (IN-CORE). IN-CORE is a research tool that will allow researchers a mechanism to study and quantify resilience and provide informative decision-making support for communities. The methodology outlined in this thesis explains the process of generating fragility functions for resilience metrics, which are typically driven by socio-economic consequences, which can be added to the IN-CORE databases once a series of field studies are conducted.

One of the tasks within the NIST CoE involves conducting several resilience field studies in communities that have been affected by disasters. The methodology presented in this thesis has been created in order to provide a mechanism to develop fragility functions that link hazard intensity and potential resilience metrics. This, in turn, will provide insight into what data should be collected in the field to allow researchers to build the necessary databases for IN-CORE. This methodology focuses primarily on the socio-economic consequences resulting from damage to physical systems. Social and economic changes can also impact physical systems, but those effects are not considered in this body of work. This thesis primarily focuses on the social consequences of physical damage and only briefly discusses economic impact studies, which are typically performed using secondary data. However, it will be important for future work to create new data collection procedures that allow economists to use primary field data to quantify fiscal impacts. That work, however, is outside of the scope of this thesis.

Presidential Policy Directive 21 (PPD-21 2013) defines resilience as “the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions.” NIST defines a community as “a place designated by geographical boundaries that functions under the jurisdiction of a governance structure, such as a town, city, or county.” However, it is also important to understand that communities are composed of smaller sub communities that are formed by people who share views, values, perspectives, and life circumstances (Kwasinski et al. 2016). By combining these two definitions the term community resilience can be better understood. We have defined two major goals for community resilience field studies:

1. To quantify the connectivity between physical damage and socio-economic consequences. This includes immediate effects such as damage, but should focus on long-term recovery.
2. To collect the data needed to develop probabilistic models of community-level resilience metrics for eventual addition to IN-CORE databases.

The methodology presented in this thesis demonstrates the procedure to achieve these goals during a field study. Chapter 2 describes a review of past protocols for conducting field studies after natural disasters and identifies gaps in the current process typically used to conduct post-disaster field reconnaissance. Chapter 3 discusses a conceptual framework for assessing resilience at the community scale that was created by NIST and identifies seven crucial resilience metrics that form the basis of this protocol concept. In Chapter 4 a diagram is presented that provides field questions that focus on the interconnectivities between the physical, social, and economic domains within a community, and a sample field study questionnaire is also provided. Throughout this thesis, the term “connectivity” is used to represent the linkage across physical, social, and economic community domains, and the term “dependency” is used when referring to linkages between physical systems only. Chapter 5 includes some practical suggestions for planning and executing resilience-focused field studies. Chapter 6 describes algorithms that were created to process field data in order to generate fragility functions for evaluating resilience metrics. These algorithms were tested using household population dislocation data from Hurricane Andrew and the results are shown in Chapter 7. Chapter 8 provides an illustrative example of a field study that focused on connecting physical damage to socio-economic consequences in support of a hindcast for Joplin, MO about five years after it was devastated by an EF-5 tornado. Finally, Chapter 9 provides final conclusions, describes the significance of this thesis, identifies data concerns, and outlines future work that should be done in this area.

2. Literature Review

Since the origin of modern disaster research, field studies have been conducted in the aftermath of disaster events to investigate and improve the built and social environments. Traditional field studies typically focus on either infrastructure performance or human behavior. Further, the majority of past field studies have focused on a single sector of the infrastructure within a community or city with the intent to, for example, improve building codes or establish public policy of some sort. Very few field researchers have attempted to investigate the interconnectivities of physical systems, economic structure, and social vulnerability within a community. As the field of disaster research shifts to the new paradigm of improving a community's resilience to natural (or other) hazards, field researchers must begin studying system interconnectivities within communities. This thesis begins by reviewing thirty-five relatively recent field studies from different disciplines and across different natural hazards with a focus placed on their stated or implied protocol. The first goal of this review is to identify common features from each field study protocol in order to lay the ground work for the development of a community resilience study protocol and provide a brief overview of the current methods, tools, and strategies that are being used for field studies. The second goal is to identify gaps in past field study protocols related to collecting data for the study of community resilience. Each study that was reviewed was carefully selected with the guidance of leading experts in disaster field studies in order to provide the reader with a broad understanding of field study protocols for various disciplines and natural disaster types.

Following this review of past field study protocols, a brief overview of the dependencies and interdependencies of critical infrastructure systems is provided in order to highlight the complexities of infrastructure systems and the difficulties that are associated with attempting to quantify the resilience of these systems.

2.1. Field Study Protocols Literature Review

In order to learn from past field study protocols and the large volume of literature that exists in disaster research, thirty-five past field/case study reports were examined. It was not the intent of this selection to be exhaustive, which would involve hundreds and even several thousand studies, but rather to select a large enough sample with breadth across the three disciplines that intertwine to form the basis of modern community resilience analysis, namely engineering/physical infrastructure, social dimensions (including epidemiology), and economics. These studies were selected by first consulting leading experts in each discipline and then choosing studies that the author believes present a case for understanding the tools and strategies that have been used to conduct field studies of various disciplines for various types of natural disasters. There are many more studies that meet these criteria and could have been included; however, it is believed that the papers presented in this thesis provide the reader with a fundamental understanding of multi-disciplinary field studies and provide direction for future field studies that will focus on community resilience. Thus the reviewed reports included: engineering (17), sociology (6), economic (7), and epidemiologic (focusing on physical and mental morbidity and mortality) (5) studies. Several of the studies were multi-disciplinary and care has been taken to consider them as such, but they have been classified by their primary objective. The reviewed reports covered a number of natural hazards including earthquakes, wildland-urban interface (WUI) fires, tornadoes, floods, hurricanes, and tsunamis. Several of the reports are classified as case studies because the authors did not go into the field to collect data; instead they analyzed data obtained by others, which is often characteristic of economic loss studies since those data are typically not available for some time after the event. The sample of reports also contains a combination of quick response and long term investigations. Quick response investigations are typically conducted quickly after the disaster, as their name implies, in order to obtain cross sectional data about the community and are useful for collecting perishable data but fall short in understanding a community's recovery over time. Long term studies are more useful for studying community resilience because they collect data that relates to the community's recovery in the years following the disaster.

Figure 2-1 presents a schematic showing the primary focus area of each of the studies that were examined as part of this literature review. This schematic shows that although several of the field studies were multi-disciplinary, none investigated all four categories where community resilience is depicted. It is important to note that while it was convenient for us to make edidemiology its own category for the purposes of this literature review, it is not being considered as its own community domain. Instead, it is typically considered to be a subset of the social domain. The studies that did investigate multiple domains within the community focused only on individual systems within the community instead of the linkages between systems that can affect a community's resilience. For each study reviewed in this chapter the data collection methods, strategies, tools, personnel, and decision making processes were identified, and then each report was summarized and critically analyzed to determine its effectiveness. It is envisioned that identifying the methods and tools used by researchers can inform what will be effective for conducting community resilience field studies. Additionally, all study methods and tools that were not effective were identified. This chapter reviews and assesses past field studies for the three key domains that, together, form the basis for understanding community resilience field studies: physical systems, social science (including epidemiology), and economics.

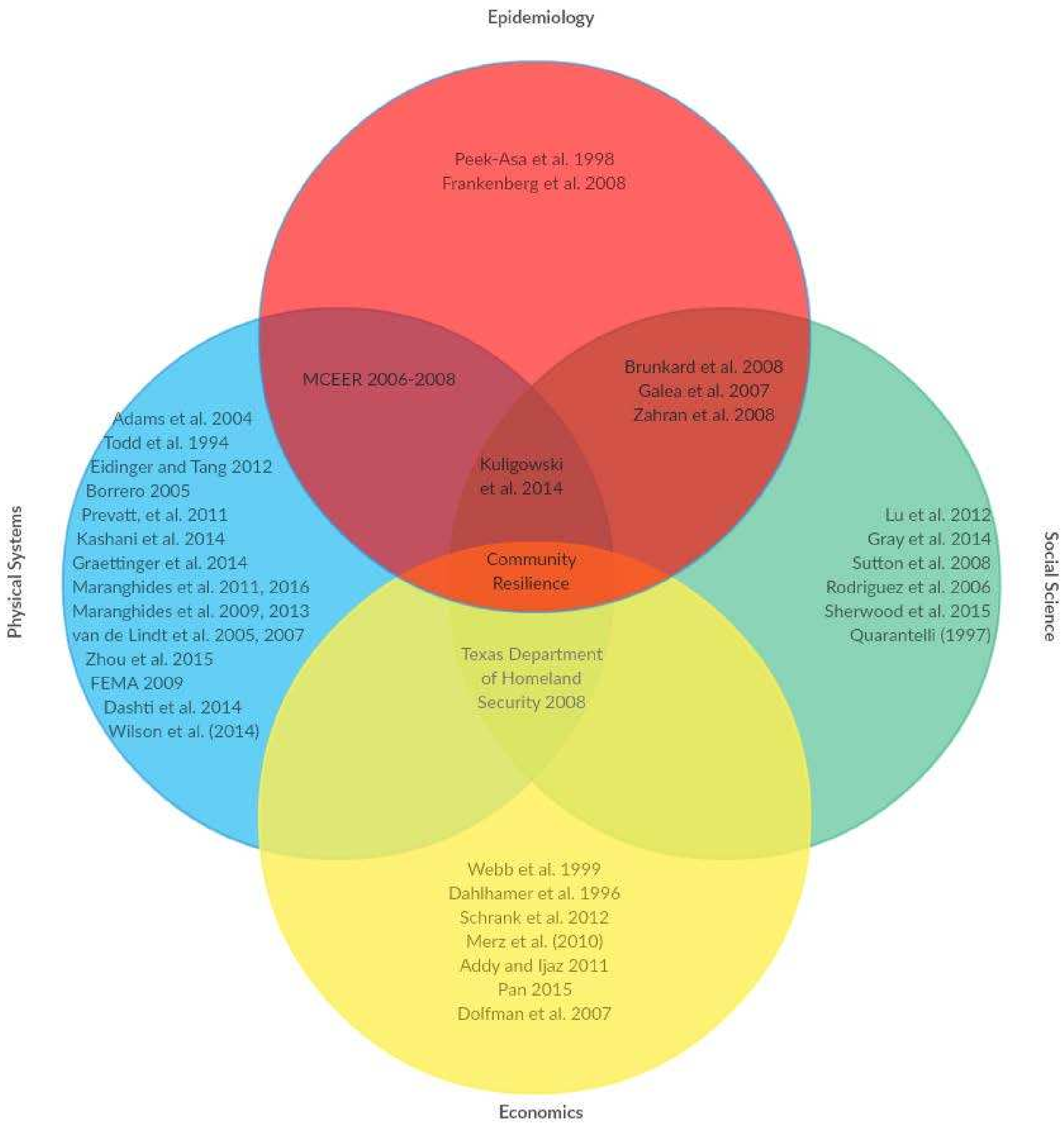


Figure 2-1: Reviewed Reports by Primary Objectives

Table 2-1 provides a list of all the reports that were reviewed, the hazard type, the location, and a summary of the researchers' methodology. While reviewing each of these reports, the primary focus was on the protocol, data collection methods, strategies, tools, and personnel that were used to collect field data.

Table 2-1: Field Study Protocols Comparison

Reference	Hazard Type	Location/Name (Year)	Study Type	Summary of Approach	Positives	Negatives
Adams et al. (2004)	Earthquake	Boumerdes, Algeria and Bam, Iran (2003)	Engineering	Pre and post-disaster satellite imagery was purchased and algorithms were used to identify low resolution damage to buildings. All images were geo-tagged and were used to guide field researchers to the most damaged building clusters. This methodology is difficult to apply to any earthquake event because building stock and construction material may change depending on the location of the earthquake. The algorithms must be modified for different sites.	Field researchers were guided to points of interested by VIEWS technology. This aids in planning of field activities and reduces wasted time in the field.	It is difficult to obtain high resolution imagery. This problem is solved through either the use of expensive high resolution instruments or algorithmic improvements as in Zhou et al. (2015).
Todd et al. (1994)	Earthquake/ Fire	Northridge, CA (1994)	Engineering	A team entered the field quickly to obtain perishable data. They tried to represent the whole community with a moderate sample size. Used notes, photos, and recorded interviews. They started near the epicenter and investigated outward, focusing on only the most damaged components of the infrastructure. They collaborated with other research organizations to obtain additional data. They also investigated the cause and effects of the post-earthquake fire.	They were able to be site immediately after the earthquake and used minimal resources to obtain data related to damage to built infrastructure.	There were elements of community resilience that were not considered in their scope. They investigated damaged structures, but lacked resources to investigate undamaged structures.
Eidinger and Tang (2012)	Earthquake	Christchurch, New Zealand (2010-2011)	Engineering	The team focused on lifelines and worked closely with private and public lifeline companies to obtain data. They supplemented this data with field notes and photos, while focusing on damaged systems that would allow them to easily collect data.	They were able to use external resources and connections with private companies and city engineers to access large amounts of	They did not emphasize the interconnectivities of lifelines and other infrastructure systems. They only investigated the most damaged systems.

					data.	
Borrero (2005)	Tsunami	Sumatra, Indonesia (2004)	Engineering	A field team was deployed to northern Sumatra seven days after the earthquake and tsunami. Their purpose was to study the characteristics of the tsunami inundation, the structural damage, and the shoreline erosion. They used field notes, interviews with community members and government officials, and aerial and ground-based geo-located images as their methods of data collection.	They were able to conduct a quick and inexpensive preliminary field investigation, and their collaboration with other entities allowed them to gain access to additional data.	They focused primarily on the wave characteristics and did not study other aspects of community resilience. Their data collection methods did not allow them to collect high resolution data.
Kuligowski et al. (2014)	Tornado	Joplin, MO (2011)	Multi-disciplinary	This holistic technical investigation analyzed the tornado hazard, damaged and non-damaged structures, lifelines, disaster warning, morbidity, mortality, and emergency response. They used traditional field techniques to collect data including transcribed interviews, photos, field inspection data, etc. The main focus was on improving codes and public policies.	They thoroughly investigated all community sectors. They were able to approximate wind speed from treefall in specific locations which helped them compare actual loading with code recommended loading.	While this study was multi-disciplinary, they did not attempt to connect disciplines in order to quantify the community's resilience. They analyzed different sectors of the community independently.
Prevatt et al. (2011)	Tornado	Tuscaloosa, AL (2011)	Engineering	Wood frame buildings that were in the path of the tornado were investigated. The team investigated transects perpendicular to the path of the tornado that were a half mile apart and a half mile long. LiDAR scanners were used to capture high resolution data.	The method of dividing the community into transects allowed them to obtain a representative sample of the	They only inspected damaged structures. The report was not multi-disciplinary, focusing on engineering aspects.

					entire community.	
Kashani et al. (2014)	Tornado	Tuscaloosa, AL (2011)	Engineering	This report outlines a methodology that can be used to estimate percentages of damage to walls and roofs after a tornado event. A wind estimation model then used these damage estimates to approximate the likely wind speeds at the structure. This methodology was also employed by Graettinger et al. (2013) after the tornado in Moore, OK. It uses terrestrial laser scanners to capture post-event geometries and aerial photography to capture pre-event geometries. Then it automatically estimates the damage based on differences in geometry using custom made GIS software. The method is tested for accuracy using data from the 2011 Tuscaloosa tornado.	Ground based scanners were used because they provide higher resolution data than aerial based scanners. They were able to provide accurate damage assessments and wind speed estimation with minimal time and effort.	Obtaining post-event geometric data is a slow process due to the use of ground based scanners. They were only able to evaluate a small sample of structures. Aerial based scanners and field teams are able to collect data for much larger sample sizes.
Graettinger et al. (2013)	Tornado	Moore, OK (2013)	Engineering	This approach was similar to the approach taken by Prevatt et al. (2011). Wood structures were investigated in perpendicular transects to the tornadoes path. However, this study introduced an automated damage assessment and wind speed estimation methodology using 3-D laser scanner data as described by Kashani et al. (2014). The authors also placed an emphasis on data collection through social media. All data points were spatial and temporal, and LiDAR scanners were used to capture high resolution data.	All team members collected all types of data which allowed for a robust data set. The focus on data collection through social media allowed them to identify areas of interest.	This was a rigorous and well performed study for the inspection of wood structures only. However, this procedure would require substantial resources if it were expanded to investigate all aspects of a community's resilience.
Maranghides (2009, 2013)	WUI	Witch Creek Canyon, CA and Rancho Guejito, CA (2007)	Engineering	Performances of residences were investigated by field researchers. The initial team was deployed 4 days after the fires. They investigated a single	Their heavy collaboration with other organizations	LiDAR is not able to see through solid objects so it was insufficient for data

				community that was highly affected by the fires. Interviews, surveys, field notes, and remote sensors were used for data collection. A combination of aerial and ground based imagery was used. The first priority of the field team was to collect perishable data (e.g., completely burned structures). Remote sensor data sources included: Pictometry, Ortho-rectified Imagery (USGS), Google Imagery, Ortho-rectified Imagery (San Diego State University), LiDAR, Property boundaries (SanGIS), and Vegetation Community Types (SanGIS). This provided oblique imagery, aerial imagery, point measurements, and vector GIS data.	allowed them to access additional, necessary information. They were able to develop a fire timeline using interviews of first responders. The report was rigorous and provided a very good understanding of the fire behavior.	collection related to burned vegetation. They were not able to gain access to certain properties, and they were not able to make conclusive observations of totally burned elements. They had some issues with inconsistencies in interpretations of the damage observations.
Maranghides et al. (2011, 2016)	WUI	Amarillo, TX (2011)	Engineering	The focus was on only one of the three areas that were affected by fire. Two to four teams spent 21 days in the field investigating performance of structures and to recommend changes to standards and codes. The study was performed in two tiers: WUI 1 was used to collect general data across the perimeter of the fire and WUI 2 was used to collect in depth fire behavior, timeline, defensive action, and structural performance. Tools used include digital cameras, aerial photography, field notes, remote sensing technology and more.	Due to lack of necessary technology, very few comprehensive WUI fire field studies have been performed. This field study was more rigorous than most other studies. They were able to enter the field within 48 hours and collect perishable data.	GIS data was too large to transfer to the remote GIS team. They suggest having the GIS team on site in the future.
MCEER (2006-2008)	Hurricane	Katrina (2005)	Multi-Disciplinary	This five volume report was a multi-disciplinary effort to study the impact of the hurricane on physical systems and response and recovery efforts.	This is one of the few studies that was truly multi-	They did not attempt to connect socioeconomic factors and damage

				They investigated advanced damage detection using remote sensing, damage to engineered structures, organizational decision making primarily in hospitals, and environmental and public health issues. They used face to face and telephone interviews to collect qualitative data, and numerous remote sensing tools, field journals, and aerial and ground-based imagery to collect quantitative data.	disciplinary. They made excellent use of interviews and remote sensing technology to collect data that was useful for studying community resilience.	to physical infrastructure. They treated physical, economic, and social issues as independent.
Van de Lindt et al. (2005, 2007)	Hurricane	Katrina (2005)	Engineering	The most damaged wood-frame structures were investigated over a three day period by a field team. This team investigated more than 27 structures (or neighborhoods) in order to determine the effectiveness of codes and construction practices. The tools that they used in the field consisted of handheld cameras and field notes. Wind speed estimates were obtained from the NOAA.	This detailed and focused study allowed investigators to understand the specific causes of failure of wood-frame structures under wind loading.	The sample they investigated only included heavily damaged structures. They did not attempt to connect the performance of wood structures to other aspects of the community.
Zhou et al. (2015)	Hurricane	Sandy (2012)	Engineering	In order to provide a detailed damage assessment of residential buildings, dozens of images were taken of each structure by field teams. These images were then reconstructed in 3D using both 123D Catch and SURE software. The results from these two methods were compared with the results from a LiDAR scanner, and it was determined that the use of SURE software is more accurate than the use of 123D Catch software.	This method allows high quality, 3D point cloud data to be captured without the use of expensive instruments such as LiDAR.	In order to obtain good results, image overlap should be about 90%. In order to capture the images of the roof, UAVs should be used. This method does not work for extremely detailed assessments (e.g., displacements <1cm).
Texas Department of Homeland Security (2008)	Hurricane	Ike (2008)	Multi-disciplinary	This case study investigated four areas: the social, built, economic, and natural environments. They did not obtain any data from the field	They were able to obtain vast amounts of data without ever	They did not identify all of their data sources. They investigated the

				themselves. Instead, they obtained data from government agencies, university researchers, and online resources. They focused on reporting the broad impacts of the hurricane and not on minute details.	entering the field through connections with other agencies and researchers.	individual aspects of community resilience, but did not discuss their interconnectivities.
FEMA (2009)	Flood	Midwest Floods in Iowa and Wisconsin (2008)	Engineering	FEMA first sent a pre-MAT in order to conduct a preliminary assessment of the flood damage. They used this preliminary data to decide if they were going to send a full MAT into the field and to develop data collection strategies. They inspected the most damaged buildings and structures to determine causes of damage and loss of functionality. Their purpose was to provide recommendations that would reduce future damage and update building codes. They also conducted brief studies of social and economic losses and disaster preparation and response effectiveness.	The study was extremely detailed and thorough in regards to damage to buildings and other structures. They were able to investigate many different communities effectively which is important for investigations of widespread disasters.	They were primarily interested in the causes of structural damage. While they did briefly discuss social and economic losses, they did not attempt to connect these losses to physical infrastructure.
Dashti et al. (2014)	Flood	Colorado Flooding (2013)	Engineering	The twitter API was used to search for keywords, user IDs, and geographic locations in tweets during the flooding. 212,672 unique tweets were collected and 2,658 of them were geo-located. These geo-located tweets were then combined with hazard maps and other remote sensing data (e.g., satellite imagery) in order to aid more detailed field research activities.	A massive data base was created by using passive data collection activities that are both inexpensive and effective. Perishable data was captured that may have otherwise been lost.	Using this method made it difficult to geo-locate. Data may not be technical or detailed. This methodology is only used as an aid to additional field study activities.
Wilson et al. (2014)	Tsunami	N/A	Multi-Disciplinary	This section identifies 10 crucial components of a post-tsunami field	The authors help identify	The protocol is very general. It

				study. It was created based on the experience of tsunami field study experts. It focuses on the logistical issues of communication, coordination, and collaboration. Some of the most important components include: staying in constant contact with the local area's event coordinator, including a local expert on your team, and sharing data with other researchers.	several important factors to conducting a field study without wasting time and resources. It also provides guidelines for accessing restricted areas.	provides advice on general procedures when dealing with local community members, the government, and other researchers.
Lu et al. (2012)	Earthquake	Haiti (2010)	Sociology: Dislocation	This study tracked the locations of 1.9 million Digicel mobile phone users 42 days before to 341 days after the 2010 Haiti Earthquake. The data from Digicel allowed them to obtain one location data point for each mobile user per day. The locations of the users were tracked to mobile phone towers which limited the study's spatial resolution. They concluded that dislocation after disasters can be predicted with decent accuracy.	Collaboration with Digicel allowed them to obtain a massive data set. It also allowed them to avoid the bias of interviews and to obtain data at any point in time or space. Cell phone use is more prevalent in developed countries.	The sample was limited because it only included Digicel users. The time and space data resolution was limited (1 data point per day and up to tens of kilometers between data points). Power outages and lack of charging stations caused further data issues.
Gray et al. (2014)	Tsunami	Sumatra, Indonesia (2004)	Sociology: Dislocation	A baseline survey was conducted before the tsunami and about 10,000 follow-up interviews were conducted afterwards. The respondents were tracked and interviewed annually for 5 years. Similar to Adams (2004), damage estimates were developed by using satellite imagery before and after the tsunami. Multivariate statistical methods were used to analyze the data.	Local students conducted the interviews and less than 1% of the respondents declined a follow-up interview. An unbiased sample of both damaged and	Some qualitative data were lost due to the large scale of the project. It was difficult to find many of the respondents from the original survey after the tsunami.

					undamaged locations was collected.	
Sutton et al. (2008)	WUI	California (2007)	Sociology: Social Media Data	The goal of this report was to use empirical data to show the importance of social media playing a role in “backchannel” communication during disaster recovery. They used a combination of an initial field reconnaissance and a secondary online survey to gather data related to the use of Information and Communication Technology (ICT) by community members during recovery. They recruited participants for their online survey using local forums, online newspapers, Craigslist, Facebook, and Flickr.	The initial field reconnaissance allowed them to develop strategies and questions for their follow up survey. They were able to reach a large number of participants using little time and effort due to recruiting on social media.	These techniques that were used to obtain qualitative and quantitative data. However, the sample was limited because only social media users were able to access the survey.
Rodriguez et al. (2006)	Hurricane	Katrina (2005)	Sociology: Community Behavior	In order to study the pro-social behavior that occurred after Hurricane Katrina, the authors relied heavily on collaboration and fieldwork done by others. They chose a specific time period to study a representative sample of the community. Firsthand accounts were considered more credible than media accounts. There was a focus on studying improvised decision making.	The authors saved time and money by building on the work of others and studying a representative sample of the community.	Any propagation of data that were collected by others would be difficult to quantify.
Sherwood et al. (2015)	Typhoon	Super Typhoon Haiyan: Philippines (2013)	Sociology: Dislocation	This study used qualitative and quantitative data to draw conclusions about dislocation in the aftermath of the 2013 Typhoon in the Philippines. The quantitative data were collected through a questionnaire that was distributed to 4,518 households in 43 municipalities within the most damaged region. The qualitative data was collected in two stages with the	The qualitative data was combined with the qualitative data to draw important conclusions. It is important for the NIST Center’s	They only investigated the most damaged region which represented a fraction of the total damaged area and dislocated population. Data were collected

				findings from the first stage informing the development of the second stage. Methods included: focus groups, individual interviews, and site visits.	protocol to have the similar capabilities of collecting both data types.	about 2 years after the event which may have caused data inaccuracies due to memory loss of the interviewees.
Quarantelli (1997)	Various	Various	Sociology: Community Behavior	This section summarizes the protocol used in hundreds of field studies conducted by the Disaster Research Center (DRC). Graduate students were trained and used to conduct field studies in a cost effective manner. One member of the team was put in leadership in order to make crucial decisions on the direction of the field study. They were prepared to travel at all times. Formal questionnaires were used, and questions were open ended. Photos were taken and interviews were recorded then transcribed.	Using graduate students for field work kept costs low. More experienced GRAs would train less experienced GRAs.	Transcribing all of the interviews was tedious and time-consuming work, and they eventually lacked funding.
Peek-Asa et al. (1997)	Earthquake	Northridge, CA (1994)	Epidemiology	In order to study the quantity and causes of injuries due to the earthquake, the authors obtained data from the Los Angeles Department Coroner. They then screened every hospital in the county to check for earthquake related check-ins. The injuries were coded using the AIS scale, and related building inspection data was purchased from the local department of building and safety. There is always a great deal of uncertainty about quantity and type of injuries following a major disaster.	They were able to link injuries to building damage states which is a crucial element to the NIST Center's protocol. The study was rigorous and comprehensive.	Complete autopsies and list of injury diagnoses were not always available, and the hospital screening process may have missed some earthquake related injuries.
Frankenberg et al. (2008)	Tsunami	Sumatra, Indonesia (2004)	Epidemiology	In order to assess the posttraumatic stress reactivity (PTSR) of over 20,000 tsunami survivors, the authors collected and analyzed survey data from coastal locations. This technique is similar to Galea (2007). Pre-event	They were able to utilize pre-disaster interviews to obtain a base line for mental	Their focus was only on PTSR not on any other mental illnesses. There were inaccuracies due to

				interviews were conducted with local residents and 97% of them were tracked down and interviewed after the event. PTSR levels were analyzed for correlation with damage states, socioeconomic factors, and numerous other demographic data.	health. The survey removed bias by including individuals from undamaged areas as well as damaged areas.	assessing mental health using a survey method instead of clinical interviews by medical experts.
Brunkard et al. (2008)	Hurricane	Katrina (2005)	Epidemiology	This case study provided an upper and lower bound estimate on deaths caused by Hurricane Katrina. They obtained their data from the Hurricane Katrina Disaster Mortuary Operational Response Team (DMORT) database and death certificates collected through Louisiana vital statistics and out-of-state coroners' offices. They then grouped and analyzed these data by cause of death, race, gender, time of death, location of death, and age.	Obtaining the data from reliable, external sources allowed them to quickly and cost effectively meet their research goals.	Mortality estimates were conservative because they included people who died months after the disaster and people who died from pre-existing conditions. It is difficult to determine whether or not the disaster was the cause of these deaths. They were not able to account for missing persons and bodies that were never found.
Galea et al. (2007)	Hurricane	Katrina (2005)	Epidemiology	Between 5 and 7 months after the hurricane, over the phone surveys were conducted with 1,043 residents of Alabama, Louisiana, and Mississippi who were affected. This survey included a screening scale, called the K6 scale of nonspecific psychological distress, to estimate mental illness in each respondent. The survey included 29 questions. The data was analyzed for association between mental illness and the	Using over the phone surveys allowed the researchers to obtain a large sample size using relatively low funds. The person delivering the survey does not necessarily	It was difficult to find and contact people who were affected by the hurricane. Using screening scales rather than clinical interviews causes less precise estimations of mental illnesses. The sample was

				following factors: age, sex, race/ethnicity, family income in the year before the hurricane, education, pre-hurricane marital status, and pre-hurricane employment status.	have to be skilled or have experience in disaster research.	limited because it did not include people who could not be reached by telephone.
Zahran et al. (2008)	Flooding	Texas (1997-2001)	Epidemiology	In order to analyze the correlation between vulnerable populations and casualties due to extreme flooding events, this study analyzed 832 floods over a four year span from 74 counties in Texas. They did not collect any field data. Instead, all of their data was retrieved from external sources (typically government agencies). They used three predictors of flood casualties: population density, local preparedness, and presence of socially vulnerable populations (e.g., low income and minority populations). They adjusted for characteristics of the natural and built environment such as number of dams and percentage of impervious surface.	They were able to obtain large mortality data sets without ever deploying into the field. They were also able to account for many important factors of mortality such as built and natural environment characteristics and socioeconomic vulnerability.	Their data was limited to the county level so they could not determine the socioeconomic status of individuals who were harmed by flooding.
Webb et al. (1999)	Earthquake and Hurricane	Loma Prieta Earthquake (1989) and Hurricane Andrew (1992)	Economic	A long-term disruption model for individual businesses was created that included five components: business and owner characteristics, previous disaster experience, direct and indirect disaster impacts, loss containment measures, and owner perceptions of the business environment. In order to model these 5 components, surveys were mailed to all businesses in two separate communities that had survived a recent disaster. These surveys were completed 6 years after the hurricane and 8 years after the earthquake. They used a combination of mail surveys and phone calls (“total	They were able to contact every business in the community due to the quick and easy nature of mailed surveys. This was a rigorous study that quantified individual business disruption in a way that no other study had done	The sample was limited because they were only able to contact businesses that had survived the disasters. They also did not account for broad economic trends that may have affected business performance. The response rate was low (27% and 34%) due to the

				design method").	previously.	impersonal nature of mailed surveys.
Dahlhamer et al. (1996)	Earthquake	Northridge, CA (1994)	Economic	This study investigated business recovery after the 1994 Northridge earthquake. Similar to Webb et al. (1999), they used a combination of mail surveys and phone calls ("total design method") to obtain data. A random sample of 1,110 Los Angeles area firms was surveyed. A three staged stratified sampling design was used, with shaking intensity and type and size of business used as stratifying variables.	This report outlines a rigorous and systematic method of quantifying business recovery after disasters. The "total design method" improves the response rate of the surveys.	There was a large amount of variance which the authors were not able to explain. Also, they only accounted for businesses that recovered and neglected those that did not recover (or closed), and they did not investigate causes for businesses performing better as a result of the disaster.
Schrank et al. (2012)	Hurricane	Katrina (2005)	Economic	This paper proposes and tests a methodology for locating and contacting demised small business owners. They purchased the 2004 D&B dataset and the 2009 D&B dataset which contain information on all businesses in a region. They were then able to determine which businesses started and which businesses ended after Hurricane Katrina. They then hired students to use a desktop search process called "record linkage" in order to obtain contact information for the most of the demised businesses.	This desk study method can be performed by students with little prior training with a higher success rate than deploying a field team, minimizing the cost of fieldwork.	The desk study is very labor intensive. D&B records have some inaccuracies. If possible, state business license records should be used instead.
Merz et al. (2010)	Flood	Various	Economic	General guidelines are provided for performing economic flood damage assessments including conducting uncertainty analyses. The differences between quantifying direct losses and indirect losses and the positives and	Many economic models used for flood damage assessments are oversimplified and do not	This report does not provide the standardized methods and strategies that are needed for future

				negatives of different economic models are discussed. There is currently no standardized method for flood data collection, but it is important for it to be developed.	quantify their error. This methodology provides a means for fixing these problems.	economic flood damage assessments.
Addy and Ijaz (2011)	Tornado	Alabama (2011)	Economic	This case study approximated the preliminary fiscal impact of several tornadoes that went through Alabama in the spring of 2011 by analyzing data from various federal and local sources. Metrics that were analyzed include changes in employment, state tax collections, Alabama Gross Domestic Product (GDP), local tax collections, and the effect of cleanup and re-building. Uncertainty was accounted for by providing low and high end estimates.	In order to simplify the analysis, multipliers from the Regional Input-Output Modeling System (RIMS II) from the BEA were used to account for unknown variables.	Their method of analyzing tax data did not allow them to estimate fiscal recovery in the community, requiring them to make additional assumptions. The report also did not account for quality of life, physical and mental health issues, and displacement.
Pan (2014) - ASCE	Hurricane	Ike (2008)	Economic	Pan developed a new framework for evaluating direct and indirect economic loss after hurricanes. He gauged the accuracy of his predictions using work from other researchers and Hazus models. Like Addy and Jiaz (2011), he relied entirely on external sources for data. He used GIS data and spatial allocation models to estimate economic loss and assign losses to small zones within the community	His case study approach allowed him to evaluate direct and indirect economic loss using data from others. His use of existing software helped him to estimate the error in the method.	There is significant uncertainty in economic loss prediction models. Estimates were not as close to the estimates as those made by other researchers.
Dolfman et al. (2007)	Hurricane	Katrina (2005)	Economic	This case study utilized data from the Quarterly Census of Employment and Wages (QCEW) program of the Bureau of Labor Statistics to analyze employment and wage patterns in	The authors provided a broad overview of the effect of the disaster on	They did not study the effect of the event on individual firms. They also focused only on

				New Orleans before and up to 10 months after the event. They utilized two methods: evaluate the concentration of jobs in each industry sector and compare with the national average and evaluate the number of jobs, total wages, and average weekly wages over time.	the New Orleans' economy. They obtained their data from external sources which saved time and resources.	wages and total employment.

2.1.1. Studies Focusing on Physical Systems

Sixteen field studies were reviewed with the primary objective of investigating the physical systems domain. The specific purposes of these field studies varied from improving building codes to simply providing a preliminary damage assessment. Although the disaster types and specific goals of each study were different, many of these field studies share common principles that may be important for field researchers to understand. The following sections will provide a brief overview of each of these sixteen field studies followed by observations and conclusions for field studies of physical systems.

Adams et al. (2004) discussed an application of remote sensing technology to damage assessment of buildings after the 2003 Boumerdes, Algeria and Bam, Iran earthquakes. The methodology described is an extension of previously developed and tested methods that have been used by research teams in the U.S., Japan, and Europe for earthquake damage assessments in urban environments. This methodology includes a Tiered Reconnaissance System (TRS) that is explained in Figure 2-2.

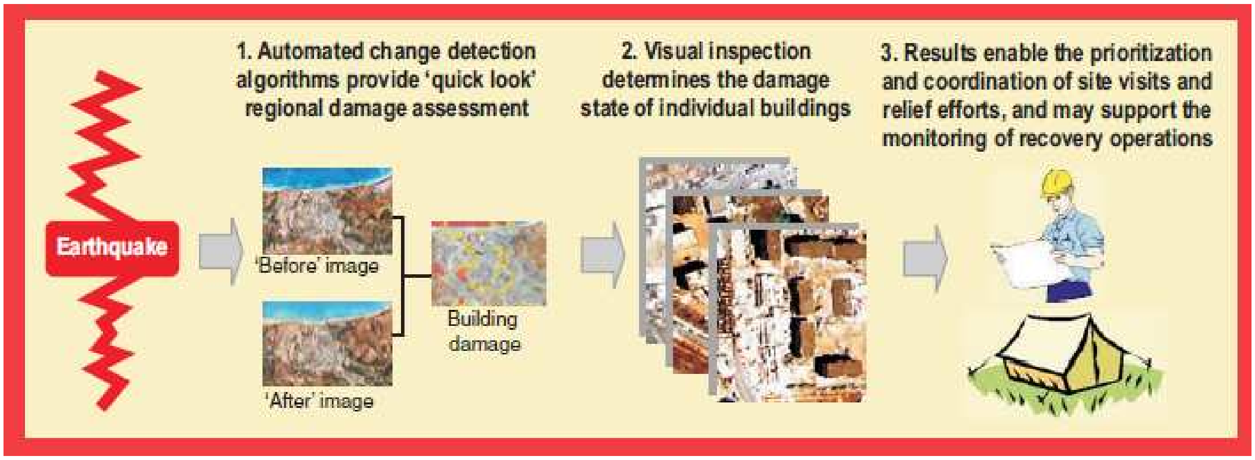


Figure 2-2: Schematic representation of the post-earthquake Tiered Reconnaissance System (Adams et al. 2004)

Satellite imagery from before and after the event was obtained from DigitalGlobe and analyzed using ENVI image processing software in order to obtain approximate building damage assessments. Building collapse was also identified using an algorithm which recognizes texture changes in the post-disaster imagery. The VIEWS (Visualizing Impacts of Earthquakes With Satellites) system translates this approximate damage assessment in order to guide field teams to locations of interest, and then enable them to record geo-located observations and damage descriptions. The authors also recommend using this system for monitoring cleanup and recovery activities. One challenge of using this method is that it is difficult to identify damage to buildings that are constructed from material that is similar in color and texture to the surrounding ground. This was an issue for the damage assessment after the Bam, Iran earthquake because the roofs were constructed from local, sand-colored material. Furthermore, it is difficult to create universally applicable algorithms because the algorithms vary by building stock and construction materials. Another issue that the authors mention is that it was difficult to obtain image resolution that was fine enough to accurately identify damage states for all buildings (Adams et al. 2004).

After the devastating and historic Northridge Earthquake that occurred near Los Angeles, CA in 1994, a field study was led by the National Institute of Standards and Technology (NIST) with the purpose of documenting the effects of the earthquake on the built environment (Todd et al. 1994). Their primary task was to document perishable information immediately following the disaster, and to be a catalyst for more in depth studies to follow. They began organizing their multi-disciplinary, multi-agency field team and preparing for the field study within hours of the event. The field team investigated damage to physical infrastructure caused by both the earthquake and post-earthquake fires, and provided recommendations for future studies and code revisions. They conducted interviews with the engineers who designed the infrastructure and obtained stamped drawing sets when possible. Their primary tools were recordings of their field observations and handheld cameras. They started their investigation near the epicenter of the earthquake and then made general observations of the damage that they saw for each building type, often assuming similar damage for similar types of buildings. They also investigated closures of medical facilities, commercial buildings, and bridges. Their approach to bridge damage assessment was to only investigate the few bridges that were most severely damaged. They were unable to inspect some bridges because demolition of the severely damaged bridges began within 24 hours of the event, presumably for public safety. When the bridge had already been demolished, they inspected what they could from what was left at the site. There were 163 bridges that were damaged, and they inspected about 5% of them. The NIST team also investigated lifeline systems at sites where they were already studying a structural system. A small section was written on airport and railroad damage, but minimal field study data were actually gathered. The post-earthquake fire data were gathered by interviews, news articles, and observations of the sites. Collaboration with other organizations was crucial for the success of this field study. The NIST team collaborated with the Earthquake Engineering Research Center (EERC) at the University of California in Berkeley, CA and the Federal Highway Administration (FHWA) to obtain additional data (Todd et al. 1994).

The American Society of Civil Engineers (ASCE) conducted a field study in order to investigate the performance of lifelines after three earthquakes devastated New Zealand between September 4, 2010 and June 13, 2011 (Eidinger and Tang 2012). The field team investigated systems such as electric power, water, wastewater, gas and liquid fuels, an airport, roads, bridges, railways, levees, post-earthquake fire, and debris management. Their goal was to evaluate the damage done to each system, document the specific causes of that damage, and make recommendations to mitigate similar damage in the future. In order to investigate the electric power network and the telecommunications they analyzed all of the damage done to systems owned by private companies. They obtained data from these private companies by establishing connections with local engineers who then connected them with local companies. They used traditional field study tools such as photographs, field notes, and interviews in order to gather data for each of the three earthquakes (Eidinger and Tang 2012).

Seven days after an earthquake and tsunami occurred in northern Sumatra, Indonesia, a rapid response tsunami survey team deployed to the Banda Aceh, Sumatra region to study the characteristics of the tsunami inundation (Borrero 2005). The data that they collected related to tsunami characteristics, structural damage, and shoreline erosion. Field data that were collected included: field observations and notes, geo-tagged photos and videos of damage and inundation indicators, interviews with government officials and relief workers, reports, maps, and other materials related to the tsunami. Information about the wave characteristics was gathered through interviews with witnesses and videos taken during the event. The field study and digital topography data were then analyzed along with satellite imagery obtained before and after the event. They were also able to use photographs taken during a helicopter flight along the coast of Sumatra. Corresponding GPS locations were recorded for images. This report was not comprehensive. It only offered a preliminary investigation of the tsunami characteristics (Borrero 2005).

After the May 22, 2011 tornado that devastated Joplin, MO, NIST conducted a preliminary post-tornado field study (Kuligowski et al. 2014). The field team arrived in Joplin two days after the tornado and spent four days there. Their purpose was to perform a preliminary investigation of the performance of structures, human behavior, and emergency communications. This initial multi-disciplinary and multi-departmental investigation led to a more in depth investigation, which was conducted over a span of two years. The goals of this more detailed study were to investigate and recommend improvements for: structures and lifelines under tornado loads, tornado warning systems, emergency response procedures, fire codes for buildings, and public policy. Prior to the release of the final report, NIST released a special publication that outlined the approach and strategy of their technical investigation (Levitan et al. 2012). This preliminary report lists four primary objectives for the technical investigation. The first objective was to determine the tornado hazard characteristics by developing wind speed estimates from both direct measurement and indirect estimation from the environment (observing treefall) using techniques similar to Prevatt et al. (2011). This was done by collecting data on meteorological conditions, pre-storm natural and built environment conditions, post-storm conditions, and historical tornado information in the area. The second objective was to investigate the causes of fatalities and injuries and to analyze the effectiveness of the emergency communications. These data were gathered from semi-structured interviews (in person and over the phone) with first responders, business owners, and friends and families of the injured or deceased and from official records, publications, transcripts, news stories, and newspaper articles. Interview questionnaires were developed from a combination of the study's objectives, eyewitness news stories, and interviews conducted by the initial reconnaissance team. All interviews were transcribed and uploaded into a data analysis software tool to be analyzed similar to Quarantelli (1997). The third objective was to evaluate the performance of damaged and non-damaged residential, commercial, and critical buildings. Field observations and design drawings were obtained and analyzed, and the current building code's effectiveness was evaluated. The fourth and final objective was to determine the performance of lifelines by collecting and analyzing data that described the lifecycle of damaged lifelines using traditional observational methods. They used all of these collected data to identify areas in building codes, fire codes, emergency communication policies, standards, and practices that require revision. (Kuligowski et al. 2014).

After the April 27, 2011 Tuscaloosa, AL tornado, a field team was assembled with the purpose of evaluating failure modes of wood frame structures (Prevatt, et al. 2011). The team arrived in Tuscaloosa five days after the event and the investigation lasted three days. The field team investigated the six mile long fraction of the eighty mile long tornado path that ran through Tuscaloosa by investigating transects that ran perpendicular to the path of the tornado. These transects were approximately half a mile in length with half a mile between each transect, and damage assessments were performed for all buildings along each transect. The data from this assessment were then used to develop Enhanced Fujita (EF) wind speed ratings and capture damage distribution spatially over the community. Field data collection equipment included digital cameras, global position system (GPS) units, smart phones, and a ground based light detection and ranging (LiDAR) scanner. Text descriptions, field measurements, and hand sketches were also recorded. Each of the 6,000 photos that were taken was geo-tagged and positioned on a map. On the last day of the study, five locations were identified for capturing high precision geometric data. Team members used laser scanner units and panoramic photos to capture more detailed data in these five locations (Prevatt, et al. 2011).

Kashani et al. (2014) proposed a method for structural damage data collection following tornadoes. The proposed method, which was implemented after the 2011 Tuscaloosa, AL tornado, was to obtain GIS point cloud data from terrestrial scanners, and then compare these post-event data with pre-event aerial images to estimate damage and wind speeds at the locations of structures of interest. GIS models were used to overlay point data sets with image layers, and then customized algorithms automatically identified buildings, and assessed their damage state by detecting roof and wall surfaces and calculating the percent damage by comparing pre-event and post-event geometry by estimating polygons and comparing geometric differences. Then, based on the percentage of structural damage, a wind speed estimation model was used to find the wind speeds at each location. It was determined that this method slightly underestimated structural damage, but accurately estimated wind speeds. It was noted that, unfortunately, the scanning process is time consuming and does not allow a large sample size to be obtained. The benefit of an aerial data collection method is that it allows researchers to gather large amounts of data in a short amount of time. However, aerial collected data are often less detailed and at a lower resolution than data collected using ground-based methods, and aerial imagery only captures the tops of objects, making it difficult to observe vertical elements of structures. For longer buildings (more than 100 meters long) the building was divided into three segments and then damage and wind speed estimates were made for each of the three segments (Kashani et al. 2014).

After an EF-5 Tornado passed directly through Moore, OK in 2013, an initial field study reconnaissance team was sent into the city to investigate the performance of wood structures and storm shelters (Graettinger et al. 2014). The goals of the study were to provide recommendations for improving building codes, improving public policy, and assisting in post-disaster social media strategies. The damage data collection strategy was to investigate transects perpendicular to the tornado's path in order to create damage contour maps (similar to Prevatt et al. 2011). They obtained geo-located damage photographs through passive data collection on social media and supplemented this approach by actively requesting damage data from the community using social media. Additional data were obtained from storm chasers, news reporters, and others who photographed the event. Three days were spent investigating residential buildings and storm shelters using ground teams and aerial photography, and over 3,000 photographs were taken. All members of the field team collected all types of data, which enabled rapid data collection and the creation of a more robust dataset. During the day team members investigated areas of interest, recorded data, and took photographs, and at night the team compiled, geo-referenced, and analyzed photographs in order to create GIS maps. They then used these maps to plan the next day's work. All data were geo-located, using custom software created at the University of Alabama called Time-Image Positioning Software (TIPS), and stored in electronic format online providing easy access for various researchers. This data set is spatial and temporal because they geo-located data points and recorded the time that each data point was obtained. The method that was described in Kashani et al. (2014) was also used in two separate locations in order to conduct automated GIS damage assessments. This allowed them to compare pre-tornado geometry to post-tornado imagery, and automatically estimate structural damage. Teams consisted of 4 to 5 members that would investigate damage along transects until they reached a point where damage was no longer visible. The "Find Your Friends Application" for the iPhone was used to keep track of team members' locations. After the data were collected team members looked at a single photo of each structure to determine the damage state and estimate an upper and lower boundary on wind speed based on the Enhanced Fujita Scale (Graettinger et al. 2014).

NIST deployed a field team four days after the October 2007 California fires (Maranghides et al. 2009, 2013). The field data collection and processing lasted fourteen months. The field data collection effort took approximately 1300 person hours over fourteen months (not all in the field). They focused primarily on the Trails development at Rancho Bernardo in which seventy-four homes out of 270 were destroyed and sixteen homes were damaged. This study included event timeline reconstruction, general fire behavior observations, and the effect of structure attributes, landscaping characteristics, topographical features, and potential wildland fire exposure on structure performance. Data collected in the field included structure particulars, specifically roof type, proximity of combustibles to the structure, and damage to wildland and residential vegetation. Some of the questions that they attempted to answer with field data included: How far within the Trails did the fire spread? To what extent did embers contribute to ignition of structures? Why did the fire spread stop when it did? Did all the structures ignite from the passage of the wildland fire front, or were some structures ignited later and why? Field researchers used prescribed field forms to record data and took over 11,000 photos. Then emergency responder data logs were obtained, and first responders and members of the Trails Homeowners Association (HOA) were interviewed in order to develop a fire timeline. A survey was then sent to each member of the community by the Trails HOA. After that the community was re-visited by field researchers who performed damage assessments of non-destroyed homes. Researchers relied heavily on collaboration with government agencies, university programs, and local organizations during the data collection process. Remote sensing data were collected from several different sources including: Pictometry, Ortho-rectified Imagery (USGS), Google Imagery, Ortho-rectified Imagery (San Diego State University), LiDAR, Property boundaries (SanGIS), and Vegetation Community Types (SanGIS). These data sources provided oblique imagery, aerial imagery, point measurements, and vector GIS data. Several data collection limitations included: lack of access to certain properties, inability to identify construction materials in photos and on the ground, inconsistencies in interpretation amongst observers, and incomplete mapping of burned features. Furthermore, LiDAR scanners cannot see through solid objects (e.g., fallen branches) which caused inaccuracies during vegetation data collection (Maranghides et al. 2009, 2013).

Within forty-four hours of a wildland-urban interface (WUI) fire beginning in Amarillo, NIST deployed a team of field researchers to perform a preliminary investigation of fire losses and fire behavior (Maranghides et al. 2011, 2016). During the twenty-one days that this team spent in the field, their primary focuses were on the effects of fire losses on topographical features, evaluation of infrastructure construction, and mitigation attempted during the event. They chose to focus only on the Tanglewood Complex fires where 183 structures were destroyed because of resource limitations. The overall goal of the study was to discover the factors responsible for the failure or successful performance of buildings and other structures, and to recommend improvements to standards, codes, and practices. They used a two-tiered approach for data collection. The first tier (WUI 1) was used to collect general data across the perimeter of the fire, and the second tier (WUI 2) was used to collect data related to in-depth fire behavior, defensive action, fire timeline, and structural performance criteria. They took over 29,000 photographs using handheld cameras, investigated 2,330 geo-located man-made features, recorded 281 instances of burned vegetation, and transcribed interviews with forty-eight first responders and homeowners. In addition, they printed descriptions of emergency services' radio logs from the day of the fire. Their field measurements related to residential structures, combustible features, non-combustible features, fire direction, fire timeline, burned vegetation and defensive actions. They also investigated undamaged structures to see why they were undamaged. In addition, pre and post fire aerial imagery were acquired for the study area. All data that was collected was put into a GIS system database. They used automated vehicle location (AVL) systems, mobile phones, global positioning systems (GPS), and other imaging technologies to allow recording of real time fire information. Formal field study data collection questionnaires were used for all structures that were investigated. The authors concluded that the field study technology that is currently available is not sufficient for the collection of comprehensive WUI fire field data, resulting in a lack of rigorous WUI fire studies. It was also difficult to collect timely aerial imagery since data is lost with time during fires. It was determined that remote sensing data collection combined with field assessments is the best means to obtain pre and post fire vegetation information. It is also impossible to determine the ignition sequence of a burned structure without eyewitness accounts. They also stress the importance of collecting both aerial and ground based imagery, and found that damaged structures provide more useful information than destroyed structures. They also emphasized the difficulty of collecting and documenting imagery over the life of the fire since fire data are lost quickly over time. The GIS data were too large to transfer to remote GIS team quickly, so they suggested having a GIS team on site. Finally, they stressed the importance of clearly defining team member roles before the team goes into the field and properly training each of the team members for their respective roles (Maranghides et al. 2011, 2016).

Hurricane Katrina made landfall on August 29, 2005 causing massive destruction and loss of life. Soon after the event, the Multidisciplinary Center for Earthquake Engineering Research (MCEER) deployed a multi-disciplinary field investigation team with the objective of improving physical systems and response and recovery efforts for future extreme events of any type. Their primary goal was to collect data that could be used to make communities more resilient, and the topics that they addressed included: organizational decision making (primarily in hospitals), advanced damage detection using remote sensing, environmental and public health issues, and damage to engineered structures. The investigation report was divided into five volumes. Volume 1 (Arendt and Hess 2006) focused on the causes and effects of hospital decision making (e.g., hospital evacuation). In order to do this, they collected qualitative data from interviews with various hospital administrators and staff members, their family members, security personnel, remediation personnel, public health officials, health association representatives, and federal, state, and local emergency experts and recorded field notes from visual inspections of the hospitals one month after the event. The focus was on 15 different care hospitals including publicly owned, investor owned, and non-for-profit. They also obtained information from news reports and web sites. Volume 2 (Womble et al. 2006) focused on remote sensing technology for damage assessments. The objective for this team was to rapidly perform building damage assessments in order to preserve perishable damage data. They used remote sensing data from optical and radar sensors, and then deployed a ground team to collect geo-referenced photographs and videos using the VIEWS (Adams et al. 2004) system in order to validate remote sensing data. They focused primarily on two areas: the Mississippi Coast and

New Orleans. The details of their field strategies and tools are described in detail in the report. Volume 3 of the series (Jenson and Ram 2007) outlined the investigation of public health, drinking water infrastructure, and wastewater infrastructure. The reconnaissance team consisted of two members: a civil engineer and a medical expert. Data for morbidity and mortality were obtained from the Centers for Disease Control and Prevention (CDC) and the Louisiana Department of Health and Hospitals (DHH). The field team visited facilities throughout Louisiana and interviewed residents, nurses, social workers, doctors, managers, Red Cross personnel, and others over a four day period. Volume 4 (Mosqueda and Porter 2007) described the investigation of damage to commercial buildings and lifelines (electric power, water supply, wastewater, telecommunication, and police and fire stations). There were two deployments: the first was within a week of the event (September 6-11, 2005) and the second was after the flood waters had receded and the evacuation order had lifted (October 3-9, 2005). Twenty-three Buildings were investigated using traditional field notes, observations and photographs. Volume 5 (O'Connor and McAnany 2008) focused on damage to bridges and tunnels. They obtained initial aerial imagery from an airplane flyover and then a field team deployed twice: September 6-11, 2015 and October 16-21, 2005. Their goal was to capture photographs of the raw damage (perishable data) caused by the event in order to understand bridge performance. Their site inspections consisted of expert observation through the recording of field notes and photos. The field inspectors kept an "Inspectors' Daily Journal" which was attached as an appendix.

From September 23 to 25, 2005 a team of researchers funded by the National Science Foundation (NSF) conducted a field investigation after Hurricane Katrina with the purpose of collecting and analyzing perishable wind damage data for residential, woodframe structures in order to suggest improvement to residential building codes and improve woodframe structure performance in hurricane winds (van de Lindt et al. 2005, 2007). In order to do this, they investigated twenty-seven damaged woodframe structures or subdivisions. Their data included structural observations and non-structural observations which were recorded in the field. They recorded damage to buildings through extensive field notes and photographs using handheld cameras. They obtained wind speed estimates at each structure by overlaying the structure locations with a wind speed map that was obtained from the National Oceanic and Atmospheric Administration (NOAA). The causes of failure for individual elements were then determined through expert forensic opinion using the collected data (van de Lindt et al. 2005, 2007).

Zhou et al. (2015) proposed a new methodology for the damage assessment of residential buildings using image-based 3D reconstruction, and then tested this method using data from Hurricane Sandy. The primary problem with using remote sensing is that it often produces low resolution imagery. This problem is usually solved through algorithm improvement as in Adams et al. (2004) or through the use of expensive, high resolution equipment such as LiDAR (see e.g. Prevatt et al. 2011; Greattinger et al. 2012). The proposed methodology for 3D reconstruction does not require a LiDAR scanner or algorithm improvement. Instead, it uses photos taken by less expensive digital cameras to reconstruct a 3D image which can be used to estimate damage to structures. In order to achieve this, dozens of photos of a single building at different angles were taken, then the 123D Catch software by Autodesk and the SURE open sourced platform were used to create the 3D reconstruction, and LiDAR point cloud data were collected to validate the results and method. The point clouds from these three methods (LiDAR, 123D Catch, and SURE) were compared, and it was determined that SURE point clouds are more accurate than 123D Catch point clouds. This study suggests that image-based 3D reconstruction can be a valuable tool for assessing the damage to buildings after a hurricane. However, if an extremely detailed damage assessment is desired (e.g., displacements < 1cm) then this method cannot be used. Photos taken with large overlaps (more than 90%) tended to produce the highest quality point clouds. Unfortunately, only small portions of the roof were able to be reconstructed because of the images were taken at ground level. This problem may be able to be resolved through the use of unmanned air vehicles (UAVs) (e.g., drones) (Zhou et al. 2015).

After Hurricane Ike, a team from the Texas Department of Homeland Security attempted to assess hurricane damage in Texas in the social, built, economic, and natural environments. They focused on broad topics instead of specific details. Their purpose was not to propose code changes or policies but simply to report the damage. They obtained their information from internal government agencies, universities, and online resources. For example, they obtained a portion of their data on the natural environment by collaborating with the Texas Parks and Wildlife Department (TPWD). Similar to many of the other studies discussed in this section, they focused primarily on damages and losses and chose not to study the undamaged infrastructure. They also investigated each of the community domains individually, but there was no discussion on their interdependencies (Texas Department of Homeland Security 2008).

After the 2008 Midwest riverine flooding, the Federal Emergency Management Agency (FEMA) deployed a Mitigation Assessment Team (MAT) with the purpose of determining if mitigation strategies employed by FEMA for buildings and other structures in Iowa and southern Wisconsin were effective (FEMA 2009). The conclusions and recommendations were intended to aid decision makers in reducing damage to structures in future flooding events and provide information that may be useful in updating building codes. A pre-MAT was deployed to perform initial inspection and determine if a MAT would be necessary. The pre-MAT entered the field about a month and a half after the flooding and spend seven days collecting field data. The full

MAT was deployed in the field for one week starting after the pre-MAT field investigation ended. They developed an investigation plan based on the pre-MAT's findings in which they attempted to investigate the most damaged communities. Data that were collected included field notes, photographs, aerial imagery, GIS information, and interviews with building owners and government officials. The field team was comprised of FEMA staff, design and construction experts, engineers, architects, building code experts, floodplain experts, hazard mitigation planners, GIS specialists, and technical writers. The community components that they investigated include: social and economic impacts, residential and commercial buildings, critical and essential facilities, mitigation techniques and planning effectiveness, and risk communication. More specifically, they investigated systems that included foundation damage, non-structural damage, interior finishes, electrical and mechanical systems, and lifelines. Their general methodology was to visit a structure that sustained flood damage, diagnose the specific causes of the damage or loss of functionality, and recommend future practices to avoid similar damage based on expert opinion (FEMA 2009).

In an effort to obtain perishable damage data after disasters, a methodology was proposed by Dashti et al. (2014) that utilizes social media and other remote sources for data collection. After the September 2013 flooding in Colorado, geo-referenced tweets of images were collected and used for estimating infrastructure damage. In order to collect data from twitter, a system that uses a four-node Cassandra cluster to store tweets from Twitter's streaming application programming interface (API) was implemented during the first nine days of the flooding. Twitter's API allows the user to search for keywords, user IDs, and geographic bounds, and then it shows all matching tweets. A total of 212,672 unique tweets were collected and 2,658 of them were geo-tagged. These tweets were then combined with hazard maps and satellite imagery. This method of damage assessment is meant to be a preliminary planning and decision making tool for future field investigations (Dashti et al. 2014).

Wilson et al. (2014) provide guidelines from multi-disciplinary tsunami reconnaissance experts on the best practices for conducting a post-tsunami field study. The protocol consisted of 10 components that are recommended to be followed by research and focused on coordination, communication, and collaboration related issues. They first address the importance of conducting ethical research in both studies that include human subject and those that do not. The ten components are:

1. Contact event coordinator: Discuss conditions of impacted area, other survey teams, and local logistical support. This will help eliminate redundant data collection efforts.
2. Prepare and share field plan: Provide event coordinate with necessary information such as: dates and locations of field work, names and affiliations of field team members, data collection plan, and dissemination plan for sharing data with others.
3. Obtain official survey badge: After approval by the event coordinator, this identification would allow access to damaged sites.
4. Include local experts on your team: Someone with pre-event knowledge of the impacted area and knowledge of local culture and language.
5. Coordinate and communicate with others: This allows your team and other teams to obtain additional data and not waste time collecting redundant data. Team members must have communications equipment that enable them to government officials in case of emergency.
6. Follow check in procedures

7. Pay attention to all safety regulations: The event coordinator should supply teams with safety regulations that must be followed. Aftershocks leading to additional tsunamis may occur.
8. Be prepared to answer questions from emergency responders, officials, and survivors: Be clear about your purpose, background, and expertise. Do not provide misleading information.
9. Follow check-out procedures and provide out-briefings: Provide a summary of the work accomplished and future work intended as well as a plan for sharing information.
10. Provide final data for others quickly: Including the individuals in the affected areas and other collaborators.

Discussion of Studies Focusing on Physical Systems

In the days immediately following a disaster, perishable data are available that are often lost during the cleanup process. In order to prevent this data from being lost, it is important to send a preliminary reconnaissance team as soon as possible after the disaster. This team can then collect some of this valuable, perishable data, and use it to aid in deciding if a more detailed field study should be conducted (Todd et al. 1994; FEMA, 2009; Kuligowski et al. 2014). There are different data collection strategies for different disaster types. For a tornado field study, it is common to investigate damage along transects perpendicular to the tornado path (Graettinger et al. 2014; Prevatt et al. 2011). However, for an earthquake field study, it is more practical to investigate starting from the earthquake epicenter and moving outward (Todd et al. 1994). Data collection strategies should be carefully planned and modified to fit the specific disaster and community. The development of a data collection strategy should be informed by preliminary data and, preferably, aerial imagery (O’Connor and McAnany 2008).

Part of the planning process includes the selection and training of field team members. It is important to have a diversity of skills and expertise within the field team (Todd et al. 1994; Kuligowski et al. 2014; MCEER 2006-2008; FEMA 2009). Every member of the field team must be trained properly for their specific task. When team members are not trained properly, the field study can become chaotic and possibly unsuccessful (Maranghides et al. 2011, 2016). Also, during the planning process, interview questionnaires should be developed for the specific disaster and community. The development of questionnaires should be informed by data from preliminary investigations (Kuligowski et al. 2014). All interviews should be transcribed and analyzed using software if resources allow (Kuligowski et al. 2014; Maranghides et al. 2011, 2016)

Technological advancements are rapidly changing the tools and methods that are being used for field data collection. Approximate damage estimates can be provided quickly by the use of pre and post event satellite imagery. These damage estimates should be used to guide field researchers to locations of interest, and not as a final product (Adams et al. 2004; Borrero et al. 2005). Ground and aerial-based scanners can be useful for collecting damage data with varying resolution. Aerial scanners collect data quickly, but the resolution can be coarse. Ground based scanners take a long time to collect data points, but the resolution is often more fine depending on the specific equipment that is used. It is most beneficial to use both ground-based and aerial data collection methods. However, it is typically not feasible to use terrestrial scanners as the primary method of damage data collection due to time and resource constraints. They are often supplemented with traditional data collection methods (field notes, photos, and videos recorded by team members). In certain situations, it may be useful to combine pre-event satellite imagery with post-event data obtained using terrestrial scanners. This allows researchers to obtain fairly accurate estimations of wind speed and structural damage (Kashani et al. 2014; Graettinger et al. 2014; Prevatt et al. 2011; Maranghides et al. 2011, 2016; Maranghides et al. 2009, 2013; Womble et al. 2006).

An alternative to remote sensing technology is to use digital photos for 3D reconstruction as in Zhou et al. (2015). Another method of obtaining geo-referenced damage data is through the use of social media (Dashti et al. 2014; Graettinger et al. 2014). In order to obtain unbiased samples, field researchers should inspect a representative sample of infrastructure that is not based on their damage states (Kuligowski et al. 2014). Throughout the field study process collaboration with other researchers, government agencies, and universities is crucial in order to gain additional data and prevent redundant data collection (Todd et al. 1994; Maranghides et al. 2009, 2013). When possible, field study data should be made available to other researchers and the public. This can be done by creating an easily accessible online database (Graettinger et al. 2014).

2.1.2. Studies focusing on Social Dimensions of Communities

In order to understand the strategies and techniques that researchers have used to collect field data that help them understand the social science domain after disasters, five field studies were reviewed that focused on studying human behavior after disasters. These five reports are summarized below.

After the Haiti earthquake of 2010, Lu et al. (2012) sought to track the locations of affected people before, during, and after the event. In order to do this, they collaborated with Digicel, the largest mobile phone operator in Haiti, to track the locations of 1.9 million anonymous people from forty-two days before the earthquake to 341 days after. It was assumed that this sample of Digicel users was representative of the entire population of Haiti. Digicel provided them with the locations (to the nearest cell tower) of all mobile phone users once per day. The spatial resolution was from 100 meters to a few tens of kilometers depending on the distance between cell towers. This alternate data collection method allowed Lu et al. to avoid the bias of interviews and to obtain data at any point in time or space. It also allowed them to accurately study population movement as a surrogate for investigating the recovery trajectory of individuals affected by the disaster. They concluded that population dislocation is reasonably predictable in the aftermath of disasters. This method may be applicable to the NIST CoE field study methodology because our field studies will focus on more developed countries which will likely have even more prevalent mobile phone use than Haiti. Unfortunately, this study had a limited sample because they were not able to track people who don't use mobile phones or don't use Digicel. This may be less important for developed countries because of more prevalent mobile phone use. The study was also limited by low resolution of time and space (1 data point per day and up to tens of kilometers between data points). Also, the data provided by Digicel did not provide any demographic or socioeconomic information about the users. Finally, the study was limited because they could not account for power outages (or lack of charging stations) and mobile phone tower disruption (Lu et al. 2012).

Gray et al. (2014) utilized a combination of techniques to estimate and model population dislocation after the 2004 Indian Ocean tsunami including: surveys, satellite imagery, and multi-variate statistical analyses. First, they obtained data from a survey that was done before the tsunami as a baseline. Then, they tracked a sample of the original responders from approximately 10,000 households and interviewed them annually for the first five years after the tsunami with plans to interview them again ten years after the tsunami. Local university students conducted the interviews after undergoing four weeks of training. These interviews were refused by less than 1% of the respondents, although the students sometimes had to visit a site up to five times over a year in order to obtain the data they needed. The interviewees were asked where they were living before, during, and after the tsunami. The authors then approximated the damage extent of the tsunami using techniques that were similar to Adams et al. (2004): pre and post disaster satellite imagery was compared to determine damage to communities. Multivariate statistical methods were then used to analyze the major socio-economic factors that affect displacement. The primary limitation of this study is that there was some difficulty in tracking the individuals from the pre-tsunami survey because many of them were missing or deceased. Also, people dislocate very quickly after disasters which makes it difficult to obtain a representative sample of the original population. The information that they got from the questionnaires had to be very broad because the sample was so large which caused them to miss some important details. (Gray et al. 2014).

Sutton et al. (2008) investigated the communication practices of community members during the October 2007 California Wildfires. Their goal was to show that “backchannel” communications supported by social media may be used more prominently in the future of disaster response. Backchannel communication occurs when community members communicate their needs to emergency responders after a disaster. Days after the fires started, the research team began collecting qualitative data from interviews and online resources. After evacuation orders were lifted, an online questionnaire was developed to investigate the use of information and communication technology (ICT) by community members. The questions on this form were developed from initial research findings and earlier research, and included multiple choice and open ended questions. The questions that were asked were related to the effectiveness of ICT use for communicating with others during the fire, evacuation, and cleanup process. They posted solicitations on social media (Facebook and Flickr), local forums, and online newspapers in the affected communities. They had 279 respondents who completed the form. This method of distributing and recruiting for the survey allowed them to reach a greater number of people with less time and money spent (Sutton et al. 2008).

In order to study the non-traditional and prosocial behavior that occurred after Hurricane Katrina, Rodriguez et al. (2006) used databases that were created by field researchers at the University of Delaware Disaster Research Center (DRC), media reports, and government agencies. They investigated five areas in the community: hotels, hospitals, neighborhood groups, rescue teams, and the joint field office (JFO). The data that they analyzed came from quick response field studies that were performed by teams that entered the field about three weeks after the event and remained there for five to ten days. The data collection activities included: interviews, observations, and the gathering of related documents. The field teams visited local response centers and interviewed local, state, and federal officials, relief workers, and evacuees. Firsthand accounts were assumed to be more credible than media accounts because in the aftermath of Katrina there were many media stories that falsely portrayed the community response as anti-social. They used the acquired data to analyze individuals' responses at three stages of the disaster: immediately before, immediately after, and long term (Rodriguez et al. 2006).

In November 2013, Super Typhoon Haiyan, the strongest storm ever recorded at landfall, hit the central Philippines causing over four million people to be displaced. In order to study and learn from this mass dislocation, Sherwood et al. (2015) used a method that was meant to explore the relationships between pre-event socioeconomic conditions, the experience of the displaced, and the obstacles to recovery. They collected quantitative and qualitative data from December

2014 to March 2015. The quantitative data were collected through a questionnaire which was designed to investigate socioeconomic conditions before and after the event and the experiences of the displaced. The survey was distributed in the region most damaged by the disaster, and all other regions were neglected. In all, 4,518 households in forty-three municipalities received the survey. To supplement the surveys, qualitative methods were used to gain a deeper understanding of the displaced persons' experiences. Qualitative fieldwork was conducted in two stages with the initial findings from the first stage informing the development of the fieldwork strategies for the second stage. These methods included: thirteen focus group discussions (one to two hours long), site visits to heavily damaged sites, and interviews (45 minutes to 2.5 hours long) with thirty-four individuals including local government officials. These individuals were selected based on characteristics that allowed the researchers to gain a wide-ranging perspective of the experiences of the displaced. Conclusions and recommendations were drawn from the trends in the quantitative and qualitative data (Sherwood et al. 2015).

From 1967 to 1988 the Disaster Research Center (DRC) conducted over 450 sociology oriented field studies. The DRC was originally established by Quarantelli at The Ohio State University, but has since moved to the University of Delaware. In this article, Quarantelli attempts to capture the general protocol that was used in these field studies. Most of the data were collected by graduate research assistants (GRAs). These GRAs had to undergo extensive training and preparation. A large emphasis was placed on having researchers at the site during the peak of the disaster recovery process. Field study kits were prepared and ready for dispatch at all times. Once in the field, formal interview guides were used. The opening questions were usually general and open ended. The guidelines given were usually loose, so researchers had to have a complete understanding of what the purpose of the study is and what data needs to be collected. Qualitative data can be collected formally through interviews or informally through casual conversation, etc. One member of the field team was placed in a leadership position and made the decisions regarding strategies and direction in the field. All interviews were audio recorded, and photographs were taken to record significant findings. When funding allowed, all recorded interviews were transcribed and used for analysis. At the end of each day in the field the researchers would meet together, discuss their findings of the day, assess whether they were meeting the goals of the project, and decide on strategies for the next day's work. Like several other organizations including NIST, they would do a reconnaissance study first, then report back and decide whether or not to do an in depth study. Since GRAs were used as field study researchers, their positions were inherently temporary. The DRC attempted to solve this problem by having a constant cycle of older, more experienced GRAs training new GRAs. Delays in the post data processing (due to GRAs work schedules) sometimes caused the final data to be flawed (Quarantelli 1997).

Discussion of Studies Focusing on Social Dimensions of Communities

Conducting field studies that focus on social issues typically involves surveys and/or interviews of various community members. Just like physical data, perishable social data are lost quickly after a disaster due to the inability to track individuals and groups, so it is important to have an initial field team enter the field rapidly following a disaster. (Sutton et al. 2008; Sherwood et al. 2015). The development of surveys and interview guides should be guided by the data that are collected after the disaster if a longer, more detailed study is to be conducted (Sutton et al. 2008; Sherwood et al. 2015). Unskilled workers can be used to conduct surveys and interviews if they are trained properly (Gray et al. 2014). When researchers are to conduct interviews or surveys in a foreign culture, it is best to train local citizens to conduct the interviews if possible, which leads to higher rates of cooperation from the affected community (Gray et al. 2014).

Sometimes, detailed social data may be available from before the disaster occurred. It is important to find and obtain any data that may have been collected in the community before the disaster. These data can serve as a baseline for data that are collected after the disaster (Gray et al. 2014). It is important to use survey methods that avoid bias in population samples (Lu et al. 2012). There are several effective methods for obtaining survey data including face to face surveys (Gray et al. 2014), online surveys and solicitation on social media (Sutton et al. 2008), mail surveys (Webb et al. 1999), and telephone surveys (Galea et al. 2007). Most importantly, it is critical that field teams communicate with government agencies, news reporters, other researchers, and private firms (e.g., cell phone companies), so that they can obtain social data for which they would otherwise not have access (Lu et al. 2012; Rodriguez et al. 2006).

The majority of these studies do not investigate specific connections between human behavior decisions and physical infrastructure systems damage and functionality which are believed to be needed to model community resilience. For example, in order to understand why a family has been displaced from their home, researchers should investigate the physical damage, social issues, and economic stressors that caused the family to make the decision to leave their home. The decision to dislocate is often driven by a combination of these (and other) issues. If this decision-making process can be modeled then community models move from data-driven models to physics or first principle models.

2.1.3. Studies focusing on Epidemiology

This section includes studies that investigated quantities, locations, and causes of death and injuries. Reports are also included that investigate mental illness and post-traumatic stress disorder (PTSD) resulting from disasters. The five reports that were reviewed include both field studies that used surveys and interviews to identify morbidity and case studies that obtained data from government agencies or other organizations. These five reports are summarized below.

In order to investigate the injuries that occurred during the 1994 Northridge earthquake that resulted in hospital admission or death, Peek-Asa et al. (1998) obtained mortality data from the Los Angeles City Coroner, and then screened all seventy-eight hospitals in Los Angeles County for earthquake related admissions. A total of 171 earthquake related injuries were identified, thirty-three of which were fatal. These injuries were coded using the Abbreviated Injury Severity (AIS) scale, which classifies the nature, severity, location, and type of anatomic structure of the injury, and then analyzed by gender, age, and cause of injury. Census data were then obtained and used to determine injury rates. The injuries were linked to specific buildings when possible (fifty-seven linkages), and the Los Angeles City Department of Building and Safety inspection data were then purchased for these buildings. This study was limited because complete autopsies and lists of injury diagnoses were not always available, and the hospital screening process may have missed some earthquake related injuries. There is always a great deal of uncertainty about quantity and type of injuries following a major disaster, and this report concludes that predicting injuries due to earthquakes is a complex process which includes many behavioral and environmental variables (Peek-Asa et al. 1998).

In order to assess the posttraumatic stress reactivity (PTSR) of over 20,000 tsunami survivors, Frankenberg et al. (2008) conducted a study that collected and analyzed survey data from Aceh, Indonesia and North Sumatra, Indonesia, using techniques similar to Galea et al. (2007). A representative sample of the population was interviewed before the tsunami as a part of the National Socioeconomic Survey (SUSENAS) which was performed by Statistics

Indonesia, and then these interviewees were located after the event (with the help of Statistics Indonesia) for a follow up interview. Ninety-seven percent of pre-event interviewees were contacted for the secondary survey. The pre-event interviews took place in 2004, the tsunami occurred on December 26, 2004, and the post-event surveys took place from May 2005 to July 2006. The survey removed bias by including individuals from undamaged areas as well as damaged areas. PTSR was measured by using a seven symptom checklist before the disaster and at the point of maximum stress during or after the disaster. Yes/No, multiple choice, and open-ended questions were all a part of these surveys. The rates of mental illness were linked to building damage estimates, and it was found that the individuals with the highest level of PTSR were from the most severely damaged areas. Approximate damage estimates were obtained using remote sensing data from NASA's MODIS sensor, reports by community leaders, and observations of field teams. The data were also analyzed for trends related to gender, age, and socioeconomic status (socioeconomic status was found to be the least significant factor). Multivariate regression analyses were used to draw conclusions from various demographic and other pertinent data (Frankenberg et al. 2008).

Brunkard et al. (2008) performed a case study that sought to document and describe Hurricane Katrina related deaths in Louisiana in order to help reduce mortality in future events. They obtained their data primarily from the Hurricane Katrina Disaster Mortuary Operational Response Team (DMORT), which is a federal response team that deals with mortuary activities in the aftermath of disasters, database and death certificates collected by Louisiana vital statistics and out-of-state coroners' offices (such data did not become available until two years after the disaster). Mortality data points were geo-located and analyzed spatially. They grouped and analyzed the data by cause of death, race, gender, time of death, location of death, and age, and then analyzed these data using advanced statistical methods to discover which population groups were most vulnerable to Hurricane Katrina. A lower bound and an upper bound mortality count were estimated by adding the deaths that occurred in the proper time frame that were originally classified as “indeterminate.” The mortality estimates that they provided were conservative because they included people who died from a number of different causes in the weeks and months after the hurricane. Many people died from pre-existing conditions (primarily the elderly), and it is difficult to determine whether or not the hurricane aggravated these diseases. The study was not able to account for missing persons and bodies that were never found. (Brunkard et al. 2008).

Galea et al. (2007) used surveys to determine the connection between DSM-IV anxiety-mood disorders and hurricane related stressors among residents affected by Hurricane Katrina. From five to eight months after the event, 1,043 individuals were given a survey over the telephone. Respondents were selected from three sources: a random sample of telephone numbers connected to households in the areas affected by the hurricane, a sample from telephone numbers of those who applied for assistance from the American Red Cross, and a sample from the hotels that sheltered evacuees. The survey included twenty-nine closed ended questions, several additional open ended questions, and the respondents were asked to rank their stress level during the hurricane on a scale of one to ten. This allowed researchers to identify traumatic and non-traumatic stressors. They used the K6 scale of nonspecific psychological distress to predict the probability that the respondent would be diagnosed with a mental disorder as a result of the hurricane. The data were analyzed for association between mental illness and age, sex, race/ethnicity, family income in the year before the hurricane, education, pre-hurricane marital status, and pre-hurricane employment status. One challenge of this study is that it was difficult to locate and contact people who were affected by the hurricane. Only 64.9% of potential respondents were eventually able to be contacted. The survey volunteers were also required to commit long term to the study so that changes could be tracked over time. This commitment level likely dropped the response rate even further. The sample was limited because it did not include people who could not be reached by telephone, and additional factors that were not mentioned in the survey may have been the cause of mental disorders. Another limitation is that they used screening scales rather than clinical interviews which results in less precise estimations of mental illnesses (Galea et al. 2007).

Zahran et al. (2008) investigated casualties due to extreme flooding events in order to determine if socially vulnerable populations see a disproportionate number of deaths due to flooding. They analyzed 832 flood events in seventy-four counties in eastern Texas from 1997–2001, primarily focusing on geographic localities characterized by high percentages of socially vulnerable populations. Three socioeconomic predictors of flood casualties were used: population density, local preparedness, and presence of socially vulnerable populations. Social vulnerability was measured based on household income and racial data from the U.S. Census. They obtained mortality data from the Spatial Hazard Events and Losses Database for the United States (SHELDUS) and the Centers for Disease Control and Prevention (CDC) which provide data at the county level. This forced them to perform their analysis at the county scale, which means that they were not able to determine the socioeconomic status of individuals harmed by flooding which they stated created intrinsic error in their models. Other important data that were collected and included in their analysis were: precipitation data (National Climate Data Center), number of dams in each county (U.S. Army Corps of Engineers), percent of impervious surface (NASA Stennis Space Center imagery), property damage (SHELDUS), FEMA socioeconomic rating (FEMA Community Rating System), population density, and social vulnerability index (US Census Bureau Population and Housing Files). Zero-inflated negative binomial (ZINB) regression models were used to analyze these data. (Zahran et al. 2008).

Discussion of Field Studies focusing on Epidemiology

Epidemiologic studies that focus on morbidity and mortality caused by disasters have a great deal of uncertainty and typically utilize data are typically gathered from remote sources (e.g., government agencies and hospitals) (Brunkard et al. 2008; Peek-Asa et al. 1998; Zahran et al. 2008). The exception to this is mental morbidity studies which often involve surveys that evaluate individuals' mental health before, during, and after a disaster. Studies of this type may be inaccurate because they rely on surveys to determine mental health instead of clinical interviews (Galea et al. 2007). It would be beneficial to obtain a mental health survey of individuals before the disaster if these data are available (Frankenberg et al. 2008). It is common for researchers to obtain approximate estimates of physical damage using satellite imagery or other quick methods in order to link morbidity and mortality to the severity of physical damage. These approximate damage estimates are sometimes validated through field observation or obtaining data from other sources (Frankenberg et al. 2008). In order to remove sample bias, data must be collected for individuals of varying levels of morbidity (no injury to death) (Frankenberg et al. 2008).

When conducting community resilience focused field studies, it is necessary to link morbidity and mortality to other community domains. In the studies that were reviewed, several of the authors connected morbidities and mortalities to physical systems. However, there are other community systems that affect mental and physical injuries during disasters. For example, a treatable injury may lead to death because the emergency responders could not perform their jobs effectively because of damage to transportation networks, or an individual's PTSR score might be extremely high because they did not receive the financial aid that they needed after a disaster. These are examples of the critical linkages that should be investigated when collecting data to model community resilience.

2.1.4. Studies Focusing on Economics

The following six studies focus on how disasters affect a community's economy. The purposes of these studies range from investigating how individual businesses were affected by a disaster to creating a model of a community's economy that estimates direct and indirect losses after a disaster.

Webb et al. (1999) conducted a field study to investigate the long term recovery of individual businesses eight years after the 1989 Loma Prieta earthquake and six years after Hurricane Andrew in South Florida. They used a modified version of Dillman's (1978) "total design method," which combines mail surveys and follow up phone calls to maximize the number of quality responses. The surveys were sent only to businesses that were open at the time of the disaster and were still in business at the time of the study. The 4,286 businesses in South Dade County had a 27.0% response rate and the 3,705 businesses in Santa Cruz County firms had a 33.6% response rate. Data collected included physical damage, duration of closure, number of lifelines lost, and disruption of operations. They were also asked whether the business was currently worse off, about the same, or better off than it was before the disaster, and the owners were asked to identify whether the changes that took place were disaster related or not. Ordinary least square (OLS) regression techniques were then used to analyze the data. The results of the surveys suggested that the greatest indicators of business interruption in order of importance were: economic sector, pre-disaster financial condition, business age, primary market (e.g., local or international), and business size. They also created a business disruption model that is based on five factors: business and owner characteristics, previous disaster experience, direct and indirect losses, measures taken to contain losses, and owner perceptions of the business environment. One large limitation of the study was that it only measured businesses that were successful in staying open after the disaster (Webb et al. 1999).

A model of business recovery was developed and tested by Dahlhamer et al. (1996) using surveys of businesses that survived the 1994 Northridge earthquake (similar to Webb et al. 1999). A random sample of Los Angeles area firms was selected for the survey by using stratified sampling, with shaking intensity, type of business, and size of business as sub-groups. A modified version of Dillman's (1978) "total design method" was used to conduct the surveys. The collected data included: Business size, disruption of business operations due to the earthquake, characteristics of the earthquake at the site, and the availability/use of external aid. The results of this study lead to two important conclusions. First, physical damage is not the only indicator of business performance. The effects of the disaster on business operations and the impacts of the disaster on the businesses' surroundings must also be investigated. Second, the aid available to businesses following disasters may not actually help them. Sometimes the aid only created more problems such as additional debt. This study was limited because it did not evaluate businesses that performed better as a result of the disaster (e.g., manufacturing and construction sector), and it did not investigate businesses that closed as a result of the disaster (Dahlhamer et al. 1996).

Studies such as Webb et al. (1999) and Dahlhamer et al. (1996), while useful, leave a gap in knowledge of small business behavior after disasters because these studies only investigated surviving businesses. After disasters, businesses often move, close, are renamed, sell, or morph into something else making it difficult to find and contact the owners. Schrank et al. (2012) proposed a methodology for tracking owners of small businesses after disasters and tested the methodology after Hurricane Katrina. The authors attempt to solve many problems related to post-disaster reconnaissance such as: timing, generalizability, and access. They first selected a representative sample of small businesses (0 – 200 employees) that were in operation prior to Hurricane Katrina by purchasing data from the 2004 Dun & Bradstreet (D&B) database, and then identified businesses that began after Katrina and businesses that had closed after Katrina by comparing the 2004 D&B database to the 2009 D&B database. Once they identified potentially demised businesses, student workers called the old phone number to see if it was operational, and if it was not operational, then they used an online search process called "record linkage" which finds information across pairs of files to determine if those pairs are associated with the same business. Using this method they were able to find and contact the vast majority of the demised business owners. In addition to this, they sent four team members into the field over a period of twelve days to try to find these business owners. The field team members were not nearly as effective at finding and contacting the demised business owners as the desktop search process. One of the limitations of this study is that D&B records have some inaccuracies. If possible, state business license records should be used instead of D&B records (Schrank et al. 2012).

Merz et al. (2010) review the current state of the art practices for economic flood damage assessments and identifies future research directions. Oversimplified approaches to economic damage assessments are often used by researchers due to lack of data and knowledge. They argue that uncertainty analyses of model inputs and assumptions should always be performed. It is important to understand the spatial and temporal boundaries of the specific study that you want to do. The authors identify 4 types of damage (direct, tangible; direct, intangible; indirect, tangible; and indirect intangible) and 3 types of special scales (micro, meso, and macro). For the NIST COE methodology, we are interested in all three of these spatial scales. The following three steps describe a procedure that is often used for the evaluation of direct fiscal flood damage:

1. Classify elements of interest into homogenous groups
2. Identify the quantity, type, and estimated values of at risk elements.
3. Evaluate vulnerability by relating flood impacts to damage to assets.

Indirect economic losses are a result of changes in the economy due to direct damages. Business interruption is a common result of indirect damages. In order to understand indirect economic damages, linkages within the economic system must be defined. Two examples of immediate short term losses after a disaster are: input/output losses to firms who are manufacturers or suppliers to the impacted businesses and reduction of demand or consumption. Indirect losses are difficult to measure which has led to the use of economic models to estimate losses. Examples of economic models include: input-output models, simultaneous equation models, and computable general equilibrium models. There are many limitations of economic data assessments. Very few data sets are publicly available and little is known about their quality. Standardized methods of flood damage data collection have not been developed, but have consistently requested (Merz et al. 2010).

Addy and Ijaz (2011) provided preliminary estimates of the fiscal impact of the numerous tornadoes that occurred in Alabama on April 27, 2011. This study is characterized as a case study not a field study because the authors analyzed data that had already been collected instead of collecting data in the field. They attempted to define the fiscal impact on the state as a whole by looking at individual metrics such as changes in employment, Alabama gross domestic product (GDP), state and local tax collections, and cleanup and rebuilding costs. They depended on several organizations for data including: Alabama Department of Finance, Alabama Department of Industrial Relations (ADIR), Alabama Department of Revenue (ADOR), U.S. Bureau of Economic Analysis (BEA), U.S. Bureau of Labor Statistics (BLS), and media reports. They used the reported sales and income tax revenues to determine the total loss of state tax revenue. As is often the case with post-disaster fiscal impact studies, there was a great deal of uncertainty in the analysis. This uncertainty was accounted for by providing low and high end estimates, and empirical multipliers were used to account for unknowns in the analysis such as recovery of waste management and construction industries. They made the assumption that economic damages occur only in 2011 and assumed values for amounts spent on cleanup, assistance, and rebuilding. These assumptions ensure that the estimates are conservative This report did not attempt to estimate the disaster's effect on important resilience metrics such as quality of life, displacement, and mental and physical health issues (Addy and Ijaz 2011).

Pan (2014) evaluated the economic loss associated with Hurricane Ike in Houston and developed a framework for loss estimation. Like several other economic studies (e.g., Addy and Ijaz, 2011), Pan analyzed data from existing databases and relied on data from government sources. Pan used GIS data and spatial allocation models to estimate direct and indirect economic losses and assign these losses to small zones within a community. The tools that he used included: GIS software, census data, Hazus models, and interviews with community leaders and business owners. His method for estimating uninsured losses relies on knowing the total insured losses and then applying a factor to predict the uninsured losses. (Pan 2014).

Dolfman et al. (2007) discuss the effects of Hurricane Katrina on the employment and wage patterns in New Orleans. They did not collect any field data during this process. Instead, they obtained their data from the Quarterly Census of Employment and Wages (QCEW) program of the Bureau of Labor Statistics. Economic patterns were compared before and up to ten months after the event, and the number of jobs lost and the total loss of wages during these ten months were estimated. They measured the economic diversity of the community by evaluating the concentration of jobs in each industry sector and comparing it with the national average. They then evaluated the changes in the total employment, total wages, and average weekly wages over time in order to track the recovery of the community. Levels of employment in the current month were compared with levels of employment in the same month of the prior year in order to remove the bias of seasonal patterns of employment. They concluded that the city of New Orleans reached its low point of job loss in November 2005 (105,300 less jobs than the previous year), after which employment began to increase slowly. The authors state that it is important to identify all tangible costs which include direct and indirect damages (including cost of emergency services). It is also commonly accepted to use depreciated values of goods that are damaged instead of full replacement costs (Dolfman et al. 2007).

Discussion of Studies Focusing on Economics

Post-disaster field studies that collect data focusing on fiscal impact to a community are rare. It is more common for researchers to obtain data from external public or private sources in order to develop models. Fiscal impact studies are similar to epidemiologic studies in that they both primarily analyze data collected by government agencies or other researchers, which are not made publicly available until several years after a disaster occurs. They also typically include large assumptions and uncertainties (Addy and Ijaz, 2011; Pan 2015). However, some survey type studies have been conducted to investigate the effects of disasters on individual businesses (Webb et al. 1999; Dahlhamer et al. 1996). The greatest difficulty while conducting these types of studies is locating and contacting owners of businesses that have closed, moved, been renamed, merged, etc. This problem can be addressed by using the time consuming process of "record linkage" to locate business owners, which was determined to be a far more effective method than using a field team to track business owners (Schrank et al. 2012). Certain industries such as construction or manufacturing may actually perform better after disasters, and future studies should investigate these effects (Dahlhamer et al. 1996).

In future community resilience focused field studies, it will be important to not only predict values of direct and indirect economic losses due to disasters, but also investigate what physical damage caused these economic losses and how these economic losses affect the everyday lives of individuals within the community. For example, economic losses may lead to loss of employment, population dislocation, or school closings. Post-disaster research must begin to be able to quantify and predict these types of secondary effects and interdependencies.

2.1.5. Discussion and Closure

There are many important lessons that can be learned from the thirty-five reports that were reviewed herein. Although several of these reviewed studies were multi-disciplinary (Kuligowski et al. 2014; MCEER 2006-2008; Texas Department of Homeland Security 2008), there is still a dearth of studies that provide insight into the interconnectivity of the physical, social (including epidemiology), and economic domains or even the interdependencies across physical infrastructure sectors within that domain. Individual networks and systems are a part of a resilient community, but all three domains, and the sectors within the domains, must work in concert and continue to be functional following an event for a community to be truly resilient.

Hence, the linkages across the physical, social (including epidemiology), and economic domains must be understood in order to study and model community resilience. Models of these linkages are constantly improving and becoming more detailed, and conducting field studies that have the ability to quantify community resilience is crucial for the future of disaster research.

There are numerous linkages that can be found through additional data inquiries related to other sectors within the physical systems domain. While many of the reviewed studies investigated the physical systems domain, they did not investigate how damage to infrastructure may have affected the social science and economic domains. For example, residential buildings are interconnected with the social science and economic domains because when a residence loses functionality (i.e., its ability to provide shelter for its residents) then the residents' physiological needs are no longer being met and they may choose to relocate which decreases economic activity in the community. As another example, religious buildings are interconnected with the social science and economic domains because when a religious building is no longer functional then individuals will lose social connections and a sense of fulfillment. Furthermore, religious organizations often provide volunteer services and financial aid for individuals in need, and if the organization has no building in which to meet, then their ability to provide these services will be impaired. These are just two example of how these community domains interact with each other to drive individual decision making. In order to conduct future community resilience focused field studies these interconnected factors that influence individual decision making must be captured by quantifiable data.

2.2. Infrastructure Dependencies Overview

In order to study a community's resilience, it is important to understand the complex infrastructure systems that affect the everyday life of its residents. These infrastructure systems include but are not limited to power generation and supply, water and wastewater treatment, oil and natural gas production, transportation, buildings, and communication. Many of these systems are dependent on each other, so if one fails the other one cannot function properly. Other systems are interdependent, meaning that they both rely on each other to function properly. This section contains a brief overview of the dependencies and interdependencies of infrastructure systems. It is not intended to be comprehensive, but only to provide a few examples of interdependencies for each physical system and the questions that might be asked in order to study them further. For a more detailed literature review of lifelines and their dependencies the interested reader is referred to NIST CGR 16-917-39 (Applied Technology Council 2016).

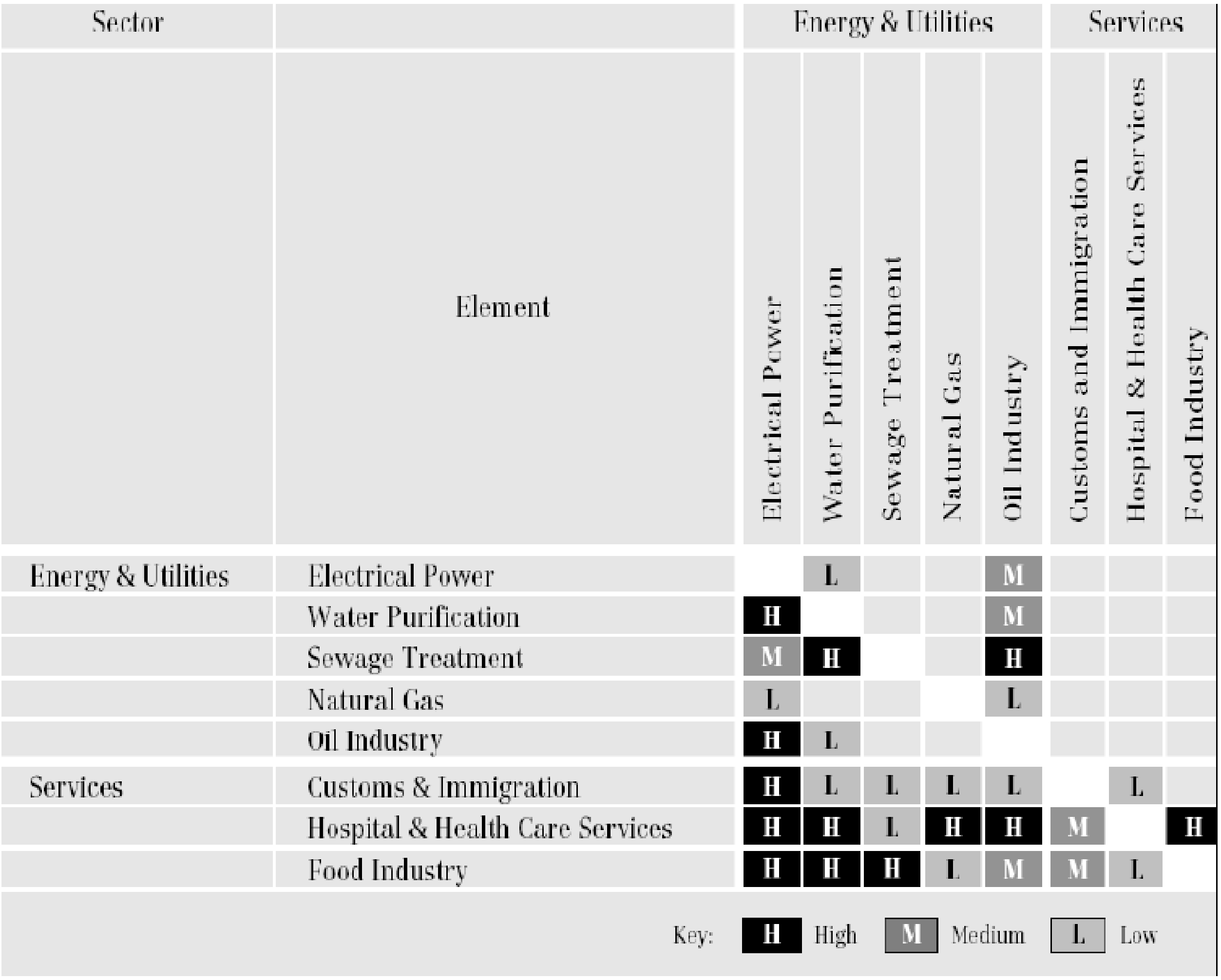
Table 2-2 was created in order to show a summary of each of the systems, their primary dependencies, and suggested field data collection methods. This is followed by further explanation of each system’s dependencies. The most significant finding of this review is that in nearly all cases, the use of backup generators and batteries greatly increases the system’s resilience and minimizes functionality interruption.

Table 2-2: Critical Infrastructure Primary Dependencies

System	Primary Dependency	Explanation	Reference	Data Needed	Data Collection Method
Power Generation	Oil and Natural Gas	Oil and natural gas provide fuel for generators.	Gursesli and Desrochers (2003); Rinaldi et al. (2001)	Was there an oil or natural gas shortage? Why?	Interview power plant manager or government official.
Water and Wastewater Treatment	Electric Power	Pumps need electric power to function. Loss of power leads to loss of pumps which leads to loss of pressure which can lead to boil-water advisories.	Gursesli and Desrochers (2003)	Did you have power outages? How did that affect water distribution and treatment?	Interview city engineer or plant manager.
Oil and Natural Gas	Communication Systems and Electric Power	Oil and natural gas producers rely on e-commerce, commodity trading, business-to-business systems, electronic bulletin boards, computer networks, and other critical business systems to operate and connect their infrastructures.	Lesar et al. (2001)	Did you lose communication between infrastructure systems? Why? How did this loss affect production and distribution?	Interview plant manager.
Transportation	Oil and Electric Power	Urban communities rely on electric signals for traffic regulation and power for rail transportation.	Gursesli and Desrochers (2003)	Did you lose power? Why? How did it affect transportation throughout the community?	Interview city engineer.
Buildings	Varies Depending on Building Purpose	Loss of functionality depends on the purpose of the building. Some businesses depend on communication systems while hospitals depend on electric power, etc.	Pederson et al. (2006)	Did your building lose functionality? Why?	Interview building manager.
Communication	Electric Power	Communication systems are largely powered by electricity.	Lesar et al. (2001)	Did you lose power? How did this affect communications?	Interview city official or company manager.

Table 2-3 (Pederson et al. 2006) shows a list of utilities and services and their dependencies. An “H” means that there is a high level of dependency, an “M” means that there is a medium level of dependency, and an “L” means that there is a low level of dependency. This matrix supports and affirms the information given previously in Table 2-2.

Table 2-3: Interdependency Matrix
(Pederson et al. 2006)



Sector	Element	Energy & Utilities					Services		
		Electrical Power	Water Purification	Sewage Treatment	Natural Gas	Oil Industry	Customs and Immigration	Hospital & Health Care Services	Food Industry
Energy & Utilities	Electrical Power		L			M			
	Water Purification	H				M			
	Sewage Treatment	M	H			H			
	Natural Gas	L				L			
	Oil Industry	H	L						
Services	Customs & Immigration	H	L	L	L	L		L	
	Hospital & Health Care Services	H	H	L	H	H	M		H
	Food Industry	H	H	H	L	M	M	L	

Key: H High M Medium L Low

Figure 2-3 (Rinaldi et al. 2001) shows a diagram of the dependencies and interdependencies for each system within a community. This diagram is not comprehensive but is believed to be the first of its kind, and it does provide good examples of the types of interdependencies that exist within a community.

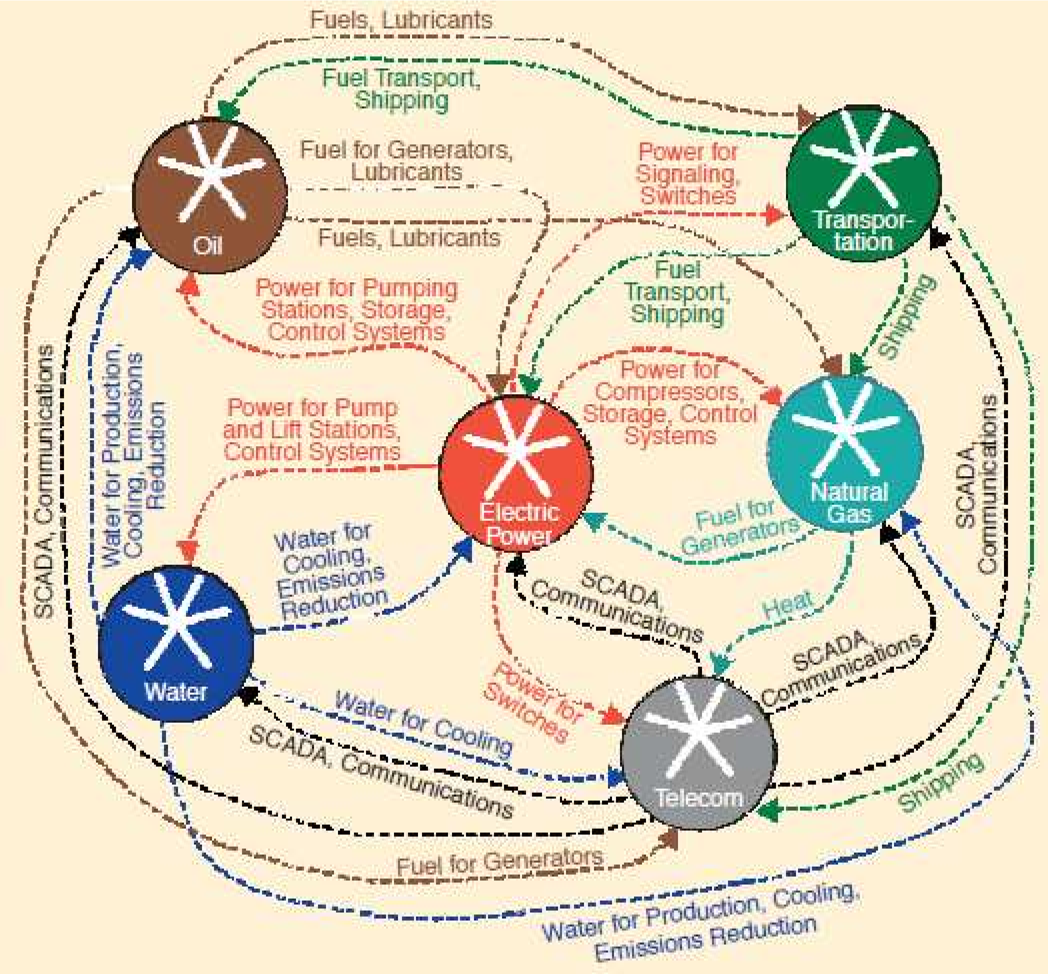


Figure 2-3: Infrastructure Interdependencies Diagram
(Rinaldi et al. 2001)

2.2.1. Power Generation

The majority of power outages are caused by physical damage to transmission and distribution lines, or occasionally to generation systems. However, the electric power infrastructure increasingly relies on oil and natural gas for electric power generation (Gursesli and Desrochers 2003). Oil and natural gas provide the fuel that is required to keep generators functioning and lubrication for the machinery. If access to natural gas and oil is cut off, power generators will cease functioning when the reserves are empty. Power generation is also highly dependent on water to cool the machines. However, since most power plants are constructed near a natural water source they do not rely on external infrastructure for their water needs. Power failure has a significant effect on the resilience of a community because of the broad range of other systems that it impacts. Figure 2-4 (Rinaldi et al. 2001) shows a diagram that illustrates the dependencies of other systems within a community on electric power.

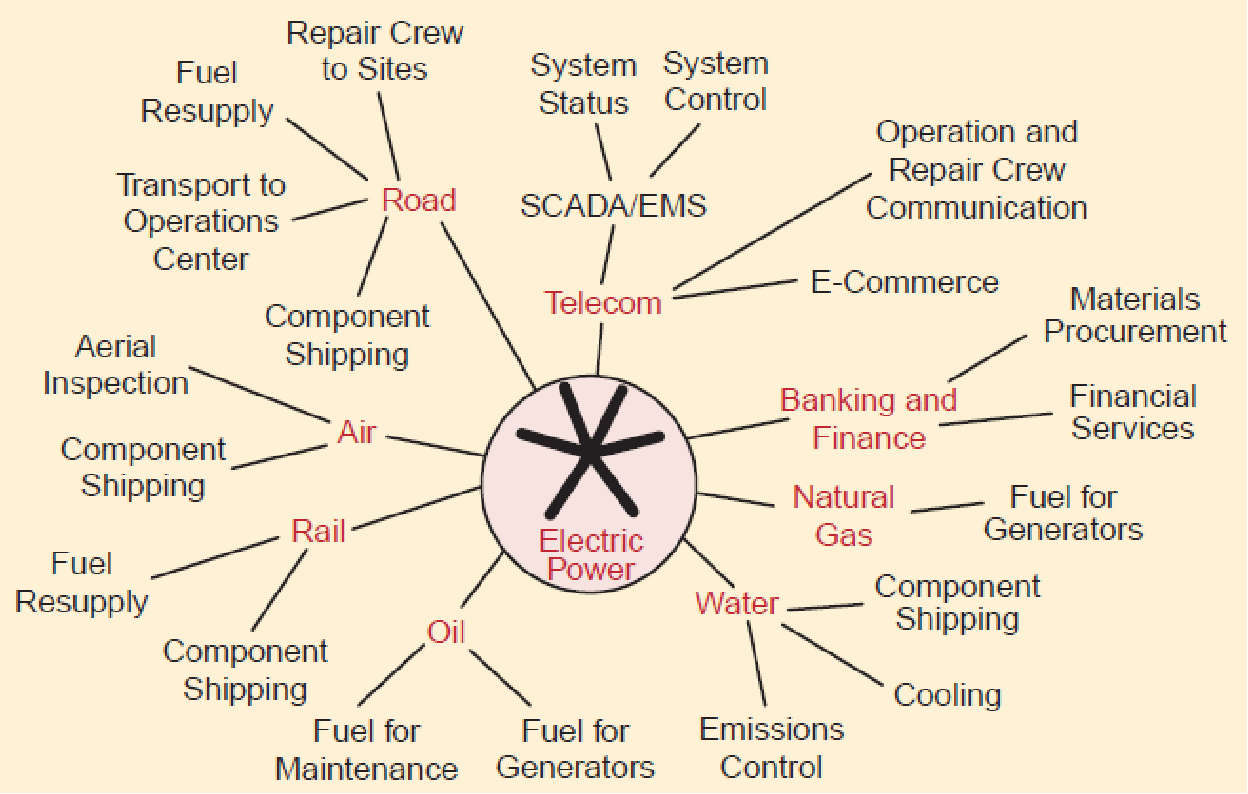


Figure 2-4: Electric Power Dependencies Diagram
(Rinaldi et al. 2001)

<u>Sample questions for plant manager (or similar) during a potential field study:</u>

Sample Question 1: Did you have failure of transmission and distribution lines? Why or why not?

Sample Question 2: Did you have enough water for cooling? Why or why not?

Sample Question 3: What is the source of your water supply? How was the source affected?

Sample Question 4: Did you have enough fuel for the power generators? Why or why not?

Sample Question 5: Where do you obtain your oil and natural from? How was the source affected?

2.2.2. Water and Wastewater Treatment

Water production is directly dependent upon power generation (Gursesli and Desrochers 2003). Power disruption may cause pumps to become ineffective which in turn causes a loss of water system pressure, which often leads to boil-water advisories, since without pressure, groundwater and potential contaminants can leak into the system. Power outages also cause sewer lift stations to stop working, which causes sewage build up and in some cases, discharge of raw sewage (Miles et al. 2015).

Sample questions for plant manager (or similar) during a potential field study:

Sample Question 1: Did you have power outages? How did they affect water treatment and transportation?

Sample Question 2: If there was a power outage, did sewer lift stations stop working? How did this affect wastewater transportation and treatment

Sample Question 3: Did you have a backup generator or batteries on site? How long can the generator or batteries supply power to your primary systems?

2.2.3. Oil and Natural Gas

According to a report by the National Petroleum Council Committee on Critical Infrastructure Protection (Lesar et al. 2001), oil and natural gas systems are primarily dependent upon information technology, telecommunications, and electric power. They also rely on e-commerce, commodity trading, business-to-business systems, electronic bulletin boards, computer networks, and other critical business systems to operate and connect their systems.

This increasing dependence on communications systems is creating new problems and complexities for oil and natural gas resilience. As refineries continue to become more automated they become more dependent on external resources such as communications systems and electric power. Most new natural gas appliances use electronic ignition and will not operate without electricity. Petroleum production and delivery also depend on transportation systems. Petroleum products are often transported through the use of pipelines, but the primary method of transporting petroleum products to the end user is through the use of barges, rail, and trucks. Therefore, if transportation infrastructure is damaged then the petroleum products will never reach their destination. In addition, gas stations require electricity in order to operate pumps, and many gas stations do not have backup generators (Gursesli and Desrochers 2003; Lesar et al. 2001).

Sample questions for oil or natural production plant manager (or similar) during a potential field study:

Sample Question 1: Did you lose communication between systems? For how long? Why?

Sample Question 2: Did you have power outages? How did they affect production and transportation of petroleum products?

Sample Question 3: What is the source of your power supply? How was the source affected?

Sample Question 4: Did you have a backup generator or batteries onsite? How long can the generator or batteries supply power to your primary systems?

2.2.4. Transportation

Most modes of transportation are dependent upon oil or gas to power their engines; however, electric power is also crucial for certain transportation systems. For example, in urban communities traffic flow is largely regulated with the use of electric traffic signals. If power to these traffic signals is cut off, traffic will be significantly disrupted. Another example is the dependence of electric trains and similar public transportation systems on electric power to function (Miles et al. 2015). These are just a couple illustrative examples of interdependencies in transportation systems, but there are many more that are not discussed herein.

Sample questions for city transportation engineer (or similar) during a potential field study:

Sample Question 1: Did you have power outages? How did outages affect electric trains and traffic signals?

Sample Question 2: What is the source of your power supply? How was the source affected by the event?

Sample Question 3: Did you lose telecommunication service? How did this affect public transportation?

Sample Question 4: Who provides this telecommunication service?

Sample Question 5: Was there an oil or gas shortage? How did this affect traffic patterns?

Sample Question 6: Was there an increased usage of public transportation after the event?

2.2.5. Buildings

Although community resilience focuses on all physical and non-physical sectors within a community, it is clear that functionality of certain buildings in a community plays a central role. The causes of loss of functionality vary depending on the purpose of the building. Most businesses depend on electric power for computer use, telecommunications, and typically their ability to function properly. Other types of buildings may depend on other systems such as water or natural gas (Pederson et al. 2006).

Sample questions for building and facility manager (or similar) during a potential field study:

Sample Question 1: What is the primary function of your building (if not apparent)? Was this function interrupted? If so, for how long?

Sample Question 2: Did you have enough water for necessary building functions? Why or why not?

Sample Question 3: What is the source of your water supply (if not apparent)? How was the source affected?

Sample Question 4: Did your wastewater systems work properly? How did this affect your building's functionality?

Sample Question 5: Did you have enough oil and natural gas (heating, cooling, and fuel source)? Why or why not?

Sample Question 6: Where do you obtain your natural gas from? How was this source affected?

Sample Question 7: Did you have power outages? How did they affect your building's functionality?

Sample Question 8: What is the source of your power supply? How was the source affected?

Sample Question 9: Did you have a backup generator or batteries onsite? How long can the generator supply power to your primary systems?

2.2.6. Communication Systems

Communication systems are primarily dependent upon electric power. Without power the systems will cease to function. As discussed previously, electric power is primarily dependent upon oil and natural gas. When the oil and natural gas reserves are depleted or when the transportation of oil and natural gas is disrupted, electricity cannot be produced and telecommunications will be cut off unless a backup generator is connected (Lesar et al. 2001).

This is an example of the complexities of physical infrastructure dependencies, and how a single system may depend on multiple other systems.

<u>Sample questions for communications coordinator (or similar) during a potential field study:</u>

Sample Question 1: Did you lose power? For how long?

Sample Question 2: Where do you obtain your power? Why was this source affected?

Sample Question 3: Did your parent server lose functionality? Why?

Sample Question 4: Did you have a backup generator or batteries onsite? How long can the generator or batteries supply power to your primary systems?

3. Identifying Resilience Metrics

In order to conduct community resilience field studies and fill the gaps in past field studies that were identified in Section 2.1, a set of quantifiable metrics must be identified. This chapter provides a brief review of two reports that have been published by NIST that describe a conceptual framework for assessing resilience at the community scale and then uses this conceptual framework to help identify the specific field data needs for seven crucial resilience metrics.

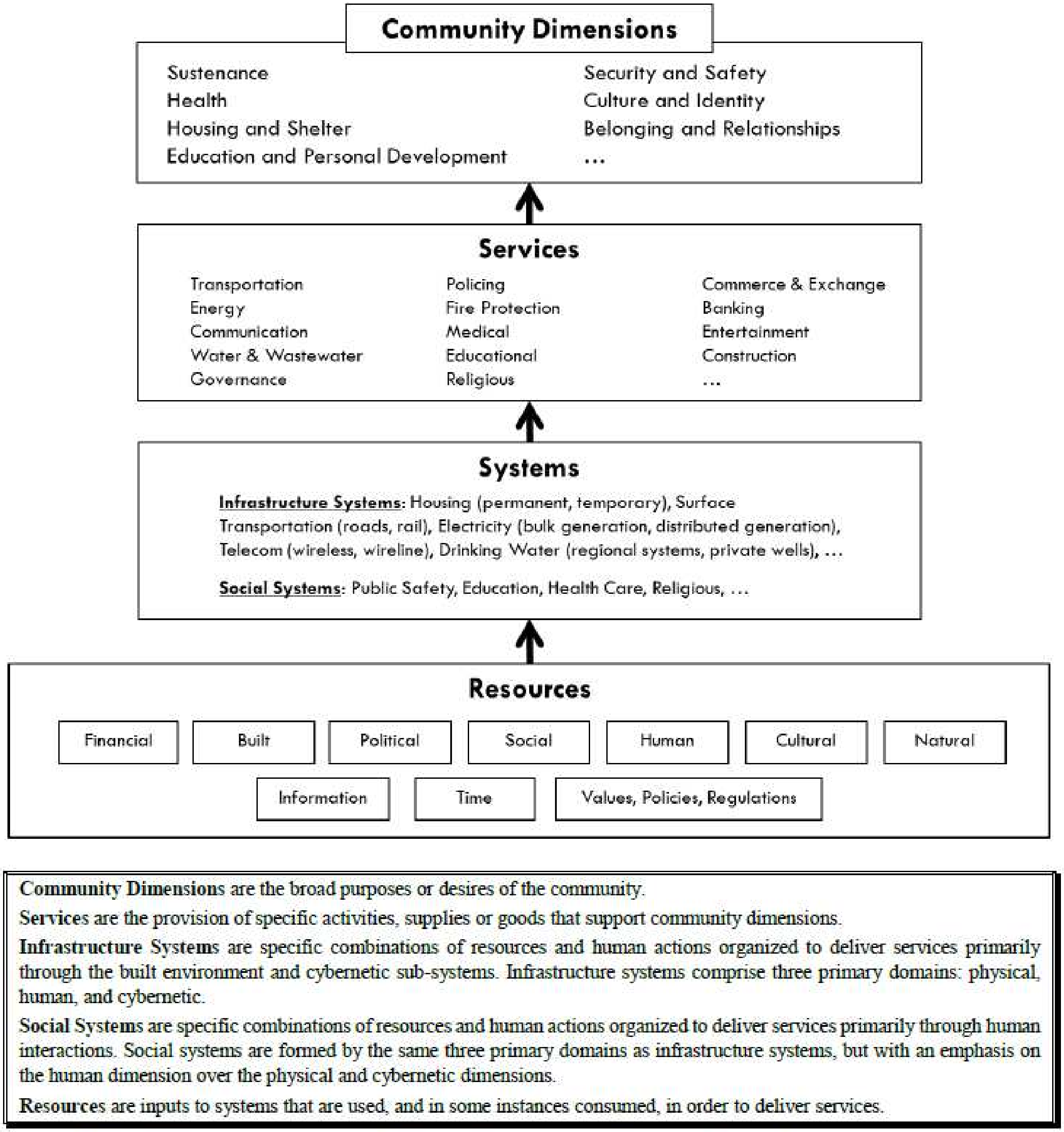
3.1. NIST Conceptual Framework for Assessing Resilience at the Community Scale

NIST has published two reports as a part of their Community Resilience Assessment Methodology (CRAM) project with the goal of providing a basis for assessing resilience at a community scale. The first report (Lavelle et al. 2015) reviewed nine existing methodologies for evaluating community resilience. Each of the nine methodologies provided a separate set of quantifiable resilience metrics. Each of them was reviewed, analyzed, and scored based on their effectiveness. The second report (Kwasinski et al. 2016) proposed a conceptual framework for assessing resilience at the community scale that combines the strengths of these existing methodologies and fills any gaps that were identified. The authors propose that it is the primary purpose of a community to allow for the provision of the following seven community dimensions:

1. Sustenance
2. Health
3. Housing and Shelter
4. Security and Safety
5. Education and Personal Development

6. Culture and Identity
7. Belonging and Relationships

These essential community dimensions are supported by community services that include communication, transportation, water, sewage, energy, education, policing, fire protection, etc. These services are fueled by resources that are separated into the following categories: financial, built, political, social, natural, time, etc. If a community loses its ability to provide these resources or these services for its members, then its ability to provide the seven community dimensions becomes impaired. Any of these community dimensions, services, or resources can be dependent on other dimensions, services, and resources. They might also be mutually dependent on each other, or interdependent. This concept is outlined in Figure 3-1 (reproduced from Kwasinski et al. 2016) below.



Community Dimensions are the broad purposes or desires of the community.

Services are the provision of specific activities, supplies or goods that support community dimensions.

Infrastructure Systems are specific combinations of resources and human actions organized to deliver services primarily through the built environment and cybernetic sub-systems. Infrastructure systems comprise three primary domains: physical, human, and cybernetic.

Social Systems are specific combinations of resources and human actions organized to deliver services primarily through human interactions. Social systems are formed by the same three primary domains as infrastructure systems, but with an emphasis on the human dimension over the physical and cybernetic dimensions.

Resources are inputs to systems that are used, and in some instances consumed, in order to deliver services.

Figure 3-1: NIST Community Dimensions
(Kwasinski et al. 2016)

The authors recommend that in order to quantify resilience, several important community dimensions must be selected and analyzed. This involves determining the services and resources that are required to achieve a certain community dimension and investigating dependencies and interdependencies. Performance indicators should be identified in order to achieve this. Some examples of performance indicators are: population dislocation, employment levels, housing availability, crime levels, etc. The terms performance indicator and resilience metric are used interchangeably throughout this thesis. Performance goals can be established for each indicator, and then the actual performance of each system as measured in the field can be compared with the performance goals in order to gain an understanding of resiliencies and vulnerabilities within a community. Figure 3-2 (Kwasinski et al. 2016) shows a visual of the end result of this conceptual framework. This plot allows us to see where a community is resilient and where it is vulnerable by looking at the difference between the black and blue lines. The black line represents the measured resilience and the blue line represents the performance goals. Community systems with very large negative gaps are colored purple or red and are in need of improvements in resilience. Community systems with no gap or a positive gap are colored green and do not necessarily need to be made more resilient based on the targets selected. This conceptual framework is the basis of the development of resilience metrics or performance indicators that are quantifiable with field study data which are described in Section 3.2.

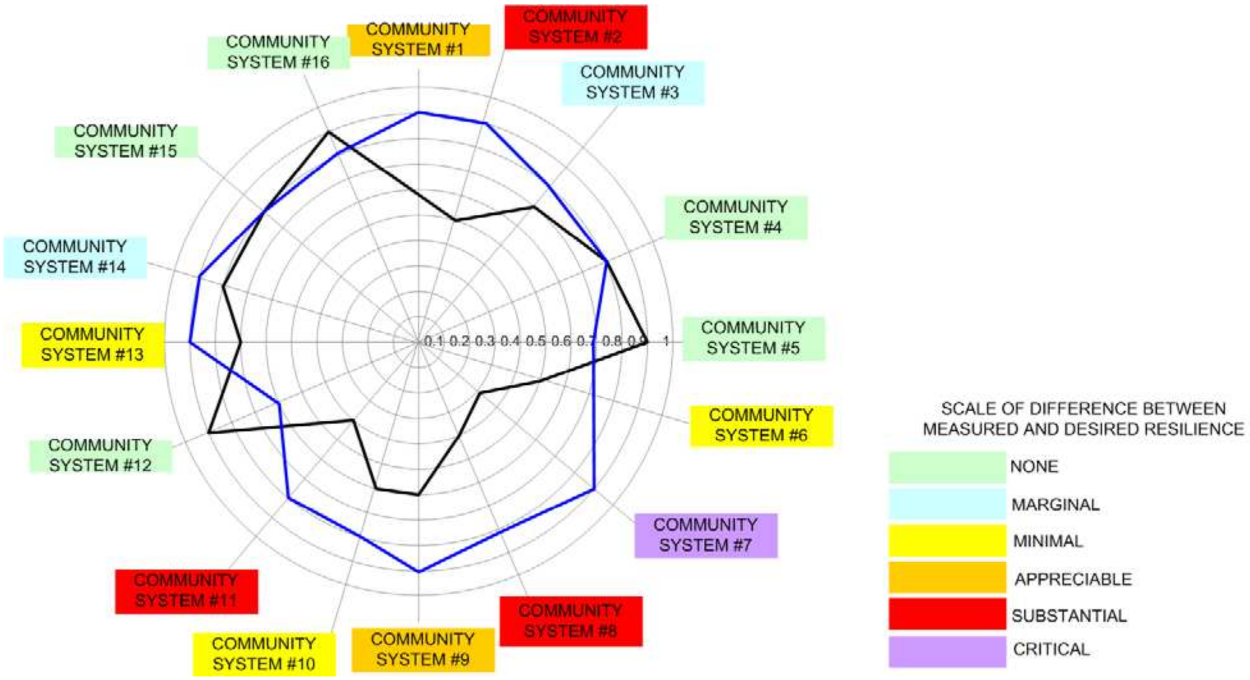


Figure 3-2: Community Resilience Assessment Tool
(Kwasinski et al. 2016)

3.2. Resilience Metrics

The field study methodology developed in this thesis is driven by a desire to measure and quantify community resilience. In order for this to be possible a clear set of resilience metrics (i.e., performance indicators) must be defined. Several examples which are believed to be good metrics, but are yet to be proven, are used throughout this thesis. The resilience metrics that are outlined below have been identified through a combination of literature review and expert opinion. The purpose of these metrics is to provide an illustrative relationship between community resilience and field study data that allows the utilization of the data processing methodology described later in this thesis. The field study concept described herein builds off of the NIST conceptual framework described in Section 3.1. In order to achieve this, the community dimensions, essential services, and resources described by the recommendations of Kwasinski et al. (2016) were incorporated into the development of a set of illustrative resilience metrics. However, these resilience metrics cannot necessarily be directly equated to the community dimensions and more development may be needed to understand how these two concepts are aligned. In the following sections seven resilience metrics are described that may be used to characterize resilience in any community; however, these metrics may need to be revised depending on the specific community and field study's goals. The seven primary resilience metrics that were selected are listed below. To see a more substantial list of metrics that can be used to describe community interconnectivities, please see Appendix A.

<u>Possible Community Resilience Field Study Metrics:</u>

1. Population Dislocation
2. Business Interruption
3. Employee Dislocation
4. Critical Facilities Impact
5. Housing Loss
6. Physical and Mental Morbidity and Mortality
7. Fiscal Impact

3.2.1. Population Dislocation

Population dislocation is an ambiguous term that can mean a number of different things depending on the cause or timing of the dislocation. For the purpose of this thesis, it is defined as the migration or displacement of an individual or family immediately following a disaster. This does not include forced evacuation or dislocation that occurs after an extended period of time. Population dislocation is believed to be one of the most important measures of a community's resilience, although this has not yet been proven. This metric primarily contributes to four essential community dimensions from the NIST conceptual framework: housing and shelter, security and safety, culture and identity, and relationships and belonging. When members of a community are dislocated, the community cannot provide these four dimensions effectively.

There is an abundance of research that has been conducted to define, measure, and model population dislocation immediately following a disaster. For the purpose collecting data that are compatible with the data processing toolbox described in Section 6, it is assumed that the primary indicator of population dislocation is residential building damage. Five classifications of damage measures or damage states are defined in the Hazus-MH Technical User’s Manual (DHS and FEMA 2011, 2015). The Earthquake Engineering Research Institute Field Study Manual (EERI 1996) takes a different approach and classifies damage to buildings by loss of market value of the building.

Using these damage classifications, field investigators can record residential damage states. Then using a field study questionnaire similar to the one in Section 4.2, the duration of dislocation of the corresponding residents can also be recorded. Using the methodology described in Section 6, these data can be processed and probabilities of exceedance of dislocation can be found for different durations of dislocation at any location. Performance goals can then be determined for these probabilities as suggested in the NIST conceptual framework. Finally, the measured probabilities can be compared with the performance goals in order to determine whether an area is vulnerable or resilient (similar to Figure 3-2). This process of finding probabilities of exceedance and comparing them with performance goals is similar for all of the identified resilience metrics.

The dislocation durations for which probabilities of exceedance are found must be divided into categories. For example, the durations can be divided into six categories, and a different probability can be produced for each category listed below.

Category 1: The residents are dislocated for 1 day or longer

Category 2: The residents are dislocated for longer than two months

Category 3: The residents are dislocated for longer than five months

Category 4: The residents are dislocated for longer than eight months

Category 5: The residents are dislocated for longer than ten months

Category 6: The residents are dislocated permanently

<u>Secondary Factors:</u>

Physical damage is not the only reason that residents decide to leave their homes following a disaster. There are many secondary factors that can have a significant effect on population dislocation. When applicable, data should also be gathered in order to modify the probabilities of population dislocation based on secondary factors. Several of the possible secondary factors are listed below. This list is not comprehensive, and any secondary factor can be considered as long as the data that are collected for that factor are correlated with the location of the residence.

1. Loss of lifelines
2. Loss of job of head of household
3. Damage to surrounding infrastructure
4. Insurance coverage
5. Household Demographics

3.2.2. Business Interruption

Businesses interruption in the aftermath of disasters can result in loss of jobs, lower incomes, and additional challenges for households, neighborhoods, and communities as they attempt to recover from disasters (Tierney 2006). In order to quantify these effects, business interruption can be measured by the number of days that a certain business is closed after a disaster. The primary indicator of business interruption is assumed to be damage to the buildings that contain businesses. This may be highly related to housing loss as 52% of small businesses are operated from the owner’s home (Pratt 2000). Using this simplifying assumption, we can predict probabilities of business interruption for different durations. This metric primarily contributes to three essential community dimensions from the NIST conceptual framework: sustenance, security and safety, and culture and identity.

Two data fields are required in order to quantify business interruption. The first data field is the damage states of the buildings that contain businesses, which can be obtained using the damage classifications described in Section 5.5. The second data field is the durations that businesses lost functionality, which can be obtained by interviewing business owners, community leaders, and government officials using a field study questionnaire similar to the one in Section 4.2. Performance goals for the probability of business closure can be determined, and gaps between the measured probabilities and the performance goals identified (similar to Figure 3-2).

The business closure probabilities can be divided into six categories based on loss of functionality duration, and a different probability can be produced for each of the six categories as listed below.

Category 1: The business is closed for 1 day or longer

Category 2: The business is closed for longer than 2 months

Category 3: The business is closed for longer than 5 months

Category 4: The business is closed for longer than 8 months

Category 5: The business is closed for longer than 10 months

Category 6: The business is closed permanently

Secondary Factors:

Physical damage to buildings is not the only reason that businesses lose functionality after disasters. There are many secondary factors that have a significant effect on business resilience, vulnerability, and recovery. When applicable, data should also be gathered for secondary factors in order to allow modified probabilities of loss of business functionality to be found. Several possible secondary factors are listed below (Tierney 2006; DHS and FEMA 2015).

1. Loss of lifelines
2. Loss of customer base
3. Damage to surrounding infrastructure
    a. Damage to transportation (shipping and receiving) networks
4. Insurance coverage
5. Economic sector
6. Pre-disaster financial condition
7. Business age
8. Primary market
9. Business size
10. Owner demographics

According to a survey performed by Webb et al. (1999), the factors that have the greatest effect on business closure are: type of business, pre-disaster financial condition, business age, primary market (e.g., local or international), and business size in that order. Several of these factors are accounted for in the field study questionnaire in Section 4.2.

3.2.3. Employee Dislocation

Employee dislocation is a second order resilience metric because it depends on two previous metrics: population dislocation and business interruption. The unit of measure for employee dislocation is the duration of time that that an employee does not report to work after a disaster, and it is assumed that its primary indicator is damage to the employee’s residence. This metric primarily contributes to four essential community dimensions: sustenance, security and safety, education and personal development, and culture and identity.

Employee dislocation is quantified by finding the number of employees that missed work for specified durations of time. In order to obtain these data, the field team should interview business owners, managers and employees in order to find out how many employees missed work and for how long. The questions that should be asked are described further in the field study questionnaire in Section 4.2. In addition, the damage states of the employees’ residences can be obtained using the damage classifications that are proposed in Section 5.5. It may be difficult or nearly impossible to perform a damage assessment of each employee’s home, but an attempt should be made to assess the damage of the homes that are easily accessible and record the corresponding duration of work missed; even providing spot checks for consistency. Performance goals for the probability of employee dislocation can be determined, and gaps between the measured probabilities of exceedance and the performance goals identified (similar to Figure 3-2).

The employee dislocation probabilities can be divided into six categories based on dislocation duration, and a different probability can be produced for each of the six categories as listed below.

Category 1: The employee is dislocated for 1 day or longer

Category 2: The employee is dislocated for longer than 2 months

Category 3: The employee is dislocated for longer than 5 months

Category 4: The employee is dislocated for longer than 8 months

Category 5: The employee is dislocated for longer than 10 months

Category 6: The employee is dislocated permanently

Secondary Factors:

Physical damage to residences is not the only reason that employees are dislocated after disasters. There are many secondary factors that have significant effects on employee dislocation. When applicable, data should also be gathered for secondary factors in order to allow modified probabilities of employee dislocation to be found. Several possible secondary factors are listed below. Additional secondary factors can be considered as long as the data that are collected for those factors are correlated with the residence location.

1. Loss of lifelines
2. Damage to surrounding infrastructure
3. Insurance coverage
4. Demographics
5. Morbidity or mortality

3.2.4. Critical Facilities Impact

Critical or essential facilities are defined as facilities that are necessary for society to function at its most fundamental level. This includes hospitals, fire stations, police stations, storage of critical substances, and schools (DHS and FEMA 2015). Impact to these facilities is measured by the duration of loss of functionality. Loss of functionality occurs when the facility is no longer able to perform its most basic function (e.g., a hospital loses functionality when it can no longer be used to treat patients effectively). It is important to note that a service (e.g., healthcare) can be provided through temporary means during the immediate aftermath of a disaster. The ability of a community to provide temporary services likely accelerates the recovery of a community. It is assumed that the primary indicator of loss of functionality is damage to the structure. This metric primarily contributes to three essential community dimensions: health, security and safety, and education and personal development.

Data that should be collected includes the damage states of critical facilities and the duration of loss of function for the corresponding facilities. Damage data can be obtained using the damage classifications that are described in Section 5.5. In order to obtain the loss of functionality data, the field team should interview the managers of the critical facilities, if possible, and any local government officials and community leaders to find out how long each facility lost functionality according to the guidelines in Section 4.2. These data can then be processed using the methodology described in Section 6.2 in order to find probabilities of exceedance of critical facility loss of functionality for different durations. Performance goals for the probability of loss of critical facility functionality can be determined, and gaps between the measured probabilities and the performance goals can be identified (similar to Figure 3-2).

The loss of functionality probabilities can be divided into six categories based on duration, and a different probability can be produced for each of the six categories as listed below.

Category 1: The critical facility loses functionality for 1 day or longer

Category 2: The critical facility loses functionality for longer than 2 months

Category 3: The critical facility loses functionality for longer than 5 months

Category 4: The critical facility loses functionality for longer than 8 months

Category 5: The critical facility loses functionality for longer than 10 months

Category 6: The critical facility loses functionality permanently

Secondary Factors:

In addition to physical damage, there are many secondary factors that have a significant effect on the loss of functionality of critical facilities. When applicable, data should also be gathered for these secondary factors in order to allow modified probabilities of loss of functionality to be found. Several possible secondary factors are listed below, and additional secondary factors can be considered as long as the data that are collected for those factors are correlated with the facilities' location.

1. Loss of lifelines
2. Damage to surrounding infrastructure
3. Insurance coverage
4. Demographics
5. Employee dislocation

3.2.5. Housing Loss

The loss of available housing in a community is believed to be an important resilience metric because it can result in population dislocation, employee dislocation, and economic loss. The unit of measure for housing loss is the duration of loss of functionality of a residence, where loss of functionality refers to the lack of a building's ability to provide shelter. It is assumed that the primary indicator of this loss of functionality is the damage state of a residence. This metric primarily contributes to four essential community dimensions from the NIST conceptual framework: housing and shelter, security and safety, culture and identity and relationships and belonging.

In order to create probabilistic models of housing loss, the damage states and durations of loss of functionality for residences must be collected. The damage states of the residences can be obtained by using classifications such as those proposed in Section 5.5. It is also common for post-event inspectors to place either green, yellow, or red tags on each residence. The color of the tag on the building describes the corresponding damage level based on a cursory inspection. It may be useful to utilize these tags as an alternative measure of damage state. An example of what they typically mean is given below, and the formal placards can be downloaded from the Applied Technology Council's website.

Green Tags: "The building has been inspected and no restrictions on use or occupancy have been found. The placard includes the date of inspection and inspector's identification number. An evaluation form is prepared and given to the building official. Events after the inspection, such as severe weather or aftershocks, could require additional inspections and a change of the placard" (Brallier 2006).

Yellow Tags: "The building has been inspected and found to be damaged as described on the placard. This placard can be used to cover a wide range of hazards that may limit use of the building or portions of the building but not make it completely unsafe. Examples of such hazards include water saturated ceiling drywall, collapsed chimney on a portion of the roof or creating a falling hazard on an adjacent structure, electrical power lines that had been inundated during flooding, or a portion of the building has collapsed but other portions do not appear to have been damaged. A yellow card may allow for limited use of the building, but restrict continuous habitation or sleeping in the building" (Brallier 2006).

Red Tags: "The building has been inspected and is damaged and unsafe. No entry is allowed, except as specifically authorized in writing by the jurisdiction. A red placard does not imply that the structure is condemned and must be demolished. Repairs can be made to mitigate the hazard. Specific hazards are noted on the placard and may include falling hazards, hazardous materials, loss of safe exits or a potential for collapse" (Brallier 2006).

In order to obtain the loss of functionality data for this metric, the field team can interview government officials, community leaders, and local residents as described in the field study questionnaire in Section 4.2. Damage data can be obtained using the damage classifications that are described in Section 5.5. These data can then be processed using the methodology described in Section 6 in order to predict housing loss probabilities. Performance goals for the probability of housing loss of functionality can be determined, and gaps between the measured probabilities of exceedance and the performance goals can be identified (similar to Figure 3-2).

The loss of functionality probabilities can be divided into six categories based on duration, and a different probability can be produced for each of the six categories as listed below.

Category 1: The residence loses functionality for 1 day or longer
Category 2: The residence loses functionality for longer than 2 months
Category 3: The residence loses functionality for longer than 5 months
Category 4: The residence loses functionality for longer than 8 months
Category 5: The residence loses functionality for longer than 10 months
Category 6: The residence loses functionality permanently

Secondary Factors:

In addition to physical damage, there are many secondary factors that have a significant effect on the loss of functionality of residential structures. When applicable, data should also be gathered for secondary factors in order to allow modified probabilities of housing loss to be determined. Several possible secondary factors are listed below. Additional secondary factors can be considered as long as the data that are collected for those factors are correlated with the residence locations.

1. Loss of lifelines
2. Damage to surrounding infrastructure
3. Insurance coverage
4. Household demographics

3.2.6. Physical and Mental Morbidity and Mortality

Morbidity and mortality are often the most reported statistics after a disaster occurs. Research is available on the prediction morbidity and mortality during disasters (e.g., Jennings 2014, DHS and FEMA 2015). However, it is rare for field study teams to attempt to investigate the number of morbidities and mortalities that are caused by a disaster because it takes months or even years to determine an approximate number of deaths and injuries due to factors such as missing persons, delayed fatalities, and unclear causes of injury, illness, or death (Brunkard 2008). This metric primarily contributes to three essential community dimensions from the NIST conceptual framework: health, security and safety, and belonging and relationships.

Simplifying assumptions have to be made in order to create probabilistic models of morbidities using the methodology described in Section 6. The primary indicator for death and injury is assumed to be damage to physical infrastructure. Data should be collected for locations and causes of morbidities and mortalities using a questionnaire similar to the one in Section 4.2. Then damage states can be evaluated for each corresponding infrastructure element using the damage state descriptions in Section 5.5. Finally, using the methodology described in Section 6, these data can be processed and probabilities of exceedance of morbidities can be found for specific locations. Performance goals can then be set for these probabilities of exceedance as suggested in the NIST conceptual framework. Then the measured probabilities can be compared with the performance goals in order to determine whether or not an area is vulnerable (similar to Figure 3-2).

In the methodology presented in this thesis, the severity of physical morbidities is described by the six severity levels shown in Table 3-1 where Severity Level 1 is no injury and Severity Level 6 is death (category descriptions taken directly from DHS and FEMA 2015). A different probability is generated for each of the six severity levels that are listed below.

Table 3-1: Morbidity Category Descriptions
(DHS and FEMA 2015)

Injury Severity Level	**Injury Description**
Severity Level 1	No injury or an injury of lesser severity that could be self-treated.
Severity Level 2	An injury requiring basic medical aid that could be administered by paraprofessionals. This type of injury would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness.
Severity Level 3	An injury requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration or exposure.
Severity Level 4	An injury that poses an immediate life threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
Severity Level 5	Instantaneously killed or mortally injured.

Mental morbidity can be just as damaging to a community as physical morbidity. This field study methodology accounts for rates of post-traumatic stress disorder (PTSD) in a community after a disaster by treating PTSD as a binary input where a person either has PTSD or does not have PTSD. Whether or not a person has developed symptoms of PTSD would need to be determined through either the use of mental health surveys or discussions with mental health professionals. This process is described further in the field study questionnaire in Section 4.2.

The quantities of each severity level for morbidity can be divided into six categories, and a different probability can be produced for each of the six categories that are listed below, and for each of the severity levels listed in Table 3-1.

Category 1: There is 1 or more of a certain morbidity category related to a certain type of infrastructure.

Category 2: There are more than 10 of a certain morbidity category related to a certain type of infrastructure.

Category 3: There are more than 30 of a certain morbidity category related to a certain type of infrastructure.

Category 4: There are more than 50 of a certain morbidity category related to a certain type of infrastructure.

Category 5: There are more than 100 of a certain morbidity category related to a certain type of infrastructure.

Category 6: There are more than 500 of a certain morbidity category related to a certain type of infrastructure.

Secondary Factors:

In addition to damaged infrastructure, there are many secondary factors that have a significant effect on morbidity and mortality rates. When applicable, data should also be gathered for secondary factors in order to allow modified probabilities of morbidity severity levels to be found. Several possible secondary factors are listed below.

1. Building function
2. Number of building occupants
3. Time of disaster
4. Community’s emergency services capacity
5. Demographics
6. Population density

3.2.7. Fiscal Impact

Fiscal impact is a crucial metric because the economy controls many important aspects of community recovery. If the economy is doing well, then the city will recover more quickly and vice versa. This metric primarily contributes to four essential community dimensions: sustenance, security and safety, education and personal development, and culture and identity. Fiscal impact is a second order metric because it is a function of business interruption, population dislocation, employee dislocation, and other metrics. This is a complex metric to quantify because there are many unknowns and constantly changing variables. It is common for fiscal impact reports to be released months or even years after a disaster occurs. Due to all of these factors, it may be difficult to gather these types of data in the field. It is typical for an economist to investigate the fiscal impact of a disaster on a community by conducting a case study; obtaining secondary data from private and publically available data bases. However, using only secondary data could result in a study missing perishable data, and collecting data in the field may add additional value to economic models, but little exploration has been done in this area. It may be advantageous to consider methods of collecting fiscal impact field data in future field studies. This work is outside the scope of this thesis.

3.2.8. Summary Table

Table 3-2 below shows a summary of the information in Sections 3.2.1 through 3.2.7. It includes each resilience metric, its primary indicator, and the minimum data that need to be collected in the field in order to enable the development of probabilistic models as described in Section 6.2. It should be noted that these metrics are only examples, and can be revised for future field studies. Although not listed in the table, additional data related to individual demographics and secondary factors should be collected if possible. Fiscal impact is excluded from this table because it cannot be modeled using the same methods as the other six resilience metrics.

Table 3-2: Resilience Metric Indicators and Data Requirements

Resilience Metric	**Primary Indicator**	**Minimum Data Needed to Model**
Population Dislocation	Physical damage to residential buildings	Durations of dislocation; damage states of residential buildings
Business Interruption	Physical damage to businesses	Durations of business closure; damage states of businesses
Employee Dislocation	Physical damage to residential buildings	Durations of employees missing work; damage states of residential buildings
Critical Facilities Impact	Physical damage to critical facilities	Durations of critical facilities closure; damage states of critical facilities
Housing Loss	Physical damage to residential buildings	Durations of loss of housing functionality; damage states of residential structures
Physical and Mental Morbidity and Mortality	Physical damage to infrastructure	Severity of physical morbidities; mental disabilities (yes or no); damage states of infrastructure

Note: These metrics are illustrative and recommended, but additional and alternative metrics should be developed based on the specific goals of the field study being planned.

4. Physical, Social, and Economic Interconnectivity

This section further develops the methodology by providing guidance on investigating the interconnectivities between the physical, social, and economic domains of a community. An interconnectivity diagram was developed that provides interview questions that might be used to connect these three community domains. In order to provide a more practical application of this interconnectivity diagram, a questionnaire was then developed that provides 27 questions and sub-questions that could be asked throughout the course of a field study. The goal of this questionnaire is to produce data that allow the modeling of the resilience metrics from Section 3.2 and the investigation of related interconnectivities.

4.1. Field Study Interconnectivity Diagram

In order to understand community resilience, the interconnectivities or linkages between the physical, social, and economic domains of a community must be identified. Figure 4-1 shows an example diagram presenting potential interview questions to relate these three domains. A diagram such as this could be used during the initial field study planning period to provide guidance and direction for investigating the interconnectivities within a community and developing a detailed questionnaire. It articulates an understanding of how a single system is connected to many other systems and can allow field teams to ask the proper interview questions that enable them to investigate this interconnectivity. Many of the original metrics that this diagram originated from are discussed in detail Masterson and Peacock et al. (2014). For a more substantial list of metrics that can be used to describe interconnectivities, please Appendix A.

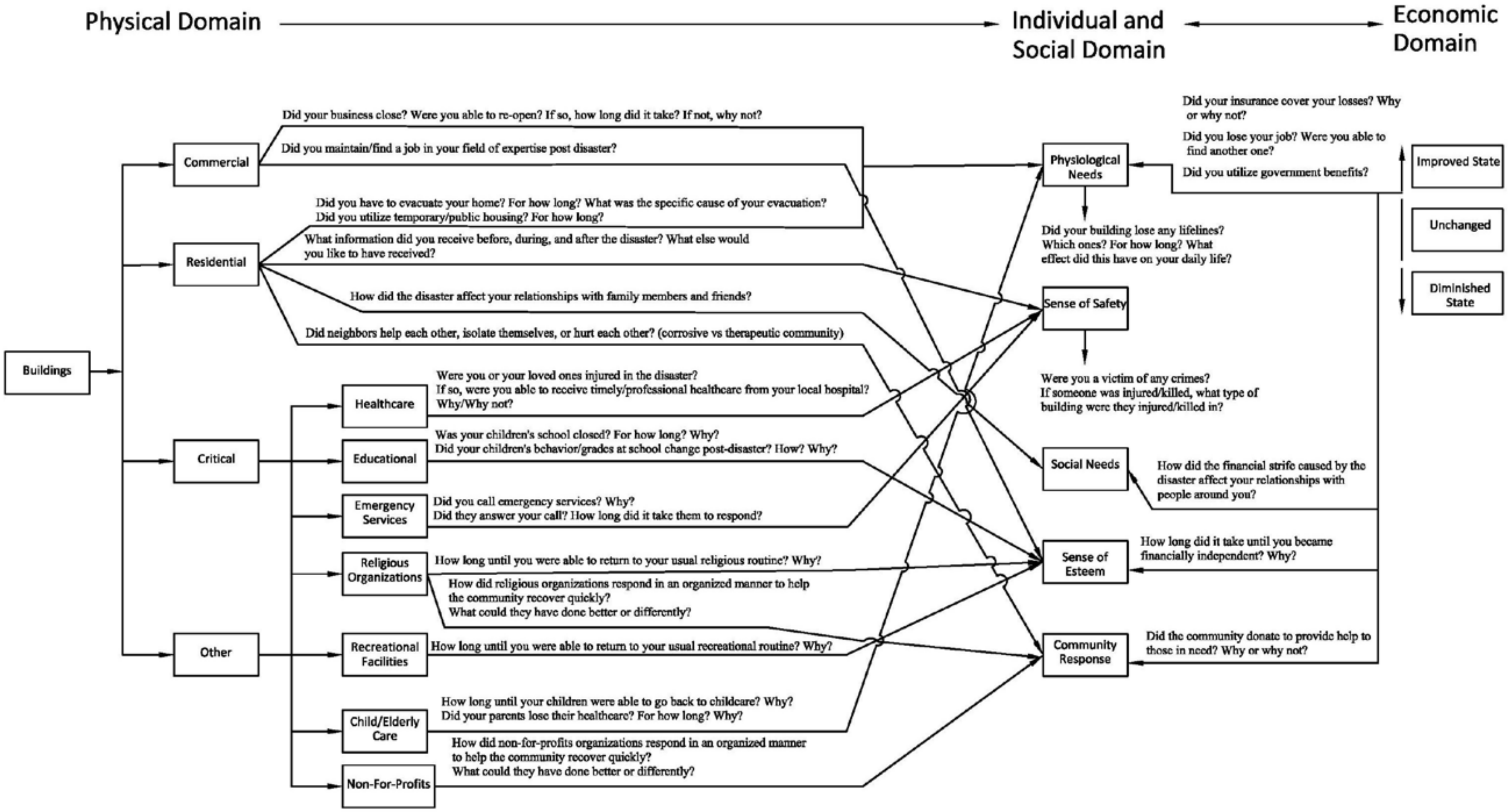


Figure 4-1: Field Study Interconnectivity Diagram
Note: An arc in an arrow means that one arrow does not intersect another arrow

4.2. Field Study Questionnaire

A sample questionnaire was developed with guidance from the field study interconnectivity diagram shown in Figure 4-1 which provides 27 questions and sub questions with the purpose of assisting in obtaining data from interviews and surveys that enable the quantification of six of the resilience metrics listed in Section 3.2. These metrics include (1) population dislocation, (2) business interruption, (3) employee dislocation, (4) critical facilities impact, (5) housing loss, and (6) physical and mental morbidity and mortality. It does not cover the seventh metric, fiscal impact, because field study data do not typically need to be collected to study these effects. In addition to quantifying resilience metrics, the data supplied by these questions will link the physical, social, and economic domains of a community.

In order to show an example of how to establish these linkages as part of a field study, the formulation of this questionnaire relies heavily on the field study interconnectivity diagram shown in Figure 4-1. However, it is important to note that the questions in this questionnaire are not the same as the questions in the interconnectivity diagram because their primary focus is on collecting the data required to quantify resilience metrics. The questions are organized first by the resilience metric that they will be used to quantify and second by the recipient of the question. The type of interconnectivity that is correlated with each of the questions is also described. There are many other questions that could be added to this list, but in order to account for time demands and resources, only these 27 were selected herein. This section only provides an example of a possible field study questionnaire. Many of these questions should be altered depending on the characteristics of the specific community and the disaster to be studied.

In addition to a questionnaire, a demographics survey should be filled out by every interviewee, which will provide data on the interviewee's gender, race/ethnicity, age, marital status, household size, education, and employment status. There should also be a separate demographics survey for businesses.

Population Dislocation

The following questions were selected because they provide data that can be used to quantify population dislocation and the related interconnectivities in accordance with the methods described in Sections 3 and 6.

Questions for community residents:

1. Did you leave your home before, during or after the disaster?
2. If so, why did you leave your home?
    a. Damage to home, loss of power/water/heating/air conditioning, loss of job, damage to surrounding roads/bridges/neighborhood, etc.
    b. Was your home insured?
3. Where did you stay while you were away from your home?
    a. Hotel, friends, family, rental, out of state, etc.
    b. How long did you stay at each of these locations?
    c. How far away from home were you?
4. When did you return to your home? What made it possible for you to return? (Insurance payout, rebuilding efforts, etc.)

Questions for community leaders/government officials/collaborating researchers:

5. How many people were displaced from their homes? For how long?
6. How many people utilized public shelters over time?
    a. Were these shelters free?
    b. How close were these shelters to the community?

Questions 1 - 6 provide data that connect residential building damage to the physiological needs of individuals (see Figure 4-1). There are many different factors that can lead to dislocation after a disaster, but the primary indicator is damage to residential buildings.

Business Interruption and Employee Dislocation

The following questions were selected because they provide data that can be used to quantify either business interruption or employee dislocation and the related interconnectivities. These two metrics are grouped together in this questionnaire because they are closely related to each other, and the questions that can be asked to obtain data for them are similar. When interviewing business owners or managers, a demographics survey that includes questions about the businesses' economic sector, pre-disaster financial condition, age, primary market (e.g., local or international), and size should be completed by each business owner.

Questions for business owners/managers:

7. What type of business do you operate?
8. Did this business close?
9. If so, why did this business close?
    a. Damage to building, loss of power/water/heating/air conditioning, loss of customer base, damage to surrounding roads/bridges/neighborhood, etc.
    b. Was this business insured?
10. When did this business re-open? What allowed it to re-open?
11. What was the total financial loss of this business due to the disaster? What was the primary cause of this loss?
12. Was this business able to access any public or private assistance to help with repairs or lost revenue?

    a. Small business loans, grants, donations, etc.

13. How many employees did not report to work and for how long? Why?

<u>Questions for community leaders/government officials/collaborating researchers:</u>

14. What assistance was given to local and corporate businesses?

<u>Questions for community residents:</u>

15. What was your job prior to the disaster?
16. Are you still employed at the same location?
    a. If yes, did you have to take any time off of work due to the disaster? How long?
    b. If no, why did you lose your job?
17. Are you employed now?
    a. If yes, where do you work now? Are you satisfied with your job?

Questions 7 - 10 provide data that connect commercial building damage to the physiological needs of employees and other community members (see Figure 4-1). Community members rely on commercial buildings remaining open in order to obtain food, water, clothing, and other necessities. Questions 13, 15, 16, and 17 provide data that quantify employee dislocation, while also describing the interconnectivity between commercial building damage, the physiological need of community members to earn money, and the sense of esteem of community members that are working in their respective fields. Questions 12 and 14 help in understanding the assistance given to businesses throughout the recovery process, although much of this is traceable through FEMA and other entities. This allows the finding of the interconnectivity between commercial building damage and community response. Question 11 investigates the broader effects of the disaster on the economy as a whole, while describing the interconnectivity between damage to commercial buildings and economic structure.

Critical Facilities Impact

The following questions were selected because they provide data that can be used to quantify impact to critical facilities and the related interconnectivities. Critical facilities are defined here as facilities that are necessary for a community to function at its most fundamental level after a disaster. This includes hospitals, fire stations, police stations, storage of critical substances, and schools. The following questions can be used in conjunction with field damage estimates to assess the total impact to critical facilities.

<u>Questions for facility managers/community leaders/collaborating researchers:</u>

18. Did critical facilities (hospitals, fire stations, police stations, storage of critical substances, and schools) close? For how long?
19. Why did critical facilities close?
    a. Damage to building, loss of power/water/heating/air conditioning, damage to surrounding roads/bridges/neighborhood, etc.
    b. Were these facilities insured? If so, which ones were or were not?

<u>Questions for community residents:</u>

20. During the disaster, did you or a family member need to utilize any critical services, such as an ambulance, hospital, fire department, or police assistance?
    a. If so, why?
    b. If so, were you satisfied with the level of care that you received? Why or why not?

Question 18 - 20 connect critical facilities to the physiological needs of community members and the sense of safety in the community (see Figure 4-1). Healthcare and emergency services are always necessary after a disaster, and these questions will help us understand how these critical facilities and emergency services performed following the disaster.

Housing Loss

The following questions were selected because they provide data that can be used to quantify housing loss and the related interconnectivities. The following questions can be used in conjunction with field damage estimates and observations of green, yellow, and red tags to assess the total impact to buildings. It should be noted here that housing loss is also studied following a natural disaster using permit data from the county or city. The following inquiries can typically be answered through a request for data, and not surveys or interviews.

21. How many housing units were damaged due to the disaster?
    a. How many of each housing type (single family home, multi family home, apartment complex, etc.) were damaged?
    b. What level of damage? How many green, yellow, and red tags were placed (if applicable)?
22. What area of the community contained homes that were the most damaged?
    a. Did levels of damage vary based on the characteristics of each neighborhood such as income level, race/ethnicity, age, etc.?
23. Which areas were able to begin rebuilding or making repairs the fastest?
    a. How many permits have been issued and at what locations?
24. Did your house lose functionality? For how long?*
25. If so, why did your house lose functionality?

    a. Damage to building, loss of power/water/heating/air conditioning, damage to surrounding roads/bridges/neighborhood, etc.
    b. Was your home insured?

*Loss of functionality refers to the lack of ability to support and provide shelter for the residents.

Questions 21, 24, and 25 provide data that connect residential building damage to the physiological needs of community members. Community members need shelter in order to survive and recover; therefore, creating resilient residential buildings is crucial to the survival of a community. Questions 22 and 23 provide data on the interconnectivity between residential building damage and pre-existing socioeconomic structures.

Physical and Mental Morbidity and Mortality

The following questions were selected because they provide data that can be used to quantify physical and mental morbidity and mortality and the related interconnectivities. Morbidity data can also be collected from external organizations in the months and years following a disaster, but this makes it difficult to find the exact locations and causes of each death.

<u>Questions for collaborating researchers and government agencies:</u>

26. Identify the location, the cause, and the severity of morbidities and mortalities.
    a. If the person was injured in a building, what was the daily occupancy of the building? (This sub-question aids in the modeling of morbidities.)

<u>Questions for physically and mentally injured persons and/or their loved ones:</u>

27. Were you physically injured during the disaster?

a. Where were you during the disaster?

b. Describe your experiences during the disaster.

c. Fill out survey that evaluates the probability that an individual developed a mental disorder due to a disaster (Galea et al. 2007).

Questions 26 and 27 provide data that connect a community's physical domain to physiological needs and a sense of safety within a community.

5. Planning and Executing Field Studies

This chapter provides practical processes and strategies that can assist field researchers in conducting community resilience field studies. It includes recommendations related to making the decision to enter the field, mandatory training for studies involving human subjects, selecting the field team, selecting necessary and optional equipment, conducting damage assessments, conducting interviews and surveys, managing time in the field, following up with field studies, and protecting and storing data. These guidelines are based on the work and opinions of sociologists and engineers with extensive field experience as well as best practices extracted from the literature review that is summarized in Section 2.1. Elements of this field study approach that must be modified based on hazard type include the damage assessment methodology, field study questionnaire, equipment selection, and data collection strategies. Parts of this chapter heavily reference the Institutional Review Board (IRB) Protocol (see Section 5.2) which was created for the NIST CoE by Lori Peek and Jennifer Tobin-Gurley and is the culmination of many years of field study experience and the combination of numerous check sheets that were created prior to entering the field. This IRB Protocol is attached to this thesis as Appendix B.

5.1. Field Study Decision Progression

The first step to making the decision of whether or not to enter the field is to conduct a desk study immediately after a disaster occurs in order to gather critical data and information remotely. These data include things like the number of deaths and injuries, critical facility damage, business damage and closures, number of people in temporary shelters, location and spread of damage, and other relevant information. This information can typically be found through news reports, articles, and collaboration with local university and industry researchers, government officials, and community leaders. However, with some exception it will be unlikely to know if resilience or a lack thereof is an issue for a community during or immediately following an event. The focus of the field study methodology outlined in this thesis is, in general, on developed countries. This may include communities within and outside of the U.S. depending on their physical infrastructure, social systems, and economic systems.

After the initial desk study, if the community is determined to be a good candidate for a community resilience field study (CRFS), then a small field team, termed a pilot team, should be sent out to conduct a preliminary investigation with the goal of collecting data that provide a broad summary of the impact to the community. The team should consist of a few people, and the duration of the study should be a few days to one week for most communities, although an event with a large spatial footprint may require additional time and resources at this early stage. Activities of this pilot team might include interviewing community leaders, business owners, and emergency response teams, preliminary documentation of damage to infrastructure systems and setting up the mechanisms for collaborating with local researchers. Once this pilot investigation is concluded, all of the preliminary data can be gathered and a decision can be made on whether or not to conduct a full, large scale field study. The data collected during the pilot study will also inform the development of field study objectives for a large scale field study.

The time at which the field study occurs will depend on several factors including type, location, and scale of the disaster, security and access limitations, and the speed of emergency response and debris management activities. For example, if a large footprint flooding event is to be studied, even the pilot team may not be able to enter the field until the water has receded and access to damaged locations is permitted. However, it is important for the team to enter the field for the first visit as soon as reasonable after a disaster in order to obtain perishable data that may be lost during the initial cleanup process.

During the planning process, before the full scale field study occurs, it is crucial for each of the field team members to gain an understanding of what data sets are to be acquired and why those data sets are important. Specific goals for data collection must be set before the team goes into the field. These goals include the type of data needed, the demographics of the participants, and the tolerance for error in the data (see Section 6.3). Each of these goals should be decided based the experience of the field study leaders.

5.2. Institutional Review Board (IRB) Protocol

Any research that involves human subjects must be approved by each participating institution’s Institutional Review Board (IRB). The IRB is a committee whose purpose is to approve, monitor, and review research involving human subjects. A detailed description of the field study methodology and any interview questionnaires must be provided to the IRB before the study is approved. Consent forms and release forms must be provided to each of the human subjects involved in the study in accordance with the submitted IRB protocol. The IRB protocol for the NIST CoE was created by Lori Peek and Jennifer Tobin-Gurley and is attached to this thesis as Appendix B. Additionally, all participating individuals must pass the Collaborative IRB Training Initiative (CITI) ethics training modules before seeing or handling any of the field study data.

5.3. Field Team Roles

In general each field study will have multiple teams that are made up of a few people each, and each team will focus on data collection for one or two community sectors. The number of teams will vary depending on the size and scope of the field study. Team member roles should include a principal investigator (PI), several team leaders, and field researchers. Optional roles include a technician, a translator (for international studies), and a possible remote data analysis or GIS expert. Examples for job descriptions, the number of people that would be typical, and logical selection criteria for each of these positions are provided in Table 5-1.

Table 5-1: Field Study Example Job Descriptions

Position Title	Number Needed	Job Description	Selection Criteria
Principal Investigator (PI)	1	Oversees all of the field teams and the progress of the field study as a whole. Makes all final decisions related to data collection strategies, team member selection, daily activities, etc. (May also act as a Team Leader).	Should have extensive experience in conducting field studies of various types. Must have completed the CITI ethics training modules.
Team Leader	1 per team	Oversees a single field team (2-4 members). Makes daily decisions related to data collection strategies and daily activities. Reports to the PI throughout the field study.	Should have experience in conducting field studies. Should be familiar with the field study protocol and have comprehensive knowledge of the sector being investigated. Should have working knowledge of field study equipment. Must have completed the CITI ethics training modules.
Team Member	1-3 per team	Observes damage states, interviews community members, takes photos and videos, records data, and performs any other tasks that are necessary to achieve the field study goals.	Should have knowledge of the goals and methods of the field study. Should have working knowledge of field study equipment. May be an engineer, sociologist, economist, or another discipline; including a student. Must have completed the CITI ethics training modules.
Technician	Varies	Solves all problems related to tools,	Must have comprehensive knowledge and experience with

		equipment and data recording.	applicable field study equipment. Must have completed the CITI ethics training modules.
Remote Data Analysis Expert	Varies	Analyzes all recorded data using the data processing techniques described in Section 6.1. Develops data collection strategies and provides insight on daily activities for teams based on data needs.	Must have a comprehensive understanding of the field study protocol and the data processing methods in Section 6. For the method presented herein, must have experience in MATLAB coding. Must have completed the CITI ethics training modules.
Translator	Varies	Translates interviews, surveys, and conversations between team members and non-English speakers (typically international studies).	Must be fluent in English and the primary language of the community being studied. Must have completed the CITI ethics training modules.

A rational team member selection process should be decided on by the PI and other core groups conducting the field study. For example, team members could be selected based on the following criteria (not in order of importance or weight):

1. Attendance of field study meetings and workshops.
2. Pre-completion of the CITI ethics training.
3. Availability during the specified duration of the fieldwork.
4. Proximity to the disaster site.
5. Interest in the field work.
6. Expertise in a relevant or important area related to the field study.
7. Cultural relevancy (e.g., a translator in a non-English speaking location).
8. The principal investigator’s judgement.

5.4. Equipment

The following equipment would typically be taken into the field to perform this type of study. This list is not comprehensive and does not include everything that a team will need throughout the course of a field study. It simply provides a checklist of equipment that is needed to achieve the fundamental goals of this methodology.

1. Smartphones: Researchers should upload damage data, GPS data, interview and survey results, and other relevant information to a common data base.
    - In order for the real time data processing procedure described in 6.3 to be successful, researchers must have access to tools that upload their data points to a common database in real time. This could be a smartphone app or similar.
2. GPS camera and video recorder (most smartphones have this capability).
3. Audio recorder for interviews
4. Safety equipment (e.g., hardhats, vests, safety glasses, etc.)
5. Means of transportation for researchers and gear
6. Laptop with MATLAB installed
7. LiDAR scanner or similar (optional)
8. Unmanned Aerial Vehicles (UAVs) (E.g., Drones) (optional)

5.5. Damage Assessments

The primary method for collecting data on damage to physical infrastructure should be through inspections of select physical infrastructure with field notes, geo-located pictures, and videos. It may also be beneficial to use a ground-based Light Detection and Ranging (LiDAR) scanner, which was used by Prevatt et al. (2011). The decision to use LiDAR or similar equipment should be made on a case by case basis depending on the disaster type and the community characteristics. It is vital that damage data be recorded for all structures that are correlated with interviews or other data collection activities to provide the linkage between physical infrastructure damage and the social science domain. This includes structures that appear damaged as well as structures that do not appear damaged, so that the sample is unbiased. Further discussion of bias in data samples is provided in Section 6.2. A portion of the damage data can be recorded by any team member of any background or discipline, but the member recoding it should annotate so questions can be traced back to them for follow up if needed.

There are several possible damage classifications for various physical infrastructure components available from research organizations such as DHS and FEMA (2011, 2015) and EERI (1996). These damage classifications include descriptions of damage states for many building types, non-structural components, roads, bridges, tunnels, and more. Depending on the hazard being studied the team should decide and agree on the classification scheme prior to entering the field. This should align with IN-CORE for CoE community resilience studies, i.e. four damage states not including a “no damage” state.

5.6. Interviews and Surveys

Prior to arriving in the field, a formal questionnaire should be developed in order to satisfy the specific data needs of the field study. The field study interconnectivity diagram (Figure 4-1) and the sample questionnaire in Section 4.2 should be referenced during the development of the field study questionnaire, but the specific questions should be revised on a case by case basis. A formal and professional format should be developed in order to make it easy for field researchers of any background to interview community members.

Data can be collected from willing participants using several different methods including face to face interviews, door surveys, mail surveys, online surveys, and more. Several recruitment methods may be employed including but not limited to: flyers, social media, word of mouth, internet searches, and newspaper articles. The delivery and recruitment methods that are chosen will vary depending on the specific field study and the resources that are available. Two types of interviews should be conducted: in depth, semi-structured interviews and closed ended survey questionnaires. The in-depth, semi-structured interviews should be conducted by at least two team members, last twenty to thirty minutes, and be audio recorded. These interviews will provide both quantitative and qualitative data that will help us understand the cause and the effect of human actions. Closed ended survey questionnaires may be conducted in person or remotely in order to provide quantitative data. A minimum of two follow-up interviews should be performed between one and three years after the event. After three years, additional follow-up interviews should be conducted as needed for the modeling of community recovery.

Interviewees must be adult volunteers and may include: business owners and managers, government officials, first responders, city planners, owners of non-profits, members of service organizations (e.g., religious leaders), school administrators, emergency managers, health care administrators, and other residents. This may include elderly and non-English speaking people, but should not include mentally disabled people, pregnant women, minors, prisoners, or students. If it is necessary to interview one or more of these vulnerable populations, then a separate request must be made to the IRB. It is important that all interviewers understand the delicacy of the situation and the vulnerabilities of the interviewees and behave ethically in accordance with their CITI ethics training. When resources allow, interviews should be recorded, transcribed, and analyzed with Atlas.ti, a qualitative data analysis software program.

5.7. Daily Activities

This section provides an example of a schedule of daily activities of the field team. An initial schedule should be created by the PI during the planning process, but it is important to note that the initial schedule will continually change based the revised data collection requirements. If it is known that the field study will have a longer duration (several weeks, but this would be rare), then it is important to develop a schedule that will be sustainable for the team members. The longer that a team stays in the field the more fatigued they will become, which could lead to a greater chance of errors and mistakes.

Table 5-2: Sample Daily Schedule for Field Studies Considered Sustainable

Time	Activity
7:30 AM – 8 AM	Full team meeting to discuss data collection strategies for the day.
8 AM – 12 PM	Individual team data collection activities.
12 PM to 1 PM	Teams meet for lunch (if possible) and discuss the morning's progress, strategy modifications, and plans for afternoon data collection.
1 PM – 5 PM	Individual team data collection activities.
5 PM – 5:30 PM	Full team meeting, debriefing, and planning for next day's activities.
6 PM – 7 PM	Full team dinner.
7 PM – 9 PM	Possible data analysis activities or free time.

5.8. Follow-Up Field Studies

Investigating community resilience specifically includes quantifying the long-term recovery of the community in the years following a disaster. In order to quantify a community's long-term recovery, follow-up field studies and data collection activities are necessary. The decision to conduct a follow up field study will vary case by case and will depend on specific data needs. Field teams may be required to return to the site multiple times over a span of several years. Follow-up data collection activities may include but are not limited to:

1. Conducting follow-up interviews and surveys with community members.
2. Taking pictures and videos of previously damaged infrastructure in order to capture its recovery over time.
3. Meeting with collaborating researchers, government officials, community leaders, business owners, etc.

It is important to note that due to the longevity of these types of field studies, the NIST CoE may have several field studies ongoing at the same time at various stages, and resources will need to be allocated accordingly.

5.9. Data Protection and Storage

In order to protect the sensitive information that is collected in the field, several safety measures must be implemented for the storage of field study data. Any physical data that are collected must be safely secured and locked in file cabinets. Any electronic data that are collected (e.g., images, field notes, audio recordings of interviews) must be secured in locked rooms on password protected computers. These data must be coded in order to protect the identities of the study participants. Specific names should not be mentioned in any publications or other works resulting from the field study, and videos or photographs of participants should only be used with the written permission of each individual.

6. Data Processing

Once the field data have been collected, they must be organized and processed. This section describes a general derivation of a formula that uses field data to produce fragility curves for evaluating resilience metrics for potential inclusion in IN-CORE. The text then describes an algorithm that has been written to process raw field data and a framework that can be used for real-time data processing and assessment of data quantity requirements.

6.1. General Derivation

The result of the following derivation is an equation that produces the probabilities of certain decision variables (i.e., resilience metrics or performance indicators), given certain damage states of corresponding infrastructure. This allows the user to process field data in order to create probabilistic models of the resilience metrics that are described in Section 3.2. This derivation references the seismic loss framework established by the Pacific Earthquake Engineering Research Center (PEER) (Cornell and Krawinkler, 2000).

<u>Variable Definitions:</u>

DV = Decision variable: Resilience metrics or performance indicators such as population dislocation, business interruption, morbidity and mortality, critical facilities impact, etc.

DM = Damage measure: E.g., one through five where damage state one represents no damage and damage state five represents complete destruction (See Section 5.5).

IM = Intensity measure: Measures of hazard intensity such as spectral acceleration, wind speed, wave height, etc.

IT = Infrastructure type: Type of building, bridge, tunnel, etc. (e.g., single story wood frame building).

l = The number of different damage states that are present in a given data set.

m = The number of different infrastructure types that are present in a given data set.

n = The number of data points given in the hazard curve data set.

<u>Assumption:</u> This is a Markovian process. Therefore, the probabilities of future events depend only on the present state, not on past events.

<u>Derivation:</u>

Using the theorem of total probability:

$$P(DV \geq dv \mid IT=it, IM=im) = \sum_{i=1}^{l} P(DV \geq dv \mid DM=dm_i, IT=it) * P(DM=dm_i \mid IT=it, IM=im) \quad [6.1]$$

$$P(DV \geq dv \mid IM=im) = \sum_{j=1}^{m} P(DV \geq dv \mid IT=it, IM=im) * P(IT=it_j) \quad [6.2]$$

Substitute [6.1] into [6.2]:

$$P(DV \geq dv \mid IM=im) = \sum_{j=1}^{m} \sum_{i=1}^{l} P(DV \geq dv \mid DM=dm_i, IT=it) * P(DM=dm_i \mid IT=it, IM=im) * P(IT=it_j) \quad [6.3]$$

Using convolution we obtain:

$$P(DV \geq dv) = \sum_{k=1}^{n} P(DV \geq dv \mid IM=im) * P(IM=im_k) \quad [6.4]$$

Substitute [6.3] into [6.4]:

$$P(DV \geq dv) = \sum_{k=1}^{n} \sum_{j=1}^{m} \sum_{i=1}^{l} P(DV \geq dv \mid DM=dm_i, IT=it) * P(DM=dm_i \mid IT=it, IM=im) * P(IT=it_j) * P(IM=im_k) \quad [6.5]$$

The final result of this derivation is $P(DV \geq dv)$ [6.5] or the probability that a decision variable is greater than or equal to a defined value. This probability of meeting or exceeding a decision variable is only applicable to the physical location or community which provides the physical, social, and hazard data. The most important result of this derivation is P(DV ≥ dv |

IM=im) [6.3] or the probability that a decision variable is greater than or equal to a defined value given an intensity measure. These probabilities of exceedance can be found and plotted for different intensity measures to yield a resilience metric fragility curve. These fragility functions can be used within IN-CORE. This equation has been written as a code which can be performed using MATLAB in order to process raw field study data as described in Section 6.2.

6.2. Data Processing Toolbox

One of the primary purposes of this thesis is to develop methods that can be used to collect data that will be integrated into the IN-CORE data base. In order to do this, a data processing toolbox was developed with the capability of producing fragility functions for the resilience metrics listed in Section 3.2. These fragility functions give a user the ability to input a particular intensity measure (e.g., wind speed) and output the probability of exceedance of certain resilience metrics (e.g., population dislocation). Figure 6-1 shows an example of fragility functions that were developed using this toolbox.

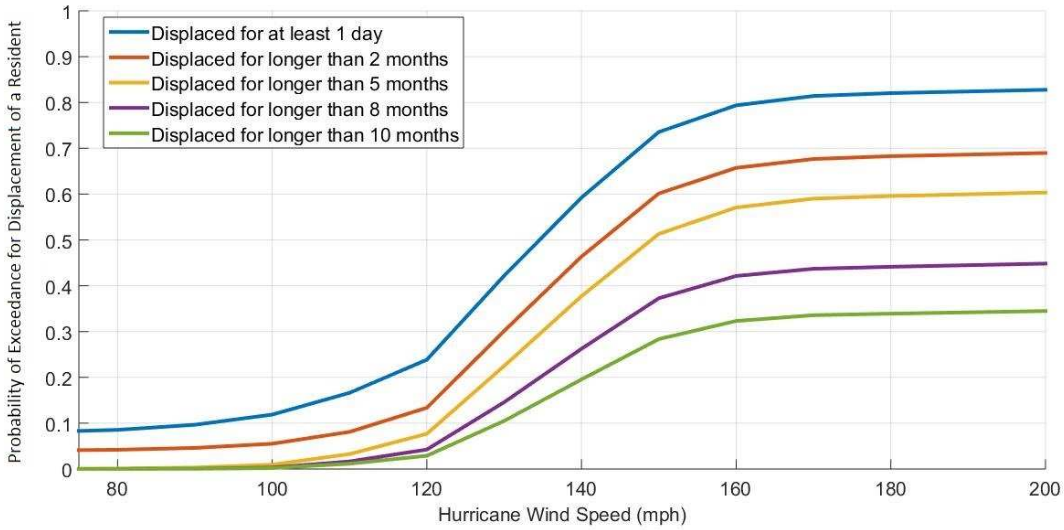


Figure 6-1: Example of a Fragility Curve for Evaluating Resilience Metrics

Note: Some population dislocation fragility curves do not begin at zero because a small number of residents were displaced even though their residences were not damaged.

The general derivation for creating resilience metric fragility functions is described in detail in Section 6.1 of this report. This data processing toolbox is an application of that derivation within MATLAB. It includes the capability to isolate the data for any secondary factor that the user specifies. For example, it can create fragilities that are shifted to account for only members of the community who are below the poverty line. This process is described in detail in the following paragraphs.

The first input that is required is the raw data from the field. This may include information/data such as household address, household demographics, building damage states, duration of displacement, etc. The user then has the option to isolate the data based on some characteristic (e.g., race). If the user chooses to isolate the data then all of the data points that do not have the specified characteristic are automatically removed from the dataset. After the dataset is isolated, the toolbox finds the probability that the specified metric is greater than a certain value given a certain damage state and an infrastructure type (e.g., the probability that a resident will be dislocated for at least one day given that their home is in damage state three and is a single story woodframe structure). This is written symbolically as $P(DV \geq dv|\ DM=dm_i, IT=it)$ where the variables are defined in Section 6.1. The toolbox finds these probabilities of exceedance by first grouping the data points into different infrastructure types and then grouping those data points into different ranges of the metric (e.g., divide dislocation data into groups where one group includes any individuals whose homes were in damage state two and were dislocated more than one day, another group includes any individuals whose homes were in damage state two and were dislocated more than two months, etc.). Once the data points are grouped, the groups are divided by the total number of data points within their respective damage states (e.g., divide by the total number of residences that were in damage state two, etc.) in order to produce probabilities of a certain decision variable given a certain damage state and infrastructure type. These probabilities can be plotted and lines can be fit to the data points as shown in Figure 6-2.

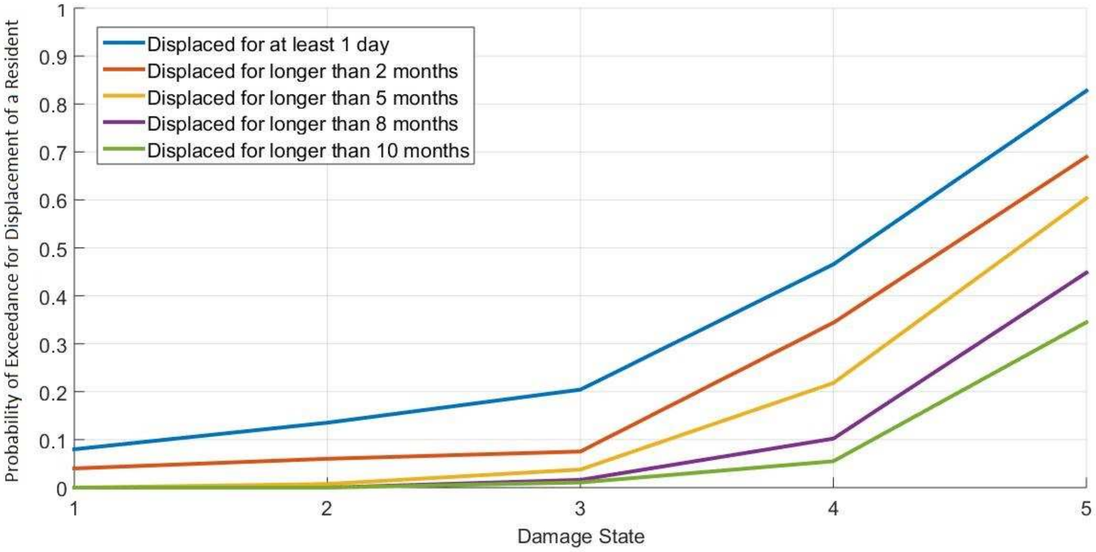


Figure 6-2: Example of Plot of P(DV≥ dv| DM=dmi, IT=it)

The next inputs are the damage fragilities in probability density function (PDF) form. These damage fragilities provide the probability that an infrastructure element is in a certain damage state given a certain intensity measure. This is written symbolically as $P(DM=dm_i \mid IT=it, IM=im)$. Then the resilience metric fragilities, which are represented symbolically as $P(DV \geq dv \mid IT=it, IM=im)$, for each infrastructure type are produced using the theorem of total probability. This is found by multiplying each of the values in the damage fragilities (e.g., the probability that a wood light frame building is in damage state two given a wind speed of 90 mph) by each of the values from Figure 6-2 (e.g., the probability that a resident will be dislocated for at least one day given that their home is in damage state three). These values are then added together for each damage state. This process is written symbolically below in equation [6.1].

$$P(DV \geq dv \mid IT=it, IM=im) = \sum_{i=1}^{l} P(DV \geq dv \mid DM=dm_i, IT=it) * P(DM=dm_i \mid IT=it, IM=im) \quad [6.1]$$

The next (optional) step is to combine the resilience metric fragility curves of different infrastructure types. This step is helpful if the user is interested in finding the probability of a certain resilience metric for a certain location in a community, and damage fragility information is known for multiple infrastructure types that are represented in the dataset. This is done by finding the probabilities that infrastructure types occur in the given dataset, multiplying these probabilities by the corresponding resilience metric fragility values (from equation [6.1]), and then summing the values for each infrastructure type. This process is written symbolically below in equation [6.2].

$$P(DV \geq dv \mid IM=im) = \sum_{j=1}^{m} P(DV \geq dv \mid IT=it, IM=im) * P(IT=it_j) \quad [6.2]$$

The resilience metric fragility curves that are found in equation [6.2] are the primary goal of this data processing toolbox. These curves can be plotted with intensity measure values on the x-axis and probability of exceedance of a certain metric values on the y-axis as shown in Figure 6-1. They can then be fit to the appropriate distribution and input into the IN-CORE data base. It is important that field data sets to be unbiased in order to create accurate fragility curves. If field researchers only collect data that have a certain characteristic in common (e.g., physical damage, dislocation, loss of job, etc.) then the fragility curve will be truncated and inaccurate. For example, if researchers were to only investigate residences that were in higher damage states, then a fragility curve that is produced from this data would be left truncated and not useful for modeling purposes. This would also apply if field researchers were to only interview dislocated residents or only focus on any characteristic that introduces bias to the sample.

The final (optional) step of the process is to use convolution to find the probability of a certain resilience metric at a given location. Then the measured probabilities can be compared with performance goals in order to determine whether or not an area is vulnerable (similar to Figure 3-2). This process does not need to be completed by the data processing toolbox because it can be done within the IN-CORE software. However, the data processing toolbox also contains this capability, for completeness.

The final input that is required before convolution can occur is a hazard curve for a specific location and disaster type. This can often be found for earthquakes on The United States Geological Survey (USGS) website, and in other publications for other hazard types. In order to find the probability of a certain resilience metric for hazard data that corresponds to a certain location, the outputs of the resilience metric fragility functions found using equation [6.2] are multiplied by the corresponding probabilities that a certain intensity measure occurs and then all values are summed. This process is written symbolically in equation [6.3].

$$\mathrm{P(DV \geq dv)} = \sum_{k=1}^{n} \mathrm{P(DV \geq dv \mid IM{=}im)} * \mathrm{P(IM{=}im_k)} \quad [6.3]$$

The whole process can be represented by substituting [6.1] into [6.2] and then [6.2] into [6.3], resulting in the equation below:

$$P(DV \geq dv) = \sum_{k=1}^{n} \sum_{j=1}^{m} \sum_{i=1}^{l} P(DV \geq dv|\ DM=dm_i, IT=it) * P(DM=dm_i\ |\ IT=it, IM=im)$$

$$* P(IT=it_j) * P(IM=im_k) \quad [6.5]$$

6.3. Data Collection Quantity Requirements

It is important for researchers in the field to know the quantity and type of data that they need to collect at the start of each day in the field. The process that is described in this section allows for rapid data analysis and error estimation which enables field team leaders to plan fieldwork and develop data collection strategies at the start of each day in the field. A method for real-time data processing in the field is needed when collecting data that seeks to connect damage to physical infrastructure and social science. Specifically, the decisions made by people and families are not known prior to entering the field and the interview taking place, thus in order to gather a representative sample across all combinations of the damage-decision space, data processing while in the field may be needed. It is recognized that the volume of data needed to achieve the quantities presented herein may not be attainable for most field studies, but nevertheless, the methodology holds in the event that this is a possibility. The first step of this process is to collect an initial field data set by following the guidelines provided in this methodology. After an initial dataset is collected, fragility curves can be produced for each of the field study metrics using the process described in Section 6.2. In order for this to be successful, researchers must have access to tools that upload their data points to a common database in real time or, at the very least, at the end of each day in the field. These fragility curves should then be fit to the appropriate distribution, which yields characteristic parameters that vary for each type of fit (typically a shape parameter and a scale parameter). In the case where a normal distribution best fits the fragility curve, these parameters will be the mean, μ, and standard deviation, σ.

After these parameters are found for the initial data set (e.g., the data that was collected during the first day in the field), the data set should be expanded by adding more data points and increasing the sample size (e.g., adding the data that was collected during the second day in the field). Characteristic parameters for the fragility curve fits can then be found for the larger, combined data set. This process is outlined in the flow chart shown in Figure 6-3. It is important for the data sets to be combined for the error to converge. As the data set gets larger, a reduction in error is expected.

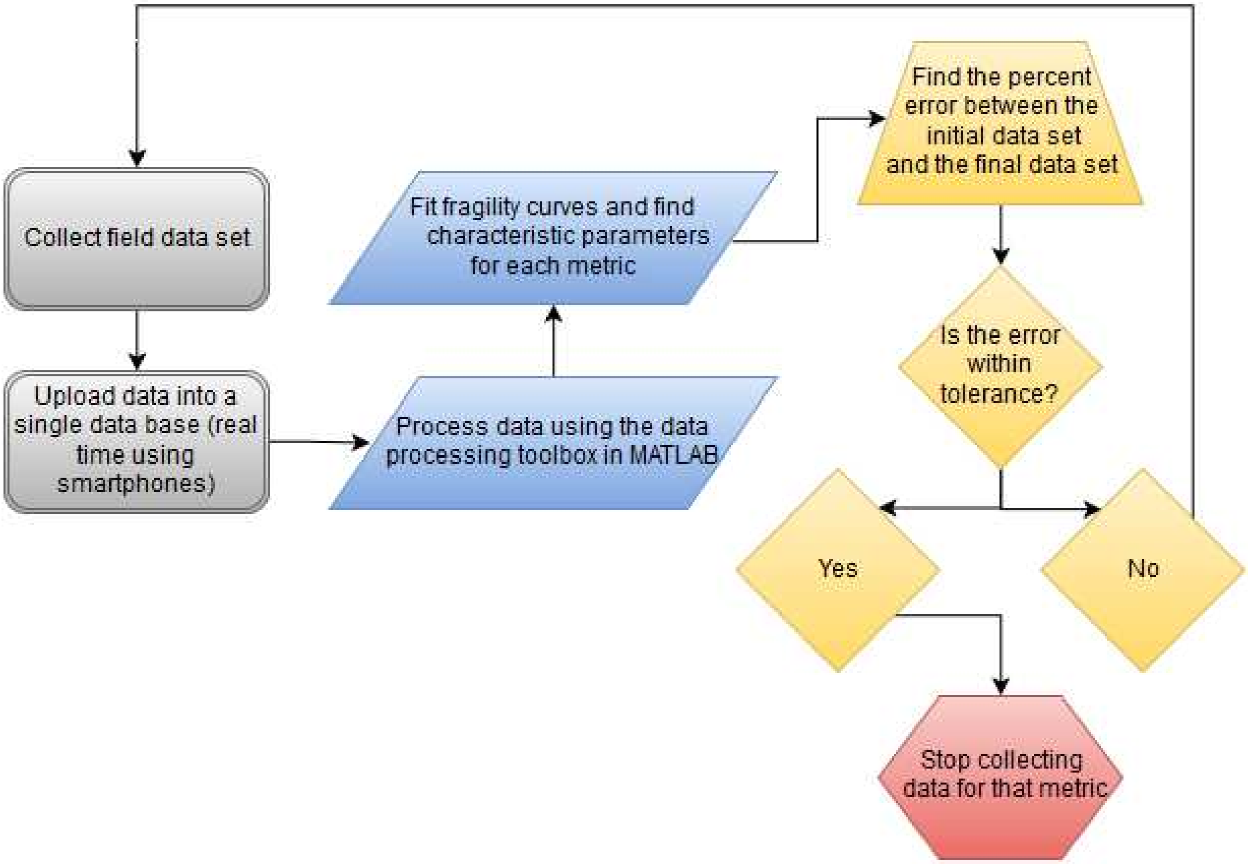


Figure 6-3: Real Time Data Processing Procedure Flow Chart

An example of using real time data processing to determine data quantity needs is given in the paragraph below:

A field study is being conducted in a community after a tornado. One of the goals of the field study is to develop population dislocation fragility functions within an allowed error, δ_{all}, of 10%. After the first day, a total of 100 homes were surveyed, and the data was processed and analyzed. The population dislocation fragility curve for these 100 data points best fits a lognormal distribution with a mean of 4.5 and a standard deviation of 0.40. On the second day, an additional 100 homes were surveyed, and the data was processed and analyzed. The population dislocation fragility curve for the total of 200 data points best fits a lognormal distribution with a mean of 4.7 and a standard deviation of 0.45. The measured error for each of these parameters is calculated below.

δ_{μ} = (0.7-0.6)/0.7)*100% = 4.4%

4.4% < 10% OK

δ_{σ} = (0.40-0.45)/0.6)*100% = 8.3%

8.3% < 10% OK

Both parameters are within the tolerance, so no additional data for population dislocation of this type need to be collected. This process can then be repeated for all other data fields.

7. Data Processing Case Study – Hurricane Andrew Data

The data processing toolbox described in Chapter 6 was tested for a sample of Hurricane Andrew population dislocation data that was provided by Walter Peacock and Nathanael Rosenheim at Texas A&M University (Peacock et al 1997). Damage fragilities for a single story wood frame structure subjected to wind loading were used for all residences because the structural system of each residence was not recorded in the provided data set. After processing these data using the techniques described in Section 6.2, a number of fragility curves were produced. These fragility curves were modified based on two secondary factors: race (white, black, or Hispanic) and housing type (mobile home, single family home, or attached apartment). These secondary factors were selected based on the data that were available. The fragility curves for all of the data and those that were shifted based on race are shown in Figures 7-1 through 7-4.

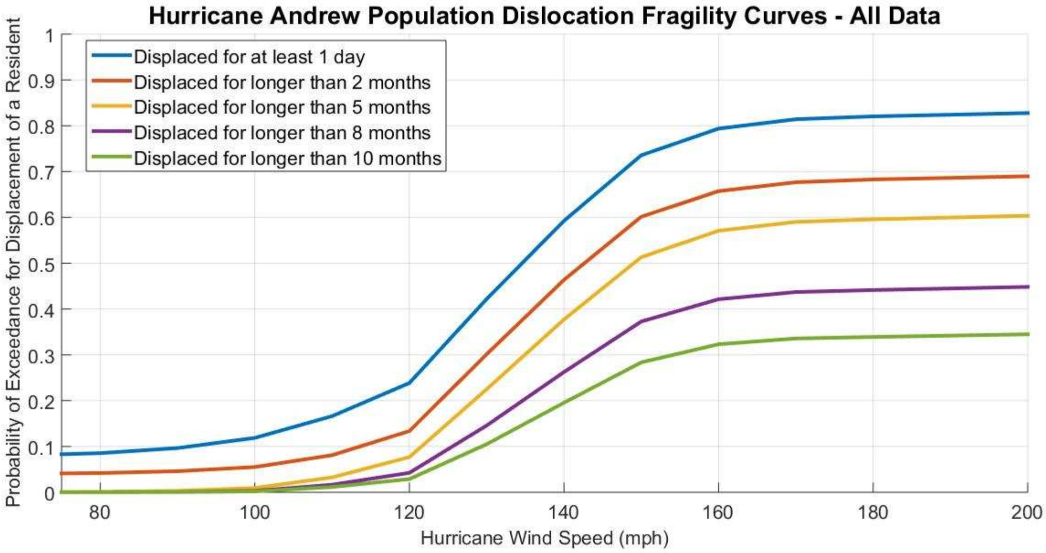


Figure 7-1: Hurricane Andrew Population Dislocation Fragility Curves - All Data

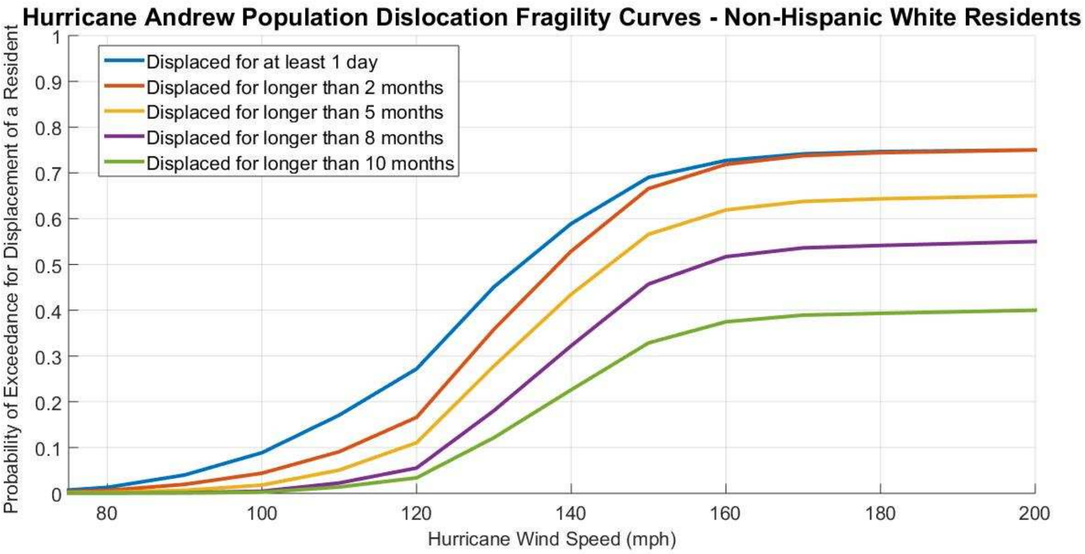


Figure 7-2: Hurricane Andrew Population Dislocation Fragility Curves - Non-Hispanic White Residents

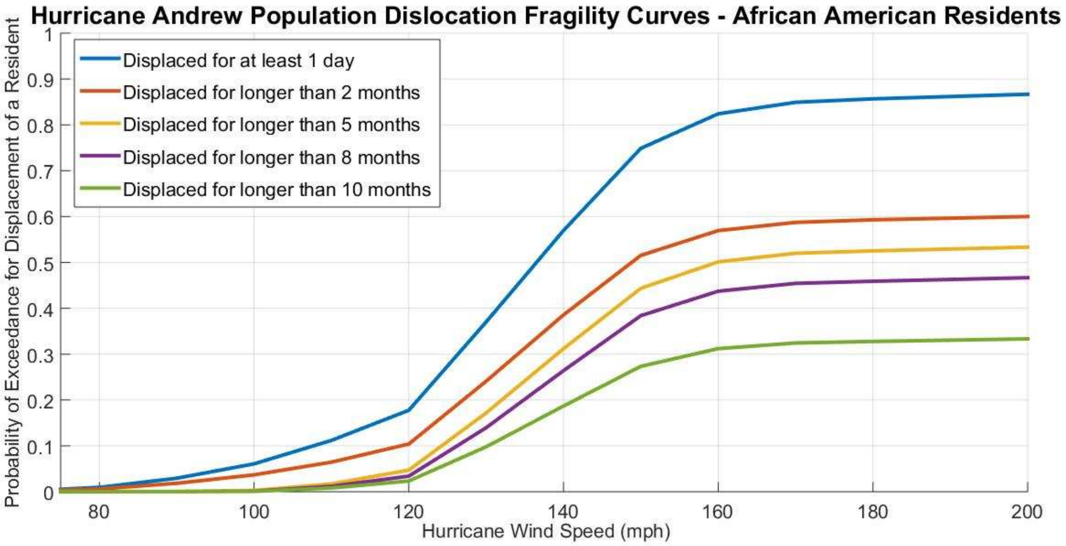


Figure 7-3: Hurricane Andrew Population Dislocation Fragility Curves – African American

Residents

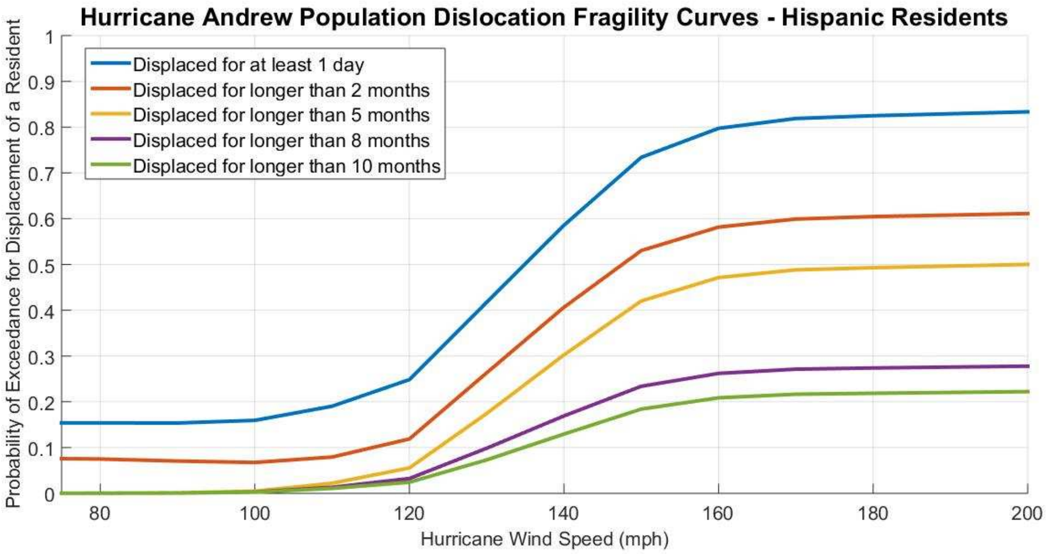


Figure 7-4: Hurricane Andrew Population Dislocation Fragility Curves - Hispanic Residents

In order to create these different fragility curves 1,097 data points were provided by Walter Peacock and Nathanael Rosenheim at Texas A&M University (Peacock et al 1997). Each data point consisted of the resident's race/ethnicity, the damage state of the residence, the housing type, and duration of dislocation. It took an extraordinary amount of time and effort to collect this robust data set. The scope of this thesis did not include conducting a formal analysis of the error in order to find the optimal number of data points, but this is important work that should be done in the future.

Several observations were made based on these results:

1. Non-Hispanic white residents are more likely to be dislocated at each duration category than the population as a whole.
2. African American residents are more likely to be displaced for at least one day, but slightly less likely to be displaced for longer durations than the population as a whole.
3. Hispanics are the least likely to be displaced for more than a month. Furthermore, the probability that a Hispanic resident leaves their home increases significantly around wind

speeds of 120 miles per hour, but the probability that a non-Hispanic resident leaves their homes sees a similar increase at less intense wind speeds of approximately 100 miles per hour.

These fragilities functions can be fit to the appropriate distribution and used within IN-CORE to help calibrate population dislocation predictions, although it is noted that many other factors are present that may affect this decision.

8. Field Study in Support of the Joplin Hindcast

This section describes a community resilience field study with the intent of supporting a hindcast for the 2011 Joplin, MO tornado. The field work took place in Joplin from July 18 to 21, 2016, approximately five years after it was hit by an EF-5 tornado. This chapter includes background on the city of Joplin, a review of existing literature related to the tornado impact and recovery, a discussion of the data requirements, and a description of the methodology used and the field data collection activities that took place. In addition, Section 8.5 is a standalone section that discusses the interconnectivities between the physical, social, and economic domains within Joplin and how the decisions made by Joplin School District related to transportation affected these interconnectivities. This standalone section is intended to show a single and direct example of how the linkage between human decision and community resilience occurs.

8.1. Introduction

The term hindcast refers to data collection activities that allow the validation of community-level models before and after an event. These are also used to validate mathematical representations of a physical or social process or system. The Joplin field study was done directly in support of developing a hindcast study of the 2011 Joplin, Missouri tornado. Data was collected through interviews with key stakeholders in Joplin, obtaining data from local organizations, government agencies, and other researchers, taking geo-located photos, and field notes. Obtaining data from other sources is important for all field studies, but it is even more important for studies taking place after community recovery has begun. Local organizations, government agencies, and other researchers often continue to collect data on the recovery of the community long after the event occurs, and it is crucial to obtain data from these groups. Once the data has been gathered and analyzed, the results of the analysis can be communicated to the entities providing data for their benefit.

The primary objective of this community recovery field study was to collect data that can be used to evaluate the accuracy of and interaction between the physical, social, and economic models that are being developed for implementation into IN-CORE. The two primary objectives for this specific field study were to gather immediate and long-term data that can be used to (1) calibrate models focused on the interaction of the domains including physical, social, and economic and (2) develop restoration and recovery functions that are driven by physical infrastructure conditions and guided by social and economic decision-making and consequences. The focus of the field teams that went to Joplin was on gathering long-term data on the community's recovery. Of particular interest was learning about the immediate impact and the long-term trajectory of Joplin's resilience and recovery including decisions that were made immediately following the event and during the recovery so that they could be modeled during the final phase of the hindcasting process. While this field study was in support of the hindcast as previously stated, this section will focus only on the field study methodology, planning, execution, and conclusions formed from qualitative data. It will not discuss the hindcast process explicitly.

8.2. Literature Review

In order to understand the physical, social, and economic consequences of the 2011 Joplin tornado, a number of published reports and journal articles were collected and reviewed. A selection of important background information from these reports is summarized in the following section.

After the May 22, 2011 tornado in Joplin, MO NIST conducted a post-tornado field study with the purpose of investigating the performance of structures, human behavior, and emergency communications (Kuligowski et al. 2014). The field team arrived in Joplin two days after the tornado and spent four days there collecting data. The methods, tools, and processes that this team used are summarized in Section 2.1.1 of this thesis. In addition to the NIST report, a number of other reports and articles were reviewed. The following paragraphs briefly describe the information that could be gathered from news articles, formal reports, and online resources related to the seven resilience metrics from Section 3.2 of this report.

Population Dislocation

Before the tornado the population of Joplin was 51,140. After the tornado the city's population dropped (in 2012 Joplin was the second fasted shrinking city in U.S) and then slowly recovered until it finally reached 51,324 in 2014, surpassing its pre-tornado population. The most recent data shows the population of Joplin at an all-time high at 51,818 in 2015 (SEMA 2016; Office of Missouri Governor Jay Nixon 2016). The exact number of dislocated persons is unknown, but 586 households that were forced to leave their homes stayed in temporary housing provided by FEMA, and 300 individuals that were dislocated by the tornado stayed in an American Red Cross shelter at Missouri Southern State University (MSSU) (FEMA 2011). All of these families had left the FEMA temporary housing units by June 9, 2013 (Onstot 2016). The schools in Joplin only lost 2% of enrolled students after the tornado, which likely means that families that were dislocated tended to stay near Joplin. It is estimated that 98% of families who lost their homes stayed within 25 miles of Joplin, either renting or buying an apartment or staying with family or friends (Smith and Sutter 2013).

Business Interruption

Many businesses (531 total) were significantly damaged by the tornado, but 485 of these businesses have re-opened since the tornado (Office of Missouri Governor Jay Nixon 2016). The rest of the businesses that were open before the tornado closed permanently after the event (Onstot 2016).

Employee Dislocation

The tornado impacted more than 5,000 employees in Joplin when 531 businesses were significantly damaged, and 3,000 individuals in the city of Joplin lost their jobs. Since the tornado, new jobs for 1,045 full-time and 818 part time employees have been created. The unemployment rate in Joplin was 7.9 percent before the tornado, and has decreased to 3.9 percent in 2015 (Office of Missouri Governor Jay Nixon 2016).

Critical Facilities Impact

This section discusses damage to those facilities in Joplin that are believed to be critical according the definition provided earlier in this thesis. Nine schools, fourteen child care facilities, two hospitals, and a number of other critical facilities were damaged or destroyed in the tornado. Two severely damaged school buildings (Joplin high school which was built in 1968 and Joplin middle school which was built in 2009) were investigated in detail by Coulbourne and Miller (2012). The performances of these two buildings were found to be similar despite their difference in age. Four new schools were constructed from 2011 to 2015, and a new hospital (205 beds) opened in March of 2015. Each of these new buildings is equipped with safe rooms to protect life safety in future tornadoes (Office of Missouri Governor Jay Nixon 2016).

Housing Loss

Eight thousand homes and buildings (about a fourth of total housing in Joplin) were destroyed or damaged in the tornado. Damaged or destroyed construction types included: pre-cast concrete, brick, metal, masonry, and wood-frame buildings (FEMA 2011). Since then 2,090 new single family homes, 1,483 apartments, and 1,293 duplex unites have been constructed, for a combined total of 4,866 new housing units (Office of Missouri Governor Jay Nixon 2016). The “rebuild Joplin” organization helped people that were underinsured rebuild their homes at little or no cost to them. All of the families had left the FEMA temporary housing units by June 9, 2013 (Onstot 2016).

Physical and Mental Morbidity and Mortality

About 1,000 people were injured and 161 people lost their lives in the tornado. $2 million were given to establish the Joplin Child Trauma Treatment Center which provides critical mental health services to children and families, and has served more than 3,800 children since the event. Almost 200 teachers were trained in identifying and caring for children that were impacted by the disaster (Office of Missouri Governor Jay Nixon 2016). Adams et al. (2015) surveyed 340 adolescents from Joplin between September 2011 and June 2012 in order to determine the rates of posttraumatic stress disorder (PTSD), major depressive episode (MDE), and substance use disorder (SUD). The results of this study showed that the rates of these conditions were: 3.7% for PTSD and MDE, 1.1% for PTSD and SUD, 1.0% for MDE and SUD, and 0.7% for PTSD, MDE and SUD. They also showed that gender and parental injury were highly correlated with these mental effects. Houston et al. (2015) conducted a separate study that surveyed 380 adults six months after the event and 438 adults 2.5 years after the event. This study showed that the PTSD relevance was 12.63% six months after the event and 26.7% two and a half years after the event.

Comparing these two studies shows that adults were highly more likely than children to develop mental disorders after the tornado.

Fiscal Impact

As of October 31, 2012 the total losses in the city of Joplin were $2,017,564 and the total losses paid by insurance companies were $1,651,650 (Onstot 2016).

8.3. Data Requirements

Because this field study was intended to support a hindcast, the data collection requirements had to be slightly altered in order to achieve the goals of the hindcast. The traditional field study methodology had to be applied to specific data collection activities that could be done in Joplin over a three day period. Parts of the traditional field study methodology were not applicable because the study occurred five years after the disaster (e.g., damage inspections did not occur). The methods of collecting data for each of the resilience metrics listed in Section 3.2 had to be changed to account for data that had already been collected because it was possible to obtain data from other researchers or online data bases. The modified data collection strategies for six of the resilience metrics are described in this section, but fiscal impacts are not discussed because they were modeled by economists who are affiliated with the NIST CoE using secondary data that were not collected in the field.

The data needs that are listed in this section were developed by assuming the ideal situation where field researchers have unlimited time and money. However, many of these data were not actually collected in the Joplin field study due to limited resources. The quantitative data that could not be collected were substituted with qualitative data from interviews with community leaders and local government officials. The following sections were written during the field study planning period before the team entered the field and are, therefore, written in future tense.

8.3.1. Data Requirements for Each Resilience Metric

Population Dislocation

There have not been any field investigations in Joplin that have specifically studied population dislocation. Therefore, we will not be able to obtain this data through collaboration with other researchers. Instead, we must conduct interviews and surveys with community members in order to find out how long they were displaced and where they went after the tornado. We can use multiple methods to obtain these data. We can either mail a survey to a representative sample of households in Joplin or we can conduct face to face interviews. If a mail survey method is implemented, Dillman's "Total Design Method" should be used to increase the response rate (Dillman 1978). Each respondent should first fill out a demographics form, which will provide crucial data that will allow us to modify the fragility curves that are developed based on race, income, gender, etc. (see Section 6.2). Guidelines for developing a population dislocation questionnaire can be found in Section 4.2.

Business Interruption and Employee Dislocation

There are several existing studies that have been conducted that provide details on damage to select commercial buildings (Kuligowski et al. 2014; Prevatt et al. 2013). However, none of these investigated the duration of closure of individual businesses or the economic effects of the tornado. Therefore, we will need to collect additional data through interviews and surveys of business owners, public officials, and community leaders. This can be done through either a combinations of mail surveys and follow up phone calls using Dillman's "Total Design Method," or through face to face interviews. Questions should be developed to provide data that can be used to quantify either business interruption or employee dislocation in accordance with the methods described earlier in this report. In addition to these questions a demographics form that also contains data fields for businesses' economic sector, pre-disaster financial condition, age, primary market (e.g., local or international), and size (Webb et al. 1999) should be completed by the business owner.

Critical Facilities Impact

Several studies were completed immediately after the tornado that captured perishable damage data related to critical facilities in Joplin (Kuligowski et al. 2014; Prevatt et al. 2013; Coulbourne and Miller 2012; FEMA 2011). These data can be obtained through collaboration with government agencies (e.g., NIST), research groups (e.g., ASCE), and university researchers. In addition, researchers at Missouri Southern State University have been monitoring the long term recovery of Joplin's buildings over the last five years. The unit of measure that we are most interested in is loss of functionality of a facility, which occurs when the facility is no longer able to perform its most basic purpose. E.g., a hospital loses functionality when its workers can no longer treat patients properly. Loss of functionality data may need to be obtained through interviews with critical facilities managers and local officials.

Housing Loss:

Similar to critical facilities impact, housing loss data can be obtained through various collaborations (Prevatt et al. 2013; Luo 2014; Kuligowski et al. 2014; FEMA 2011). Additional loss of functionality data may need to be obtained through interviews with homeowners and local officials or through tax assessor data.

Physical and Mental Morbidity and Mortality

Several studies on physical and mental morbidity and mortality were conducted after the event (Kuligowski et al. 2014; Curtis and Fagan 2013; Paul and Stimers 2012, 2014). The data from these studies should be sufficient for basic model validation. Curtis and Fagan (2013) developed a database containing name, age, gender, date of death, and location of death for all mortalities caused by the tornado. Kuligowski et al (2014) obtained several databases that included deaths, injuries, and disease information; however, data on the locations of the injured persons were somewhat limited. Two significant studies on mental morbidity have been conducted. Adams et al. (2015) surveyed 340 adolescents from Joplin after the event in order to determine the rates of posttraumatic stress disorder (PTSD), major depressive episode (MDE), and substance use disorder (SUD), and Houston et al. (2015) conducted a separate study that surveyed 380 adults six months after the event and 438 adults two and a half years after the event. These researchers and organizations should be contacted in order to share data and related information.

Physical Infrastructure Interdependencies:

Understanding physical infrastructure interdependencies is an important part of studying the resilience and recovery of communities. Building functionality is often dependent on numerous utilities. Utility damage and restoration data have already been collected by others (Kuligowski et al. 2014), and we can use these existing data to study physical interdependencies between electric power, water, oil and natural gas, transportation, and communication infrastructure. Additional data may be gathered through interviews and collaboration with utility managers and owners.

8.3.2. Summary of Data Requirements

One of the objectives of the field study portion of the Joplin hindcast is to collect data that can be used to quantify the following six resilience metrics: population dislocation, business interruption, employee dislocation, critical facilities impact, housing loss, and physical and mental morbidities and mortalities. Some of the data that we need are already available through collaboration with others (e.g., damage to buildings and morbidities and mortalities). However, other data that would ideally be collected by the team include:

1. A representative, random sample (both damaged and undamaged homes) of durations of dislocation of community members, duration of time away from work, corresponding residential damage states, and resident demographics.
2. A representative, random sample (both damaged and undamaged buildings) of business' duration of closure, corresponding building damage states, and business characteristics (economic sector, pre-disaster financial condition, business age, primary market (e.g., local or international), and business size).
3. Durations of loss of functionality of critical infrastructure and residential buildings, corresponding damage states, loss of lifelines, and wind speed (estimate) at structure (optional).
4. Supplemental physical and mental morbidity data, corresponding infrastructure damage state, and individual demographics.

8.4. Methodology

8.4.1. General Process

Planning for the Joplin field study began about a month and a half before the teams actually entered the field. During this planning period, weekly meetings were held with potential field team members in order to discuss the goals and objectives of the study. Completion of the Institutional Review Board (IRB) CITI ethics training was a pre-requisite for all potential team members because the data included information on human subjects. The team members were selected based on their interest, availability, and area of expertise. On June 27, six sub-groups were created according to their primary objective: Housing (4 members), Buildings (3 members), connectivity (4 members), and networks (3 members). These teams are described further in Table 8-1. Each group then focused primarily on their respective objectives in preparing for the field study.

Table 8-1: Joplin Field Study Teams

Team	**A. Housing 1**	**B. Housing 2**	**C. Connectivity 1** (Social Science and Physical Infrastructure)	**D. Connectivity 2** (Social Science and Physical Infrastructure)	**E. Networks** Distributed systems – transportation, EPN, water	**F. Buildings** (All except residential)
Members	Sara Hamideh and Shane Crawford	Maria Koliou and Sam Spector	Lori Peek and Hassan Masoomi	Jennifer Tobin-Gurley and Todd Clapp	John van de Lindt, Suren Chen, and Navid Attary	Hussam Mahmoud Stephanie Pilkington, and Mehrdad Memari
Team Composition	1 Engineer and 1 Sociologist	2 Engineers	1 Engineer and 1 Sociologist	1 Engineer and 1 Sociologist	3 Engineers	3 Engineers
Primary Objective	To collect data that aids in developing fragilities for residential buildings.	To collect data that aids in developing fragilities for residential buildings.	To collect data that aids in modeling connectivities between physical, social, and economic domains.	To collect data that aids in modeling connectivities between physical, social, and economic domains.	To collect data that aids in modeling water, power, gas, traffic, and debris.	To collect data that aids in developing fragilities for non-residential buildings.

The initial task of each group was to determine the data needed in order to understand and model their respective community domains. Each group conducted preliminary research to identify data that were available from secondary sources (e.g., online resources or published works), and to determine which data needed to be collected from primary sources (e.g., data collection activities in the field). All data from secondary sources were collected and compiled before the team entered the field. The four sub-groups met each week in order to share their progress from the previous week. Since this field study was in support of a hindcast, it had different goals than the methodology presented in this thesis. One of these differences is that the team was not attempting to collect data in order to create probabilistic models of resilience metrics, so the methodology outlined in Chapters 3 and 6 was not applied directly for Joplin.

The NIST CoE collaborated with Professor Andrew Graettinger and several of his students from the University of Alabama and Professor Steve Smith at Missouri Southern State University who mapped the recovery of infrastructure along the tornado route on six month intervals over the last five years. Professor Smith provided maps of the City of Joplin that included data on building footprint, height, damage, and zoning. Several of these maps were plotted in 4’ x 6’ or 3’ x 4’ and used throughout the planning and execution of the field study.

Two weeks before deployment, the meeting matrix that is shown in Table 8-2 was created. The purpose of this matrix was to organize meeting schedules in order to send only one or two team members to speak with each interviewee. This lessened the burden on the interviewees and ensured small, focused discussions. After it was determined which city offices we wanted to contact, the city manager was contacted in hopes that he would enables meetings with other city officials. Then all of these officials were called by the principal investigator (PI) in an attempt to set up interviews between July 18th and July 21st.

Table 8-2: *Joplin Field Study Meeting Matrix*

	Group	Team	Team Lead	Building Permit Office	Mercy Hospital Admin	Fire Chief	Appraiser	City Manager	Empire Power co.	Missouri American Water	Traffic Engineer	Rostan Solution (Debris)	Director Planning	Emergency Management Dept. 4CEM	Joplin Schools Admin	Long Term Recovery Committee Contact	Contractors
2016 Primary Contact				Bryan Wicklund (Chief Building Official)	Tracy Godfrey and Gary Pulsipher (co-presidents)	James Furgerson	Connie Hoover (Jasper) and Gloria Gourley (Newton)	Sam Anselm	Bradley Beecher (President and CEO)	Matt Barnhart (Operations Manager)	David Hertzberg	Sam Rosania (Vice President)	Troy Bolander	Keith Stammer	Norm Ridder (Interim Superintendent)	Keith Stammer	Various
2011 Primary Contact				Unknown	Gary Pulsipher (President)	Mitchell Randles	Connie Hoover (Jasper) and Gloria Gourley (Newton)	Mark Rohr	Bradley Beecher (President and CEO)	Matt Barnhart (Operations Manager)	Unknown	Sam Rosania (Vice President)	Troy Bolander	Keith Stammer	C.J. Huff (Superintendent)	Keith Stammer	Various
	A	Housing Recovery 1	Sara Hamideh	X			X	X					X				
	B	Housing Recovery 2	Maria Koliou														X
	C	Connectivity 1	Lori Peek		X										X	X	
	D	Connectivity 2	Jennifer Tobin-Gurley		X										X	X	
	E	Networks	John van de Lindt					X	X	X	X	X	X	X			
	F	Buildings	Hussam Mahmoud	X	X	X									X		
	G	General	Therese McAllister										X	X			

The PI then developed a rough schedule to be followed by the combined field team. This schedule is shown in Table 8-3. Each individual team leader prepared their specific team's schedule based on this general template.

Table 8-3: Joplin Field Study General Schedule

Date	**Time**	**Activity**
Monday, July 18th	Varies	Field team leaders arrive in Joplin. Preliminary meetings between field team leaders and city officials.
	Afternoon	The rest of the team arrives in Joplin and travel to hotels.
Tuesday, July 19th	8 AM – 9 AM	Full team morning meeting.
	9 AM – 12 PM	Individual team data collection activities.
	12 PM to 1 PM	Lunch and full team meeting.
	1 PM – 6 PM	Individual team data collection activities.
	7 PM – 9 PM	Dinner and full team meeting.
Wednesday, July 20th	8 AM – 9 AM	Full team morning meeting.
	9 AM – 12 PM	Individual team data collection activities.
	12 PM to 1 PM	Lunch and full team meeting.
	1 PM – 6 PM	Individual team data collection activities.
	7 PM	Dinner on your own.
Thursday, July 21st	9 AM – 12 PM	Final team debriefing, data sharing, and action items.
	12 PM – 5 PM	Possible final meetings with contacts and depart Joplin.

This schedule was revised in the field according to the PI's judgment and data needs. For example, full team meetings were held each day from 4PM to 5PM instead of during or after dinner. Also, several team members including the PI attended additional interviews in the morning of Thursday, July 21st. In order to avoid scheduling conflicts the final team debriefing which included data sharing and action items was held on Wednesday afternoon. At this final meeting, the data from all of the team members was downloaded onto one central hard drive. Sharing data before leaving the field prevented issues with transferring data remotely since team members came from multiple locations across the U.S. It was also requested that each team leader submit a “two-pager” which outlines their team’s objectives, the work that they completed, the data that they collected, and the data that still need to be collected. Each team submitted their two-pager to the PI before leaving Joplin. An example of a two-pager is shown in Section 8.4.3. One week after leaving Joplin, a virtual meeting was held with the combined team, at which each group briefly summarized the work that was completed and the data that were collected and discussed the next steps that should be taken in order to complete the hindcast.

8.4.2. Equipment

- All team members had smartphones which were used for communication and the taking of geo-located photographs.
- GPS Devices (DeLorme Earthmate PN-Series) – three units from the University of Alabama (UA).
    - The students from UA were trained to use these units
- Cameras (D-SLR or smartphone).
- Nikon camera that had the capability of exporting data to ArcGIS.

8.4.3. Connectivity Team Activities

As an example of the daily activities of each team, this section will discuss the specific tasks and data collection activities that were conducted by the two connectivity teams. During the preparation phase, these two teams worked together to collect preliminary data and plan data collection activities in the field. A meeting was held on July 1st with the four team members and the P.I. in attendance in order to discuss a preparation work plan. Each member of the team prepared a list of data that they believed was most important to collect in the field, and then two primary focuses were selected: schools and healthcare. These two subjects were selected because we believed that it was more important to obtain in-depth knowledge on a couple of topics than to obtain less comprehensive data about a broad scope of topics. Six action items were then identified as follows:

1. Go through transcripts of old interviews and pull out data or anecdotes that are related to the study and share them with the full team.
2. Find and record recent news stories that have come out of Joplin related to our interests.
3. Research secondary data sources: what is available publically and privately (e.g., enrollment data, CDC).
4. Look at each of the five components of physical infrastructure for schools and see how they affect the way that people behave or modify physical interdependencies.
5. Create a map of Joplin containing: locations of all schools and hospitals and their relative damage level and recovery over time and which students went to which schools before and after.
6. Identify key points of contact within Joplin healthcare and School District and set up interviews with them.

These six tasks were all completed prior to the field investigation. It was then determined that four of the most important questions that needed to be answered included:

1. What information do we already have and how do we avoid redundant data collection?
2. Who can help us obtain healthcare and education data?
3. How did damage to hospitals effect the long term lives of individuals (e.g., being forced to travel long distances to obtain care)?

4. Which institutions are able to adapt and which are not (e.g., mental health facilities are able to adapt by going door to door while still working at a high level of productivity)?

The following pages contain a summary of the work that was completed in field by the connectivity team and work that still needed to be done. This “two-pager” was originally created by Lori Peek, and then edited by the connectivity team before leaving Joplin.

Connectivity Team – Joplin, Missouri Hindcast Field Investigation

July 21, 2016

Contributors:

Jennifer Tobin-Gurley, Todd Clapp, Hassan Masoomi, Lori Peek, and John van de Lindt

Objective

To collect qualitative and quantitative data regarding the interconnections between the built, social, and economic environments, with a special emphasis on schools and the health care sector.

Summary of Field Work

On Tuesday, July 19, Wednesday, July 20, and Thursday, July 21 the connectivity interviewed the following key stakeholders:

- Facilities Director, Joplin Schools
- Director of Transportation, Joplin Schools
- Assistant Superintendent of Operations, Joplin Schools
- Vice President Clinical Services, Ozark Center (Mental Health)
- Coordinator of Crisis Services and Accreditation, Ozark Center (Mental Health)
- Associate Professor and Chair, Department of Social Work, MSSU and Chairperson of the Long-Term Recovery Committee

- Chairperson, Joplin Citizens Advisory Recovery Team
- Director of Facilities, Mercy Hospital
- Director of Safety, Mercy Hospital

Data gathered prior to the investigation:

- The team mapped and traced the location of schools and hospitals before and in the five years after the tornado.
- The team searched for and compiled all publically available data sets.
- The team researched and compiled specific impacts of the disaster related to the built, economic, and social environments.

Data gathered during the field investigation:

- In-depth, qualitative data regarding community recovery in the form of field notes and 5 audio recordings that will be transcribed verbatim as soon as possible.
- Spreadsheet containing 2011-2012 student homeless population information and post-disaster bus routes for Joplin Schools.
- Joplin schools facilities director offered to provide building plans for old and new buildings via email.

Main Points:

- Schools
    - 3 Phases:
        1. Get students back in school by August 2011. This required summer repairs and build out of the mall school and identification of other temporary locations.

2. Pass bond issue to secure money for new schools. Put out RFQ's. Start rebuild of new schools.
3. Safe room installations.

- Some schools were over 100 years old, other (e.g., the high school) were built in the 1950's. East Middle School was a fairly new build.
- YouTube video, Bus Rescue: https://www.youtube.com/watch?v=P8RCTSijtn4
- Pre-tornado there were 81 buses. Went up to 98 after the tornado. Now they are running 83.
- They ran 41 buses for summer school in 2011. Offered both summer and winter camps to occupy the students.
- Buses drove over a million miles.
- Pre-tornado they served 7,000 students, now they serve 7,500 students.
- Made changes in the way they speak about inclement weather over the bus radios.
- Made sheltering changes. Used to recommend getting out and laying in a ditch, now they recommend staying in the bus if they cannot get to a storm shelter.
- The younger the children the more likely to move away permanently
- Expected 15-18% attrition due to tornado, but only saw approximately 3% at high school and 8% across elementary schools
- The high school was back to pre-tornado enrollment about two years after the event.
- 4 hope counselor's assigned to high school
- 15 high school faculty lost homes
- 4,200 of 7,500 in district displaced

  - West Elementary, 90% poverty rate
  - Kids helped pass the bond measure by voter turnout. Vote passed by 47 votes. 70 kids registered to vote.
  - If the tornado would have occurred during school hours there may have been hundreds of student/staff injuries and several deaths due to flying debris and collapsed ceilings
- Mental Health, Ozark Center
  - 8 buildings lost, 2 buildings had roofs destroyed, last building rebuilt November 2015 (Autism Center, funded by $3Million estate fund)
  - Temporary command center was the only building with power, had to use as substance abuse center
  - 425 employees pre-tornado, 600 employees now
  - 35 buildings
  - The population of served mental health patients went from 13,000 to 14,500 after the tornado; these individuals were drawn from a four county region of approximately 250,000-300,000
  - Therapists for children increased from 2 to 14
  - Major adult needs didn't present until year three after the tornado, then a substantial uptick in needs
  - Cumulative losses mattered…losing home, school, job, accumulated and resulted in more severe symptomatology
  - 60% of children that were seen after the tornado had trauma histories
  - Autism facility destroyed, which was hard because they need care every day

  - Lots of medications destroyed, got new shipments in to be distributed thanks to Governor of Missouri mobilizing resources
  - Percent of people not able to go back to work one month following: <.5%
  - Executive director of the Ozark Center rote $14 Million in grants in the first 18 months
  - Jasper counties in the top ten counties in the US for high suicide rates since 2001. Large increase in child suicide.
  - 40% increase in domestic violence rates
  - 80% increase in substance abuse

What is Still Needed

- We were not able to secure an interview with a representative from Freeman hospital system.
- More quantitative data to summarize the interlinkages and connectivity issues most of interest for the model (e.g., damage to students' residences linked to absences or behavioral issues).
- School data – enrollment data (e.g., number of students who left the district and number of students who were new to the district in the years following the tornado); educational attainment data (e.g., drop-out rates pre-post tornado; test scores; average GPA per class; etc.).
- Hospital data – data on admissions, by health outcome, over time.

8.5. Connectivity Illustrative Example - School Bus Routes

The following section was originally written as a standalone technical memo and then modified for this thesis. Therefore, some of the details may reiterate points that were mentioned in previous sections of this chapter.

8.5.1. Introduction

Joplin is in the southwest part of the state of Missouri. The northern section of the city is in Jasper County and the southern section is in Newton County. The population of Joplin is 51,818 (2015) and swells to approximately 250,000 during the daytime due to the large metropolitan area surrounding Joplin. The total population of the area within 40 miles of Joplin is 400,000 which makes it the fourth largest metropolitan area in Missouri. The primary industries near Joplin are education, health, agriculture, construction, transportation, retail trade, and manufacturing. Before 2011 there were two hospitals, six post-secondary educational institutions, one public high school, three private high schools, and many junior high schools and elementary schools located in or near the city (FEMA 2011; Kuligowski et al. 2014).

Joplin is in an area of the Midwest that is often called "Tornado Alley" due to its high tornado risk. The 80 mile area surrounding Joplin experienced 766 tornadoes from 1950 to 2011; however, only twenty-four percent of these were rated EF-2 or greater on the enhanced Fujita Scale and only one EF-2 or greater tornado has impacted Joplin directly (1971). (FEMA 2011, Kuligowski et al. 2014).

8.5.2. Tornado Impact (Kuligowski et al 2014)

On Sunday May 22, 2011 at 5:41 PM an EF-5 tornado devastated a six mile long and one mile wide path through Joplin, MO. It was the most deadly tornado in the U.S. in more than sixty years, killing 161 and injuring more than 1,000 people. Total economic losses were nearly $3 billion making it the most costly tornado ever recorded (Kuligowski et al. 2014). In total, 553 businesses and 7,500 residential structures were damaged. The reason that this tornado was so much worse than many of the tornadoes in the past is because it went through a densely populated area with many commercial buildings, schools, and healthcare facilities, whereas most tornadoes only impact rural regions (Kuligowski et al. 2014).

The event was on the same day as the graduation ceremony for Joplin High School, which occurred at Missouri Southern State University. The high school was severely damaged, but nobody was inside during the event. It lost several components which included the gymnasium, the auditorium, and many other buildings on site that were damaged, making the high school unusable. Joplin East Middle School was also severely damaged and lost functionality after the tornado. Other schools that were damaged included Irving Elementary School, St. Mary’s Catholic Elementary School, and Emerson Elementary School, and even more schools were less severely damaged.

The damage to roadways was severe, and three million tons of debris added to the transportation issues in Joplin. The daytime swelling of the population of Joplin increased the stress on the transportation networks. Many commuters were forced to find alternate routes which increased traffic flow on undamaged streets (City of Joplin 2012). Many utilities were affected including power, water, gas, and telecommunications. Empire District Electric lost towers, poles, substations, high voltage lines, and in-facility power distribution systems, causing 20,000 customers to lose power. Power was restored to most users within nine days of the event. 4,000 service lines were damaged which caused water leaks and decrease in water pressure and prevented two elevated storage tanks from functioning. A boil advisory was in affect for five and a half days after the event. Water that was used for fire protection services was restored after four days. A single water treatment plant was also damaged. 55,000 feet of gas main and 3,500 gas meters were disrupted which affected 3,500 community members. Seventy percent of the damaged mains were repaired one year after the event. Twenty-one cell towers lost function, and many wireline network cables were damaged, resulting in difficulty with phone calls for a few days while still being able to text.

8.5.3. Joplin Field Study

From July 18 to July 21, 2016 a multi-disciplinary team of engineers and sociologists from the NIST CoE went to Joplin, MO to conduct a community resilience field study five years after the tornado. The team's objective was to collect qualitative and quantitative data regarding the interconnections between the built, social, and economic domains of the effected community. During the preparation phase, the team collected preliminary data and planned data collection activities in the field. Weekly phone meetings were held with the team members in order to discuss a preparation work plan. Each member of the team prepared a list of data that they believed was most important to collect, and then two primary focuses were selected: schools and healthcare. These were selected because it was decided that obtaining depth of knowledge on a couple topics was more important than obtaining minimal data on a broad scope of topics; thereby enabling a better understanding of the connectivity in the objective outlined above. The following five tasks were also completed during the preparation phase:

1. A team member went through transcripts of old interviews that took place soon after the disaster and pulled out data or anecdotes that were related to connectivities in order to share them with the full team.
2. A team member found and recorded recent news stories that came out of Joplin and were related to our objective.
3. A team member identified secondary data sources to determine what data were available publically and privately (e.g., enrollment data, student absences, etc.).

4. A team created maps of Joplin containing locations of all schools and hospitals and their corresponding damage levels and recovery over time and the school district zoning areas before and after the event.
5. Team members identified key points of contact within Joplin healthcare and education systems and set up interviews with them for the site visit.

It was then determined that four of the most important questions that needed to be answered included:

1. What information do we already have and how do we avoid redundant data collection?
2. Who can help us obtain healthcare and education data and how do we contact them?
3. How did damage to schools and hospitals effect the lives of individuals in the years that followed (e.g., being forced to travel long distances to get to school)?
4. Which institutions are able to adapt and which are not (e.g., mental health facilities are able to adapt by going door to door while still working at a high level of productivity while schools are confined to a centralized location)?

Two weeks before deployment, a meeting matrix was created that allowed us to lessen the burden on the interviewees and conduct small, focused discussions. City officials that we wanted to contact were called by the principal investigator (PI) in an attempt to set up interviews. On Tuesday, July 19, Wednesday, July 20, and Thursday, July 21 the connectivity team interviewed the following nine key stakeholders:

1. Facilities Director, Joplin Schools
2. Director of Transportation, Joplin Schools
3. Assistant Superintendent of Operations, Joplin Schools
4. Vice President Clinical Services, Ozark Center (Mental Health)

5. Coordinator of Crisis Services and Accreditation, Ozark Center (Mental Health)
6. Associate Professor and Chair, Department of Social Work, MSSU and Chairperson of the Long-Term Recovery Committee
7. Chairperson, Joplin Citizens Advisory Recovery Team
8. Director of Facilities, Mercy Hospital
9. Director of Safety, Mercy Hospital

These interviews were audio recorded and then transcribed verbatim. In-depth, qualitative data related to community recovery were collected from each interview. Flexibility as a team was crucial. For example, while interviewing the Facilities Director of Joplin Schools, we were introduced to the Director of Transportation at Joplin Schools with whom we then conducted an impromptu interview. The Director of Transportation provided us with a spreadsheet containing locations of temporary residences of the students who were displaced due to the tornado. The locations of these displaced students were mapped out and are shown in Figure 8-1, and the Facilities Director of Joplin Schools offered to provide building plans for old and new buildings via email. Some of the main takeaways from the interviews with Joplin School District employees are described in the next section.

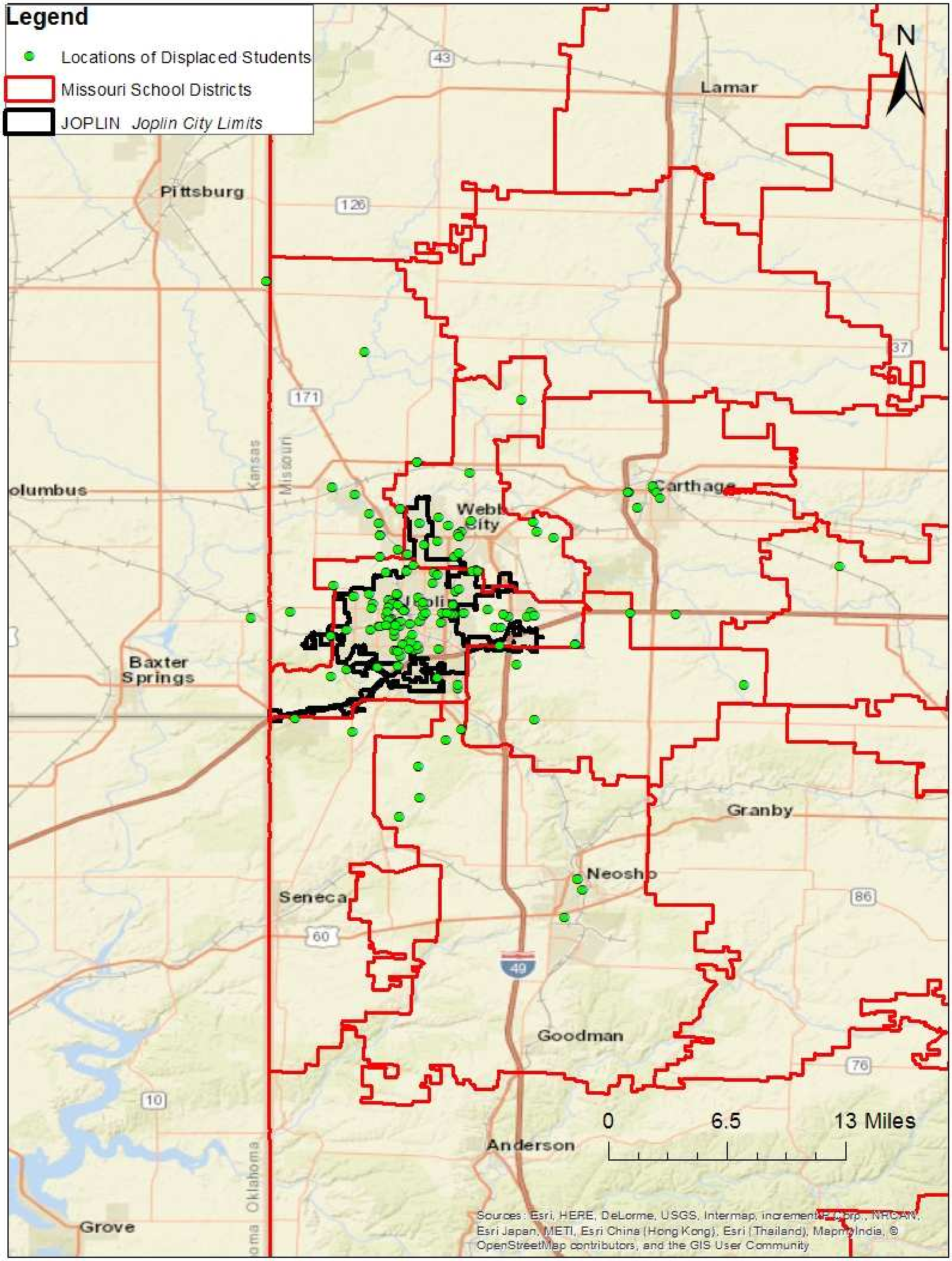


Figure 8-1: Joplin Schools Displaced Students' Locations (Data from Pettit 2016)

8.5.4. Joplin School District's Actions

This section describes the qualitative data that were gathered from interviews with Joplin School District employees. It focuses on the actions that were taken by the school district in the immediate aftermath of the tornado related to transportation issues and bus routes. Four of the actions that were taken by the school district are described below.

1. Immediately after the tornado they sent buses to help St. John's Regional Medical Center (SJRMC) with the evacuation of patients (School Bus Rescue 2012).
2. They left the pre-tornado bus routes intact after the tornado and continued to make stops at locations where housing was badly damaged. At times there were no pickups, but some parents took their children to these stops.
3. People who had been displaced within thirty-five minutes of Joplin (living with family, friends, or rental) were picked up and taken to the same school that they had attended pre-tornado.
4. After school, they bused some high school children from school to the location of their after school activities.

In order to organize the transportation of displaced students, the school buses or parents took displaced students to Beacon School, a school for at risk children or children with behavioral issues from twelve surrounding districts, in Joplin as a morning hub, and then Joplin buses would pick up students from Beacon School and take them to their respective schools. In the afternoon, Eastmorland Elementary School was similarly used as a busing hub. In order to execute these decisions the school district had to increase their number of operational buses from eighty-one before the tornado to ninety-eight after the tornado, requiring them to lease ten new buses for two years. They also increased the mileage of the buses from about seven hundred thousand miles per year before the tornado to over one million miles per year after the tornado, but this did not result in an increase in fuel costs because they purchased fuel contracts for long durations in advance.

In addition to transportation, the school system offered several services that helped community members in the immediate aftermath of the tornado. The first thing that the school district did after the tornado was contact families of each student in order to identify the child's status and location immediately following the tornado. They started summer classes just three weeks after the tornado, offering a longer summer session in 2011 than in previous years, and they offered optional classes over the winter break. The school district's push to open school on time (August 17, 2011) allowed students' and parents' lives to get back to normal as quickly as possible. Finally, school staff members were trained over the summer to better understand and support the affected students with issues that they were facing (Kanter and Abramson 2014; Johnson 2016; Pettit 2016; Sachetta 2016).

8.5.5. Potential Effects of Joplin School District's Actions

This section discusses the potential effects that the school district's transportation related decisions had on the community, specifically on the students and their families. It first discusses social impacts such as quality of life, school attendance rate, grades, and school discipline trends, and then it describes the economic cost for the school district and the families of the students.

8.5.5.1. Social Effects

The decision to leave the pre-tornado bus routes intact was important because as people rebuilt their homes the bus stops were already in place when they returned, and it allowed parents to bring their kids to the bus stops that they were familiar with before the tornado. This helped parents and students to anticipate the post-tornado bus routes. Even though this allowed children to continue attending their former schools, there were some issues with this plan that affected students and parents. The bus routes that were developed for displaced students extended commute times, which lead to a loss of quality of life for the students. Displaced children got out of school at 2:45 pm but often didn’t get home until 6 pm, according to the transportation director. The decision of the school district to offer classes over the summer and winter breaks and to provide free transportation was crucial to the social recovery of the community. This allowed parents to focus on rebuilding their family and work structure without the added responsibility of children at home during the daytime, and it allowed children to share their experiences in a safe, social environment at school (Kanter and Abramson 2014, Johnson 2016, Pettit 2016, Sachetta 2016).

To supplement the qualitative data that were collected through interviews with school district employees, quantitative data were found in publically available, online data bases created by the Joplin School District. The data that were found included yearly enrollment, attendance rate, ACT test scores and rate, number of suspensions and suspensions rate, and English, Math, Science, and Social Science test scores. Figures 8-2 through 8-11 (data from Missouri Department of Elementary and Secondary Education 2016) show how each of these categories changed over time in Joplin School District.

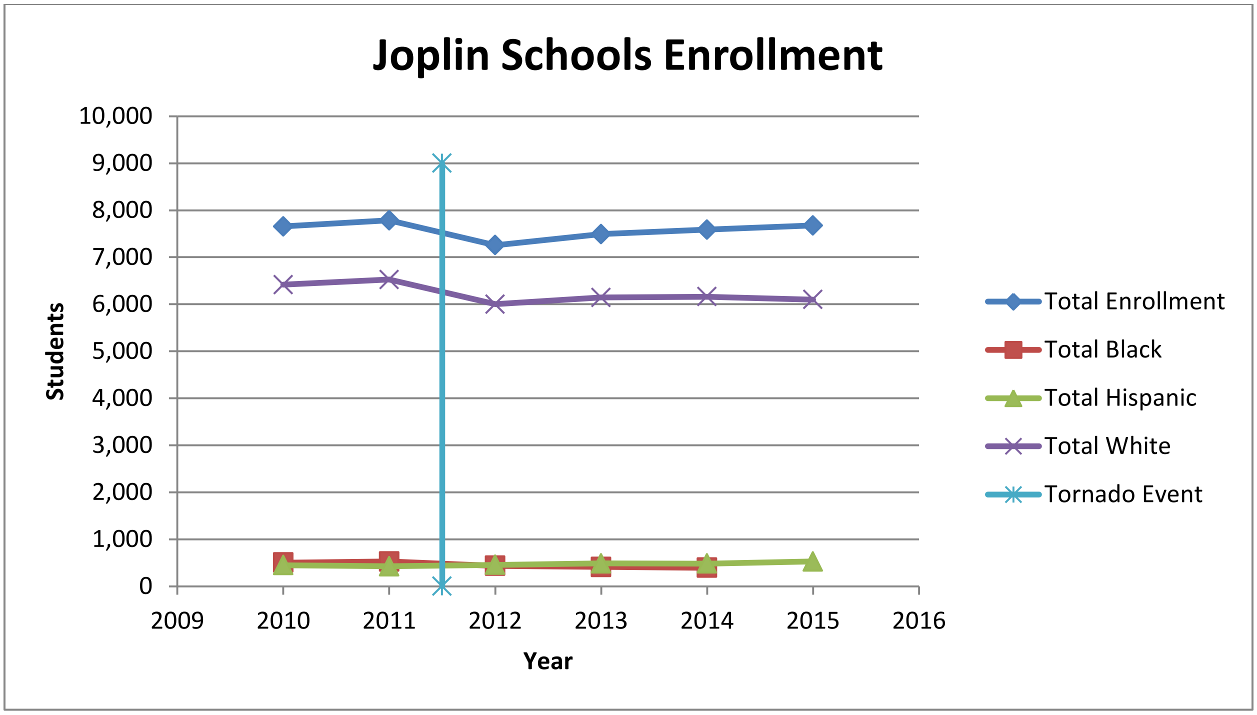


Figure 8-2: Joplin Schools Enrollment Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

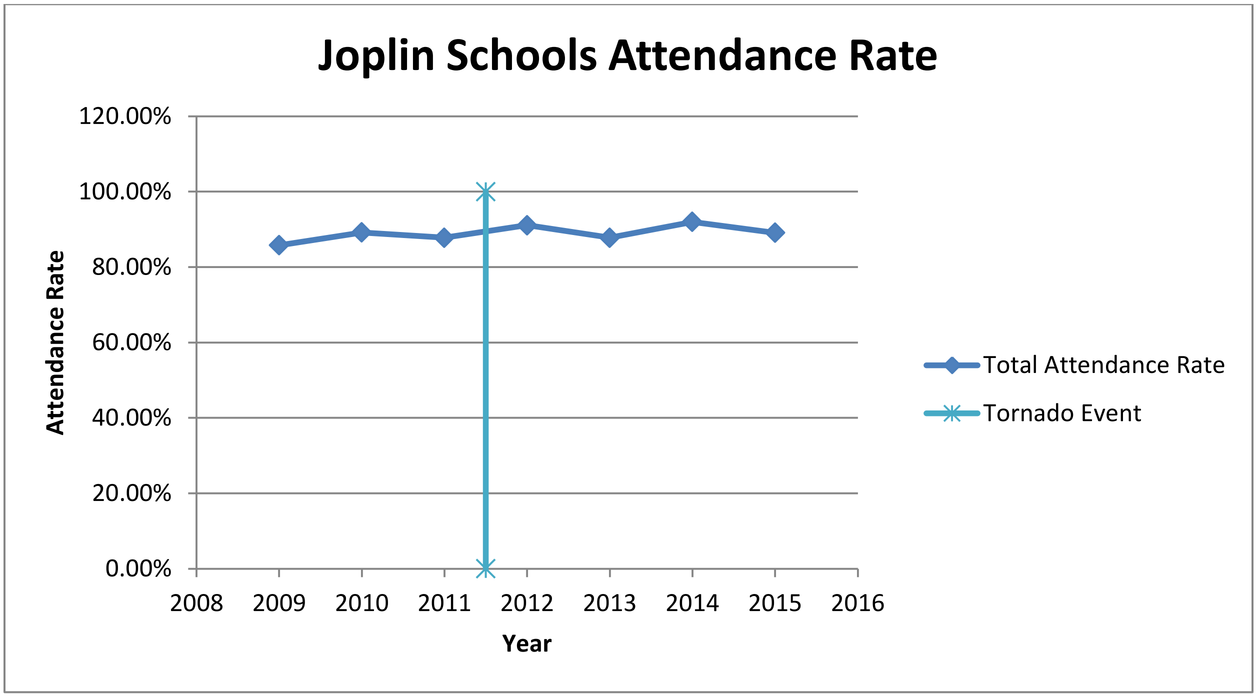


Figure 8-3: Joplin Schools Attendance Rates Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

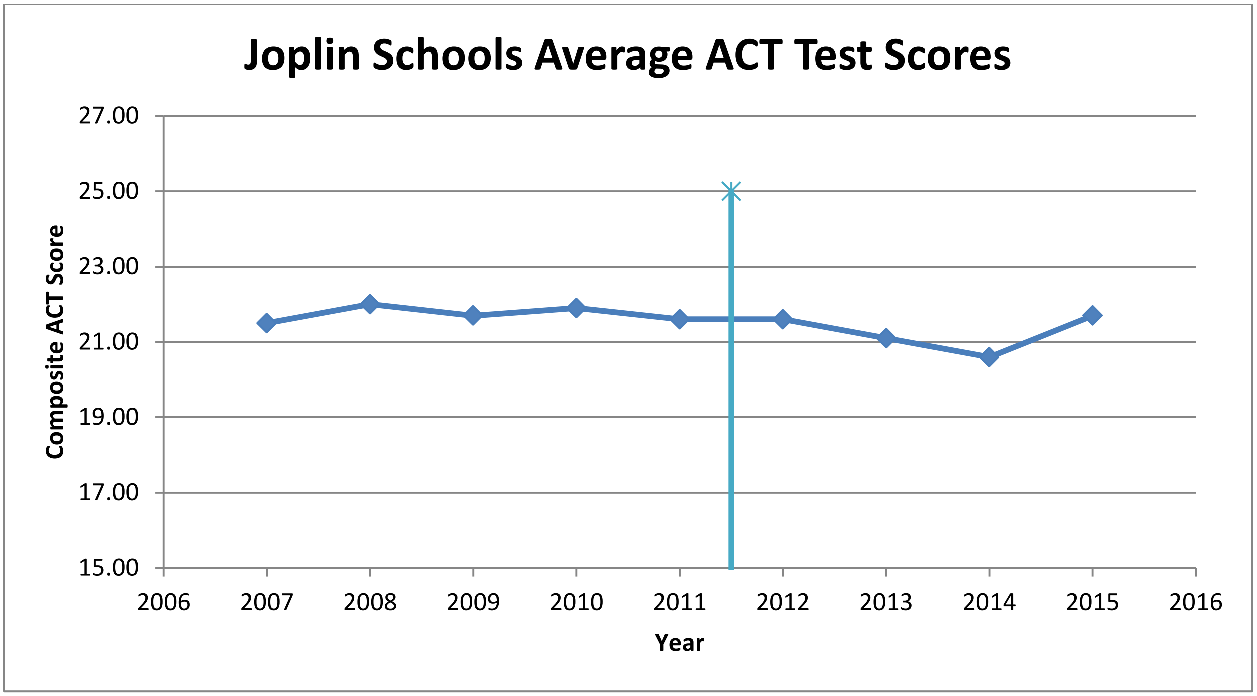


Figure 8-4: Joplin Schools ACT Test Scores Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

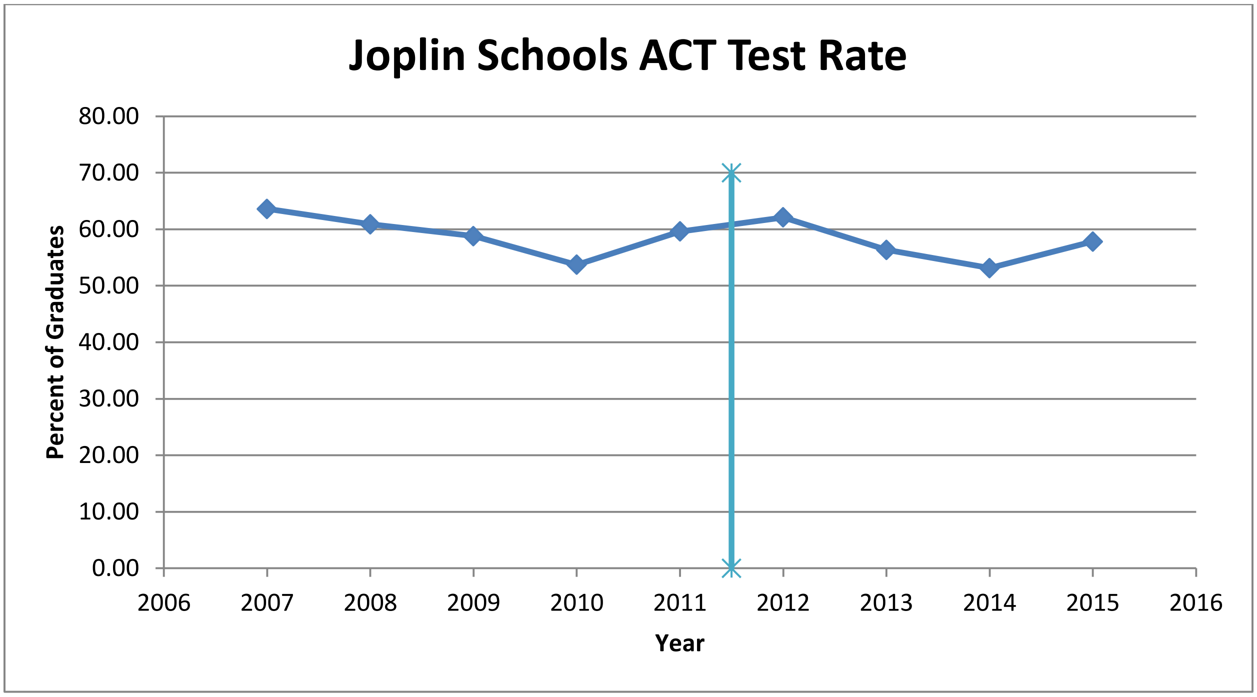


Figure 8-5: Joplin Schools ACT Test Rates Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

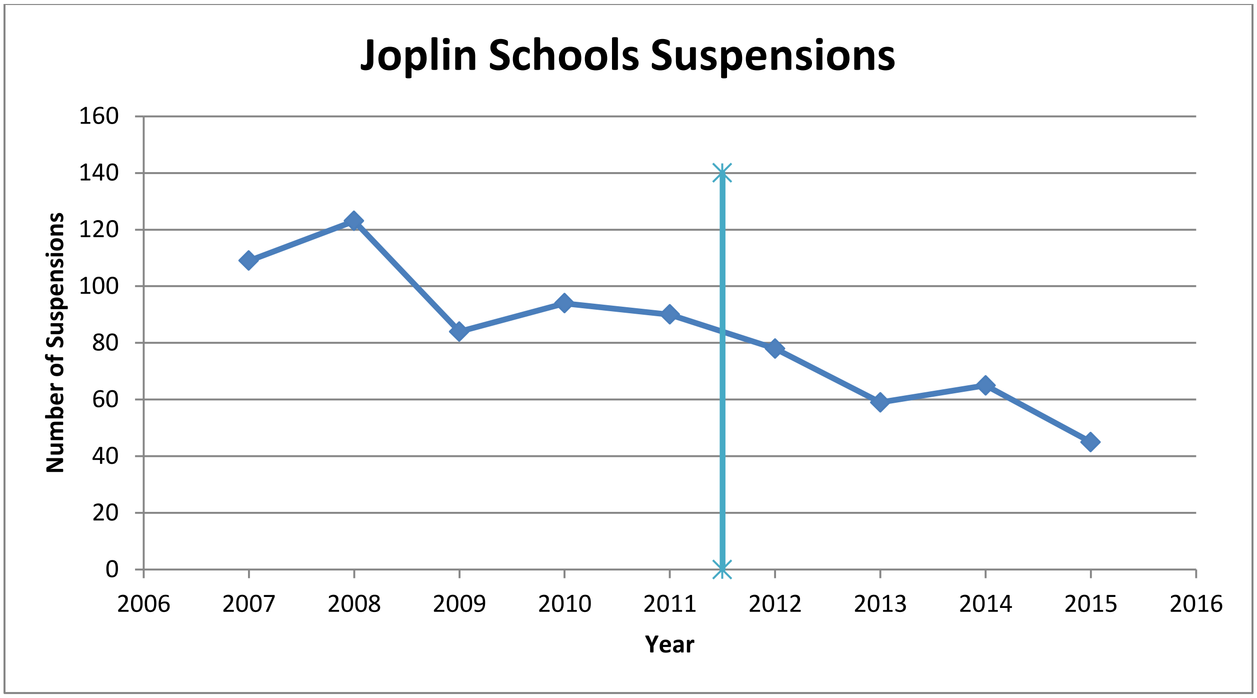


Figure 8-6: Joplin Schools Suspensions Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

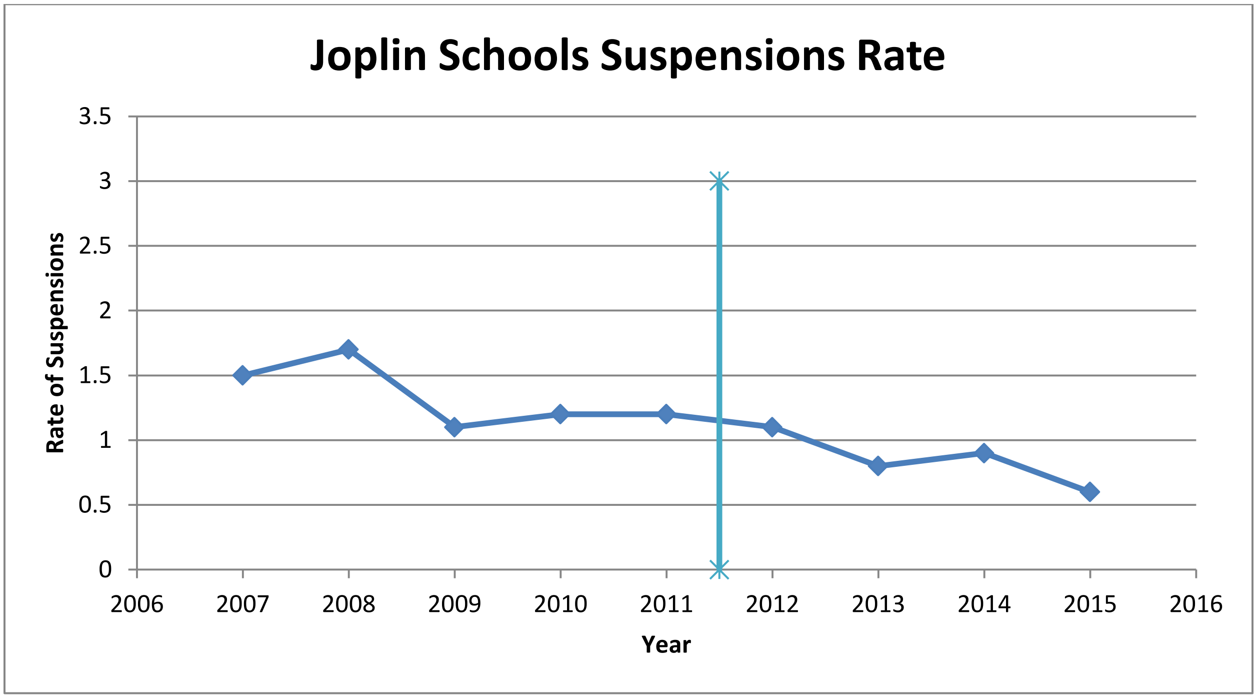


Figure 8-7: Joplin Schools Suspension Rates Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

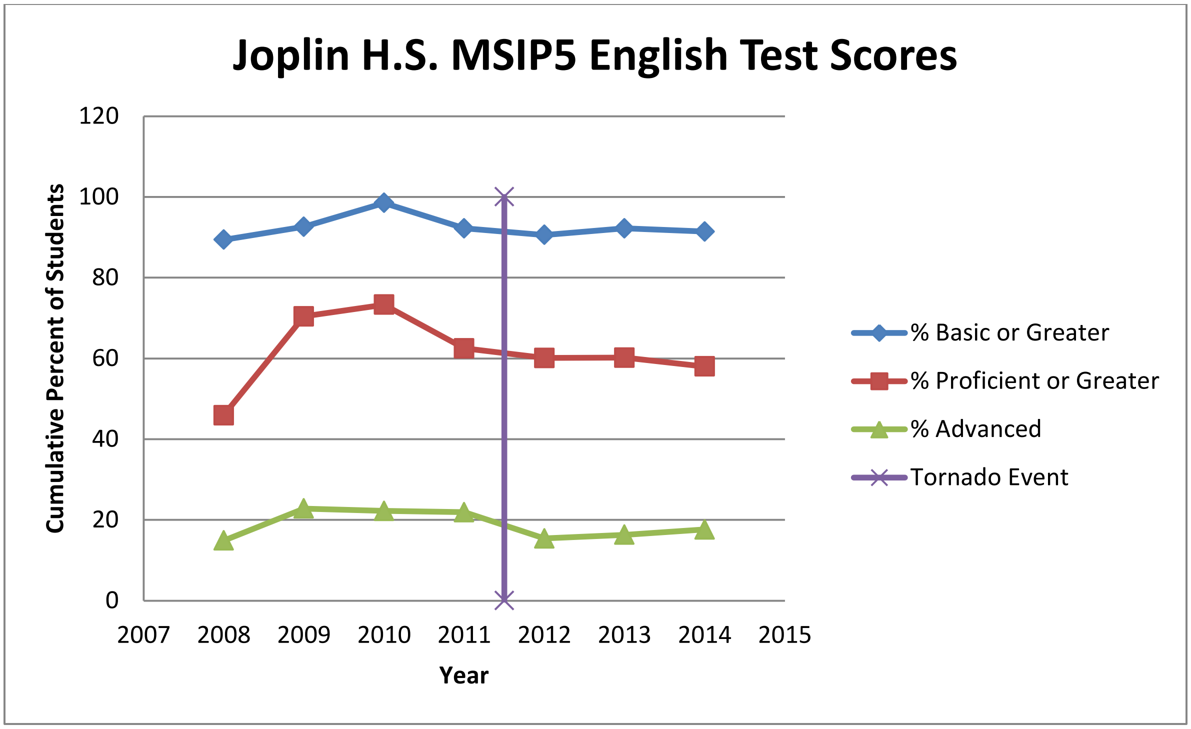


Figure 8-8: Joplin High School English Test Scores Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

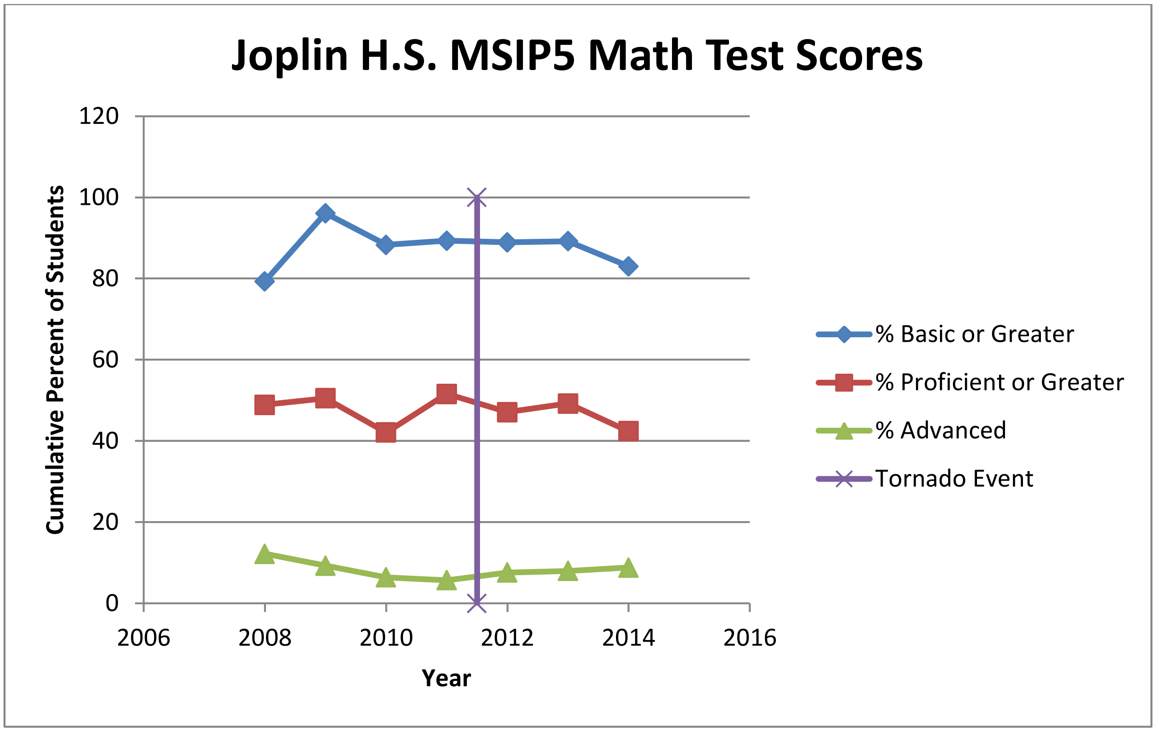


Figure 8-9: Joplin High School Math Test Scores Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

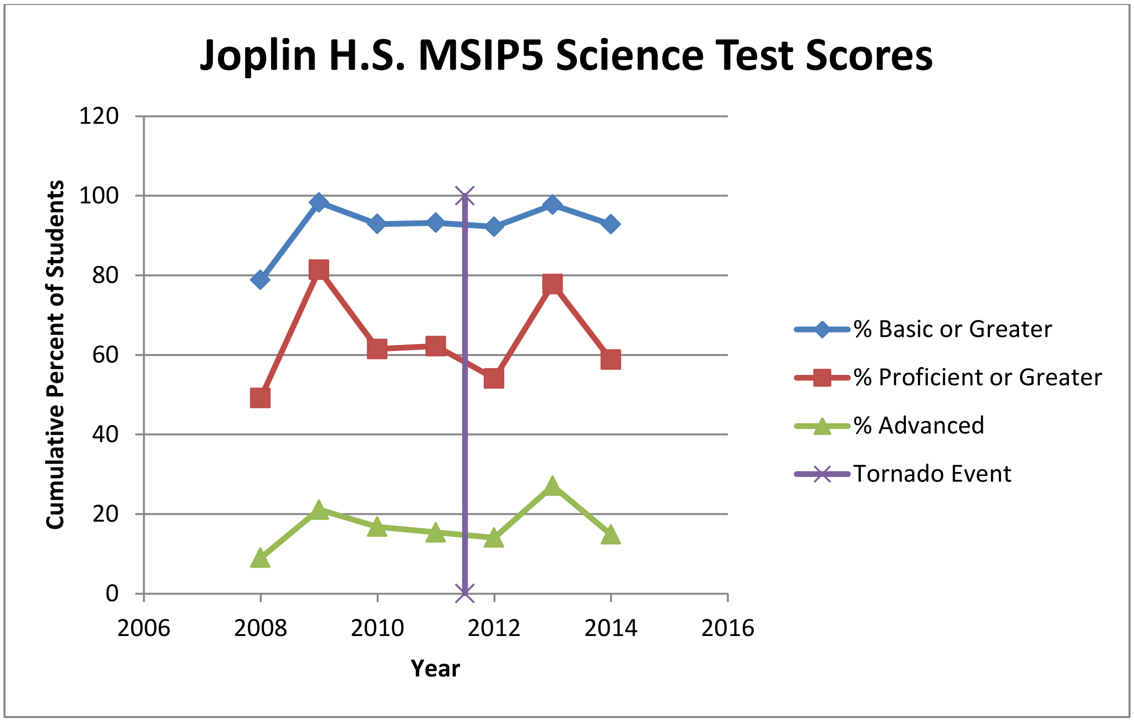


Figure 8-10: Joplin High School Science Test Scores Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

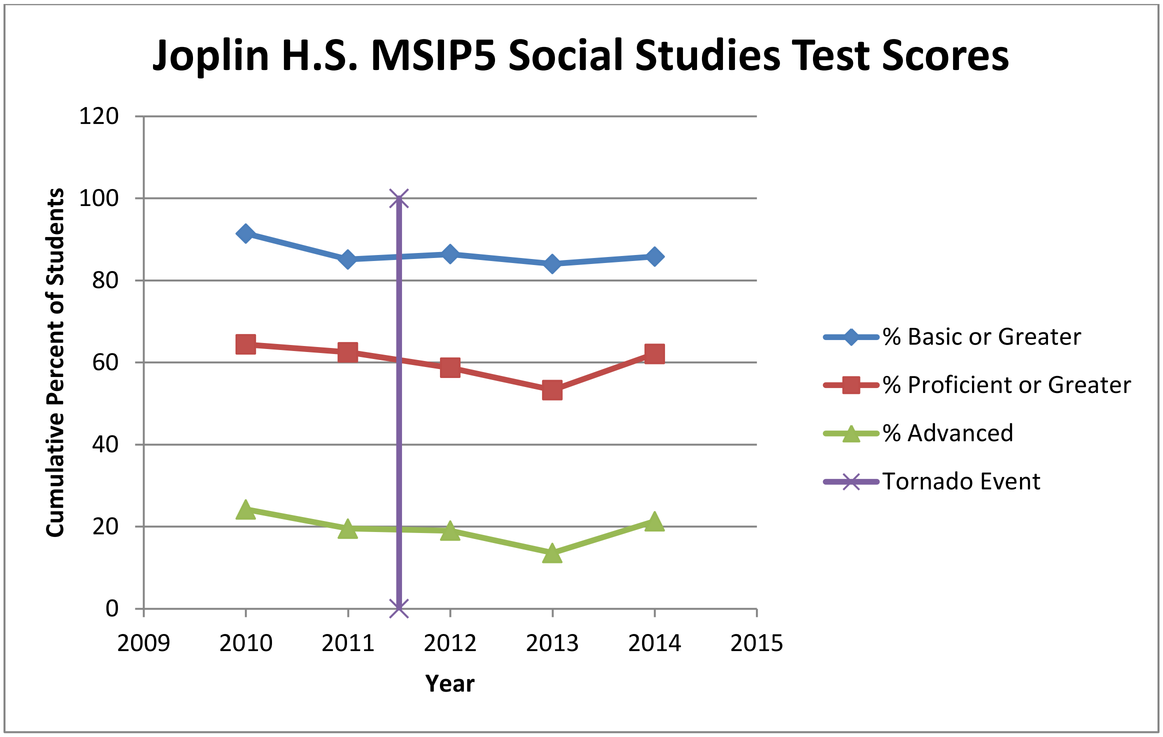


Figure 8-11: Joplin High School Social Studies Test Scores Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

Figures 8-2 through 8-11 show several interesting trends in the social and academic behavior of students in Joplin in the years after the tornado. The total enrollment dropped slightly in the first year after the tornado, but then it began to increase every year for the next four years. The enrollment in 2015 was nearly back to the enrollment before the tornado. Of the students who remained enrolled, the attendance rate increased slightly. This may be due to the decisions made by the school district that helped transport the children to school and the damage that was done to students' homes making school a better alternative than home. The dropout rate increased slightly (0.9%) in the year after the tornado, but then it decreased below its level prior to the tornado. ACT test scores of high school students remained constant in the year after the tornado, and fluctuated up and down in succeeding years. School suspensions decreased significantly in the years following the tornado; however, it is unknown whether this decrease was due to the behavior of the students or the flexibility of the staff. The high school English, Math, Science, and Social Science grades fluctuate over the years depending on the subject, and there is no clear increase or decrease in performance.

All of this evidence suggests that, on average, the social and academic lives of students in the Joplin School District were not significantly impacted in a negative way in the years after the tornado. In an interview with Kerry Sachetta (Sachetta 2016), the high school principal at the time of the tornado, he expressed his surprise that enrollment dropped far less than the school district originally expected. This may be the result of the decisions made by the school system to provide transportation and support systems for the many victims of the tornado. All students and teachers were affected by this disaster in some way, and the school district played a critical role in their recovery.

8.5.5.2. Economic Effects

Figure 8-12 shows that the total expenditures of the Joplin School District increased significantly in the years after the tornado. Before the tornado (2011) the schools total expenditures were about $63 million, and after the tornado (2012) their expenditures increased to about $112 million, a seventy-eight percent increase from the previous year. This increase in expenditures is likely due to many contributing factors including moving the high school to a temporary location, beginning the reconstruction process, access to federal funds, hiring new mental health counselors, leasing new school buses, and hiring new bus drivers. Joplin School's expenditures continued to increase for three years after the tornado before finally leveling off in 2015 at $176 million (Missouri Department of Elementary and Secondary Education 2016).

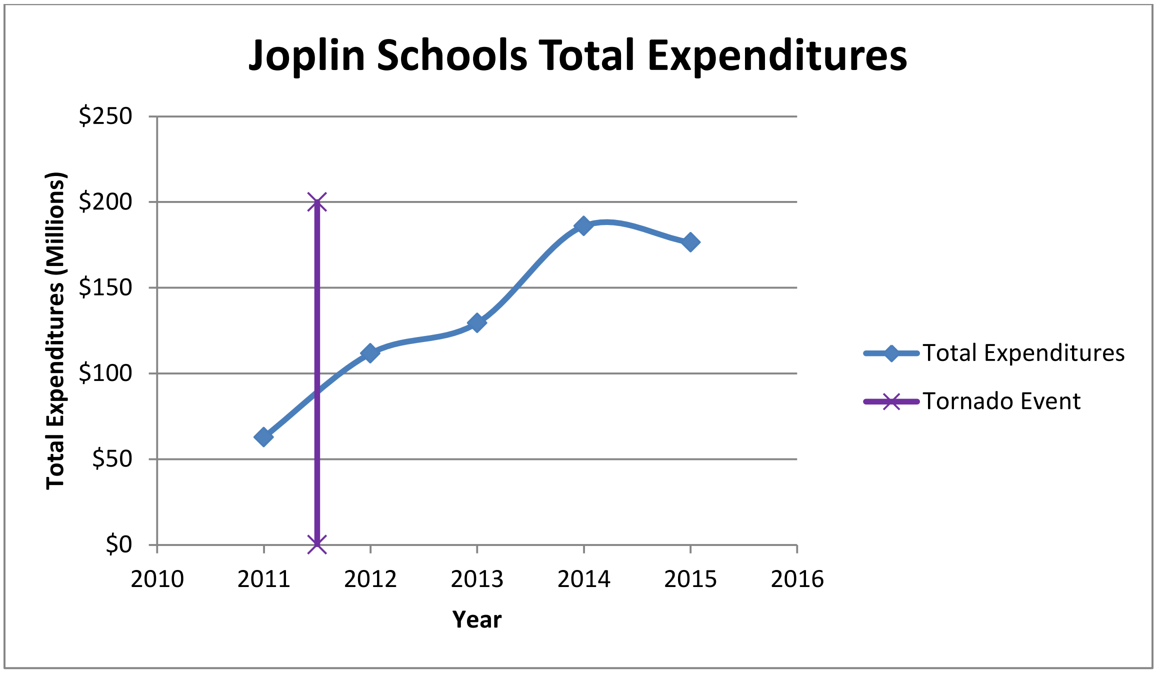


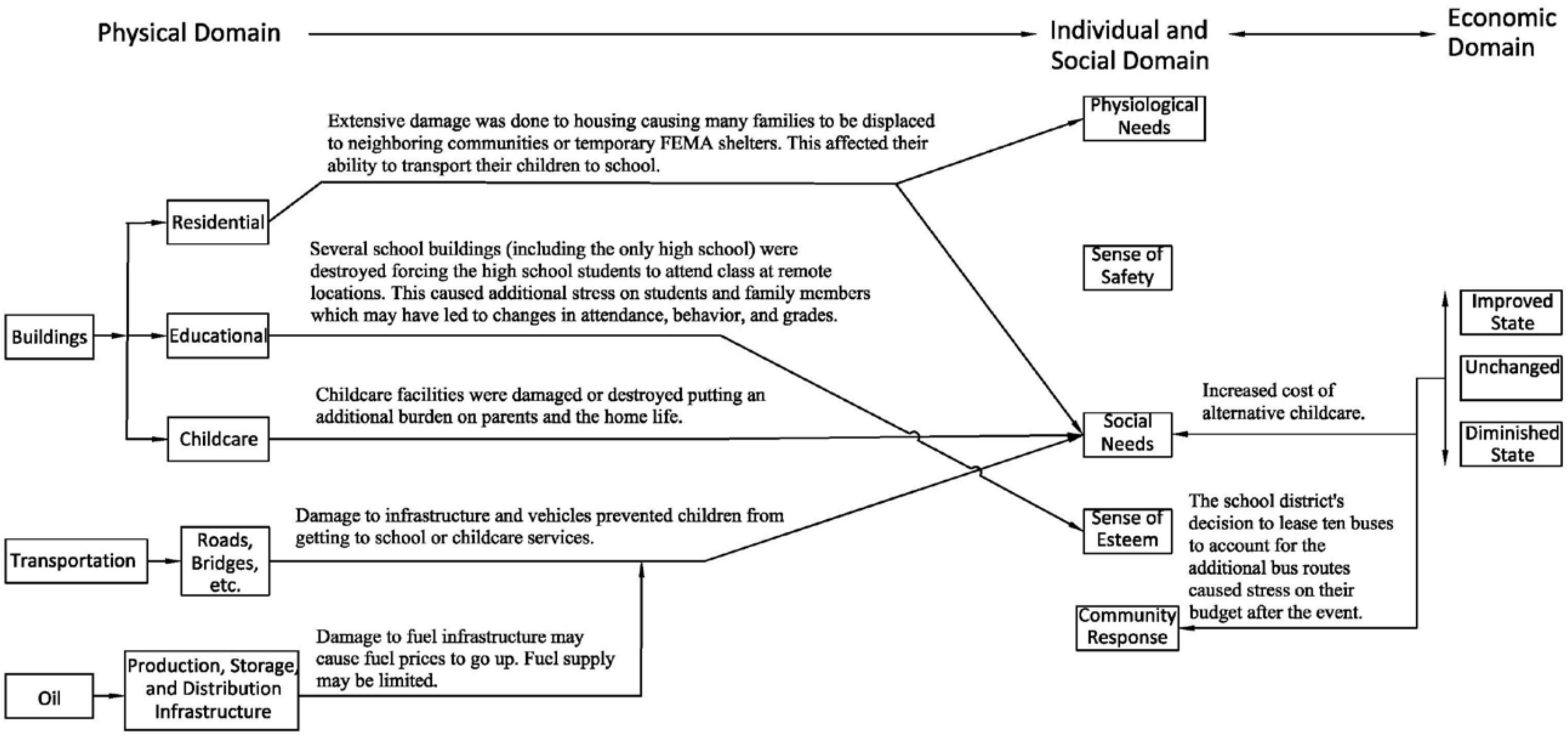
Figure 8-12: Joplin Schools Total Expenditures Over Time
(Data from Missouri Department of Elementary and Secondary Education 2016)

8.5.6. Physical, Social, and Economic Interconnectivity

This section discusses how the physical, social, economic community domains of Joplin are interconnected, and how the decisions that were made by the school district affected these connectivities. The tornado caused devastating physical damage to school buildings, residences, and surrounding infrastructure leading to social and economic consequences. These consequences affected the daily commute of students, the routes that they took to school, and nearly every aspect of their lives. The school district's decisions in the aftermath of the tornado helped to kept dislocated families engaged in the community and prevented students from missing school. Their decision to continue having the buses stop at the pre-tornado bus stops even though the nearby houses may have been completely destroyed helped to return a sense of normalcy to the community, and it prevented confusion among parents about where to drop off their children and what routes the buses would be taking to school. Also, it is possible that the school district's bus route decisions helped to keep the attendance rate high which prevented a significant drop in the graduation rate and test scores.

After the tornado occurred parents were scrambling to take care of many responsibilities including clearing debris, working with insurance companies, taking care of children, and maintaining employment. This situation may have been overwhelming for many parents, and the destruction of several child care facilities created additional challenges. In order to alleviate part of the parents' stress, the school district decided to open summer school within three weeks of the tornado, utilizing about forty buses to transport students to and from summer school. In the past the school district had only offered transportation to and from summer school for students with special needs, but in the summer of 2011 they offered transportation services to all students. The summer school enrollment at Joplin Schools increased dramatically during the summer of 2011, and the free bus service was a significant contributing factor. Joplin Schools also held classes during the winter break of 2011-2012 for the first time in order to help families in need of childcare. This additional childcare service through school during the summer and winter breaks may have prevented relational strain among children and between parents and children. Therefore, in the wake of the physical destruction of numerous family residences, the school district was able to provide parents with transportation to free childcare services, which allowed them to focus on other aspects of their individual recovery such as home repair and employment. The large summer school enrollment also gave students the opportunity to help each other recover by sharing their common experiences. This pro-social environment may have helped the students recover more quickly from this traumatic event.

Figure 8-13 illustrates the interconnectivities influencing the school district's decisions made after the tornado. One example of an interconnectivity that this figure illustrates is seen through damage to childcare facilities. Childcare facilities were damaged and closed after the tornado, which falls in the category of physical damage to buildings. This affected community members' social lives because parents had to find alternative childcare or keep their children under their own supervision while they were trying to rebuild their homes, deal with job issues, etc. These social decisions also have economic costs such as the increased price of alternative childcare. The transportation decisions made by the school district changed the relationship of these interconnectivities by providing free transportation and childcare to parents over the summer after the tornado. This allowed the parents to focus on other aspects of their recovery and may have even improved social relationships between parents and children. This also shifted the financial burden off of the families and on to the school district. The families no longer had to pay for alternative childcare, but the school district had to pay for additional summer staff and busing. This is just one example of a complex interconnectivity that can be seen in Figure 8-13.



Extensive damage was done to housing causing many families to be displaced to neighboring communities or temporary FEMA shelters. This affected their ability to transport their children to school.

Several school buildings (including the only high school) were destroyed forcing the high school students to attend class at remote locations. This caused additional stress on students and family members which may have led to changes in attendance, behavior, and grades.

Childcare facilities were damaged or destroyed putting an additional burden on parents and the home life.

Damage to infrastructure and vehicles prevented children from getting to school or childcare services.

Damage to fuel infrastructure may cause fuel prices to go up. Fuel supply may be limited.

Increased cost of alternative childcare.

The school district's decision to lease ten buses to account for the additional bus routes caused stress on their budget after the event.

Figure 8-13: Field Study Interconnectivity Diagram for Joplin School District Busing System

8.5.7. Summary and Conclusion

Over a three day period from July 18^{th} to 21^{st}, 2016 a multidisciplinary team of engineers and sociologists went to Joplin, Missouri five years after it was devastated by a tornado in order to gain an understanding of how the physical, social, and economic domains of the community are interconnected. The team interviewed nine key stakeholders in the health care and education industries in order to understand their experiences in the five years after the tornado and how the damage to physical systems affected the social and economic aspects of schools and healthcare systems. This section focused specifically on school systems, the decisions that they made after the tornado, and how these decisions affected students and their families socially, economically, and academically.

One of the most interesting decisions that were made by the school district was to expand bus services to provide transportation of displaced students to their pre-tornado schools and to provide transportation to summer school for all students. This action allowed parents to have access to free and easy childcare so that they could focus on their personal and overall family recovery. It also provided a healthy, pro-social environment for students to recover mentally from their traumatic experiences. This decision affected the economic situation of the school district because they had to lease ten new buses for two years, hire new drivers, and increase mileage on the buses. This is just one example of how damage to physical systems caused the school district to make decisions that affected the social and economic aspects of families that were affected by the tornado. Several additional examples were provided in this section, and an interconnectivity diagram was created which provides an illustration of these complex interconnectivities.

The conclusions that have been made about interconnectivities related to school bus routes are not certain because of the qualitative nature of the data that was collected. In future field studies it will be important to be able to quantify conclusions that stem from interviews with community members. For this example on school bus routes, a possible data collection strategy would be to give a survey to a sample of parents of students that were affected by the tornado. This survey could ask questions related to how busing to and from school impacted their daily lives after the event. E.g. one question could be, “Was your home life less stressful, equally stressful, or more stressful as a result of the school district’s decision to provide free transportation to summer programs?” This would allow qualitative data to be quantified, and more certain conclusions could then be made about the interconnectivities. A similar data collection strategy can be applied to any form of qualitative data in future field studies.

As researchers continue to expand their knowledge of community resilience, it is crucial for them to understand the complex interconnectivities that exist in every community. These interconnectivities are difficult to quantify and model because of the many unknown variables that exist within communities. However, if we are to be successful in our endeavor to quantify a community’s resilience, then these interconnectivities must be understood and modeled. The best way to begin this process is to conduct field studies that collect qualitative and quantitative data that is focused on interconnectivities.

9. Summary, Conclusions, and Recommendation

This thesis focused on the connectivities between physical damage and socio-economic dimensions of a community following a disaster. The methodology discussed herein can be used in the aftermath of any natural disaster to collect data that can be used to help quantify community resilience. The two primary goals of this methodology were to collect data that allow researchers to study community resilience and interconnectivities and to create probabilistic models of crucial resilience metrics that can inform a software platform called IN-CORE. The material presented herein is expected to contribute to the body of work within the NIST Center for Risk-Based Community Resilience Planning.

In order to develop this protocol, an in-depth literature review was performed. The goal of this literature review was to learn lessons from previous field studies and to identify gaps that must be filled in order to conduct community resilience focused field studies. In addition, an overview of the dependencies and interdependencies that exist within communities' physical systems was provided. Seven resilience metrics or performance indicators were identified from existing literature and expert opinion, and a method for collecting field study data that quantify these metrics was described. A diagram that illustrates the interconnectivities between the physical, social, and economic community domains was created and used to develop a sample field study questionnaire. An algorithm that has the capability of processing field study data to create resilience metric fragilities was derived and written as a MATLAB program, and a case study using population dislocation data from Hurricane Andrew was performed in order to create population dislocation fragility functions. These fragility functions were then modified to account for different resident demographics and housing types. Finally, a community resilience field study was conducted in Joplin, MO, five years after the May 22, 2011 tornado that devastated their community. During this field study, data was collected through quantitative and qualitative methods in order to validate models of the community before, immediately after, and five years after the event. One of the primary focuses of this study was on the interconnectivities between physical damage to schools and healthcare facilities and socio-economic consequences, and how the decisions that were made by Joplin School District affected each of these domains within the community.

This thesis made the following five contributions to the discipline of community resilience research:

1. A literature review of 35 field study reports related to engineering, sociology, epidemiology, and economics was conducted and the results of this review were submitted for publication. This literature review was unique because it focused on the protocols of past disaster field studies, and identified gaps that should be filled when conducting future community resilience-focused studies.
2. This thesis is the first attempt that has been made to create a methodology for conducting post-disaster field studies that seek to quantify community resilience metrics. This methodology was informed by the aforementioned literature review.
3. New progress was made in developing a method to link physical damage to social dimensions (including epidemiology) and economics using data collected during a field study. This progress includes field study questions that were developed to find the links between these three community domains, and an algorithm that generates probabilistic models of social and epidemiology related metrics based on physical damage to infrastructure.

4. In order to create a new framework for conducting community resilience focused field studies, seven metrics were identified, and field data needs for quantifying these metrics were described. The selected metrics were meant to provide possible direction for field teams and may change as more is learned about community resilience but serve as examples for the work presented herein.
5. A field study was conducted in Joplin, MO five years after a tornado took place, which provided an illustrative example of how one might develop the linkages between damage to physical systems and social and behavioral sciences. This particular study, while lacking the ability to collect large amounts of quantitative data, provided insight into the interconnectivities of physical damage done to school buildings, decisions made by school leaders, and social and economic outcomes in the lives of students and parents. This field study was also unique because it was among only a few studies that have been conducted that collect data that allow the modeling of a community's recovery in the years after a disaster.

Two conclusions that were made from the work described herein are listed below. There are many more specific conclusions that were made throughout this thesis, but the two listed below provide insight into the broader perspective of conducting community resilience field studies.

1. Unlike the majority of past field studies, community resilience field studies focus on the recovery of a community over time. In order to collect the data that is required to model this recovery, field teams must return to the community at defined intervals in the years after the disaster occurs.

2. In the aftermath the tornado, Joplin School District's decision to expand bus services in order to provide transportation for displaced students to their pre-tornado schools and to provide transportation to summer school for all students likely had a positive effect on the social and economic lives of parents as well as behavioral and academic effects on the students based on qualitative evidence.

There are several issues that may result in inaccurate or insignificant data. The first concern is that samples for damage data collection cannot be selected based on the fact that they are damaged or of interest in some way. If data samples are selected based on a certain characteristic, then those data will be biased, and the fragility curves that are created with those data will be inaccurate (this is explained further in Section 6.2). The second concern is that damage states of infrastructure must be clearly defined and not subject to the judgment of the inspector. Two different people observing the same physical system should classify it under the same damage state every time. Team members may be engineers, sociologists, economists, or some other discipline; therefore, classifying damage states must be simple and reproducible.

The work that has been done on this methodology has revealed the following 12 areas of study that need to be further developed.

1. As research in the area of community resilience becomes more prevalent, several gaps in conducting community resilience field studies will need to be filled. Few of the 35 field study protocol reports that were reviewed (see Figure 2-1) collected data related to all three community domains, and those few studies that were multi-disciplinary did not place an emphasis on the interconnectivity of each of these domains. This thesis provides guidance for field study teams that seek to collect data that help quantify the

interconnectivities between damage to physical infrastructure and social community resilience metrics, but it has not yet been tested in a full scale field study.

2. Once this type of field study has been conducted, the methodology presented herein should be revised to account for new knowledge that is gained related to fieldwork and data analysis.
3. Additional work is needed to create a protocol for collecting data that attempts to quantify interdependencies between physical infrastructure systems. This thesis provides a brief overview of these interdependencies and provides some guidance for data collection activities, but it must be further developed.
4. This methodology only briefly mentions the role of economics in community resilience field studies. In order to create a more complete field study protocol, additional interconnectivities between the economic domain and the physical and social domains should be identified and related data collection activities should be described and tested in the field.
5. The primary indicator of each of the seven community resilience metrics identified is damage to physical infrastructure. However, many other factors have been identified that significantly contribute to each of these metrics. The algorithm that was developed in Chapter 6 allows community resilience fragility curves to be shifted based on secondary factors, but the sample size that is required to produce these curves with an acceptable error has not yet been defined. Error analysis needs to be conducted for field data sets to establish the data quantities that are needed to produce unbiased fragilities.
6. Additional work should be done to determine how many data points need to be collected to obtain a representative random sample of a community.

7. Multivariate statistical methods should be developed that model empirical probability curves as a function of many different factors so that they better reflect reality.
8. Techniques that allow the modeling of resilience metrics using insufficient data should be developed.
9. The real-time data processing system that was described in Section 6.3 is only possible if a large amount of data is being collected in the field. A system that communicates to field teams how much of each type of data must be collected should be developed for field teams with limited time and resources.
10. The derivation that is described in Section 6.1 was intended to process data points that correspond to individual infrastructure systems (e.g., each data point corresponds to one home). In the future it will be important to be able to investigate groupings or clusters of infrastructure systems (e.g., each data point corresponds to a neighborhood) and their impact on the community. This idea has been well developed in the NIST Planning Guide (NIST 2016).
11. Community resilience benchmarks should be developed that identify the threshold of acceptable probabilities of different resilience metrics (e.g., it is acceptable for a certain household within a community to have a 0.1% probability of being dislocated for more than one month after that community experiences a category 4 hurricane event). This will allow community leaders to identify their community's vulnerabilities and make risk-informed decisions that best serve the future of their community.
12. A standardized data ontology for field studies should be created. This will allow efficient collaboration and communication between disaster researchers.

References

Adams Z, Danielson C, Sumner J, McCauley J, Cohen J, Rugiero K. 2015. “Comorbidity of PTSD, Major Depression, and Substance Use Disorder Among Adolescent Victims of the Spring 2011 Tornadoes in Alabama and Joplin, Missouri.” Psychiatry. 2015;78(2):170-85.Washington School of Psychiatry. Online: http://www.ncbi.nlm.nih.gov/pubmed/26168094

Adams, B.J. Huyck, C. K. Mansouri, B. Eguchi, R. T. Shinozuka, M. (2004): “Application of High-Resolution Optical Satellite Imagery for Post-Earthquake Damage Assessment: The 2003 Boumerdes (Algeria) and Bam (Iran) Earthquakes.” Research Progress and Accomplishments: 2003-2004, Multidisciplinary Center for Earthquake Engineering Research (MCEER), 173-186. Online: http://mceer.buffalo.edu/publications/resaccom/04-sp01/12_eguchi.pdf

Addy, Samuel. Ijaz, Ahmad. June 2011. “Preliminary Economic and Fiscal Impacts of the April 27, 2011 Tornadoes on Alabama.” The University of Alabama Center for Business and Economic Research. Online: https://encrypted.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwj08fjKp_MAhUKtYMKHUp0BBcQFggcMAA&url=http%3A%2F%2Fcber.cba.ua.edu%2Fpdf%2FEconomic%2520Impact%2520of%25202011%2520Tornadoes.pdf&usg=AFQjCNH_JOo37R_dZILXfsIniTHLLk72kQ&sig2=Nf3CgnIEOJm0uDzUxXEmiw

American Society of Civil Engineers (ASCE). July 23, 2006. “Code of Ethics.” Online: http://www.asce.org/code-of-ethics/

Applied Technology Council (2016). *NIST CGR 16-917-39- Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery*. National Institute of Standards and Technology (NIST). Gaithersburg, MD. April 2016. Online: https://www.nist.gov/document/nist-gcr-16-917-39-2pdf

Arendt, L. A. Hess, D. B. (2006). *Hospital Decision Making in the Wake of Katrina: The Case of New Orleans*. MCEER Special Report Series – Engineering and Organizational Issues Before, During and After Hurricane Katrina. Volume 1. Online: https://mceer.buffalo.edu/publications/catalog/reports/Hospital-Decision-Making-in-the-Wake-of-Hurricane-Katrina-The-Case-of-New-Orleans-MCEER-06-SP01.html

Brallier, Paul A. 2006. "Communicating the Damage: Post-Disaster Building Placards and Marks." Civil and Structural Engineer's Association. Online: http://cenews.com/article/4758/communicating-the-damage-post-disaster-building-placards-and-marks

Borrero, Jose C. 2005. *Field Survey of northern Sumatra and Banda Aceh, Indonesia and after the Tsunami and Earthquake of 26 December 2004*. Seismological Research Letters Volume 76, Number 3, May/June 2005. Tsunami Research Center, University of Southern California. Online: http://srl.geoscienceworld.org/content/76/3/312.full.pdf+html

Brunkard, Joan. Namulanda, Gona. Ratard, Raoult. August 28, 2008. "Hurricane Katrina Deaths, Louisiana, 2005." Disaster Medicine and Public Health Preparedness. Lippincott Williams & Wilkins. Online: http://www.ncbi.nlm.nih.gov/pubmed/18756175

Cornell, A. Krawinkler, H. 2000. "Progress and Challenges in Seismic Performance Assessment." PEER Center News.

Coulbourne W, Miller J. 2012. “Performance of School Buildings in the Joplin, MO Tornado.” American Society of Civil Engineers (ASCE). Online: http://ascelibrary.org/doi/abs/10.1061/9780784412367.088

Curtis A, Fagan W. 2013 “Capturing Damage Assessment with a Spatial Video: An Example of a Building and Street-Scale Analysis of Tornado-Related Mortality in Joplin, Missouri, 2011.” Annals of the Association of American Geographers, 103:6, 1522-1538, DOI: 10.1080/00045608.2013.784098. Online: http://dx.doi.org/10.1080/00045608.2013.784098

Dahlhamer, James M. Tierney, Kathleen J. 1996. *Rebounding From Disruptive Events: Business Recovery Following the Northridge Earthquake*. Disaster Research Center at the University of Delaware. Online: http://udspace.udel.edu/handle/19716/650

Dashti, S. Palen, L. Heris, M. P. Anderson, K. M. Anderson, S. Anderson, T. J. (2014). “Supporting Disaster Reconnaissance with Social Media Data: A Design-Oriented Case Study of the 2013 Colorado Floods.” University of Colorado Boulder. Federal Highway Administration. Proceedings of the 11th International ISCRAM Conference – University Park, PA. May 2014. Online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwietaCw0tXMAhVm3IMKHQdcDncQFggdMAA&url=https%3A%2F%2Fcmci.colorado.edu%2F~palen%2Fpalen_papers%2FDashtiPalenetalgeoreconnaissance.pdf&usg=AFQjCNFkEs3Mgnr9BmK6Xge5BgJpmmNn2g&sig2=KGLZESM8adONbrrbNTCHPA

Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA). 2011. *Hazus – MH MR5 Advanced Engineering Building Module (AEBM) Technical and*

User's Manual. Washington, D.C. Online: http://www.fema.gov/media-library/assets/documents/20469

Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA). 2015. *Earthquake Model Hazus – MH 2.1 Technical Manual*. Washington, D.C. Online: http://www.fema.gov/media-library/assets/documents/24609

Dillman, Don A. 1978. Mail and Telephone Surveys: The Total Design Method. New York: Wiley.

Dolfman, Michael L. Fortier, Wasser, Solidelle Fortier. Bergman, Bruce. "The effects of Hurricane Katrina on the New Orleans economy." Montly Labor Review – June 2007. Online: http://www.bls.gov/opub/mlr/2007/06/art1full.pdf

Earthquake Engineering Research Institute (EERI). 1996. *Post-Earthquake Investigation Field Guide*. Online: https://www.eeri.org/projects/learning-from-earthquakes-lfe/post-earthquake-investigation-field-guide/

Eidinger, John. Tang, Alex K. February 2012. *Christchurch, New Zealand Earthquake Sequence of MW 7.4 September 04, 2010, MW 6.3 February 22, 2011, MW 6.0 June 13, 2011: Lifeline Performance*. American Society of Civil Engineers (ASCE). Technical Council on Lifeline Earthquake Engineering Monograph No. 40. Reston, VA.

Federal Emergency Management Agency (FEMA). 2009. *Midwest Floods of 2008 in Iowa and Wisconsin – Building Performance Observations, Recommendations, and Technical Guidance*. FEMA P-765. Mitigation Assessment Team Report. October 2009. Online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiIlt2LmdbMAhVp7IMKHVWEAfMQFggdMAA&url=http%3A%2F%2Fwww.fema.gov%2Fmedialibrarydata%2F20130726172250450903%2Ffema_p_765

.pdf&usg=AFQjCNGb_9F2YYgaw1cZQFz7Urh0f3Z2gQ&sig2=h3OXzKd3ZATpYXrYtJZFUA

Federal Emergency Management Agency (FEMA). 2011. *The Response to the 2011 Joplin, Missouri, Tornado – Lessons Learned Study*. December 20, 2011. Online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiGgb_Fh4jOAhUmyoMKHYMzCz0QFggeMAA&url=http%3A%2F%2Fkyem.ky.gov%2FWho%2520We%2520Are%2FDocuments%2FJoplin%2520Tornado%2520Response%2C%2520Lessons%2520Learned%2520Report%2C%2520FEMA%2C%2520December%252020%2C%25202011.pdf&usg=AFQjCNEAUQkJFdGZVRVxNbjaAqgtOHcq8Q&sig2=KtHNgVUuJveaxxN3IwOypg

Frankenberg, E. Friedman, J. Gillespie, T. Ingwersen, N. Pynoos, R. Rifai, I. U. Sikoki, B. Steinberg, A. Sumantri, C. Suriastini, W. Thomas, D. 2008. “Mental Health in Sumatra After the Tsunami.” American Journal of Public Health. September 2008, Vol 98, No. 9. Online: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2509591/

Galea, S. Brewin, C. R. Gruber, M. Jones, R. T. King, D. W. King, L. A. McNally, R. J. Ursano, R. J. Petukhova, M. Kessler, R. C. 2007. “Exposure to Hurricane-Related Stressors and Mental Illness After Hurricane Katrina.” Arch Gen Psychiatry. 2007 December; 64 (12: 1427-1434). Online: http://www.ncbi.nlm.nih.gov/pubmed/18056551.

Graettinger, Andrew J. Ramseyer, Chris C. E. Freyne, Seamus. Prevatt, David O. et al. March 2014. *Tornado Damage Assessment in the aftermath of the May 20th 2013 Moore Oklahoma Tornado*. Online: https://encrypted.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwiX65St9p_MAhXEmoMKHWY7ABoQFggcMAA&url=http%3A%2F%2Fesride

v.caps.ua.edu%2FMooreTornado%2FImages%2FMooreTornadoFinalReport.pdf&usg=AFQjCNGN5S6qz-8pAUaylROY7i6CfmHWtg&sig2=SVl56GZaCjYNfKxCqcd5jg

Gray, Clark. Frankenberg, Elizabeth. Gillespie, Thomas. Sumantri, Cecep. Thomas, Duncan. January 2014. “Studying Displacement After a Disaster Using Large Scale Survey Methods: Sumatra After the 2004 Tsunami.” Ann Assoc Am Geogr. Online: http://www.ncbi.nlm.nih.gov/pubmed/24839300

Gursesli, Orhan. Desrochers, Alan A. 2003. “Modeling Infrastructure Interdependencies Using Petri Nets.” IEEE Control Systems Magazine. Online: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1244625

Houston B, Spialek M, Stevens J, First J, Mieseller V, Pfefferbaum B. 2015. “2011 Joplin, Missouri Tornado Experience, Mental Health Reactions, and Service Utilization: Cross-Sectional Assessments at Approximately 6 Months and 2.5 Years Post-Event.” PLoS Curr. 2015 Oct 26;7. Online: http://www.ncbi.nlm.nih.gov/pubmed/26579331

Jennings, Elaina N. 2015. A Multi-Objective Community-Level Seismic Retrofit Optimization Combining Social Vulnerability With an Engineering Framework For Community Resilience. Ph.D. Dissertation. Colorado State University. Online: https://encrypted.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwj_jZnwZHMAhVBtYMKHToMDWUQFggcMAA&url=http%3A%2F%2Fdisaster.colostate.edu%2FData%2FSites%2F1%2Fcdra-research%2Fcdra-thesesanddissertations%2Fjennings_elaina_dissertation.pdf&usg=AFQjCNFxA1BhHa7dXsB-E1HRTHB-8OvtLg&sig2=RvOz5z9dVitJ8GzZIE-XPQ

Jenson, J. N. Ram, P. (2007). *Public Health and Environmental Infrastructure Implications of Hurricanes Katrina and Rita*. MCEER Special Report Series – Engineering and

Organizational Issues Before, During and After Hurricane Katrina. Volume 3. Online: https://mceer.buffalo.edu/publications/catalog/reports/Public-Health-and-Environmental-Infrastructure-Implications-of-Hurricanes-Katrina-and-Rita-MCEER-07-SP02.html

Johnson, Mike. 2016. Personal Interview. Facilities Director at Joplin Schools. July 19, 2016.

Kanter, Robert K. Abramson, David. 2014. "School Interventions After the Joplin Tornado." Prehosp Disaster Med. 2014;29(2):214-217. Online: http://www.ncbi.nlm.nih.gov/pubmed/24655748

Kashani, Alireza G. Crawford, Patrick S. Biswas, Sufal K. Graettinger, Andrew J. Graue, David. 2014. "Automated Tornado Damage Assessment and Wind Speed Estimation Based on Terrestrial Laser Scanning." American Society of Civil Engineers (ASCE) J. Comput. Civ. Eng. Online: http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29CP.1943-5487.0000389

Kuligowski, Erica D. Lombardo, Franklin T. Phan, Long T. Levitan, Marc L. Jorgensen, David P. March 2014. *Technical Investigation of the May 22, 2011, Tornado in Joplin, Missouri.* National Institute of Standards and Technology (NIST). NCSTAR 3. Gaithersburg, MD. Online: http://dx.doi.org/10.6028/NIST.NCSTAR.3

Kwasinski, Alexis. Trainor, Joseph. Wolshon, Brian. Lavelle, Francis M. January 2016. *A Conceptual Framework for Assessing Resilience at the Community Scale*. National Institute of Standards and Technology (NIST) GCR 16-001. Gaithersburg, MD. Online: http://dx.doi.org/10.6028/NIST.GCR.16-001

Lavelle, Francis M. Ritchie, Liesel A. Kwasinski, Alexis. Wolshon, Brian. December 2015. *Critical Assessment of Existing Methodologies for Measuring or Representing Community Resilience of Social and Physical Systems*. National Institute of Standards and Technology (NIST) GCR 15-1010. Gaithersburg, MD. Online: http://dx.doi.org/10.6028/NIST.GCR.15-1010

Lesar, David J. Dunham, Archie W. Wise, William A. Nichols, Marshall W. June 2001. *Securing Oil and Natural Gas Infrastructures in the New Economy*. National Petroleum Council. Online: nvlpubs.nist.gov/nistpubs/gcr/2015/NIST.GCR.15-1010.pdf

Levitan, Marc L. Phan, Long T. Kuligowski, Erica D. Lombardo, Franklin T. Jorgensen, David P. May 2012. *Investigation Plan NIST Technical Investigation of the May 22, 2011, Tornado in Joplin, Missouri*. National Institute of Standards and Technology (NIST). Special Publication 1132. Gaithersburg, MD. Online: http://dx.doi.org/10.6028/NIST.SP.1132

Lou J. 2014. *Impacts, Assessments, and Responses: Interdisciplinary Perspectives on Tornadoes*. A dissertation submitted to Texas Tech University. Online: https://ttu-ir.tdl.org/ttu-ir/handle/2346/58910

Maranghides, Alexander. Mell, William. Ridenour, Karen. McNamara, Derek. July 2011. *Initial Reconnaissance of the 2011 Wildland-Urban Interface Fires in Amarillo, Texas*. National Institute of Standards and Technology (NIST) Technical Note 1708. Gaithersburg, MD. Online: http://www.nist.gov/manuscript-publication-search.cfm?pub_id=908719

Maranghides, Alexander. McNamara, Derek. February 2016. *2011 Wildland Urban Interface Amarillo Fires Report #2 – Assessment of Fire Behavior and WUI Measurement Science*. National Institute of Standards and Technology (NIST) Technical Note 1909. Gaithersburg, MD. Online: http://dx.doi.org/10.6028/NIST.TN.1909

Maranghides, Alexander. Mell, William. April 2009. *A Case Study of a Community Affected by the Witch and Guejito Fires*. National Institute of Standards and Technology (NIST)

Technical Note 1635. Gaithersburg, MD. Online: http://www.nist.gov/manuscript-publication-search.cfm?pub_id=902864

Maranghides, Alexander. McNamara, Derek. Mell, William. Trook, Jason. Toman, Blaza. May 2013. *A Case Study of a Community Affected by the Witch and Guejito Fires: Report #2 – Evaluating the Effects of Hazard Mitigation Actions on Structure Ignitions*. National Institute of Standards and Technology (NIST) Technical Note 1796. Gaithersburg, MD. Online: http://www.nist.gov/manuscript-publication-search.cfm?pub_id=913155

Masterson, J. H., Peacock, W. G., Van Zandt, S. S., Grover, H., Schwarz, L. F., & Cooper, J. T. (2014). *Planning for Community Resilience*. Island Press. Online: http://www.springer.com/us/book/9781610915861

Missouri Department of Elementary and Secondary Education. 2016. “Joplin School District.” Missouri Comprehensive Data System. Online: http://mcds.dese.mo.gov/quickfacts/sitepages/districtinfo.aspx?ID=__bk8100030043009300130043008300

Missouri Department of Elementary and Secondary Education. 2016. “District Report Card.” Missouri Comprehensive Data System. Online: http://mcds.dese.mo.gov/guidedinquiry/School%20Report%20Card/District%20Report%20Card.aspx

Missouri Department of Elementary and Secondary Education. 2016. “Achievement Level 4 – Public – Historical.” Missouri Comprehensive Data System. Online: http://mcds.dese.mo.gov/guidedinquiry/Achievement%20Level%20%204%20Levels/Achievement%20Level%204%20Report%20-%20Public%20-%20Historical.aspx

Missouri Department of Elementary and Secondary Education. 2016. “School Finance Report.” Missouri Comprehensive Data System. Online: https://mcds.dese.mo.gov/guidedinquiry/District%20and%20School%20Information/School%20Finance%20Report.aspx

Mollerus M. 2013. “Joplin Residents Still Displaced, Struggle to Heal, Two Years Post Tornado.” KOMU 8 News Station. Wednesday, May 22, 2013. Online: http://www.komu.com/news/joplin-residents-still-displaced-struggle-to-heal-two-years-post-tornado-44613/

Mosqueda, G. Porter, K. A. (2007). *Damage to Engineered Buildings and Lifelines from Wind, Storm Surge and Debris in the Wake of Hurricane Katrina*. MCEER Special Report Series – Engineering and Organizational Issues Before, During and After Hurricane Katrina. Volume 4. Online: https://mceer.buffalo.edu/publications/catalog/reports/Damage-to-Engineered-Buildings-and-Lifelines-from-Wind-Storm-Surge-and-Debris-following-Hurricane-Katrina-MCEER-07-SP03.html

Multidisciplinary Center for Earthquake Engineering Research (MCEER). (2006-2008). *MCEER Special Report Series Volumes 1-5 – Engineering and Organizational Issues Before, During, and After Hurricane Katrina*. Online: http://mceer.buffalo.edu/publications/catalog/categories/report-types/Hurricane-Katrina-Series.html

Merz, B. Kreibich, H. Schwarze, R. Thieken, A. “Assessment of economic flood damage.” Review Article. Nat. Hazards Earth Syst. Sci., 10, 1697-1724, 2010. Online: www.nat-hazards-earth-syst-sci.net/10/1697/2010/

Miles, Scott B. Jagielo, Nora. Gallagher, Hannah. July 2015. “Hurricane Isaac Power Outage Impacts and Restoration.” American Society of Civil Engineers (ASCE). Journal of Infrastructure Systems. Online: http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29IS.1943-555X.0000267

National Institute of Standards and Technology (NIST) (2016). *Community Resilience Planning Guide for Buildings and Infrastructure Systems Volumes I and II*. NIST Special Publication 1190. May 2016. Online: http://dx.doi.org/10.6028/NIST.SP.1190v1 and http://dx.doi.org/10.6028/NIST.SP.1190v2.

O’Connor, J. S. McAnany, P. E. (2008). *Damage to Bridges from Wind, Storm Surge and Debris in the Wake of Hurricane Katrina*. MCEER Special Report Series – Engineering and Organizational Issues Before, During and After Hurricane Katrina. Volume 5. Online: https://mceer.buffalo.edu/publications/catalog/reports/Damage-to-Engineered-Bridges-from-Wind-Storm-Surge-and-Debris-in-the-Wake-of-Hurricane-Katrina-mceer-08-sp05.html

Office of Missouri Governor Jay Nixon. 2016. “Joplin Rising – Five Years of Incredible Progress.” Online: https://governor.mo.gov/joplinrising

Onstot L. 2016. “Fact Sheet – City of Joplin – May 22, 2011 EF-5 Tornado.” City of Joplin, Missouri. May 2016. Online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwih9b3i4jOAhXB7IMKHSWJBS8QFgggMAA&url=http%3A%2F%2Fwww.joplinmo.org%2FDocumentCenter%2FView%2F1985&usg=AFQjCNEUxnyLhDY99LDwULfRBhoAf2hsEA&sig2=0-H3sl1U8JwMoJ-ryymFkA

Pan, Q. 2014. “Estimating the Economic Losses of Hurricane Ike in the Greater Houston Region.” American Society of Civil Engineers (ASCE). Natural Hazards Review. Online: http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29NH.1527-6996.0000146

Paul B, Stimers M. 2012. “Exploring probable reasons for record fatalities: the case of 2011 Joplin, Missouri, Tornado.” Nat Hazards (2012) 64:1511–1526. Online: http://link.springer.com/article/10.1007/s11069-012-0313-3

Peacock, Walter Gillis, Betty Hearn Morrow, and Hugh Gladwin Editors. 1997. Hurricane Andrew: Ethnicity, Gender and the Sociology of Disaster. London: Routledge. Online: https://www.amazon.com/Hurricane-Andrew-Ethnicity-Sociology-Disasters/dp/0415168112

Pederson, P. Dudenhoeffer, D. Hartley, S. Permann, M. August 2006. *Critical Infrastructure Interdependency Modeling: A Survey of U.S. and International Research*. Idaho National Laboratory. Idaho Falls, Idaho. Online: https://inldigitallibrary.inl.gov/sti/3489532.pdf

Peek-Asa, C. Kraus, J. F. Bourque, L. B. Vimalachandra, D. Yu, J. Abrams, J. 1998. “Fatal and hospitalized injuries resulting from the 1994 Northridge earthquake.” International Journal of Epidemiology 1998;27;459-465. Online: http://ije.oxfordjournals.org/content/27/3/459.full.pdf

Pettit, David. 2016. Personal Interview. Director of Transportation at Joplin Schools. July 19, 2016.

PPD-21 (2013) Presidential Policy Directive/PPD-21, The White House, February 12, 2013. Online: http://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.

Pratt, J.H. 2000. “Homebased business: the hidden economy.” Small Business Research Summary, 194; Office of Advocacy, United States Small Business Administration, Washington, DC

Prevatt D, Coulbourne W, Graettinger A, Pei S, Gupta R, Grau D. 2013. *Joplin, Missouri, Tornado of May 22, 2011 – Structural Damage Survey and Case for Tornado-Resilient Building Codes*. American Society of Civil Engineers (ASCE).

Prevatt D, van de Lindt J, Graettinger A, Coulbourne W, Gupta R, Pei S, Hensen S, Grau D. 2011. *Damage Study and Future Direction for Structural Design Following the Tuscaloosa Tornado of 2011*. Online: https://encrypted.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwiCx6agipvMAhXqnIMKHdvfBy8QFggcMAA&url=https%3A%2F%2Fembed.widencdn.net%2Fdownload%2Fssttoolbox%2Ftz9hcumiym%2Ftuscaloosatornadoreport2011.pdf&usg=AFQjCNFjDl86XVQ234JCQwT7ccPD0LqdIg&sig2=UU04PsgCg3qZvGmR-oW1wA

Quarantelli, E. L. 1997. “The Disaster Research Center Field Studies of Organized Behavior in the Crisis Time Period of Disasters.” International Journal of Mass Emergencies and Disasters. March 1997, Vol. 15, No. 1, pp. 47-69. Online: http://www.ijmed.org/articles/406/

Rinaldi, Steven M. Peerenboom, James P. Kelly, Terrence K. December 2001. “Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies.” IEEE Control Systems Magazine. Online: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=969131

Rodriguez, H. Trainor, J. Quarantelli, E. L. 2006. “Rising to the Challenges of a Catastrophe: The Emergent and Prosocial Behavior following Hurricane Katrina.” The ANNALS of the American Academy of Political and Social Science. March 2006. Online: http://ann.sagepub.com/

Sachetta, Kerry. 2016. Personal Interview. Joplin High School Principal. July 20, 2016.

“School Bus Rescue.” February 13, 2012. Online: https://www.youtube.com/watch?v=P8RCTSijtn4

Schrank, H. L. Marshall, M. I. Hall-Phillips, A. Wiatt, R. F. Jones, N. E. 2012 “Small- business demise and recovery after Katrina: rate of survival and demise.” Nat Hazards (2013) 65:2353-2374. Online: http://link.springer.com/article/10.1007%2Fs11069-012-0480-2

Sherwood, A. Bradley, M. Rossi, L. Guiam, R. Mellicker, B. 2015. *Resolving Post-Disaster Displacement: Insights from the Philippines after Typhoon Haiyan (Yolanda).* Internal Organization for Migration (IOM). Brookings. Washington D.C. Online: http://www.brookings.edu/research/reports/2015/06/15-philippines-typhoon-haiyan-displacement-solutions

Smith D, Sutter D. 2013. “Response and Recovery after the Joplin Tornado: Lessons Applied and Lessons Learned.” May 6, 2013. Online: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2261353

State Emergency Management Agency (SEMA). 2016. “Five years after tornado, Census shows Joplin population reaching all-time high; new “Joplin Rising” website features stories, data on city’s remarkable recovery.” SEMA News Release. May 19, 2016. Online: http://sema.dps.mo.gov/news/newsitem/uuid/45c390a3-19e2-4197-af4f-5f8495635331

Sutton, Jeannette. Palen, Leysia. Shklovski, Irina. 2008. “Backchannels on the Front Lines: Emergent Uses of Social Media in the 2007 Southern California Wildfires.” Proceedings of the 5th International ISCRAM Conference – Washington, DC, USA, May 2008.

Online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiEvtnG1eTMAhWjzIMKHdlWBxcQFggdMAA&url=http%3A%2F%2Fwww.jeannettesutton.com%2Fuploads%2FBackchannelsISCRAM08.pdf&usg=AFQjCNEVlsxo1UcwfmM8ACxiG8xMs7S1iw&sig2=NXQx8NvsNK7S1NEruc35cA

Texas Department of Homeland Security. December 2008. *Hurricane Ike Impact Report*. Online: https://encrypted.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwjN7IjVipvMAhXinIMKHUJ3CzIQFggcMAA&url=https%3A%2F%2Fwww.fema.gov%2Fpdf%2Fhazard%2Fhurricane%2F2008%2Fike%2Fimpact_report.pdf&usg=AFQjCNHftECnkfnH2cyudMts0XzOAiSoYw&sig2=4mHj-2PPFe7HnMNopFIV5w

Tierney, K. 2006. “Businesses and Disasters: Vulnerability, Impacts, and Recovery.” Pp. 275-296. *Handbook of Disaster Research*. New York: Springer. Online: http://link.springer.com/chapter/10.1007%2F978-0-387-32353-4_16

Todd, Diana. Carino, Nicholas. Chung, Riley M. Lew, H. S. Taylor, Andrew W. Walton, William D. Cooper, James D. Nimis, Roland. May 1994. *1994 Northridge Earthquake Performance of Structures, Lifelines, and Fire Protection Systems*. National Institute of Standards and Technology (NIST) Special Publication 862. Gaithersburg, MD. Online: http://www.nist.gov/manuscript-publication-search.cfm?pub_id=908750

van de Lindt J. W. Graettinger, A. J. Gupta, R. Pryor, S. E. Skaggs, T. D. Fridley, K. J. 2005. *Damage Assessment of Woodframe Residential Structures in the Wake of Hurricane Katrina*. National Science Foundation (NSF). Online: https://encrypted.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjIsqGei5vMAhWCloMKHe6fDbUQFggeMAA&url=http%3A%

2F%2Fwww.cof.orst.edu%2Fcof%2Fwse%2Ffaculty%2Fgupta%2FKatrina%2FHurricane.pdf&usg=AFQjCNEpdYZPuiUk4I7ufgBUeUTMhkCk6w&sig2=noaFa9ZsHshEeG3aQIAV5g

van de Lindt J. W. Graettinger, A. J. Gupta, R. Skaggs, T. D. Pryor, S. E. Fridley, K. J. 2007. *Performance of Wood-Frame Structures during Hurricane Katrina*. American Society of Civil Engineers (ASCE). Journal of Performance of Constructed Facilities, March/April 2007. Online: http://ascelibrary.org/doi/10.1061/%28ASCE%290887-3828%282007%2921%3A2%28108%29

Webb, Gary R. Tierney, Kathleen J. Dahlhamer, James M. 1999. *Preliminary Paper – Predicting Long-Term Business Recovery From Disaster: A Comparison of the Loma Prieta Earthquake and Hurricane Andrew*. University of Delaware Disaster Research Center Preliminary Paper #292. Online: http://udspace.udel.edu/handle/19716/668.

Wilson, R. Wood, N. Kong, L. Shulters, M. Richards, K. Dunbar, P. Tamura, G. Young, E. 2014. "A protocol for coordinating post-tsunami field reconnaissance efforts in the USA." Nat Hazards. Online: http://link.springer.com/article/10.1007/s11069-014-1418-7.

Womble, J. A. Ghosh, S. Adams, B.J. Friedland, C. J. (2006). *Advanced Damage Detection for Hurricane Katrina: Integrating Remote Sensing and VIEW Field Reconnaissance*. MCEER Special Report Series – Engineering and Organizational Issues Before, During and After Hurricane Katrina. Volume 2. Online: https://mceer.buffalo.edu/publications/catalog/reports/Advanced-Damage-Detection-for-Hurricane-Katrina-Integrating-Remote-Sensing-Images-and-VIEWS-Field-Reconnaissance-MCEER-06-SP02.html

Lu, Xin. Bengtsson, Linus. Holme, Petter. 2012. "Predictability of population displacement after the 2010 Haiti earthquake." Proceedings of the National Academy of Sciences of the United States of America (PNAS) July 12, 2012. Vol. 109, no. 29. Online: http://www.pnas.org/content/109/29/11576

Zahran, Sammy. Brody, Samuel D. Peacock, Walter G. Vedlitz, Arnold. Grover, Himanshu. (2008). *Social vulnerability and the natural and built environment: a model of flood casualties in Texas*. Blackwell Publishing. Malden MA. Online: http://cdra.colostate.edu/Data/Sites/1/cdra-research/zahran-peacock-vedlitz2008.pdf

Zhou, Zixiang. Gong, Jie. Guo, Mengyang. 2015 "Image-Based 3D Reconstruction for Posthurricane Residential Building Damage Assessment." American Society of Civil Engineers (ASCE). J. Comput. Civ. Eng. Online: http://ascelibrary.org/doi/abs/10.1061/(ASCE)CP.1943-5487.0000480.

Appendix A: Interconnectivity Metrics

This appendix contains a list of metrics that can be related back to the interconnectivity diagram shown in Figure 4-1. Many of these metrics can be grouped by demographics. If demographics information is available for any metric then it should be investigated (i.e., metrics can be grouped by geographical location within city, race/ethnicity, religion, income level, social class, gender, age, language, education level, disability, household size/type, etc.).

<u>Population Dislocation Metrics:</u>

General:

- a. Total/Percentage of population evacuated/not evacuated
- b. Total/Percentage of population returning over time
- c. Total/Percentage of population never returning
- d. Reason for dislocation

1. Dislocation ⇐⇒ Commercial Facilities
    - a. Total/Percentage of employees dislocated
    - b. Total/Percentage of employees dislocated
    - c. Total/Percentage of commercial facilities damaged
2. Dislocation ⇐⇒ Residential Facilities
    - a. Total/Percentage of residential facilities damaged
    - b. Total/Percentage of population dislocated from residence
        - i. Time until return to residence
        - ii. Total/Percentage of population never returning to residence
    - c. Total/Percentage of population utilizing temporary public housing
        - i. Hotel records of visitors over time

3. Dislocation ←→ Healthcare Facilities
    a. Total/Percentage of people unable to receive care from local area
    b. Total/Percentage of people receiving healthcare from external sources
4. Dislocation ←→ Educational Facilities
    a. Number of students missing from school systems over time
    b. Number of students enrolled in school system pre and post disaster
5. Dislocation ←→ Religious Organizations
    a. Total/Percentage decrease/increase in attendance within/outside community
    b. Total/Percentage of religious employees dislocated
6. Dislocation ←→ Recreational Facilities
    a. Total/Percentage decrease/increase in attendance within/outside community
    b. Total/Percentage of recreational facility employees dislocated
7. Dislocation ←→ Child/Elderly Care
    a. Total/Percentage decrease/increase in elderly residency within/outside community
    b. Total/Percentage decrease/increase in children enrolled in childcare facilities
    c. Total/Percentage of child/elderly care employees dislocated
8. Dislocation ←→ Roadways
    a. Increase/Decrease in traffic flow on major highways headed in/out of community over time.
9. Dislocation ←→ Railroads
    a. Increase/Decrease in ticket sales on trains going into/out of the community
    b. Increase/Decrease in ticket sales on local/light rail
    c. Increase/Decrease in industrial train traffic

10. Dislocation ←→ Airports
    a. Increase/Decrease in ticket sales on planes going into/out of the community
    b. Increase/Decrease in industrial airplane traffic
11. Dislocation ←→ Public Transportation
    a. Increase/Decrease in use of public transportation (i.e., buses, taxis, etc.)
12. Dislocation ←→ Improved Economy
    a. Number of jobs created by recovery
        i. Percentage of jobs that are permanent/temporary
        ii. Increase in population of city
            1. Increase in tax base due to increase in population
13. Dislocation ←→ Diminished Economy
    a. Number of jobs lost due to disaster
        i. Decrease in population of city
            1. Loss of tax base due to decrease in population

<u>Morbidity Metrics:</u>

1. Morbidity ←→ Commercial Facilities
    a. Number of injuries caused by starvation, thirst, extreme cold
2. Morbidity ←→ Healthcare Facilities
    a. Number of patients at hospitals
    b. Number of patients in critical condition
    c. Number of patients with specific injuries. I.e., head trauma, heart attack, etc.
3. Morbidity ←→ Emergency Services
    a. Number of emergency calls

   b. Number of emergency response actions taken

4. Morbidity ←→ Child/Elderly Care
   a. Total/Percentage of elderly people injured (nursing home records)
   b. Total/Percentage decrease/increase in child care service participation
5. Morbidity ←→ Physical Infrastructure
   a. Total/Percentage of the population sustaining injuries
      i. Number of people injured in each category of infrastructure (i.e., 3 people injured while inside of residential facilities; 5 people injured while on bridges; 2 people killed while in public parks)
      ii. Severity of injuries
      iii. Specific cause of injury (i.e., Collapse of roof on top of person; Impact from debris from bridge, etc.)
6. Morbidity ←→ Economic Structure
   a. Insurance payment of medical bills
   b. Citizen payment of medical bills
      i. Percentage of injuries covered/not covered by demographics

<u>Mortality Metrics:</u>

1. Mortality ←→ Commercial Facilities
   a. Number of deaths caused by starvation, thirst, extreme cold
2. Mortality ←→ Healthcare Facilities
   a. Number of patients deaths at hospitals
   c. Statistics of specific causes of deaths (i.e., head trauma, heart attack, etc.)
3. Mortality ←→ Emergency Services

    a. Number of identified bodies
    b. Number of unidentified bodies
    c. Number of funerals held
4. Mortality ←→ Child/Elderly Care
    a. Total/Percentage of elderly deaths (nursing home records)
5. Mortality ←→ Physical Infrastructure
    a. Total/Percentage of population deaths
        i. Number of deaths in each category of infrastructure (i.e., 3 people killed while inside of residential facilities; 5 people killed while on bridges; 2 people killed while in public parks)
        ii. Specific cause of death (i.e., Collapse of roof on top of person; Impact from debris from bridge, etc.)
6. Mortality ←→ Economic Structure
    a. Insurance payment of life insurance
        i. Percent of deaths covered/not covered by demographics

<u>Physiological Needs Metrics:</u>

1. Physiological Needs ←→ Commercial Facilities
    a. Total/Percentage of commercial buildings damaged/destroyed
        i. Level of damage (green, yellow, and red tags)
        ii. Number of retail stores never repaired (demolished)
    b. Number of retail stores closed
        i. Average time until re-opened
        ii. Number of retail stores never re-opened

    c. Total/Percentage of population receiving free resources (i.e., Food stamps, donated clothes, etc.)

2. Physiological Needs ←→ Residential Buildings
    a. Total/Percentage of residential buildings damaged/destroyed
        i. Level of damage (green, yellow, and red tags)
        ii. Number of residences never repaired (demolished)
3. Physiological Needs ←→ Healthcare Facilities
    a. Total/Percentage of healthcare facilities damaged/destroyed
        i. Level of damage (green, yellow, and red tags)
        ii. Number of healthcare facilities never repaired (demolished)
    b. Total/Percentage of capacity lost (beds lost)
        i. Total patients treated over time
4. Physiological Needs ←→ Child/Elderly Care
    a. Total/Percentage of child/elderly care facilities damaged/destroyed
        i. Level of damage (green, yellow, and red tags)
        ii. Number of child/elderly care facilities never repaired (demolished)
    b. Total/Percentage of capacity lost
        i. Total enrollment/residency over time
5. Physiological Needs ←→ Transportation
    a. Are the citizens able to get to work/stores?
    b. Length of roadway, sidewalk, railroads damaged/destroyed
        i. Damage level. I.e., usable or not usable
        ii. Time until restored

    c. Number of bridges, tunnels, airports damaged/destroyed
        i. Damage level (i.e., usable or not usable)
        ii. Time until restored
    d. Total public transportation vehicles destroyed
        i. Time until return to original capacity

6. Physiological Needs ←→ Water Network
    a. Total/Percentage of end users without access to clean water
    b. Damage to WWTPs
        i. Level/location of damage
            1. Reason for damage
        ii. Water quality over time
        iii. Time until restored to full production levels
    c. Damage to water mains, sanitary sewers, and storm sewers
        i. Number of leaks
        ii. Time until restored
        iii. Number of pipelines abandoned/demolished
    d. Total/Percentage of wells damaged
        i. Damage Level
        ii. Time until return to full production
        iii. Number of wells abandoned/demolished
    e. Total/Percentage of storage tanks damaged
        i. Damage Level
        ii. Time until return to full capacity

        iii. Number of storage tanks abandoned/demolished

7. Physiological Needs ←→ Economic Structure
    a. Insured vs. uninsured losses
    b. Total local, state, and federal aid granted

<u>Sense of Safety Metrics:</u>

General:

a. Crime rates over time
b. General sense of safety over time (Obtain through survey)
c. Amount of debris in town
    i. Time until cleaned up

1. Sense of Safety ←→ Healthcare Facilities
    a. Total/Percentage of healthcare facilities damaged/destroyed
        i. Level of damage (green, yellow, and red tags)
        ii. Number of healthcare facilities never repaired (demolished)
    b. Total/Percentage of capacity lost (beds lost)
        i. Total patients treated over time
    c. Equipment lost
    d. Number of patients turned away
    e. Average patient waiting time
    f. Number of local residents treated at outside healthcare facilities

2. Sense of Safety ←→ Emergency Services
    a. Total/Percentage of police/fire stations damaged/destroyed
        i. Level of damage (green, yellow, and red tags)

        ii. Number of police/fire stations facilities never repaired (demolished)
    b. Total/Percentage of police/fire fighter vehicles/equipment damaged/destroyed
    c. Time until return to full functionality

3. Sense of Safety ⇔ Electrical Payments Network
    a. Total/Percentage of end users without power
    b. Damage to generation facilities
        i. Level/location of damage
            1. Reason for damage
        ii. Electricity production over time
        iii. Time until restored to full production levels
    c. Damage to EPN substations
        i. Time until restored
        ii. Number of substations abandoned/demolished
    d. Damage to power lines/towers
        i. Number of towers damaged
        ii. Time until restored
        iii. Number of towers abandoned/demolished

4. Sense of Safety Needs ⇔ Fuel Supply
    a. Damage to fuel production/distribution facilities
        i. Level/location of damage
            1. Reason for damage
        ii. Production over time
        iii. Total amount stored over time

        iv. Time until restored to full production levels
    b. Length of fuel pipes damaged

5. Sense of Safety ←→ Telecommunications
    a. Total/Percentage of end users without phone service/cell service
    b. Damage to telecommunication facilities
        i. Level/location of damage
            1. Reason for damage
        ii. Time until restored to full production levels
    c. Damage to phone cables/towers
        i. Number of towers damaged
        ii. Time until restored
        iii. Number of towers abandoned/demolished

6. Sense of Safety ←→ Gas Supply
    a. Total/Percentage of end users without gas
    b. Damage to gas production facilities
        i. Level/location of damage
            1. Reason for damage
        ii. Time until restored to full production levels
    c. Damage gas main
        i. Number of leaks
        ii. Time until restored
        iii. Length of gas main abandoned/demolished
    d. Damaged gas meters

            i. Number of meters damaged
            ii. Time until restored

7. Sense of Safety ←→ Other Built/Natural Infrastructure
    a. Total Dams/Levees/similar infrastructure damaged
        i. Time until restored
        ii. Total/Percentage never repaired (demolished)
    b. Total contaminated soil
        i. Time until cleaned up

8. Sense of Safety ←→ Economic Structure
    a. Unemployment rate over time
    b. Number of people utilizing government benefits over time

<u>Additional Metrics:</u>

1. Community Response ←→ Educational Facilities
    a. Survey of parent satisfaction with school system post disaster
2. Sense of Esteem ←→ Recreational Facilities
    a. Total/Percentage of recreational facilities damaged
    b. Capacity lost
    c. Total participants before and after
        i. Percentage decrease/increase

Appendix B: Institutional Review Board (IRB) Protocol

PROTOCOL
Social, Behavioral & Education Research
Colorado State University
Protocol # 15-6003H
Date Printed: 10/06/2015
Protocol Title: Center for Risk-Based Community Resilience Planning: A NIST-Funded Center of Excellence
Protocol Type: Social, Behavioral & Education Research
Date Submitted: 09/14/2015
Important Note: This Print View may not reflect all comments and contingencies for approval. Please check the comments section of the online protocol.
Questions that appear to not have been answered may not have been required for this submission. Please see the system application for more details.
----
* * * Subject Population * * *
Subject Population(s) Checklist
Select All That Apply:
X Adult Volunteers
X Elderly
X Employees
X Other (i.e., non-English speaking or any population that is not specified above)
It is possible that in some communities we will be interviewing people who speak other languages. In this case, we would be sure to translate all documents and make sure one of the interviewers speaks the same language as the participant. Also, although we are not seeking out pregnant women or students as part of our sample, we cannot guarantee that a woman we interview will not be pregnant, nor would it be ethical to ask. It is also possible that some of the adults in our sample might be in college (i.e. students) at the time of the interview. Please let us know if you prefer we check those boxes as well.
----
* * * Study Location * * *
Study Location(s) Checklist
Select All That Apply - Note: Check "Other" and input text: 1. If your location is not listed, or 2) If you would like to list details of your already-checked location (e.g., specific school within a school district)
Aims Community College
Colorado Department of Public Health & Environment
X Colorado State University
X Other (In the box below, list your study location if not checked above. You may also list details of your already-checked location (e.g., specific school within a school district)
This purpose of this protocol is to obtain a pre-approval for a 5-10 year research project that will include post- disaster field research with human subjects. Given that future disaster locations are unknown, the NIST Field Research Team will amend this IRB protocol as each research location is determined following an event and before any field research is conducted on any occasion.

With that said, generally speaking, our team is likely to conduct field investigations in communities affected by wind (e.g., tornado, hurricane), seismic (e.g., earthquake), or flood events.

----

* * * General Checklist * * *

General Checklist

Select All That Apply:

X Cooperating/Collaborating Institution(s) –Institution where recruitment will occur OR Institution where Collaborating PI will conduct associated research.

Colorado State University (lead institution), Texas A&M University, Texas A&M Kingsville, University of Illinois Urbana-Champaign, Louisiana State University, Rice University, Oregon State University, University of Washington, University of Oklahoma, Cal Poly Pomona, University of Kansas , National Institute of Standards and Technology **Please see attachment for a full contact list of all research participants and their respective institutions. Every person involved in the broader NIST project has been invited and strongly encouraged to complete the training now.

X Federally Sponsored Project
X Program Project Grant
X Interview
X Study of existing data
X Survey/questionnaire

----

* * * Funding * * *

Funding Checklist

National Institute of Standards and Technology

Principal Investigator Bruce Ellingwood, John van de Lindt

Y For Federal projects, are contents of this protocol the same as described in Federal proposal application?

Y Is this an Umbrella protocol?

N Is this protocol under an Umbrella protocol?

----

* * * Expedited Paragraphs * * *

PLEASE READ: The criteria for expedited review are listed below. Please review these criteria to evaluate if your protocol meets the expedited-review criteria. For expedited review, a protocol must be no more than minimal risk (i.e., "not greater than those ordinarily encountered in daily life") AND must only involve human subjects in one or more of the following numbered paragraphs. If none of the expedited criteria are appropriate for your project, please move to the next screen without selecting any of these criteria; your protocol will be reviewed by the full IRB. Note: The IRB will make the final determination if your protocol is eligible for expedited review.

Expedite Criteria:

X 6. Collection of data from voice, video, digital, or image recordings made for research purposes.

X 7. Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.)

----

* * * Purpose, Study Procedures, Background * * *

Original Protocol Number (e.g., 07-226H)

Title (Please indicate if the protocol title is different from the proposal title)

Center for Risk-Based Community Resilience Planning: A NIST-Funded Center of Excellence

Complete Sections 1 - 11. Specify N/A as appropriate. Do not leave any sections blank.

1. Purpose of the study

a) Provide a brief lay summary of the project in < 200 words. The lay summary should be readily understandable to the general public.

The Center of Excellence for Risk-Based Community Resilience Planning, funded by the National Institute of Standards and Technology and led by researchers at Colorado State University with nearly a dozen partner institutions, is designed to accelerate the development of system-level models and databases that will provide the technology for enhancing community resilience. This is a five-year project that involves dozens of detailed research tasks to be carried out by experts at several universities from engineering, the social sciences, economics, and many other disciplines. One of those tasks involves a series of field studies in up to five locations to be carried out over the five-year duration of the project, in disaster-affected communities. In short, the goal of this task is to collect immediate post-event data, as well as data in the longer term aftermath of the event, in order to understand post-disaster recovery and community resilience.

b) What does the Investigator(s) hope to learn from the study?

In order to understand community resilience in the aftermath of disaster, it is critical that researchers gather post-event (or "baseline") data, as well as data over time so that recovery can be understood as it unfolds, and placed in proper context. To understand what makes a community "resilient" or what attributes facilitate "bouncing back" from disaster, researchers must track recovery across time. With this in mind, the goal of the field investigations portion of this much larger project is twofold. First, the investigators involved hope to learn as much as possible about impacts to and the post-disaster recovery of physical, social, and economic systems in the aftermath of an event. Second, the lessons learned will be quantified and added to a computer algorithm that will ultimately enable researchers and community leaders the ability to study resilience and optimize investments in community resilience. Put simply, the investigators need to learn about the complexity and processes of post-disaster recovery "on the ground" while then translating that information into quantifiable algorithms or "outputs" that can be incorporated to a computer model.

2. Study Procedures

a) Describe all study procedures here (please do not respond "See Attachment Section"). The box below is for text only. If you would like to add tables, charts, etc., attach those files in the Attachment section (#11). *Once we have identified disaster sites, one per year, that are appropriate for our study, we will submit amendments for final approval.

** Our NIST research team wants to learn about community resilience in the aftermath of disaster. Our first step in moving forward with this particular task was to identify a group of potential field response researchers. These are researchers with varying backgrounds (e.g., engineering, sociology, planning) who could potentially participate in the research study. These researchers have all completed the required CITI ethics training. In addition, in the fall of 2015, the potential field researchers will participate in a quick response disaster research workshop, via webinar, to be led by Lori Peek and Jennifer Tobin-Gurley. This will help prepare the researchers for the realities of conducting post-disaster field investigations with human subjects, the need for following IRB protocols and field research protocols, etc. Peek and Tobin-Gurley have participated in and led several such workshops in the past. Following IRB approval, and once an acceptable disaster setting (e.g., of appropriate hazard type, magnitude, etc.) has been selected, we will choose a final field study team to travel to the site of the disaster. The team will be chosen based on (1) pre-completion of the required CITI ethics training; (2) completion of the field research workshop; (3) proximity to the disaster site; (4) availability to travel to the disaster site with the team during a specified period of time so that everyone can be in the field at one time; (5) area of expertise as related to disaster type (e.g., the wind engineers on the project may be more likely to travel with the team to a tornado disaster as opposed to the seismic or geotechnical engineers); (6) interest in the disaster event; (7) cultural relevancy (e.g., a large population of non-English speaking residents would require a team member that is fluent in the dominant language. We will also make sure to have all consent and other informational forms translated and presented to the participant in their primary language); and (8) the principal investigators' (van de Lindt and Ellingwood) judgment regarding the size and best composition of the team. The timing of the study will likely vary depending on the magnitude of the event. If the event is a relatively “small scale” disaster, with few lives lost, relatively little transportation disruption, etc., the team may enter the field just days or even a week after the disaster onset. In the case of a larger scale catastrophe, the study team may not enter the field for several weeks after the disaster, especially if the study site is closed to outsiders for some period of time during the emergency response and rescue phase. The entire team will travel together to the study site. The principal investigators have determined that this is typically the most effective, and safest, way to carry out these large scale investigations, as all members of the team can be on the ground at one time and can share information with one another. Once the principal investigators and the IRB has agreed that the time is right to enter the field, field study data collection methods will include: (1) in-depth semi-structured interviews (see questions in attachment); (2) brief in-person, closed ended survey questionnaires; and (3) photos of building and community damage for future documentation of recovery. More detail on each of the methods is included below:

(1)Individual interviews will be conducted by two members of the team, working together (one lead, one assistant), to ensure the best data collection and also maximal safety of all team members. The interviews, which will last about 15-30 minutes each, will be audio recorded, transcribed, and analyzed using an iterative coding process supported by a qualitative software program (e.g., Atlas.ti). During the initial wave of data collection, when community disruption will be the highest, we will focus on community leaders / stakeholders and residents who are willing and available to speak with our team. We will use various methods to recruit participants, including flyers, message board posts on virtual forums, word of mouth, newspaper and internet searches to identify and then contact community leaders, etc. (See appendix attachment for example language that we would post to recruit participants.) One of our primary goals of recruitment will be to minimize respondent burden (e.g., we will NOT ask a school principal for a letter of support so we can interview all of his/her teachers; instead we will ask to interview the principal to get a broader perspective). Upon each face-to-face meeting, we will explain the research project and gain signatures of informed consent. Once a participant has been identified and has agreed to be a part of the study, he/she will be presented with the university approved

IRB form (see attached). (2)The survey questions (see attachment) will be administered at the end of the open-ended interview. The survey will be administered via an electronic device (e.g., iPad), in person, and the questions will be asked out loud and recorded on the spot into the device. This will allow for easier quantification of some results. We are currently working to finalize the close-ended questions with the team and will upload as an amendment as soon as possible. (3)Participants will be asked to complete a demographic form (see attachment) so that the team can compile basic demographic information regarding respondents and contact them for possible follow-up interviews. Please see two attachments – one for respondents who are key stakeholders who are representing their organizations; another for affected residents.

(4)Photographs of building and community damage will be taken in order to track rebuilding, reconstruction, and recovery processes over time. This is a method that has been used by many of the engineers on the NIST team. They follow various protocols regarding the taking of photos, including only taking publically viewable/available photos when permission is not attained. Meaning, the engineers frequently take photos of damaged buildings and infrastructure as part of the quick response portion of the research. These photos typically have no human subjects and therefore no permissions attached to them as the damage is "viewable from the street" and building owners or occupants are typically not available at the time the photos are taken. For example, in a typical engineering project not involving human subjects, the protocol is that for a commercial building they cannot go onto the property without permission. If it is a school or public building, the researchers can usually (~50%+) get access from the police at a barricade with proper identification. For residential structures, they can take photos from the lot line or walk closer to the perimeters when they are not occupied. It is usually not possible to obtain permission for residential buildings, but sometimes they knock on the door, present a business card (while wearing a hard hat with the university on it), and explain what they are doing. They are sometimes invited in, but they only document the damage to the structure, not the personal stories of residents. These structural photos are important to gather baseline data to understand building impacts and to capture recovery over time. In the rare event that individuals are visible in any of the damage photos that the team takes, their faces will be blurred out to protect Page 9 of 18 identities or permission will be attained to use their photos. In this study, we are interested in both the documentation of structural damage and the personal stories of disaster survivors. Therefore, a similar protocol will be followed for any public spaces in terms of photographing buildings. However, when we photograph private spaces and human subjects, a permission form will be acquired from all individuals or organizational representatives (see attached permission form).

b) State if audio or video taping will occur. Describe how the tapes will be maintained during and upon completion of the project. Describe what will become of the tapes after use (e.g., shown at scientific meetings, erased, etc.). Original data access is limited to project investigators and will be maintained for the three-year archive period following the conclusion of the study. All investigators on the larger project have been notified that only those who have completed the required ethics training and who are listed as part of the potential field study team will have access to this data. All physical data will be stored in a locked file cabinet and all electronic media will be saved in locked offices on the password protected computers of the principal investigators. A linked-list will be created where all identifiable information will be replaced with code numbers. The same code will be used for the audio recording, field notes, and photographs from each site. No names will be attached to this documentation.

Audio recordings that contain identifiable information will only be seen/heard by team members. Photos produced through the field work that contain identifiable information will only be seen/viewed by team members unless express written permission is provided by anyone identifiable in those images. c) State if deception will be used. If so, provide a rationale and describe debriefing procedures. Submit a debriefing script in the Attachment section (#11).

No deception will be used under any circumstance. 3. Background/Rationale a) Briefly describe past findings leading to the formulation of the study, if applicable. Community infrastructure systems that are essential to the economic security and social well-being of any nation/state/community are susceptible to damage due to extreme environmental and geophysical hazards, such as hurricane wind storms and floods, tornadoes, earthquakes, tsunamis, and wildfires, as well as anthropogenic hazards such as industrial accidents. The human and economic losses and social disruption caused by failure of infrastructure systems is often disproportionately high in relation to the physical damage to such systems. The potential exists for even larger losses, given the shifts of population and economic development to hazard-prone coastal areas of the United States and global climate change. The aftermath of recent disasters, such as Hurricanes Katrina and Sandy, earthquakes in Haiti, Chile, New Zealand and Japan, and Cyclone Haiyan in the Philippines have revealed the importance of disaster mitigation policies that focus on the resilience of the community as a whole, rather than those that simply address safety and functionality of individual infrastructure facilities and broader engineered and social and economic systems. Herein, the resilience of a community is defined by the ability of its physical and non-physical infrastructure (core built environment, social institutions, and its people) to return to a level of normalcy within a reasonable time following the occurrence of an event. Resilience reflects the community's preparedness and ability to respond to and recover from a disaster. Enhancing community resilience is a national imperative (see Presidential Policy Directive 21). Despite significant progress in disaster-related science and technology, natural and human-caused disasters in the United States are responsible for over $55 billion in average annual costs in terms of injuries and lives lost, disruption of commerce and economic networks, property damaged or destroyed, the cost of mobilizing emergency response personnel and equipment, and recovery of essential services (NIST, 2010, NAE, 2012). The state of the art regarding the performance of individual constructed facilities (e.g., bridges, buried piping, electrical substations) and the integrity of individual infrastructure systems (electrical, gas, and water distribution systems) during extreme events is reasonably mature. Most research on community resilience has focused on the response of civil infrastructure systems to specific extreme natural hazards, such as earthquakes (e.g., Bruneau, et al., 2003). Such systems are interconnected, however, and their functioning is dependent on the availability and functioning of other connected systems (Rinaldi, et al., 2001).

Furthermore, the distinctive features of each hazard (e.g., advance warning time, area affected, type and severity of damage, populations displaced) have caused hazard mitigation methodologies to be strongly hazard-dependent. Multiple hazards, and the differences in community response to them, or synergies that might be achieved in policies to mitigate risk or enhance community resilience under multiple hazards, have received only limited attention. Similarly, while each facility and infrastructure system has its own characteristic response to a natural hazard, the performance of these systems during and following a disaster are positively correlated due to the extended spatial scale of the hazard and the interconnected nature of their successful (or unsuccessful) operations within the community. These positive spatiotemporal correlations are an essential ingredient of resilience assessment, but are not reflected in current loss estimation platforms. The numerous sources of uncertainties associated with the life cycle performance of infrastructure systems make a risk-informed decision-making approach to assess facility and community risks and to identify cost-effective strategies to enhance community resilience absolutely essential. Finally, the reality of climate change may require modifications to existing decision methods based on life-cycle metrics for mitigating competing hazards and enhancing community resilience with time horizons extending over the next century and for allocating risks equitably between the current and future generations.

The past three decades have seen significant advances in the science of reducing the impacts of extreme natural hazards on individual physical facilities and infrastructure networks. Much of this research has been incorporated into design and construction practice through our system of codes and standards, which is the primary vehicle in the United States (US) for managing risks to the built environment. In the current

US regulatory system, codes and standards apply to individual facilities and focus on preservation of life safety under severe events. Resilience, however, is a concept best applied to communities rather than to individual infrastructure facilities and individual networks because community resilience goals are based on social needs and objectives (such as post-disaster recovery) which are not reflected in codes, standards and other regulatory documents. Of the four attributes of resilience suggested by Bruneau, et al. (2003) – robustness, rapidity, redundancy, and resourcefulness – only one – robustness – is affected by provisions in codes and standards. Functionality and time to recovery following the occurrence of an event are equally important but are not reflected in building regulation.(Footnote: The SPUR Program in San

Francisco (Poland 2011) is attempting to establish a set of performance objectives for critical buildings in different performance categories exposed to different earthquake intensities and with different functionality needs. While the SPUR Program provides an example of community resilience planning for one type of infrastructure system (critical facilities) and one hazard (earthquake), more general metrics, criteria and guidelines based on measurement science are required for communities with different hazard exposures, social needs and resources.) Science-based measurement tools to evaluate performance and resilience at community scales, fully integrated supporting databases and risk-informed decision frameworks to support optimal life-cycle technical and social policies aimed at enhancing community resilience do not exist.

Furthermore, there is a lack of consensus on appropriate metrics for community resilience and how they might be incorporated into design criteria for the built environment.

Fundamental Research Issues

A review of the literature [e.g., McAllister (2013); United Nations Office for Disaster Risk Reduction

(UNISDR (www.unisdr.org)]] has identified a number of critical challenges confronting the development of a resilient built environment, among them: 1) Quantitative metrics and tools for assessing community resilience are required to improve resilience in the built and modified natural environment. Community resilience objectives and policies should be developed for regional hazards, include goals and performance criteria based on the role of each facility or infrastructure system in the community, should be consistent and fully incorporated in the design standards and codes for new buildings and infrastructure systems, and should be tailored to the needs of each community. 2) Community resilience plans and guidance are needed to help communities plan for hazard-specific performance, and for restoring community infrastructure systems in a cost effective and timely manner. Such planning needs to consider infrastructure interdependencies, resources available for planning, mitigation, recovery, and special performance goals and measures for critical/essential systems. 3) Existing building and infrastructure systems must be considered in community resilience planning as well as new construction, recognizing that existing buildings (a) may not meet current codes and standards; (b) in many cases cannot be modified economically to meet modern design and construction practices; and (c) may have deteriorated due to structural aging. 4) Codes and standards with consistent performance goals for all buildings and infrastructure systems are a key component for achieving a resilient community, but such consistency is seldom achieved. Transportation systems are designed and maintained by cities or states, which may not adopt current model codes and standards, or may exempt significant requirements; electric power, communication, and water systems rely on industry standards, focusing on reliability of service rather than system performance during or after hazard events.

---

* * * Subject Population * * *

4. Subject Population - In the space below, please describe the participants that you are requesting to recruit (include requested participant number and description of each group requested).

a) Requested Participant Description (Include number that you plan to study and description of each group requested, if applicable).

The research will involve up to 200 adults in each post-disaster community over the course five years.

1. Approximate # of participants in each community (will include specific number in each amendment)
2. Description of groups to study: Community leaders / stakeholders including: local business owners and business managers, local government officials including elected leaders, emergency managers, first responders, city planners, leaders of non-profits and other service organizations such as religious leaders, health care administrators, school administrators, and residents (e.g., renters, home owners, mobile home residents).
3. All adults, including employees, elderly, pregnant women, non-english speakers, could potentially be included in the study. However, it is important to note that the study team will seek out individuals who are knowledgeable about the community and about disaster impacts on the community. The team will also be particularly sensitive to not include individuals who have experienced the most devastating losses (e.g., if someone has lost a family member or friend in the disaster, they likely would be excluded from the study out of respect for their privacy and the grieving process).

b) What is the rationale for studying the requested group(s) of participants?

Community resilience depends on the performance of the built environment and on supporting social, economic, and public institutions that, individually and collectively, are essential for immediate response and long-term recovery within the community following a disaster. The resilience goals of a community are based on social needs and objectives that are specific to its character –its prior experience with natural hazards, the vulnerability/resilience of the population, economic and financial drivers and resources, and local building regulations and construction practices. The performance of the built environment in the US, which is a key factor in community resilience, is largely determined by codes and standards, which are applicable to individual facilities and have the primary objective of preserving life safety under severe events. Current codes do not address facility performance in the period of recovery following an event.

Moreover, design of inter-dependent transportation systems, utilities, and communication systems currently is based on different criteria. In the present environment, there is no assurance that all systems required for community resilience will perform at a consistent level during and following a hazard.

Furthermore, science-based measurement tools to evaluate performance and resilience at the community scales, fully integrated supporting databases, and risk-informed decision frameworks to support optimal life-cycle technical and social policies aimed at enhancing community resilience do not exist. In light of the importance of understanding community resilience and in order to build robust models that can be used to increase the resilience of a community, it is necessary that we speak to participants in a post-disaster context to learn how the disaster has impacted them, what influences their resulting behavior and what determines their recovery trajectory. Specifically, we need to learn from leaders and residents about decisions that they made before, during, and after a disaster event so that we can better map out and quantify recovery and resiliency trajectories.

c) If applicable, state the rationale for involvement of potentially vulnerable subjects to be entered into the study, including minors, pregnant women, economically and educationally disadvantaged, and decisionally impaired people. Specify the measures being taken to minimize the risks and the chance of harm to the potentially vulnerable subjects.

Our team plans to only interview adult participants in this study. We understand that this population may contain persons such as women, minorities, non-English speakers, and economically and educationally disadvantaged.

Moreover, during the immediate disaster period, even those not considered traditionally "vulnerable" may have had their lives minimally to significantly disrupted. Our team is aware of this dynamic and is very sensitive to it. This is one of the primary reasons we plan to initially focus (immediate post-disaster phase) on community leaders and stakeholders, as they tend to be the leaders who are used to serving as spokespersons for their organizations and institutions. Our team also plans to observe various residence types (e.g., mobile homes, apartments, single family homes, etc.) to understand the different disaster impacts on the physical infrastructure and on the individuals living in those structures. Again, we will be careful to invite residents to participate, never coercing them, and encouraging them to share their stories on their own terms.

To date, the research team has conducted multiple research projects in the U.S. and internationally with adults and children who were directly affected by a disaster. None of those individuals became distraught during the interviews. At the end of the interviews, almost everyone expressed appreciation for having had the opportunity to tell their story.

Based on our experiences with post-disaster social science research, we believe that a negative psychological response to these interviews is unlikely. However, we recognize that some persons may be reminded of unpleasant experiences related to the disaster. Thus, participation is completely voluntary, and the person can end the interview at any point. We will also share mental health referral resources with the participants. If at any point the interviewer notices that the participant is experiencing emotional pain or trauma, the recording will be stopped and the participant will be reminded that they have the right to permanently end the interview with zero negative consequences at any time.

d) If women, minorities, or minors are not included, a clear compelling rationale must be provided. Examples for not including minors: participant must be a registered voter; the drug or device being studied would interfere with normal growth and development; etc.

N/A

e) State if any of the subjects are students, employees, or laboratory personnel. They should be presented with the same written informed consent. If compensation is allowed, they should also receive it. N/A

f) Describe how potential subjects will be identified for recruitment. Examples include: class rosters, group membership, individuals answering an advertisement, organization position titles (i.e., Presidents, web designers, etc.). How will potential participants learn about the research and how will they be recruited

(e.g., flyer, email, web posting, telephone, etc.)? Attach recruitment materials in the Attachment section (#11). Important to remember: subjects cannot be contacted before IRB approval.

We will recruit participants through multiple channels. Because these will be quick response field studies in the immediate aftermath of disaster, we will need to simultaneously be attentive to and respectful of the post-disaster context. Several of the field study leads, including Peek, Tobin-Gurley, Peacock, Van Zandt, and others have extensive experience with conducting quick response research involving human subjects in disaster-affected areas. Similarly, all of the engineers on the team have been involved in rapid response studies where they have collected highly perishable data on damaged or destroyed buildings and infrastructure.

Over the years the social scientists have honed and refined their approaches to recruitment, and often find participants through multiple channels including: word-of-mouth (friends, colleagues, responders in affected areas often help to find target populations); flyers posted in strategic areas (business districts, emergency response centers, etc.) (see attached recruitment flyer); newspaper stories and social media posts calling for participants, etc. We will pursue similar channels with this project, and as noted above, at all times will work to minimize respondent burden.

In addition, because this is a study of resilience and thus requires that we study the community over time, we have added a portion to our IRB consent form, asking respondents if they are willing to be contacted for follow up interviews.

---

* * * Subject Population * * *

4. Subject Population (continued)

g) Identify the inclusion and exclusion criteria.

1. Exclusion: We will not actively recruit individuals who have lost family members or friends in the disaster, out of respect for their situation. With that said, if individuals with those experiences reach out to us (for example, in response to a recruitment flyer) they will not be automatically excluded from the study.

Again, we just will attempt to be sensitive to this dynamic, should it arise.

2. Inclusion: We will focus primarily on decision makers, leaders, and others, at least initially, who can give us a big picture perspective regarding the impacts of the disaster. We will also select some homeowners, renters, business owners and others who have experienced various degrees of damage to their property or surrounding infrastructure so we can better understand resilience in context. Persons who will be invited to participate will be able to speak to broader social trends that can be quantified and used to improve the modeling of community resiliency modeling of community resiliency.

h) Compensation. Explain the amount and schedule of compensation, if any, that will be paid for participation in the study. Include provisions for prorating payment.

N/A

i) Estimate the probable duration of the entire study. This estimate should include the total time each subject is to be involved and the duration the data about the subject is to be collected (e.g., This is a 2-year study. Participants will be interviewed 3 times per year; each interview will last approximately

2 hours. Total approximate time commitment for participants is 12 hours.)

- There will be a minimum of three interviews for approximately 15-30 minutes each spread over a one to three year duration (approximate).
- The initial timing, the number of interviews, and the duration of those interviews will be determined, in part, by the scale of the disaster. For instance, in a smaller scale disaster, our team might be able to mobilize and move into the field within a matter of days; in a larger scale event, like Katrina, weeks may pass before we begin the investigation due to logistical complications with entering a badly damaged region. A study of a smaller scale disaster (like the Windsor tornado) might be completed in a year. A study of a larger scale disaster, like Sandy or Katrina, could go on for many years. Resilience is a difficult concept to measure as it must be measured over time, and the time scale of recovery varies based on the initial disaster impact.
- Three to five communities will be studied in years 1-5 of the grant. If additional funding is received for years 6-10, additional communities would eventually likely be included. For now, though, the

Center is only funded for the first five years.

----

* * * Risks * * *

5. Risks (Input N/A if not applicable)

US Department of Health & Human Services (HHS) Regulations define a subject at risk as follows: "...any individual who may be exposed to the possibility of injury, including physical, psychological, or social injury, as a consequence of participation as a subject in any research, development, or related activity which departs from the application of those accepted methods necessary to meet his needs, or which increases the ordinary risks of daily life, including the recognized risks inherent in a chosen occupation or field of service."

a) For the following categories, include an estimate of the potential risk. Input N/A if not applicable.

There is a minimal possibility of psychological risk in this study because 1) Participants have already experienced an upsetting event, i.e., the disaster and 2) We will be asking them questions about their own experiences with or their communities' disaster impacts and longer term recovery. That being said, we do not expect there to be any serious harm associated with participating in this study, however, there are no immediate benefits either. Over the longer term, the study itself is designed to inform policy and practice to improve the resilience of people living in disaster-affected communities.

b) In case of overseas research, describe qualifications/preparations that enable you to evaluate cultural appropriateness and estimate/minimize risks to subjects.

International studies are possible, but highly unlikely given time and budget constraints. It would have to be in a developed country that has similar buildings and infrastructure systems, political structures, etc. (for instance, in the highly unlikely event that an international location were selected, it would be a place, like New Zealand, where the physical, social, and economic environments are such that results can be applicable to communities in the U.S. However, if we are in a community that has a high non-English speaking population, we will make sure a team member that is fluent in the dominant language conducts the interview. We will also make sure to have all consent and other informational forms translated and presented to the participant in their primary language. Again, this is a highly unlikely scenario and we realize any such change to this base IRB protocol would require a detailed and extensive amendment.

c) Discuss plans for ensuring necessary medical or professional intervention in the event of a distressed subject.

We will include information regarding local mental health specialists on the consent form and will recommend that participants seek additional help or withdraw from the study if they appear distressed at any point. We have created such flyers and forms for other disasters that we have studied, and have members of the team who are quite skilled at assembling these types of documents. We take providing this information seriously, and will create this type of flyer as soon as we have agreed that we will move into a study community.

d) If audio/video taping will be used, state if it could increase potential risk to subject's confidentiality.

We cannot promise anonymity to informants in this research, but we can offer confidentiality in that no names will be used in any written reports or publications that are issued from the study.

----

* * * Benefits,Procedures to Maintain Confidentiality * * *

6. Benefits

a) Describe the potential benefit(s) to be gained by the subjects or how the results of the study may benefit future subjects. Indicate if there is no direct benefit to the participants.

Potential Benefits to Participants:

There are no direct benefits to participants as they will not be compensated for their time. However, as described above, the entire project is designed to provide longer term benefits.

Potential Benefits to Society:

The primary contributions of this research to society include the eventual development of a computational environment that can be used by decision makers to help them optimize investments in community resilience.

We plan to actively promote our research and the products generated well beyond scholarly audiences to ensure that the general public, disaster recovery practitioners and organizations, and others in hazard-prone communities have access to the information generated. This project is poised to influence both scholarly and broader social domains through contributions to graduate student training, enhanced public discourse, and increased community resilience.

The applicants (Van de Lindt and Ellingwood) and collaborator (Peek) along with the many other investigators on this study have a demonstrated track record in basic research, applied and evaluation activities, and policy translation.

7. Procedures to Maintain Confidentiality

a) Describe the procedures in place that will protect the privacy of the subjects and maintain the confidentiality of the data. If a linked list is used, explain when the linked list will be destroyed. Provide a sample of the code that will be used, if applicable.

All physical data will be stored in a locked file cabinet and all electronic media will be saved on a password-protected computer in locked offices. A linked-list will be created where all identifiable information will be replaced with code numbers. The same code will be used for the audio recording, field notes, and photographs from each participant. No names will be attached to this documentation. We cannot promise anonymity to informants in this research, but we can offer confidentiality in that no names will be used in any written reports or publications are issued from the study. The use of any images (still or video) that compromise anonymity and

confidentiality as above will only be done with the written permission of all individuals identifiable in the image.
b) If information derived from the study will be provided to the subject's personal physician, a government agency, or any other person or group, describe to whom the information will be given and the nature of the information.
c) Specify where and under what conditions study data will be kept, how samples will be labeled, who has access to the data, and what will be available and to whom. Federal Regulations require that study data and consent documents be kept for a minimum of three (3) years after the completion of the study by the PI. For longitudinal projects, the PI may be required to keep the data and documents for a longer time period.
Data access is limited to project team investigators who have completed the required ethics training and will be maintained for the three-year archive period following conclusions of the study. No facial images will be used in any outlet without express written permission.
Audio recordings that contain identifiable information will only be seen/heard by team members who have completed the required ethics training. Photos produced through the research that contain identifiable information will only be seen/viewed by team members unless express written permission is provided by anyone identifiable in those images (see attached consent form). All raw data will be stored on password protected computers in locked offices and a linked-list will be created where all identifiable information will be replaced with code numbers.
----

* * * Potential Conflict of Interest * * *
8. Potential Conflict of Interest
Although you have already submitted CSU's official Conflict of Interest form (COI/COC) to the University, it is the IRB's responsibility to ensure that conflicting interests related to submitted protocols do not adversely affect the protection of participants or the credibility of the human research protection program at CSU.
Please answer questions a-d below. Please note that if you indicate that you have a potential conflict of interest in relation to this protocol, your CSU COI/COC Reporting Form must reflect this potential conflict.
Link to CSU's Conflict of Interest policy: http://www.provost.colostate.edu/print/coirev.pdf.
a) N In connection with this protocol, do you or any of the protocol investigators or their immediate family members (i.e., spouse and legal dependents, as determined by the IRS) have a potential conflict of interest?
b) N/A If you do have a potential conflict of interest, is this reported in your current COI/COC?
c) N/A If you do have a potential conflict of interest, is there a management plan in place to manage this potential conflict?
d) N/A If you do have a potential conflict of interest, is this potential conflict of interest included in your consent document (as required in the Management Plan)?
If you have reported a possible conflict of interest, the IRB will forward the title of this protocol to your Research Associate Dean to complete your COI file.
For more information on CSU's policy on Conflict of Interest, please see the Colorado State University
Academic Faculty and Administrative Professional Manual Sections D.7.6 & D.7.7:
http://www.facultycouncil.colostate.edu/files/manual/sectiond.htm#D.7.6.
Link to CSU's Conflict of Interest policy: http://www.provost.colostate.edu/print/coirev.pdf .
----

* * * Informed Consent * * *

9. Informed Consent See sample consent forms at http://web.research.colostate.edu/ricro/hrc/forms.aspx

NOTE: In order to complete this protocol, you must upload either a Consent Form or an Alteration of
Consent Form (i.e., Cover Letter or Verbal Script) OR (if neither of those apply to your project) you must complete the Waiver of consent information.

In the space below, provide consent process background information, for each Consent Form, Alteration of
Consent Form (i.e., Cover Letter or Verbal Script), or Waiver of consent. You will not be able to submit this protocol without completing this information.

Informed Consent

Title NIST Consent Form

Consent Information Type Consent

Consent Form Template X Attachment NIST Consent Form FINAL

Who is obtaining consent? The person obtaining consent must be knowledgeable about the study and authorized by the PI to consent human subjects.

NIST Researchers

How is consent being obtained?

In person, in writing

What steps are you taking to determine that potential subjects are competent to participate in the decision making process?

We will discuss the consent form with each participant and make sure they understand its contents prior to the interview.

----

* * * Assent Background * * *

10. Assent Background

All minors must provide an affirmative consent to participate by signing a simplified assent form, unless the
Investigator(s) provides evidence to the IRB that the minor subjects are not capable of assenting because of age, maturity, psychological state, or other factors.

See sample assent/consent forms at http://web.research.colostate.edu/ricro/hrc/forms.aspx

If applicable, provide assent process background information for each Assent Form, Alteration of Assent Form (i.e., Cover Letter or Verbal Script), or Waiver.

Assent Background

----

* * * Attachments * * *

11. Attachments

Attach relevant documents here. These could include: Collaborating Investigator's IRB approval and approved documents; Conflict of Interest information; Debriefing Script; Grant/Sub-contract; HIPAA
Authorization or Waiver Form from HIPAA-covered entity; Interview/Focus Group Questions; Investigator's
Brochure; Letters of Agreement/Cooperation from organizations who will help with recruitment; Methodology section of associated Thesis or Dissertation project; Questionnaires; Radiation Control Office approval material; Recruitment Material (e.g., flyers, email text, verbal scripts);

Sponsor 's Protocol; Surveys; Other files associated with protocol (can upload most standard file formats: xls, pdf, jpg, tif, etc.) Please be sure to attach all documents associated with your protocol. Failure to attach the files associated with the protocol may result in this protocol being returned to you for completion prior to being reviewed. Students: Be sure to attach the Methods Section of your thesis or dissertation proposal. All PIs: If this protocol is associated with a grant proposal, please remember to attach your grant. To update or revise any attachments, please delete the existing attachment and upload the revised document to replace it.
Document Type Other Protocol Material
Attachment MASTER Contact List
Document Name MASTER Contact List
Document Type Interview/Focus Group Questions
Attachment NIST Interview Guide FINAL
Document Name NIST Interview Guide FINAL
Document Type Other Protocol Material
Attachment DemographicInfoOrganizationsFINAL
Document Name DemographicInfoOrganizationsFINAL
Document Type Other Protocol Material
Attachment DemographicInfoResidentsFINAL
Document Name DemographicInfoResidentsFINAL
Document Type Recruitment Material (e.g., flyers, email text, verbal scripts)
Attachment Field Studies Recruitment Flyer
Document Name Field Studies Recruitment Flyer
Document Type Grant/Sub-Contract
Attachment NIST Award_70NANB15H044
Document Name NIST Award_70NANB15H044
Document Type Other Protocol Material
Attachment Photo Release Form
Page 18 of 18
Document Name Photo Release Form
----
* * * Obligations * * *
Obligations (Researcher's Responsibilities)
The Principal Investigator is ultimately responsible for the conduct of the project. Obligations of the Principal Investigator are:
Conduct the research involving human subjects as presented in the protocol, including modifications, as approved by the Department and Institutional Review Board. Changes in any aspect of the study (for example project design, procedures, consent forms, advertising materials, additional key personnel or subject population) will be submitted to the IRB for approval before instituting the changes (PI will submit the "Amendment/Revision" form);
Provide all subjects a copy of the signed consent form, if applicable. Investigators are required to retain signed consent documents for three (3) years after close of the study;
Maintain an approved status for Human Subjects Protection training. Training must be updated every three (3) years (Contact RICRO to check your current approval/renewal dates). For more information: Human Subjects
Training Completed?

Submit either the "Protocol Deviation Form" or the "Report Form" to report protocol Deviations/Violations, Unanticipated Problems and Adverse Events that occur in the course of the protocol. Any of these events must be reported to the IRB as soon as possible, but not later than five (5) working days;

Submit the "Continuing Review" Form in order to maintain active status of the approved protocol. The form must be submitted annually at least four (4) weeks prior to expiration, five (5) weeks for protocols that require full review. If the protocol is not renewed before expiration, all activities must cease until the protocol has been rereviewed;

Notify the IRB that the study is complete by submitting the "Final Report" form.

X The Principal Investigator has read and agrees to abide by the above obligations.
