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Holistic Resilience Quantification Framework of Rural Communities

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HOLISTIC RESILIENCE QUANTIFICATION FRAMEWORK OF RURAL COMMUNITIES

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Civil Engineering in the College of Engineering at the
University of Kentucky

By
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Lexington, Kentucky
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2020

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ABSTRACT OF THESIS

HOLISTIC RESILIENCE QUANTIFICATION FRAMEWORK OF RURAL COMMUNITIES

Communities need to prepare for anticipated hazards, adapt to varying conditions, and resist and recover rapidly from disturbances. Protecting the built environment from natural and man-made hazards and understanding the impact of these hazards helps allocate resources efficiently. Recently, an indicator-based and time-dependent approach was developed for defining and measuring the functionality and disaster resilience continuously at the community level. This computational method uses seven dimensions that find qualitative characteristics and transforms them into quantitative measures. The proposed framework is used to study the resilience of rural communities' subject to severe flooding events. Harlan County in the Appalachian region is chosen as a case study to evaluate the proposed resilience quantification framework subject to severe flooding. The results show the validity of the proposed approach as a decision-support mechanism to assess and enhance the resilience of rural communities.

KEYWORDS: community resilience, natural disasters, mitigation, decision framework, multi-hazard, rural communities

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04/20/2020
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HOLISTIC RESILIENCE QUANTIFICATION FRAMEWORK OF RURAL COMMUNITIES

By

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Director of Thesis

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April 20, 2020
Date

DEDICATION

I would like to dedicate this work to my family and to all the communities that have been affected by natural disasters.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my advisor Dr. Mariantonieta Gutierrez Soto for her advice, endless support and guidance throughout this process. I would like to thank the members of my committee, Dr. Allison Gibson, Dr. Issam Harik, and Dr. Reginald Souleyrette, for offering their recommendations and for evaluating my research. They pushed me to grow as a student and civil engineer, I am very thankful for that. Their knowledge has allowed me to improve not only as a researcher, but also as a person.

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1.1 What is Community Resilience?

The *National Infrastructure Protection Plan* established by the United States Homeland Security defines resilience as the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies. Cimellaro et al. (2010) define resilience as the capacity of engineering and socio-economic systems to recoil after a severe disaster. McAllister (2016) defines resilience as “the concept that addresses the way that communities prepare for and recover from disruptive events.” Baho et al. (2017) express resilience as the period required for an ecosystem to reassemble to pre-disturbance conditions. Cere et al., (2017) describe community resilience through the material property application of elasticity. “Elastic” resilience signifies the idea of returning to the preexisting equilibrium, which refers to the static concept of resilience. Consequently, the “ductile” resilience interpretation is seen as a progression of continuous self-alteration and modification that can be construed as bouncing forward, which refers to the dynamic concept of resilience.

The resilience of a community or a system within the community is most often compared to its performance. The manner at which the system absorbs the damage of the impact and then recovers describes the performance, i.e., resilience (Ayyub, 2014). Figure 1.1 shows how a system’s performance is measured before, at, and after an impact. The system’s performance is measured on the y-axis while the time is on the x-axis. The time at which the incident occurs, is denoted as t_i, the time at which the failure occurs is t_f, and the time at which the system commences its recovery is labeled as t_r. ΔT_d, ΔT_f, and ΔT_r are the time durations of the disruption, failure, and recovery, respectively. Three failure events are portrayed in the graph labeled as $f_{graceful}$, $f_{ductile}$, and $f_{brittle}$, meaning a graceful failure, a ductile failure, and a brittle failure. Six different recovery patterns are shown: r_1, r_2, r_3, r_4, r_5, and r_6, signifying a better than new recovery, a good as new recovery, a better than old recovery, a good as new recovery, a good as old recovery, and a worse than old recovery, respectively. These different failure types and recovery patterns give perspective into how differently and unique a community can react after the impact of an incident. The initial and residual capacity and strength after the disturbance describes its degree of robustness.

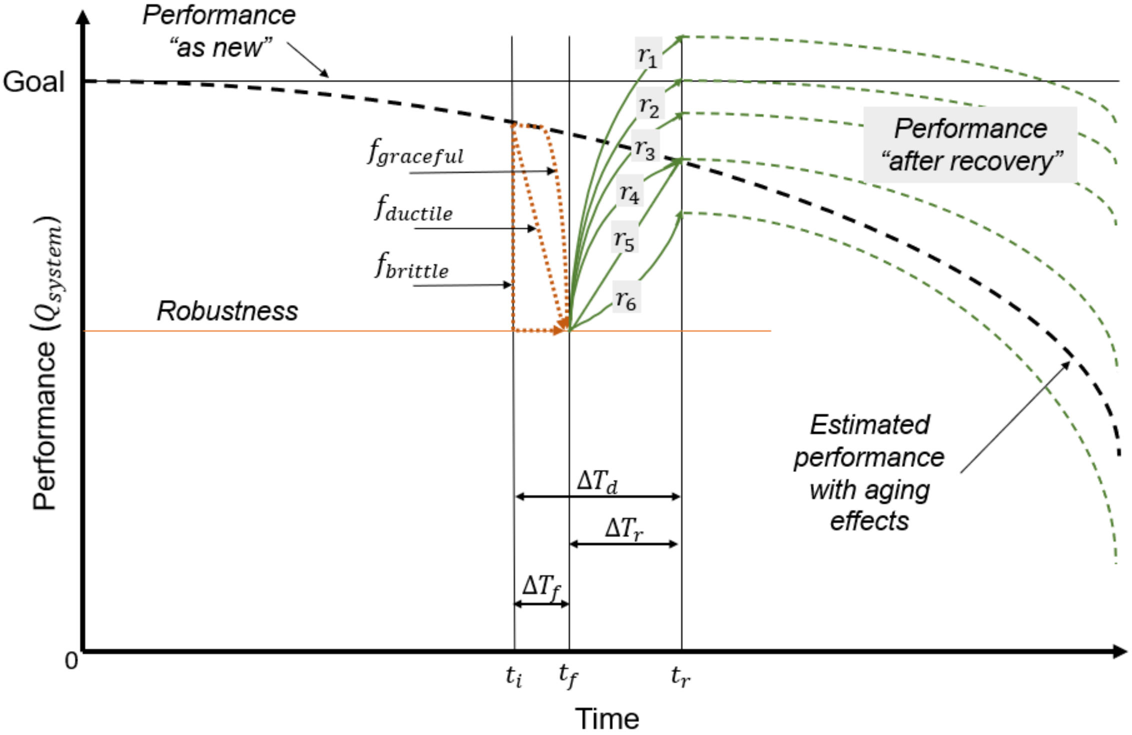


Figure 1. 1 Resilience through system performance (adapted from Ayyub, 2014).

The resilience of the community can be measured by the loss of resilience, meaning the number of days it took for the community's functionality to return to its original state. This helps demonstrate which areas of the community are most vulnerable, therefore, requiring more attention and funding allocation. Effective mitigation measures have been a subject of research in the last decades and such improvements can be applied before or after a disruptive event. Robustness is defined as "the strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function" (Bruneau et al., 2003). There are many strategies of mitigation measures that improve robustness of the built environment. One innovative approach is using supplementary damping to structures. One innovative approach is using vibration control devices installed in civil structures to improve the resilience towards extreme natural hazards. Examples of these advance mitigating devices include base isolation (Gutierrez Soto and Adeli, 2018), fluid viscous dampers (Gutierrez Soto and

Adeli, 2013a), tuned mass dampers (Gutierrez Soto and Adeli, 2013b), and semi-active devices (Gutierrez Soto and Adeli, 2017; Gutierrez Soto and Adeli, 2019). Although these advanced devices have been proven effective for protecting structures subjected to wind and earthquake loading, this solution has not been widely adopted in the United States. Recently, El-Khoury et al. (2018) investigated a risk-based life cycle cost approach to achieve optimum design of structures that have vibration control devices installed.

Community resilience is characterized by the following terms: mitigation, preparedness, functionality, recovery, and response. Mitigation and preparedness are two different concepts related to community resilience that are important to distinguish. Preparedness is the action taken to improve emergency response for the aftermath, while mitigation is an action taken to reduce or eliminate long-term risk to hazards (Baxter, 2013). Functionality is a factor that measures a structure's recovery status and its capability to remain serviceable (Baxter, 2013). Examples being hospitals delivering healthcare promptly, and water distribution systems delivering potable water to a community (McAllister, 2016).

FEMA, the Federal Emergency Management Agency, published a "how-to guide" on the mitigation of potential terrorist attacks (Kennett et al. 2005). The objective of this guide is to offer information on the proper steps necessary in assessing risk and then applying the proper risk management plan to the community when under a threat of attack (Kennett et al. 2005). The risk assessment process model can be seen in Figure 1.2. The first step in the risk assessment process model is to gather a threat/hazards assessment, where the threat is identified and measured, and an asset value assessment, identifying the value of buildings that need to be protected. These two assessments compile the vulnerability assessment addressing the community's overall potential vulnerability. Next the risk assessment is compiled allowing the identification of possible mitigation options. Finally, the most appropriate mitigation strategies are then assembled into a risk management plan for the community.

Present design codes and standards emphasize on the building's lifecycle, and present regulations address the dependability on the utilities' functionality, however these documents generally do not direct attention to the resilience or interdependency issues (McAllister, 2016). It can be observed through the efforts of enhancing the seismic resilience of communities (Bruneau et al., 2003) and the research performed on community-driven disaster planning for long-term mitigation recovery plans (Chacko et al., 2016) that a solution comprehending and satisfying the interdependent relationships within a community is still not well-understood.

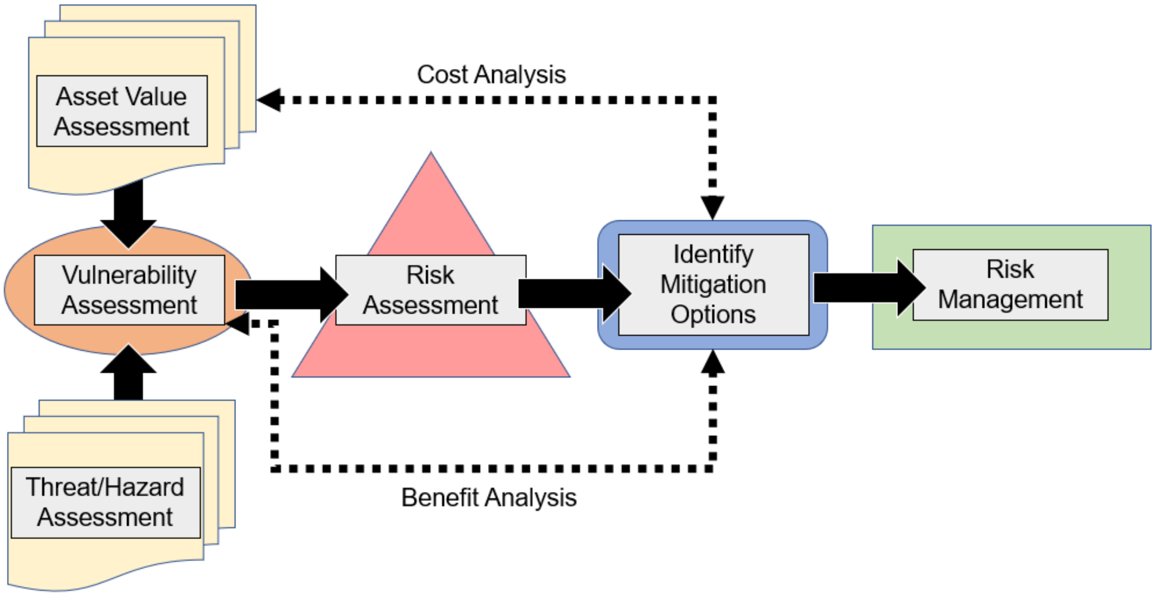


Figure 1. 2 Risk assessment process model (Adapted from: Kennett et al. 2005)

1.1.1 Interdependent Relationships

A reliable and quantitative methodology for economic risk-analysis modeling that accounts community interdependencies is needed to properly predict direct and indirect costs of destruction to properly prepare for a hazard event. The interdependencies such as social, human health, safety and general welfare, physical systems, security, protection, emergency response, business continuity, and buildings are critical in the search of solutions to achieve community resilience and this has yet to be properly instituted in pre-decision modeling strategies (Cimellaro 2018). Shih et al. (2018) describe the building blocks of a resilient community as one that contains solid connections amongst all points of the community such as between neighbors, between neighborhoods and community organizations, and between local government and nongovernmental groups. Cimellaro et al. (2018) analyzed the role of interdependencies by investigating the resiliency of a hospital. The authors developed a discrete event simulation model imitating the dynamic operation of complex systems used to analyze the resilience of a hospital subjected to earthquake loading. A hospital is defined as a departmental unit where an internal interdependent organization along with the physical dimension at different levels is what drives a successful operation on a day to day basis. The authors used the following interdependent attributive parameters: the number of beds, the number of doctors, and the operation efficiency. The predetermination of the resilience of a hospital during a natural disaster can be vital in decision-making for future events and directly correlate into the resilience assessment of a community. Cimellaro et al. (2014) proposed a resilience index to evaluate the resilience of a region affected by a disaster considering infrastructure interdependency using the 2011 Tohoku Earthquake in Japan as a case study. First, a resilience index was given to every infrastructure in the region combined with others by weighted factors. Then, the regional resilience index is calculated based on the weighted factors of each infrastructure.

Murray-Tuite (2006) applied a man-made hazard event in the Washington DC area of Reston, Virginia during a late evening and examined the transportation systems for resilience with ten parameters: redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. A traffic assignment-simulation methodology was applied to the event and was examined through different degrees of vulnerability based on government support, public attention, and capacities such as adapting and coping. Koliou et al. (2018) investigated the resilience of natural gas systems considering the interconnectivities between pipelines, port facilities, fuel delivery, and airport and train operations.

Another approach to investigating interdependent relationships to achieve resilience in a civilian community is examining resilience from the ecology perspective. Baho et al. (2017) approached the intent for resilience from an ecological standpoint. The environment in which organisms live in are not only affected by natural disasters, but also by agriculture, land-use and climate change, species invasions, and infectious diseases. The authors' approach to ecological resilience is broken down into four parts: (1) scale, (2) adaptive capacity, (3) thresholds, and (4) alternative regimes. The scale part considers the amount of species having the same functional traits, the impact of disturbance dispersed upon the ecosystem in study, and range of responses to disturbance, in order to grasp the overall physical and psychological impact. The adaptive capacity part considers the ecosystem's response to environmental disturbance or changes. It takes into consideration how differently rare species react to environmental change. The thresholds part considers reorganization of an ecological community after a disturbance, and the alternative regimes part covers the idea of an ecosystem adapting new roles in the surviving community. These four attributes are used together to measure resistance, persistence, variability, and recovery. By evaluating and calculating the numerous characteristics of resilience, the general resilience assessment will move one step forward toward understanding the general resilience of ecosystems and other complex systems.

1.1.2 Current Resilience Guides

The public's understanding of community resilience is critical; and thus, providing adequate resources are needed to improve resiliency. This has led to the development of seven guides: (1.) the National Institute of Standards and Technology (NIST) Community Resilience Planning Code, (2.) the San Francisco Bay Area Planning and Urban Research (SPUR) Association Framework (3.) Baseline Resilience Indicators for Communities (BRIC) (4.) The Community and Regional Resilience Institute's (CARRI) Community Resilience System (5.) The Oregon Resilience Plan (6.) the National Oceanic and Atmospheric Administration (NOAA) Coastal Resilience Index, and (7.) The Communities Advancing Resilience Toolkit (CART). These resilience guides are summarized in Table 1.1 and compared based off four parameters: (1.) the definition of resilience stated in the respective guide, (2.) type of guide, (3.) the degree of community interaction, and (4.) interdependent relationships addressed for within the guide for successful community functionality. Although all seven are considered US resilience guides, most of the material and messages are not stake-holder friendly thus claiming as unsuitable for accessible public adoption. The *Oregon Resilience Plan* is a document addressed to the public officials within Oregon, not the stakeholders who reside in the community (OSSPAC, 2013). The guide was made to influence policy makers. The Community and Regional Resilience Institute's *Community Resilience System* Report however addresses the leadership team within a community and then implements interactive workshops with the civilians. Within the community resilience system report, all key interdependent relationships fell into similar categories of transportation, medical facilities, emergency management services, water, and telecommunication services, except for in CART. This was the only guide to address faith-based organizations (Pfefferbaum, 2011).

The *Federal Emergency Management Agency* (FEMA) provides two guides for community resilience: *Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards* (Baxter, 2013) and *Are you Ready? An In-depth Guide to Citizen Preparedness* (FEMA, 2004) provide step-by-step procedures for community members. The following guides were not included in Table 1.1 because of their tended audience being local rather than on a national scale. FEMA's *Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards* is an informative document made to help communities identify natural disasters/hazards and know the proper mitigation steps to take after. The guide addresses: drought, earthquake, extreme temperatures, flood, tornado, tsunami, wildfire and multiple hazards. For each disaster, recommended mitigation actions are summarized for the purposes of local planning and regulations, structure and infrastructure projects, natural systems protection, and education and awareness programs (Baxter, 2013). The *Are you Ready? An In-depth Guide to Citizen Preparedness* brochure is intended to aid citizens in learning the proper protection measures needed against all categories of hazards. The in-depth guide teaches you to improve, train for, and have emergency plans that should be done before, during, and after a disaster to protect people, property, and the community in totality (FEMA, 2004).

1.2 Static Computational Models

Modeling community resilience through numerical simulations has attracted research in recent years. Ouyang and Dueñas-Osorio (2012) studied a time-dependent assessment using a power transmission grid in Harris County, Texas with output given as post-blackout improvement factors and different resilience strategies. The results showed that when the post-blackout improvement factors were small, the resilience curves were decreasing functions, and vice versa for large improvement factors. Nazari et al. (2013) introduced a procedure in computing the probability of the collapse of a two-story wood frame townhouse due to the aftershock of an earthquake.

Table 1. 1 US community resilience guides for natural disaster

Community Resilience Guides				
Name	Definition of Resilience	Type of Guide	The Degree of Community Interaction	Interdependent Relationships
1. NIST Community Resilience Planning Code	The ability of a community to prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions	A six-step planning process for local governments; 6-Step-Process: (1.) Form a collaborative planning team. (2.) Understand the situation, (3.) Determine goals and objectives, (4.) Plan development, (5.) Plan preparation, review, and approval, (6.) Plan implementation and Maintenance	This guide allows provides the community with information how to properly plan for community resilience; a planning team that provides leadership and engages public, non-profit, and private stakeholders, are primarily who this guide is intended to be read by	Healthcare facilities, schools, retail districts, business facilities, (supply chains, delivery networks, workforce etc.) transportation network, electricity, fuel, water, wastewater systems, and communication/information access; energy systems
2. SPUR Framework	SPUR defines San Francisco's "seismic resilience" as its ability to contain the effects of earthquakes when they occur, carry out recovery activities in ways that minimize social disruption, and rebuild following earthquakes in ways that mitigate the effects of future earthquakes."	SPUR outlines seismic performance goals and evaluates then through this 3-step process (1.) before the disaster (defining resilience, the dilemma of existing buildings, building it right the first time, lifelines, safe enough to stay) (2.) emergency response (the culture of preparedness, the hub concept) (3.) after the disaster (rebuilding our transportation infrastructure, on solid ground)	The SPUR framework provides a 3-step process for policy makers to take into considerations for future seismic design codes for the San Francisco Bay area.	Community planning, economic development, good government, housing, regional planning, transportation; hospitals, police and fire stations; medical provider offices, airports for commercial traffic; public shelters

Table 1.1 US community resilience guides for natural disaster (continued)

3. Baseline Resilience Indicators for Communities (BRIC)	"...resilience is as a set of capacities that can be fostered through interventions and policies, which in turn help build and enhance a community's ability to respond and recover from disasters…"	BRIC provides a methodology and a set of indicators to measure the present conditions influencing disaster resilience within communities	BRIC is a set of indicators established for a community to rate their own community and better their circumstances and chances for their preparedness plans.	BRIC uses a DROP, disaster resilience of place "model to establish indicators for a community. Each set of indicators are different per community. The indicators take the following into considerations when weighing in high to low: ecological, social, economic, infrastructure, institutional capacity (mitigation), community competence
4. The Community and Regional Resilience Institute's (CARRI) Community Resilience System	"Resilience is the ability to anticipate risk, limit impact, and bounce back rapidly through survival, adaptability, evolution, and growth in the face of turbulent change."	The Community Resilience System (CRS) is composed of six stages, that build on each other to help a community become more resilient. In each stage, the community is guided through a series of actions. The first 3 stages are: Stage 1 – Engage the Community at Large, Stage 2 – Perform a Community Resilience Assessment, Stage 3 – Develop a Shared Community Vision	CARRI conducted monthly interactive workshops to provide information, situational updates and actionable insights, advice, and support before, during, and after disasters and crises. The workshops were free, featured nationally recognized expert panels, and were organized to follow a PREDICT.PLAN. PERFORM. A web-based set of tools and resources to make the process and knowledge base is available to a wide array of communities.	Utility supply facilities; food supply; private businesses; economy, financial resources, workforce, public safety, energy, water, natural environment, public health, education, arts, entertainment, and recreation, etc.

Table 1.1 US community resilience guides for natural disaster (continued)

5. The Oregon Resilience Plan	"…preserving our communities and workforce to help businesses bounce back quickly from a natural disaster…"	A guide for government officials to evaluate their community based on a set of questions (yes or no questions, open response, etc.) aiming to reduce risk and improving recovery for the next Cascadia earthquake and tsunami. This plan evaluates Oregon's buildings, lifelines, and social systems, and proposes a plan to develop a sustained program of replacement, retrofit, and redesign to make Oregon resilient.	Private investigation amongst professionals in their areas provided this plan as an informational resource for policy makers to take into consideration. Not a community interactive guide. The three research topics were: (1.) Determine the likely impacts of an earthquake and tsunami, and estimate the time required to restore functions (2.) Define acceptable timeframes to restore functions an earthquake; and (3.) Recommend changes in practice and policies	Business and workforce continuity, critical and essential buildings, transportation, energy, information and communications, water and wastewater systems; electricity, police and fire stations
6. NOAA's Coastal Resilience Index	"Resilience is determined by the degree to which the community is capable of organizing itself to increase its capacity for learning from past disasters."	Method for community leaders to perform a self-assessment of their community's resilience to coastal hazards, identifying weaknesses a community may want to address prior to the next hazard event and guiding community discussion. The Index is not intended for comparison between communities.	This report is intended for community planners, natural resource managers, or similar professionals who might be involved with development of community emergency plans for coastal hazards and structural development. This report is primarily intended for positions representing a city, a town, small groups of towns, or a county.	Critical facilities and infrastructure, transportation issues, community plans and agreements, mitigation measures, business plans, and social systems

Table 1.1 US community resilience guides for natural disaster (continued)

7. The Communities Advancing Resilience Toolkit (CART)	“Resilience can be thought of as an attribute (an ability or capacity), a process, and/or an outcome associated with successful adaptation to, and recovery from, adversity.”	CART is a community intervention that brings stakeholders together to address community issues through assessment, group processes, planning, and action. The CART process is (1.) Generate a Community Profile, (2.) Refine the Profile, (3.) develop a Strategic Plan, and (4.) Implement the Plan. It addresses the need for interaction from CART Team and partners, community work groups, community planning groups, and community leaders and groups.	CART contains very interactive tools designed to be used by the stakeholder in a community. CART Tools to be done but the community members: (1.) CART assessment survey, (2.) Key informant interviews, (3.) data collection framework, (4.) community conversations, (5.) neighborhood infrastructure maps, (6.) community ecological maps (7.) stakeholder analysis, (8.) SWOT analysis, (9.) Capacity and Vulnerability assessment	Infrastructure, stakeholders, ecology, social service agencies, economic development organizations, business associations, housing, transportations, libraries, faith-based organizations, education

References: (1.) NIST. (2015)."Community resilience planning guide for buildings and infrastructure systems"; (2.) SPUR. (2009)."When is a building safe enough?"; (3.) CARRI. (2013). "Community and Regional Resilience Institute, Community Resilience System"; (4.) Cutter (2014)."The geographies of community disaster resilience"; (5.) Oregon (2013)."The Oregon Resilience Plan: Reducing risk and improving recovery for the next Cascadia Earthquake and Tsunami"; (6.) NOAA. (2010). "Coastal resilience index: A community self-assessment"; (7.) Pfefferbaum (2013). "The Communities Advancing Resilience Toolkit (CART): An intervention to build community resilience to disaster

Using incremental dynamic analysis, fragility curves were created for the building under four different intensity scenarios: mainshock-only, maximum considered earthquake level mainshock-aftershock, design earthquake level main shock-aftershock, and a 0.8 g level mainshock-aftershock. The results showed that the probability of structural failure has no significant relation to the aftershock therefore deeming it as unnecessary to implement aftershock design in performance based seismic design.

Francis and Bekera (2014) developed a resilience assessment framework consisting of five components: (1.) system identification, (2.) vulnerability analysis, (3.) resilience objective setting, (4.) stakeholder engagement, and (5.) resilience capacities. A case study was performed on the fictional city of Micropolis evaluating the electric power infrastructure resilience in Category 3 and Category 5 hurricane storm surge zones. The underground electric power infrastructure east of the railroad, the infrastructure east of the railroad in the commercial area only, and the infrastructure as-is in totality was assessed through three different scenarios. The results indicated that undergrounding electric power infrastructure east of the transmission line attained higher resilience and entropy resilience scores.

Rather than evaluating the community as a whole, other frameworks assess the individual buildings' resilience that make up the community. Burton et al. (2015) proposed a framework for computing each building's damage measures that inform, repair, and replace activities through hazard, damage, and structural analyses. From there, a new decision variable is derived from the limit states describing the recovery of functionality at the building level. Originally developed by the Pacific Earthquake Engineering Research Center at the University of California - Berkeley, Burton et al. (2015) applied the performance-based earthquake engineering framework to model the post-earthquake recovery of a community of residential houses. The collective occupancy loss over the recovery period can be obtained from the recovery curve. This provides insight into the long-term economic impact on the community. HAZUS, Hazards United States Multi-Hazard, and OpenQuake (Pagani et al. 2014) were used to simulate scenario earthquakes. HAZUS is a software tool developed for the US Federal Emergency Management Agency (FEMA) by the National Institute of Building Sciences (NIBS) and is utilized as a standardized methodology for estimating physical, economic, and social impacts of disasters using GIS technology (FEMA, 2003). OpenQuake is a web-based platform used for the integrated assessment of earthquake risk developed by the Global Earthquake Model Foundation. The hazard analysis in the framework was based on the ground motion intensities in the study region location for multiple scenario earthquakes. The structural performance was measured by story drift, residual story drift, and floor acceleration. The damage analysis was determined based on the deficiencies for structural analysis components. The building damage was then categorized into one of four 1.) safe and operational, 2.) safe and usable during repair, 3.) safe but not repairable, or 4.) unsafe. Individual house fragility curves were generated to enable the creation of a global community fragility curve.

Guidotti et al. (2016) used the implementation of a six-step probabilistic method for a critical infrastructure assessment on the virtual community of Centerville after the impact of a 6.5 magnitude earthquake. The six steps are: (1.) generate a network model for the system, (2.) generate the hazard for the network area, (3.) assess direct physical damage to network components through fragility curves, (4.) define the network damage state weighed through network dependencies, (5.) assess functionality loss (e.g. ability to provide essential goods and services), and (6.) predict recovery time for network functionality. The potable water distribution network system was evaluated separately and then once again based on the cascading effects due to its dependency on the electric power network. The probabilistic procedure includes models of damage, functionality, and recovery. The results showed a higher standard deviation for the coupled water distribution network and electric power network system than the water distribution network system alone, reflecting a higher level of uncertainty. The recovery time also increased through coupled networks.

Flint et al. (2016) approached a resolution towards community resilience during multi-hazard disasters by optimizing building's subsystems (i.e. soil, foundation, structure, and envelope) while still in the early design stage. This holistic approach was focused on the effects on mid-rise commercial buildings exposed to hurricane, earthquake, and tsunami hazards. The framework consists of three modules: Module (1.) a soil, foundation, structure, and envelope system generator, Module (2.) a multi-hazard performance assessment, and Module (3.) a set of multi-objective optimization algorithms that optimizes repair and recovery strategies. Module 1 identifies Soil, Foundation, Structure and Envelope (SFSE), systems that have the potential for optimal performance at a given site. Module 2 assesses multi-hazard exposure, SFSE system performance before and after hazard events, and life-cycle metrics associated with construction, operation, repair, and recovery. Finally, Module 3 uses a multi-objective decision-making algorithm to simultaneously optimize several conflicting objectives. Disregarding envelope systems, the authors found 92 potentially viable SFSE systems compared to the 132 total systems.

Advancements in risk analysis assessments provide decision-making capabilities for implementing disaster risk reduction plans. A probabilistic risk assessment is a systematic and comprehensive methodology used to evaluate risks associated with a complex engineered technological entity or the effects of stressors on the environment (Salgado et al. 2016). Risk in this type of analysis measures the severity of the consequences and the likelihood of occurrence. The total risk is calculated through the sum of the products of consequences multiplied by the probability of the negative activities' likelihoods of occurring. Salgado et al. (2016) developed a comprehensive approach to probabilistic risk assessment to obtain physical risk indicators through damage and loss events. This probabilistic risk assessment platform was used to perform a risk assessment for the city of Medellin, Colombia using seismic hazard, exposure and socioeconomic descriptors as predictive event data indicators. Bozza et al. (2017) modeled the city of Sarno, Italy as a hybrid social–physical network and evaluated resilience using synthetic and time-independent resilience measures during a seismic and landslide scenario.

Kammouh et al., (2018a) proposed a framework using distribution/density, composition, and socio-economic indicators as input leading to an output of a resilience function showing the serviceability of the community for a given period following the disaster. Fragility curves are useful in quantifying the structural damage attained after an event (Kammouh et al. 2018b). Alternatively, the restoration phase has also actively been modeled for purposes of better understanding the structural performance. Kammouh et al. (2018b) used the data from 32 earthquakes to plot restoration curves for four lifelines: power, water, gas and telecommunication. These results calculated the downtime for each lifeline and showed how the power system was always the first to recover with the telecommunications systems recovering second. Power systems were brought up quicker and with shorter downtime since the other critical lifelines were dependent on power to operate. Salman and Li (2018) proposed a framework that integrates a probabilistically weighted deterministic hazard analysis model, the system performance level, a network component measure and a life-cycle analysis using power networks located in Charleston, SC and New York, NY. Nateghi (2018) proposed a resilience framework using data from the impact of Hurricane Katrina on an electric power distribution system located in the Central Gulf Coast Region. Resilience was modeled by hazard characteristics, system topology and the area's climate and topography using a multivariate tree boosting algorithm. The results from the model predicted the number of outages, the number of customers without power and the total cumulative outage durations.

1.3 Dynamic Computational Models

1.3.1 Game Theory

Game theory, first developed by John Von Neumann and Oskar Morgenstern (1928), has been used to study strategic and economic interactions in rational decision makers. It is a discipline in mathematics that aims at modeling situations in which decision-makers must choose specific actions that have mutual, and possibly conflicting, consequences (Sun et al. 2017). The "use of game theory enables the modeling and analysis of multiple players/decision makers. Each is involved in his own optimization problem but with interactions with other decision-makers through objective functions and constraints. This allows the modeler/analyst to capture the complexity and scale of humanitarian post-disaster operations in a more accurate and astute manner" (Nagurney et al. 2019).

Game theory has also been used to model poverty. Factors such as: income, education, health, inequality, social exclusion, and security can explain the poverty paradigm (Passino, 2016). The application of *poverty models* rationalizes the social interdependency of a community. A poverty model is an influence diagram with quantitative measures assigned by importance. In Figure 1.3*,* the poverty model is specified. Wealth, health, and knowledge are the basis of what dictates the degree of poverty for an individual or community.

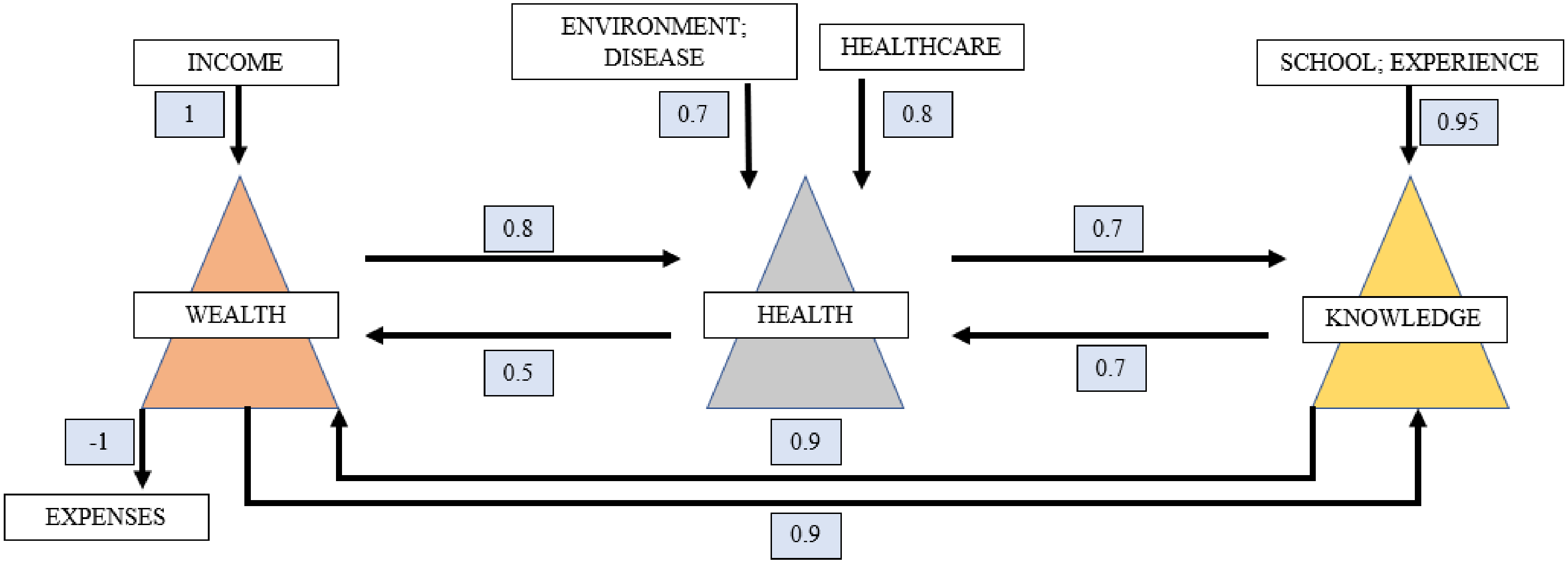


Figure 1.3 Poverty Model

Wealth gives you the ability to adopt better health habits. Without good health, your ability to go to school and gain more knowledge is impossible. Income positively dictates your wealth, but expenses affect it negatively. The environment a person lives in and the healthcare a person has affects their health, and the school and experience an individual has impacts their degree of knowledge. By using this elaborate definition of poverty, a solution for the greater good of a community when faced under a natural disaster can be found.

Game theory can reveal new knowledge in optimizing decision-making schemes for the players (e.g. buildings, community, government officials, and emergency management team) involved. Chakravarty (2011) proposed using game theory to address resource allocation between the government and multiple private and public companies when faced with a disaster. Zhuang et al. (2012) applied game theory in preparedness management in natural disasters. The players in this scenario are federal, local, and foreign governments, private citizens, and adaptive adversaries. Their goal is to seek protection for their lives, property, and critical infrastructure against man-made and natural disasters.

In 2005, the destruction impacted by Hurricane Katrina in the U.S., estimated from between $100 billion to $125 billion (Nagurney, 2017). Disaster management is comprised of decision makers' tactics and direction from the government, private entities, and nonprofit establishments, singling out game theory as an applicable practice to emphasize (Seaberg et al., 2017). Game theory can be of two types: cooperative or non-cooperative. The cooperative game theory calculates the gain of each player in a supportive-everyone wins methodology while noncooperative game theory focuses on the specific moves' players should rationally make to win individually. Every game is comprised of three elements which are players, player actions, and payoff functions (Muhuri et al. 2017).

Rubas et al. (2008) studied a non-cooperative 3 player (USA, Canada, and Australia) game to evaluate the economic linkage between a country using climate forecasts or not. Vasquez et al. (2013) modeled a non-cooperative game for the usage of project scheduling when prioritizing which actions should be taken first after a disaster such as the 2011 Fukushima, Japan nuclear accident. Vahidnia et al. (2013) implemented a geographic agent-based model to simulate agent interaction finding the best forms of evacuation and relief when in the wake of a disaster. Chan (2015) simulated a game theory inspired network for predicting mitigation strategies per disaster or attack.

Alvarez et al. (2019) used a cooperative game to model land use management for flood retention as a useful tool for flood risk management. The game is situated around the accordance of possible agreements among landowners and the establishment of cost / benefit criteria through land development agreements. Chen et al. (2016) investigate the evolution of cooperation between individuals on a public goods game model that considers a person's reputation as well as behavior diversity. Lai et al. (2015) applied game theory for computing the combination weight of flood risk.

When deciding the best evacuation plan after a natural disaster, the first step is understanding the pedestrians' movement. When in a state of disaster recovery, Peng et al. (2014) revealed the practicality of concentrated rural settlement through the usage of game theory. Muhuri et al. (2017) proposed a cooperative game theory-based methodology for road traffic management in a disaster situation. The vehicles acted as players in the game and each vehicle's goal was to reach its destination by choosing the shortest travel time path without disrupting the other vehicles' paths. The payoff was calculated considering its arrival time, priority and velocity. 200 random vehicles were evaluated as players in a disaster area consisting of six road blockages.

Bouzat and Kuperman (2014) use Prisoner's Dilemma game theory approach for optimizing the best pedestrian room evacuation routes. The two by two symmetric games were used where the players, the pedestrians, have access to the same set of strategies and payoffs. Eid et al. (2015) thrive to find an optimum balance between post-disaster insurance plans bought by resident families, retailed by insurance companies, and post-disaster relief executed by a government agency by using the evolutionary stable strategy. The resident families acted as the main controller of the game's environment, and the insurance companies and the government operated as supportive players for analysis.

Attacker-defender games model several players defending a resource or territory and a number of attackers attempting to destroy or capture that defended resource or territory (Sims, 2016). Many times, these games are represented through payoff matrices or decision trees. Hamilton and McCain (2009) used an attacker-defender game for the development of defense strategies when a community is being threatened with a smallpox attack. Hausken et al. (2009) introduced a two-player, attacker-defender game to study the trade-offs among financing in protection from natural disasters or man-made attacks. In this circumstance, the defender is finding a solution on how to properly allocate investments based off different defense mechanisms by investing in defense against either a natural disaster, terrorism, or both. Ferdowsi (2017) implemented a zero-sum noncooperative game consisting of an attacker who seeks to alter the conditions of the gas-power-water critical infrastructure to upsurge the power generation fee and a defender who distributes communication resources to local areas to oversee the infrastructure. Although Ferdowsi (2017) used this application for the case of a manmade disaster, it can also be directly correlated to the community's lifeline dependencies during a natural disaster.

Haphuriwat and Bier (2011) used an attacker-defender game theory model to embody the resource distribution problem during natural disasters for emergency response management. Horiuchi (2012) presented a modified Hawk-Dove game (Maynard-Smith, 1982) for showing the situation during and after a disaster where people assemble groups to support each other through the recovery stage of disaster management. In a Hawk-Dove game, when speaking in terms of resources, the best payoff results from two doves sharing the resources equally, but in this scenario a Dove-Hawk-Bourgeois game is being played, where the doves are in competition for the resources. Although using a static model rather than a dynamic, Lei (2008) structured a risk probability analysis model to cultivate a decision analysis prototype for the alleviation of numerous different disasters through the applications of game theory.

Ergun et al. (2014) used a cooperative game of telecommunications optimization for maximizing supply chain effectiveness when in response to a disaster. Nagurney et al. (2019) introduced an integrated financial and logistical game theory model for humanitarian organizations or non-governmental organizations. In the occurrence of a natural disaster, an influx of resources is sent to the affected area. More than half of the items that arrive at a disaster site are nonpriority items. Victims are then suffering more because they do not receive the critical needed supplies in a timely manner due to the disorganization of dealing with the nonpriority supplies. Noncooperative games were played with the relief item movements and the utilities of the non-governmental organizations and then applied to the situation through game theoretic algorithms.

Coles and Zhuang (2011) introduced a method to provide and aid decision makers in emergency surroundings on how to choose and sustain relationships to advance resource utilization in a disaster. Mulyono (2015) used game theory to model a community's effectiveness in establishing resilient energy production, distribution, and consumption when impacted by a disaster. Zhuang and Bier (2007) investigated resource allocation stabilization for the protection of natural disasters. The attacker-defender game model used was both consecutive and instantaneous with the attacker having an incessant degree of effort. Smyrnakis and Leslie (2010) use a stochastic fictitious play model to determine the proper steps to take in the response phase of disaster management. For more global issues, namely global climate change, Vasconcelos et al. (2015) modeled the effectiveness of a multi-centered architecture of several minor scale agreements through the application of the evolutionary game theory of polycentric governance.

Table 1.2 displays the summary of the literature review on recent research that studied game theory during a natural or manmade hazard scenario.

1.3.2 Agent-based modeling

Efforts to model resilience through game theory applications are still relatively new. Eid and El-adaway (2018) used an agent-based model for post disaster recovery simulations to address how the primary fixation in achieving sustainable disaster recovery lies in two ideas: 1.) integration of stakeholders into the recovery decision-making processes, and 2.) impact of redevelopment, economically, environmentally, and socially speaking, on the host communities' vulnerabilities to hazard events. The five-step research methodology implemented social, economic, and environmental vulnerability assessments, and used residents, the economic sector, insurance companies, and government agencies as the four interacting agents in the agent-based model. The holistic approach was applied to three Mississippi coastal counties during the aftermath of Hurricane Katrina. The results categorized the regions by vulnerability with each region of the three counties being measured from least vulnerable to above average vulnerability for the environmental vulnerability assessment enabling an overall sustainability plan to be put into place for each county.

Table 1. 2 Game theory studies in natural and manmade hazards

<table>
<tr><th colspan="9">Game Theory</th></tr>
<tr><th>Author(s)</th><th>Year</th><th>Game Type</th><th>No. of Players</th><th>Player Type Interaction</th><th>Hazard type</th><th>Application</th><th>Resources to allocate</th><th>Focus</th></tr>
<tr><td>Zhuang &Bier</td><td>2007</td><td>Attacker-Defender; Nash Equilibrium</td><td>2</td><td>attacker-defender</td><td>natural or man-made</td><td>defense against terrorism and natural disasters</td><td>defensive investments</td><td>Security</td></tr>
<tr><td>Lei</td><td>2008</td><td>payoff matrix</td><td>2</td><td>worker-company</td><td>natural or man-made</td><td>safety prevention measures</td><td>company profit</td><td>Disaster Risk Management</td></tr>
<tr><td>Rubas, Mjelde, Love, Rosenthal</td><td>2008</td><td>non-cooperative game</td><td>3</td><td>USA-Canada-Australia</td><td>natural</td><td>agricultural production decisions</td><td>economic measures</td><td>climate forecasts</td></tr>
<tr><td>Hausken, Bier, & Zhuang</td><td>2009</td><td>Attacker-Defender</td><td>2</td><td>attacker-defender</td><td>natural or man-made</td><td>Terrorist attack or natural disaster</td><td>Money investment in defense</td><td>Security</td></tr>
</table>

Table 1.2 Game theory studies in natural and manmade hazards (continued)

Hamilton and McCain	2009	three-player, attacker-defender game	3	attackers, healthcare professionals	natural or man-made	smallpox attack defense	defense strategies	Disaster Risk Management
Smyrnakis & Leslie	2010	stochastic fictitious play	>2	ambulance-ambulance	natural	Natural disaster	ambulance to affected areas	disaster management
Chakravarty	2011	Stackelberg setting	3	Buyer-Vendor-Vendor	natural or man-made	contingent responses from the buyer setting up contracts with both vendors	relief supplies	Disaster response
Coles & Zhuang	2011	Partnership	2	Actor-Actor	natural or man-made	emergency management	resources and services	Disaster recovery
Haphuriwat & Bier	2011	Attacker-Defender	2	attacker-defender	natural or man-made	emergency planning	budget allocation	Security
Horiuchi	2012	Hawk-Dove game	2	Human-Human	natural or man-made	Resource allocation within a community	disaster relief resources	disaster management

Table 1.2 Game theory studies in natural and manmade hazards (continued)

Zhuang, Coles, Guan, He, & Shan	2012	non-cooperative game	5	(federal, local, foreign) government- private citizens-adaptive adversaries	man-made and natural disasters	disaster preparedness	private and public investment	societal resilience
Vasquez, Sepulveda, Alfaro, & Osorio-Valenzuela	2013	non-cooperative game	3	project activity	man-made	project scheduling	workload of resources	Disaster response
Bouzat & Kuperman	2014	Prisoner's Dilemma and Stag Hunt games	2 to 4	Pedestrian-Pedestrian	natural or man-made	emergency evacuation tactics	evacuation	Pedestrian evacuation
Peng, Shen, Zhang, & Ochoa	2014	Nash Equilibrium	2	local government-farmers	natural	rural residential land exchange	profit and costs of land	post-disaster reconstruction

Table 1.2 Game theory studies in natural and manmade hazards (continued)

Ergun, Gui, Heier Stamm, Keskinocak, & Swann	2014	cooperative game	2	agencies	natural	information technology optimization	supplies	Disaster response
Chan	2015	cooperative game	2	Human-Human	natural or man-made	determining an appropriate budget	public-policy options	Security and disaster mitigation
Eid, El-Adaway, & Coatney	2015	Evolutionary stable strategy	3	resident family-insurance company-government	natural	insurance plans	insurance plans	Disaster financial mitigation
Lai, Chen, Wang, Wu, & Zhao	2015	cooperative game; Nash Equilibrium	2	Subjective weight-objective weight	natural	flood-risk evaluation	comprehensive weight in flood-risk evaluation	Flood mitigation; flood risk management
Vasconcelos, Santos, & Pacheco	2015	cooperative game	2	rich-poor	man-made	reduction of green-house-gas emissions	green-house-gas emissions contribution	climate change; environmental sustainability and mitigation

Table 1.2 Game theory studies in natural and manmade hazards (continued)

Vahidnia, Alesheikh, & Alavipanah	2015	geographic agent-based model	4	agents	natural	simulation of agent interaction in evacuation and relief	relief supplies and evacuation routes	Evacuation and Disaster Relief
Mulyono	2015	N-player game	2	electricity users	natural or man-made	smart power grid	electricity	Electricity need in disaster response
Ferdowsi, Sanjab, Saad, & Mandayam	2017	zero-sum non-cooperative game; attacker-defender	2	owner-adversary	man-made	cyber-physical system attack	communication resource allocation	Security of cyber-physical systems
Muhuri, Das, & Chakraborty	2017	cooperative game	200	vehicle-vehicle	natural or man-made	road traffic	waiting time/ travel time path	disaster traffic management
Álvarez, Gómez-Rúa, & Vidal-Puga	2019	cooperative game	3, 5, 5	Landowner-Landowner	natural	flood control and risk management	land use and property rights	Land use management for flood retention
Nagurney, Salarpour, & Daniele	2019	Generalized Nash Equilibrium	2	humanitarian organization-humanitarian organization	natural or man-made	humanitarian organization operations	budget, freight capacity, relief supplies	Disaster Risk Management

In attempting to model community resilience, four different forms are commonly known among researchers: technical (i.e. capability to function and perform), organization (i.e. organization's aptitude to manage the system), social (i.e. society's effort in dealing with the services' deficiencies), and economical (i.e. the competence to decrease both indirect and direct economic costs) (Cimellaro et al. 2016). As previously mentioned, Bruneau et al. (2003) describe four resilience attributes: robustness, redundancy, resourcefulness, and rapidity. The PEOPLES framework is an example of a framework that incorporates all four types of resilience and the four attributes approaching the concept of a multiagent system (Cimellaro et al. 2016). PEOPLES is beneficial for the influence of decision makers when under emergency situations due to its ability to identify different resilience aspects of a community split into seven dimensions. Within each dimension, lies a number of indicators with quantitative indices available for the user's input. At last, the performance functions of each dimension are aggregated into a single serviceability function that embodies the performance of the community after natural disasters. The framework consists of a simulations-based approach and an indicator-based approach (Cimellaro et al. 2016).

Each approach applies an extreme event scenario to the community and performs a fragility analysis. The performance metrics of losses, restoration time, performance index, and resilience index are compared amongst the other layers. This framework was applied to the city of San Francisco after the 1989 Loma Prieta Earthquake (Kammouh et al. 2019). The physical infrastructure dimension was the only dimension of the resilience framework evaluated in this scenario. The results showed a need for better resilience in facilities compared to lifelines.

There is potential for modifying this approach by integrating other game-theory concepts in the sociotechnical network and the impact on *community* resilience. The BDI, beliefs-desires-intentions, agent model developed by Zoumpoulaki et al., (2010) is integrated into the different dimensions and components for defining the interdependencies in the PEOPLES framework. Schut and Wooldridge (2000) and Zhang and Hill (2000) have previously implemented BDI intelligent agents into their work, but this specific BDI design incorporates the Five Factor Model (Costa and McCrae, 1992), OCEAN, which includes five personality traits, Openness, Conscientiousness, Extraversion, Agreeableness and Neuroticism. The multiagent BDI architecture is very similar to a simple reflex agent, but the BDI perception relies heavily on the agent's emotional and personality states. The perception phase is first and begins with the agent obtaining new information based off its surroundings through sensors. As the perception is informed, the agent's previously stated beliefs are updated then are run through an appraisal process. The emotional state gets updated based off its new beliefs and then a desire is generated based off its weighted personality and emotion vectors. The appropriate OCEAN personality traits are then assigned to each agent, and then all actions are formed to replicate human actions during an emergency situation.

1.4 Flood Resilience

Many community resilience frameworks have been investigated for natural disasters, primarily earthquakes, but flooding caution should be emphasized. Climate change and human influences perturb stream flow and the sediment distribution in river systems (Sofia et al. 2020). Flooding not only causes sediment deposition, but also erodes embankments and alters fluvial geomorphic properties (Sofia et al. 2020). Periodic minor flooding impedes human livelihood and creates a less predictable living environment (Sung et al. 2018). Prevalent and more perilous flooding is anticipated due to the effect of extreme climate change and sea level rise. Also, as the temperature rise of oceans continue to occur, intense storm activity is predicted (English et al. 2017), which puts communities in severe risk.

In order to mitigate against flood damage, the National Flood Insurance Program suggests elevating the house, but this action makes the house more vulnerable to larger wind exposure. It is difficult to reduce vulnerability from wind and flood damage concurrently because mitigating solutions may contradict each other. One alternative solution can be amphibious construction in coastal regions to help mitigate hurricane damage from flood and wind damage (English et al., 2017). An amphibious structure relies on buoyancy to offer momentary flotation (i.e. floating docks) and vertical guidance to prevent lateral movement. The first commonly known approach to flood management has been to examine the structural deficiencies of hydraulic systems such as levees or dams and then construct newer and better ones (Sung et al. 2018). This strategy implemented in order to achieve stability and predictably towards flooding, in reality, increases the area's fragility to rare floods in the long run.

Various studies have taken an understanding to the levee effect and have re-examined flood management through different options rather than structurally (Montz and Tobin, 2008). The *levee effect* suggests that intermittent and calamitous disasters are the result of over dependability of structural engineering solutions (Di Baldassarre et al. 2015). Miguez et al. (2019) investigated urban flood control through a systematic approach in finding the optimal design for the Dona Eugenia watershed of the metropolitan area of Rio de Janiero, Brazil. MODCEL, a hydrodynamic model, was used for flood mapping 50-year design alternatives. An index was used to evaluate the flood risk through variables such as socioeconomic dependencies. A flood resilience index was used to assess the resilience through the assessment of its future response to a flood greater with which its design was designed for. Finally, the economic feasibility is determined through depth damage curves for residential housing and project design and construction costs. The results showed that the originally believed most sustainable option regarding flood control was of the river restoration approach was not the best economically feasible choice. The economic factor was too high due to the low-income demographic of the residents in the area. Results showed that the river restoration required the adaption of homes and these changes would be detrimental rather than beneficial for the community.

Falter et al. (2016) estimated flood losses for the German part of Elbe catchment by applying a process-based model cascade with the usage of a rainfall-runoff model, a 1D channel routing model, a 2D hinterland inundation model, and a flood loss estimation model. This four-part procedure known as the regional flood model, RFM, was continuously performed over the period of 1990-2003, 14 years. RFM showed a large range of uncertainties within the data. Three floods occurred during the simulation period enabling a large percent in error in the 1D hydraulic model set-up. Sung et al. (2018) implemented a conceptual model of human-flood interaction facilitated by flood control strategies considering instabilities in the Ganges-Brahmaputra delta in southwest Bangladesh. Taking seasonal water level fluctuations and rising land-sea level difference into account in the model community's flood protection system, the results showed that adaptive forms of flood control strategies outperformed nonadaptive ones.

1.5 Urban Resilience vs. Rural Resilience

When distinguishing rural communities vs. urban communities, a prioritization to urban areas during a state of emergency is more prevalent than in rural areas. Between the years 2010 and 2016, a tremendous drop in rural population has occurred along with higher poverty and unemployment rates (USDA, 2017). Tierney (2013) describes rural communities as "under resourced places in which the capacity to anticipate, cope, and adapt has been seriously compromised."

Mukherjee et al. (2017) investigated resilience in rural India using the key predictors of severe weather-induced sustained power outages. The authors found that there was a lack of attention from utility companies in terms of hardening the electric infrastructure or investing in operation and maintenance in rural areas. Compared to urban areas, less priority is given to rural areas in terms of disaster recovery efforts which inevitably leads to longer recovery periods for rural communities (Mukherjee et al. 2017). Communities with a large percent of commercial electricity consumption are communities with a huge percent of commercial enterprises such as shopping centers, grocery stores, and social facilities. Urban areas are where most of these facilities are built in. Since such commercial facilities' main objective is to be aesthetically pleasing to the public for more clientele, there is a huge urge for fast recovery. Since rural communities contain less of these commercially owned facilities and the land is more of personal usage, the recovery period will be entailed longer (Mukherjee et al., 2017).

When applying for grants and financial resources, urban communities have superior prerogative due to a larger vulnerable population and more prominent infrastructure at hand (Caruson and MacManus, 2011). With federal support being scarce for rural areas, investing in community resilience becomes an even more challenging goal (Aldrich and Meyer, 2015). With the infrastructure of rural communities lacking quality and proper zoning and building enforcements (Schwab, 2016), being impacted by a natural or manmade disaster encourages the local government to attempt to increase resilience through stricter or newer building codes. These new changes make it difficult for former residents to afford property with the new improved standards causing gentrification to ensue (Ganapati et al. 2013).

Although more people make up urban communities, rural communities have a better sense of social capital (Jerolleman, 2020). Cutter et al., (2016) used a resilience index BRIC, Baseline Resilience Indicators for Communities, to investigate the impact of rural characteristics on a community's resilience. The authors' findings reported that rural communities had a strong social capital, social connectivity amongst the community, allowing a better communitive response to unexpected events. For example, in 2005 during the aftermath of the destruction Hurricane Katrina produced, rural Louisiana boat owners hurried to New Orleans to help rescue those trapped on top of residential roofs (Jerolleman, 2020). Another example was during the 2011 Virginia Tornado where local churches sheltered and provided goods, neighboring families assisted each other with clearing debris, and outside regional people came to offer aid causing the residents to only need to stay at the shelter for two days (LaLone, 2012).

Although the social capital element helps with disaster recovery, better hazard mitigation planning needs to be accounted for. Inadequate resources, more isolated towns, insufficient experts or consultants in the disaster mitigation field, and poor housing stock all disable proper community planning (Horney et al. 2017). Recovery committees do not have enough people or personnel to fill it, therefore leaving the community in danger. Disaster prevention should be seen as a public good (Jerolleman 2020). Mining-related incidents and other environmental and technological disasters have been focused on being prevented by the local governments of rural communities, but more frequently occurring natural disasters such as flooding, should be better invested in instead (Scott et al. 2012). Within the Appalachian Region of the United States, flooding has either been the cause or destroyed projects to better the region such as during the constructions of the Racine, Ohio water treatment plant and storage in 2004, the Water Valley, Mississippi sewer in 2007, and the waste water treatment solutions for West Virginia's coal region in 2010 (Appalachian Regional Commission, 2013).

The Appalachian Region is a 205,000 square-mile region in the US composed of 420 counties whose economies relied heavily on mining and coal exploration. When those industries were no longer needed in those areas, a high poverty rate spiked resulting to over 30% in 1960. Today most of these areas are still recovering and are 42% rural (Appalachian Regional Commission). Kentucky is one of the 13 states a part of the Appalachian Region.

38 out of 120 counties are a part of Appalachian Kentucky. Due to its recovering economy, resources and government funds are still minimal therefore when approached by a natural hazard, it could have severe consequences. As prevalent as floods are, by using a disaster pre-decision tool to estimate losses local officials and politicians can form more efficient emergency preparation plans and prioritize community investments.

With flooding in rural communities being a prominent dilemma yet to be solved, a pre-decision framework may be the best solution. A modified PEOPLES framework is proposed in this research to study the resilience of rural communities' subject to severe flooding events. Harlan County in the Appalachian region is chosen as the case study. In order to gather data that can be used as input, a scenario flood will be applied to Harlan County through the FEMA HAZUS flood model. The flood investigated will be set in February, reflecting the February 2018 flood that caused immense damage to the county (Marie, 2019).

CHAPTER 2. PROBLEM FORMULATION

2.1 Problem Synopsis

In 2015, three United Nations global policies were implemented: 1.) the Sendai Framework, 2.) The Sustainable Development Goals, and 3.) The Paris Agreement on Climate Change. In March 2015, 187 United Nations member states agreed on the adoption of the Sendai Framework (2015-2030). The Sendai Framework was developed in Sendai, Japan and aims at merging current and past community resilience research to reduce the number of lives lost in natural and manmade hazards each year globally (Aitsi-Selmi et al. 2016). The Sendai Framework emphasizes the need to “enhance the scientific and technical work on disaster risk reduction and its mobilization through the coordination of existing networks and scientific research institutions at all levels and in all regions, with the support of the United Nations Office of Disaster Risk Reduction Scientific and Technical Advisory Group (UNISDR 2015).”

Natural hazards continue to pose a challenge to the built environment and understanding the impact of these hazards in a community is a complex problem. Hazards are geographically dependent. Rural Kentucky most common hazard are flood events. Although the fatality rate is higher for earthquake events, prolonged property damage is significant during flood events. Furthermore, with federal support being scarce for rural areas, investing in community resilience becomes a difficult challenge. Predicting the potential losses of one natural hazard can support in understanding the effects of critical decisions in allocating limited resources.

Within the state of Kentucky, many floods have occurred, causing flood resilience to be incredibly prevalent even today. For the reason that the need for resilient infrastructure is vital for society, this research focuses on a holistic approach to quantify the resilience of Rural Appalachia. This research studies a renowned resilience framework, PEOPLES, to Harlan County, Kentucky, after a major flood event. The flood investigated is set in February, reflecting the February 2018 flood that caused $24,726,412 worth of damage to Southeastern Kentucky (FEMA-4361-DR). The novelty of this research is threefold: (a.) an accessible indicator-based PEOPLES approach is used as opposed to the traditional simulation-based approach, (b.) the aim of this study is focused on rural communities as opposed to the prevalent resilience frameworks for urban communities, and (c.) a unified way of addressing the effects of multiple hazards.

2.2 Methodology: PEOPLES

PEOPLES is an indicator-based framework that identifies different resilience aspects of a community split into seven dimensions. The dimensions are: 1.) population and demographics, 2.) environmental and ecosystem, 3.) organized governmental services, 4.) physical infrastructure, 5.) lifestyle and community competence, 6.) economic development, and 7.) social-cultural capital. Within each of the seven dimensions, qualitative measures are interpreted into quantitative measures. This methodology combines technical and non-technical characteristics and incorporates the interdependent relationships within a community into the overall resilience index. An interdependency matrix technique applies levels of importance to different components based on functionality dependability. This framework provides decision-makers the opportunity to quantify the long-term benefits and evaluate preliminary decisions towards strategic planning for a rural community development. A closer step towards flood resilience allows communities to penetrate the deficiencies within their community to be able to take the preparations to improve their resilience towards natural disasters. Frameworks that quantify the resilience of Rural Appalachia can open the door for evaluating resilience of rural communities worldwide subjected to multiple hazards.

Bruneau et al. (2003) describe four resilience attributes (four R’s): robustness, redundancy, resourcefulness, and rapidity. The PEOPLES framework incorporates all four attributes of resilience, allowing a holistic resilience quantification approach aiding decision makers before, during, and after emergency situations. PEOPLES incorporates the four forms of resilience among researchers through the following performance measures: technical (i.e. capability to function and perform), organization (i.e. organization’s aptitude to manage the system), social (i.e. society’s effort in dealing with the services’ deficiencies), and economical (i.e. the competence to decrease both indirect and direct economic costs) (Cimellaro et al. 2016).

The technical, organizational, social, and economic performance measures within a community can be identified by the integration of the four R’s (Bruneau et al. 2003). Robustness is seen technically as the degree of avoidance in damage, organizationally as the ability to continue community essential functions, socially as casualty avoidance and disorder in the community, and economically as avoidance of direct and indirect losses (Bruneau et al. 2003). Redundancy is measured technically by the extent of backup plans and extra supplies available, organizationally as the number of alternative shelters and relocation sites accessible, socially as the amount of community needs options, and economically as the additional number of inventories and suppliers (Bruneau et al. 2003). Resourcefulness is assessed technically as the amount of damage detection methodologies present, organizationally as the number of plans and amount of resources put in place in order to manage the damage and disturbance, socially as the amount of resources for community needs options, and economically as the capacity to recovery financially from an unexpected impact (Bruneau et al. 2003). Finally, the level of rapidity is defined technically through the recovery-period necessary for the entire community to return to its original state, organizationally by the minimal time necessary for key services to be restored, socially by the average recovery time needed for societal levels to return as before, and economically by the average recovery-period needed for the economy to return to its original, functioning state (Bruneau et al. 2003).

Figure 2.1 shows the seven dimensions from the PEOPLES framework, each dimension overlapped with the map overlay of Harlan County, KY. Harlan County is located in Southeastern Kentucky, and it is an area with intersecting attributes important to take into consideration when studying resilience against natural hazards in totality. The PEOPLES framework can be used through two approaches: 1.) Simulation-Oriented Approach, or 2.) Indicator-Oriented Approach (Cimellaro et al. 2016).

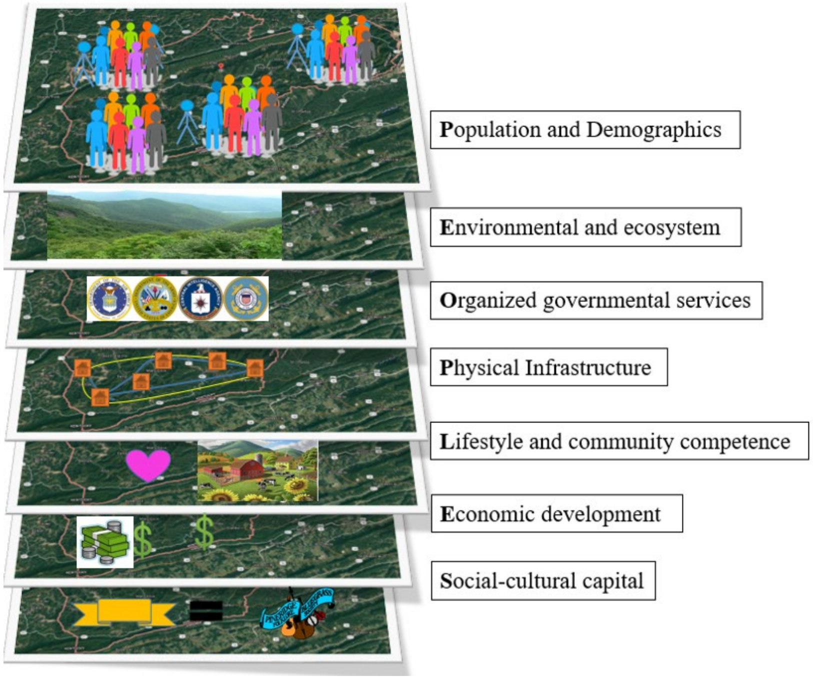


Figure 2. 1 PEOPLES seven dimensions for Harlan County

The simulation-oriented approach methodology is visually justified in Figure 2.2. First, the community is assessed through the four *R*'s of resilience, robustness, resourcefulness, redundancy, and rapidity (Bruneau et al. 2003) to establish the pre-event conditions. Then, a scenario disaster is applied to the community under investigation. The hazard damage data is then analyzed through the combined framework organizing physical lifelines (i.e. power and water) into network models and the non-physical lifelines (i.e. emergency medical professionals and the fire unit) into agent-based models. The PEOPLES framework adapted a Beliefs-Desires-Intentions (BDI) agent-based model developed by Zoumpoulaki et al. (2010) to simulate the non-physical lifelines (e.g., the emergency management team and fire brigade response during the hazard event). Then, that data is organized into the seven dimensions, $\beta_{1\ldots7}$, and used to create a community resilience index. Next if the community resilience index insufficiently characterizes the community, the index is reexamined through "Breaks and Importance Identification" and "Supply and Opportunity Assessment" identifying any missed features about the specific community needed to satisfy the simulation. Finally, the community is evaluated through the four R's again and newer built performance measures produce another community resilience index.

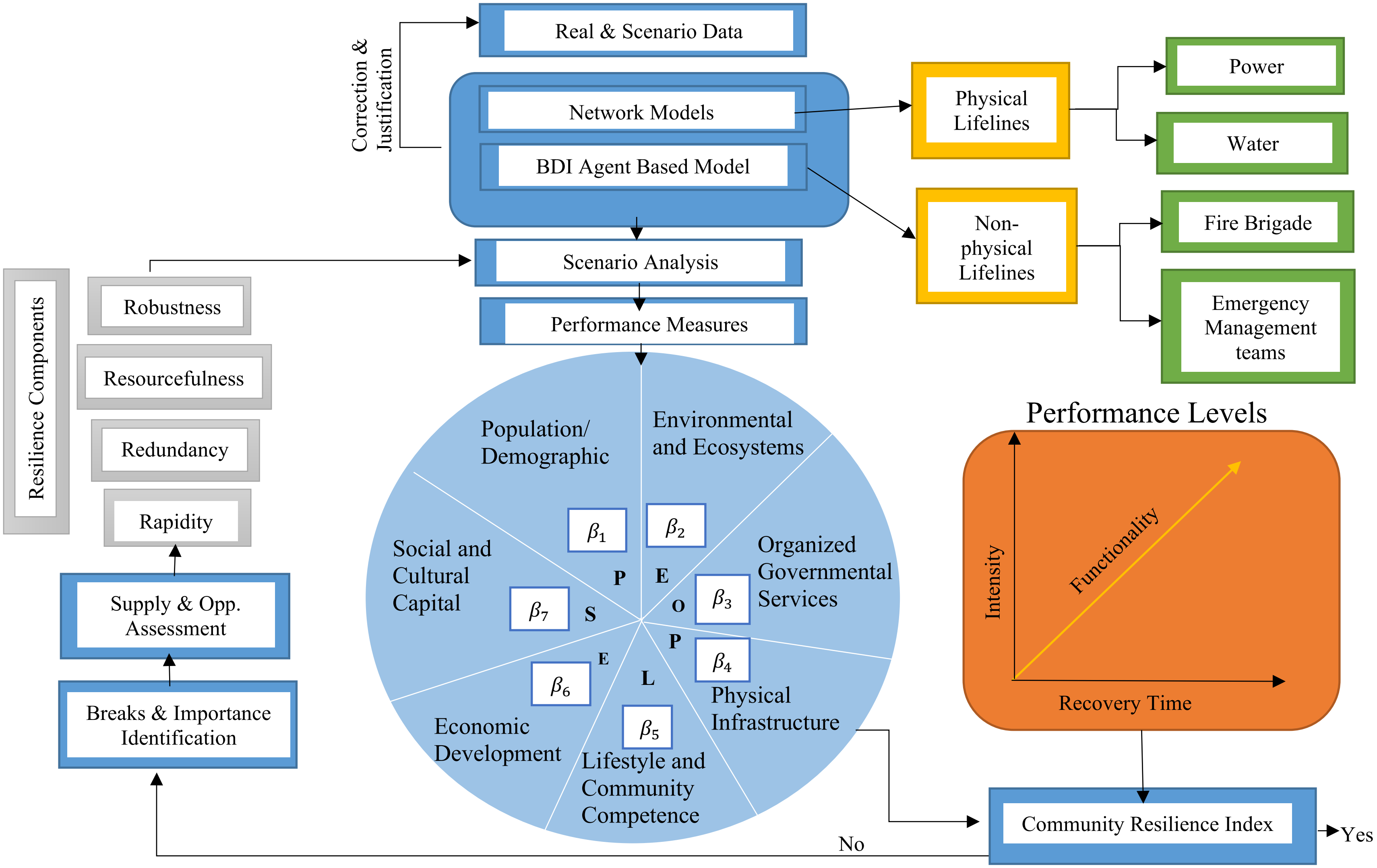


Figure 2. 2 PEOPLES simulation-oriented approach explained through the ABM and network

Although the simulation-oriented approach uses newer agent technology, the indicator-oriented approach offers a more accessible solution for local government officials within rural communities. This tool provides decision makers with quick and easy solutions for preliminary decisions in comparison to the simulation-oriented approach which is more time consuming and expensive to run (Cimellaro et al. 2016). With the indicator-oriented approach, there are many more options in data attainment as with the simulation-oriented approach, the simulation is assumed to already have permanent data. Using the indicator-oriented approach allows various simulations to be run, allowing the community to be studied as a dynamic relationship and data to be continuously modified. The proposed modified framework is a unified approach to quantify resilience of rural communities

This approach evaluates the scenario hazard on the community through a layered framework based off the dimensions: population and demographics, environmental and ecosystem, organized governmental services, physical infrastructure, lifestyle and community competence, economic development, and social and cultural capital. Within each of the seven dimensions, lies multiple components with a characteristic associated with the theme of the specified dimension, and within each component lies various indicators which take the qualitative measures and interpret them as quantitative measures.

The hierarchical relationship is shown in Figure 2.3. The variables *D, C, I,* and *M* represent the dimension, component, indicator, and measure, respectively, with the subscript 1, 2, through i to denote each group sequentially. Each measure is identified as either static or dynamic, values not affected by the event or values sensitive to the event, respectively, and then standardized with respect to the baseline measure specified. There are 115 indicators in total available for the user's input (Kammouh et al. 2018). Gathering data from all the variables compiles the degradation of the system over the recovery also known as the loss of resilience, LOR, measure by using Eq. 1 (Kammouh et al. 2019):

$$LOR = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt \tag{1}$$

where $Q(t)$ is the functionality of the system, T_C is the control time, and t_0 is the time at which the event occurs, and t_1 is the time at which the community's serviceability recovers to its original state (without considering the aging effects). The area under the final serviceability function is the total resilience of the applied community.

In order to compile an accurate resilience curve for the community, the variables must be structured appropriately. First, the layered levels of the framework are assigned importance factors. Importance factors are applied to the dimensions, components, and indicators to assign superiority within its applied community. The factors range from 1 to 3, with 1 being of least importance (Cimellaro et al. 2016). For example, within the Physical Infrastructure dimension 23 importance factors are appointed. These factors assign importance to the variables within each dimension according to resilience. The higher the importance factor, the higher the importance to the overall system's resilience.

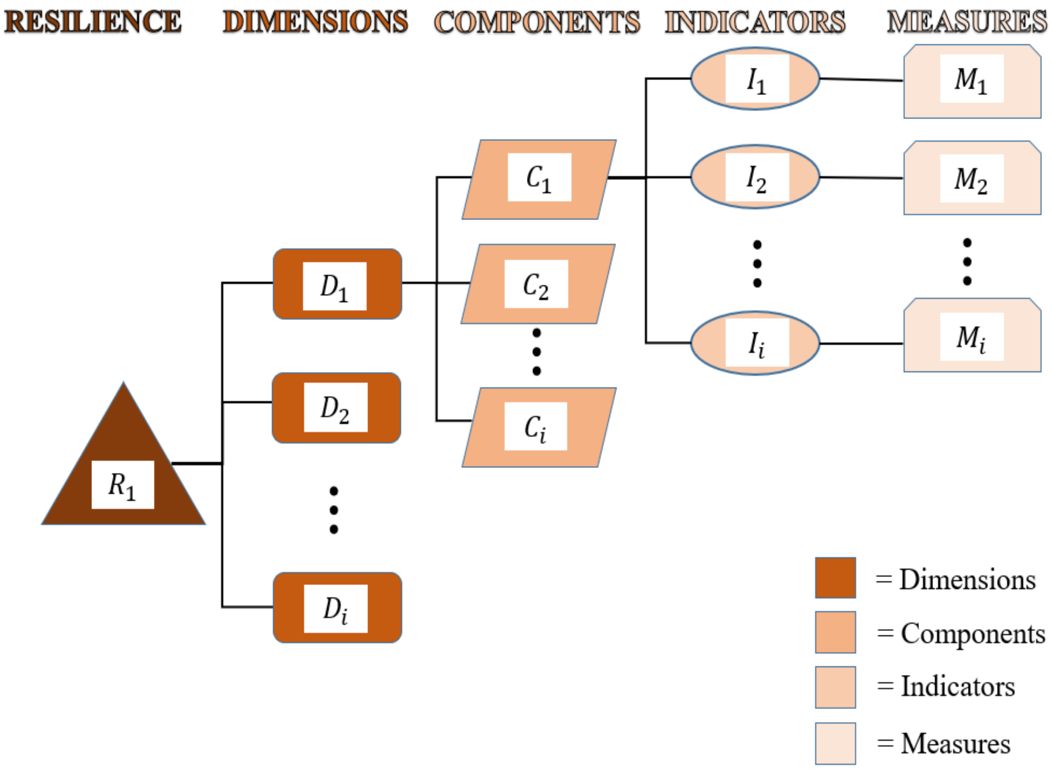


Figure 2.3 The dimensions, components, indicators, and measures of PEOPLES

Next, in order to assign rank amongst indicators, components, and dimensions, an interdependency matrix technique is performed producing interdependency factors. The interdependency factors are used to eliminate irrelevant or overlapping measures. All corresponding indicators per component are analyzed, all components per dimension are analyzed, and all seven dimensions are analyzed amongst themselves. The interdependency matrix technique can be visually explained in Table 2.1. A square matrix is formed for each level starting from the lowest level, the indicators. The first row and column are the indicators above and adjacent to each cell. The values in the matrix are either 0, meaning the component's functionality does not depend on the indicator, or 1, meaning the component's functionality does depend on the indicator, (Kammouh et al., 2019). The values are then added vertically, and the sums correspond to the interdependency factors for each indicator. The same is performed for the components per each dimension and then finally with all seven dimensions to create the final community resilience index.

Then, the importance factors and interdependency factors are used to create a weighted factor that is applied to each variable's functionality function using Eq. 2 (Kammouh et al. 2019)

$$w_i = \frac{\alpha_i \beta_i}{\sum_{i=1}^{n} \alpha_i \beta_i} \cdot n \tag{2}$$

where w_i is the weighting factor of the i^{th} variable, α_i is the importance factor of the i^{th} variable, β_i is the interdependency factor of the i^{th} variable, and n is the number of variables in the calculated array. For example, when computing the weighting factor for the lifelines component for the physical infrastructure dimension, *n* would be 13 for the 13 indicators within that specific component. The revised functionality function becomes Eq. 3 (Kammouh et al. 2019)

$$Q_i^* = w_i \cdot Q_i \tag{3}$$

where *i* indicates which specific variable is used, Q_i^* is the new functionality function, w_i is the weighted factor, and Q_i is the original functionality function.

Finally, each indicator, component, and dimension's functionality function are aggregated into a single functionality function that embodies the overall resilience performance of the community after natural disasters as seen in Eq. 4 (Kammouh et al. 2019).

$$R(t) = \sum_{i=1}^{D=7} w_i(t) \cdot D_i(t) \tag{4}$$

where w_i is the weighting function of the i^{th} dimension; and D_i is the functionality function of dimension i. *D* equals 7 due to the seven dimensions in PEOPLES.

Table 2. 1 Interdependency matrix technique

Indicator	Sturdier housing types	Temporary housing availability	Housing stock construction	Community services	Economic infrastructure exposure	Distribution commercial facilities	Hotels and accommodations	Schools
Sturdier housing types	1	0	1	0	0	0	0	0
Temporary housing availability	0	1	1	0	0	0	0	0
Housing stock construction	0	0	1	0	0	0	0	0
Community services	1	0	1	1	1	1	1	1
Economic infrastructure exposure	0	0	1	0	1	1	0	0
Distribution commercial facilities	0	0	0	0	1	1	0	0
Hotels and accommodations	0	0	1	0	0	0	1	0
Schools	0	0	1	0	0	0	0	1
$\sum$ =	2	1	7	1	3	3	2	2

The dimension i's functionality function is computed by Eq. 5 (Kammouh et al., 2019)

$$D_i(t) = \sum_{j=1}^{n_i} w_{i,j}(t) \cdot C_{i,j}(t) \tag{5}$$

where $w_{i,j}$ is the weighting function of component j under dimension i, $C_{i,j}$ is the functionality function of component j under dimension i, and n_i is the total number of components under dimension i. The component i's functionality function is computed by Eq. 6 (Kammouh et al., 2019)

$$C_i(t) = \sum_{k=1}^{n_{ij}} w_{i,j,k}(t) \cdot I_{i,j,k}(t) \tag{6}$$

where $w_{i,j,k}$ is the weighting function of indicator k under component j, which belongs to dimension i, $I_{i,j,k}$ is the functionality function of indicator k under component j, which belongs to dimension i, and n_{ij} is the number of indicators under component j, which belongs to dimension i. Using Eq. 4 as reference, the community's resilience in totality is expanded into Eq. 7 (Kammouh et al. 2019)

$$R = \int_{t=t_o}^{t_c} R(t)\, dt = \left\{ \sum_{i=1}^{D=7} w_i(t) \cdot \left[\sum_{j=1}^{n_i} w_{i,j}(t) \cdot \left(\sum_{k=1}^{n_{ij}} w_{i,j,k}(t) \cdot I_{i,j,k}(t) \right) \right] \right\} dt \tag{7}$$

Finally, to achieve the resilience index, each variable's functionality function compiles a serviceability curve that is also aggregated and put into one whole serviceability curve for the community as displayed in Figure 2.4. All seven dimensions of the PEOPLES framework are measured by their components, the indicators within each component, and the measures assigned for interpreting each indicator. The seven dimensions of the PEOPLES framework use specific equations and points of reference for dimensions' measures.

This indicator-based approach framework was applied to the city of San Francisco after the 1989 Loma Prieta Earthquake (Kammouh et al., 2019). The results showed a need for better resilience in *facilities* compared to *lifelines*. The recovery time for residential homes to return back to their original states was 120 days, approximately. All indicators within the components were assigned importance factors of 3 except for community services and economic infrastructure exposure within the *facilities* component.

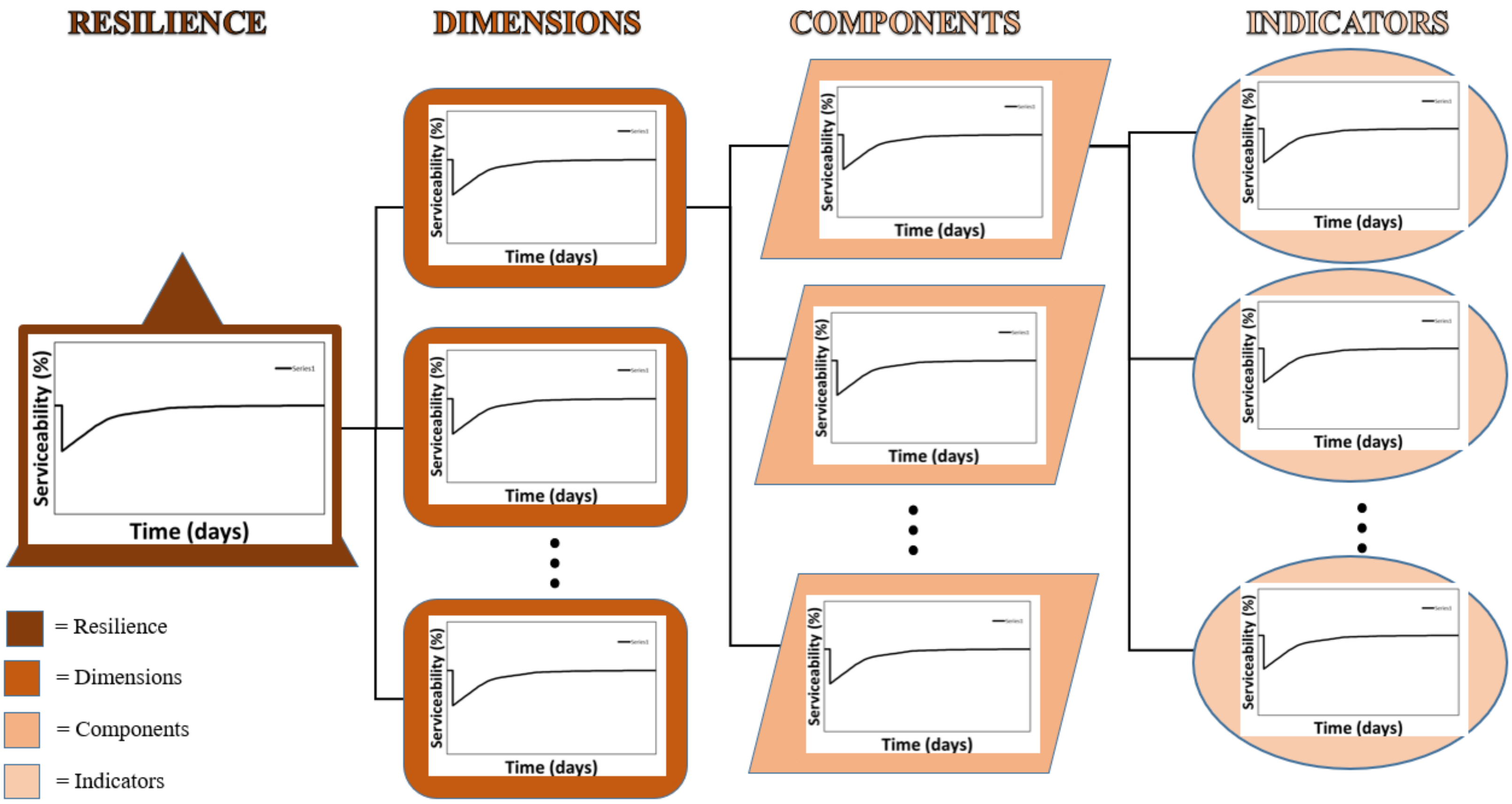


Figure 2.4 The serviceability curves for the community shown through the levels of the variables, dimensions, components, and indicators

CHAPTER 3. RESILIENCE QUANTIFICATION OF HARLAN COUNTY, KENTUCKY

3.1 Case Study: Harlan County, Kentucky

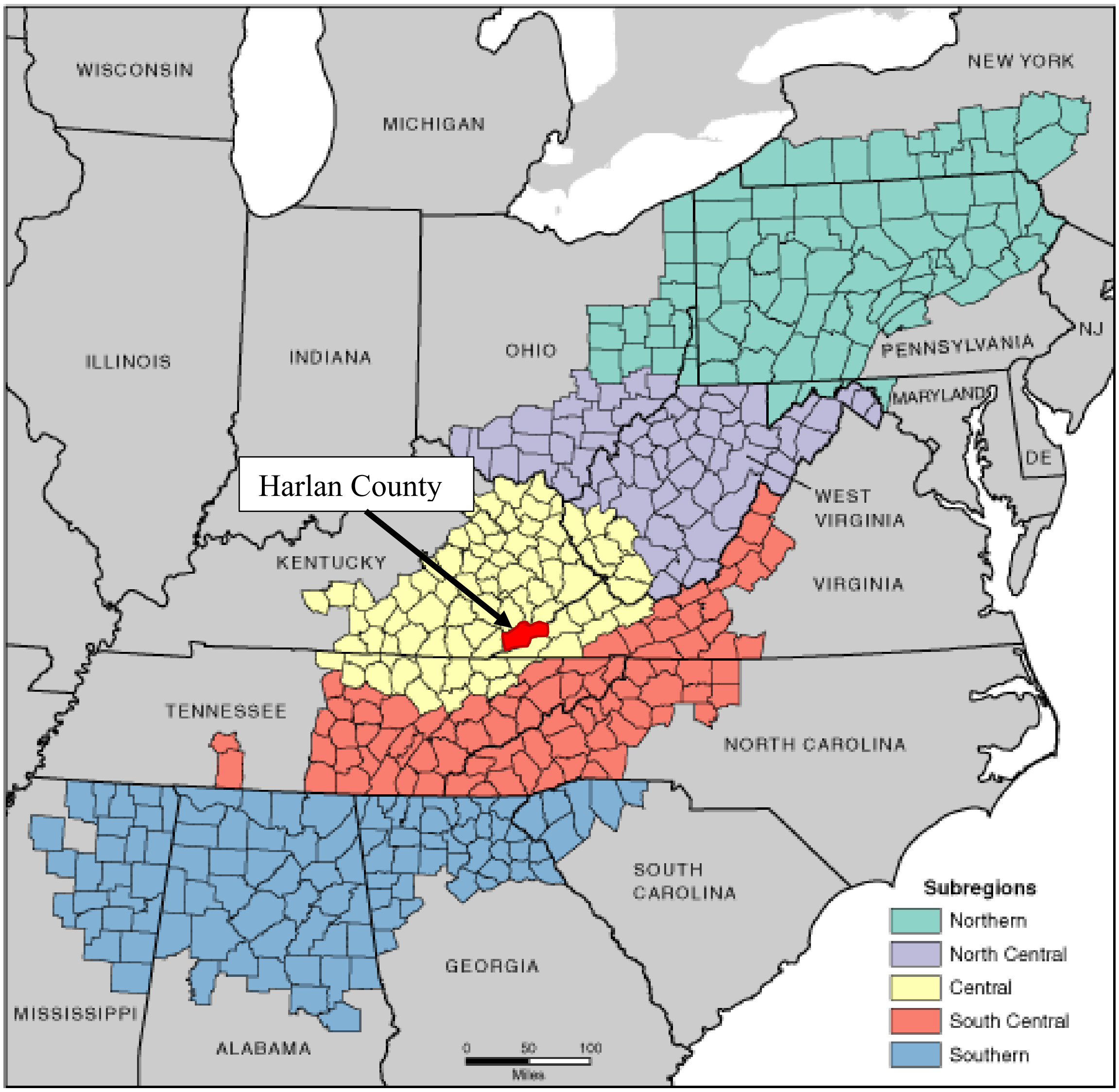


Figure 3.1 Map of US Appalachian Region with Harlan County (Source: www.arc.gov)

Within the state of Kentucky, many floods have occurred causing flood resilience to be extremely prevalent even today. The state of Kentucky has had a total of 79 disaster declarations (FEMA, 2020), the first being in January 1957 (DR-66) and the most recent in March 2020 (DR-4497) with the most recent due to severe storms in April 2019 (DR-4428). A disaster declaration is an emergency declaration that declares a plea for financial and physical aid through FEMA, the Federal Emergency Management Agency, funding. The state has one of the lowest emergency management budgets of $59,070,300 labeling it as one of the country's most unprepared states for natural disasters (WKYT, 2018). Rural Kentucky is at constant battle with landslides, mudslides, rockslides, flooding, tornadoes, and severe storms including extreme rain and wind problems (Whiteman, 2013). The FEMA DR-4428 report declared Kentucky in a state of disaster during February 6 to March 10, 2019 for severe storms, straight-line winds, flooding, landslides, and mudslides. $740,193.88 were allocated from public grants (FEMA DR-4428).

Five significant floods have occurred in the state of Kentucky dating back to 1937, 1945, 1977, 1997, and 2010 (NOAA, 2018). Harlan County, as outlined in Figure 3.1, experienced one of the worst floods since the 1977 flood in February 2018 (Marie, 2019). The habitants are still recovering from the June 2018 flood damage and with the added disaster impact, more roads were left so damaged they were forced to be closed. Water had crested at 22.6 feet well over the 16 feet flood stage consideration, with precipitation at 5.4 inches from 4:00 am Saturday to Sunday evening (Asher, 2018). Churches, fire stations, and the courthouse acted as shelter areas for the public. With Harlan County relying heavily on the agricultural business, this negatively contributed to its declining low economy.

The Harlan County Emergency Management Team performs Damage Assessment Reports after every natural disaster recording the degree and details of the damage done to public and residential infrastructure. Damage Assessment Reports from June 2016, February 2018, and February 2019 flood events were given to the researchers for purposes of aiding the physical infrastructure input for the PEOPLES framework. The Damage Assessment Reports are split into several sections depending on if it is public or residential infrastructure. The public infrastructure forms are composed of 11 sections: location information and damage, damage values, facility information, detailed damage, insurance information, contacts, notes, photos, special needs, environmental issues and impacts, and state/FEMA review. The residential property forms are composed of 10 sections: location information and damage, damage values and demographics, detailed damage, insurance information, contacts, notes, photos, special needs, environmental issues and impacts, and state/FEMA review. For the February 2018 flood, 3 out of the total 25 Damage Assessment Reports reported back affected, and 12 out of 16 from the February 2019 flood were reported back with “major damage.” A sample of representative assessments reports obtained are in Appendix 1.

In order to validate the proposed methodology for resilience quantification of rural communities, the HAZUS Flood Model will first be used to apply a scenario flood to Harlan County, Kentucky. The scenario flood applied will be a 100-year flood based off the February 2018 flood. Then, estimation losses will be retrieved and used as input into the PEOPLES framework for the community resilience evaluation. The indicator-oriented approach methodology is investigated in this research. There is a total of seven dimensions with a sum of 29 components and 116 indicators. For example, the physical infrastructure dimension consists of two components, facilities and lifelines. Eight indicators pertain to the facilities component, and thirteen indicators belong to the lifelines component. The input measures for each indicator are specified in Table 3.1. Each indicator is described by a measure and input as a quantitative value.

The input data is obtained by multiple databases, including the US Census Bureau, ArcGIS, EIA (US Energy Information Administrative), USGS (Unites States Geological Survey), KYTC (Kentucky Transportation cabinet), City-Data, ARC (Appalachian Regional Commission), Civic Dashboards by Open Gov, Kentucky Department of Fish and Wildlife Resources, Kong et al. (2008), Dai et al. (2016), Exumet et al. (2005), USDA (United States Department of Agriculture), Commonwealth of KY: State Board of Elections, Tri Cities Heritage Development Corporation, CRE (Community Resource Exchange), USNRC (United States Nuclear Regulatory Commission, FEMA, National Park Service, Kentucky Adult Education U-Skills, Kentucky Emergency Management, EWG (Environmental Working Group), Kentucky Department of Agriculture, KET (Kentucky Educational Television), National Climate Assessment, and KYDLG (Kentucky Department for Local Government).

Table 3.1 Physical Infrastructure dimension measures

4. Physical Infrastructure		
4.1 Facilities		
Index	Indicator	Measure
4.1.1	Sturdier housing types	% housing units not manufactured homes
4.1.2	Temporary housing availability	% vacant units that are for rent
4.1.3	Housing stock construction quality	100-% housing units built prior to 1970
4.1.4	Community Services	%Area of community services (recreational facilities - parks - historic sites - libraries - museums) total area /SV
4.1.5	Economic infrastructure exposure	% commercial establishments outside of high hazard zones /total commercial establishment
4.1.6	Distribution commercial facilities	%Commercial infrastructure area per area /SV
4.1.7	Hotels and accommodations	Number of hotels per total area /SV
4.1.8	Schools	Schools area (primary and secondary education) per population /SV
4.2 Lifelines		
Index	Indicator	Measure
4.2.1	Telecommunication	Average number of Internet - television - radio - telephone and telecommunications broadcasters per household /SV
4.2.2	Mental health support	Number of beds per 100 000 population /SV
4.2.3	Physician access	Number of physicians per population /SV
4.2.4	Medical care capacity	Number of available hospital beds per 100000 population /SV
4.2.5	Evacuation routes	Major road egress points per building /SV
4.2.6	Industrial re-supply potential	Rail miles per total area /SV
4.2.7	High-speed internet infrastructure	% population with access to broadband internet service
4.2.8	Efficient energy use	Ratio of Megawatt power production to demand
4.2.9	Efficient water use	Ratio of water available to water demand
4.2.10	Gas	Ratio of gas production to gas demand
4.2.11	Access and evacuation	Principal arterial miles per total area /SV
4.2.12	Transportation	Number of rail miles per area /SV
4.2.13	Wastewater treatment	Number of WWT units per population /SV

■	= Dimension
▩	= Component
▨	= Indicator
□	= Measure

For example, Table 3.2 shows the input used for the Facilities and Lifelines components within the Physical Infrastructure dimension. Seven main inputs must be inserted into the PEOPLES software: w (the weighting factor), Nat (nature, meaning static, s or dynamic, d, q_{0u} (serviceability before the event), SV (the standard value/reference point to which the indicators are measured), q_1 (the serviceability after the event), q_r (the serviceability after recovery), and T_r (the restoration time in days). q_1 and q_r values must be normalized by the user and divide the quantities over SV.

Table 3.2 Facilities and Lifelines inputs for the Physical Infrastructure dimension

Physical Infrastructure									
4.1 Facilities *(Importance: 2)*									
INDEX	INDICATOR	w	Nat	q_{0u}	SV	q_0	q_1	q_r	T_r
4.1.1	Sturdier housing types	0.81	d	0.117	1	0.12	0.10	0.12	480
4.1.2	Temporary housing availability	0.41	d	0.245	1	0.25	0.20	0.25	480
4.1.3	Housing stock construction quality	2.85	d	56.3	65.8	0.86	0.78	0.86	480
4.1.4	Community Services	0.27	d	0.4	1	0.40	0.20	0.40	480
4.1.5	Economic infrastructure exposure	0.81	s	0.85	1	0.85	-	0.85	-
4.1.6	Distribution commercial facilities	1.22	d	0.176	1	0.18	0.15	0.18	480
4.1.7	Hotels and accommodations	0.81	d	8	10	0.80	0.40	0.80	720
4.1.8	Schools	0.81	d	18	20	0.90	0.85	0.90	480
4.2 Lifelines *(Importance: 3)*									
4.2.1	Telecommunication	1.56	d	0.973	1	0.97	0.49	0.97	480
4.2.2	Mental health support	0.13	s	150	150	1.00	-	1.00	-
4.2.3	Physician access	0.26	s	50	100	0.50	-	0.50	-
4.2.4	Medical care capacity	0.59	s	150	150	1.00	-	1.00	-
4.2.5	Evacuation routes	0.52	s	0.563	1	0.56	-	0.56	-
4.2.6	Industrial re-supply potential	0.59	d	100	2526	0.04	0.03	0.04	480
4.2.7	High-speed internet infrastructure	0.39	d	0.542	1	0.54	0.27	0.54	480
4.2.8	Efficient energy use	2.15	d	0.733	1	0.73	0.60	0.73	480
4.2.9	Efficient water use	1.37	d	0.0014	1	0.00	0.00	0.00	480
4.2.10	Gas	0.98	d	0.264	1	0.26	0.14	0.26	480
4.2.11	Access and evacuation	1.56	d	186	200	0.93	0.75	0.93	480
4.2.12	Transportation	1.76	s	100	2526	0.04	-	0.04	-
4.2.13	Wastewater treatment	1.17	s	4	6	0.67	-	0.67	-

3.2 The Hazards U.S. Multi-Hazard

The Hazards U.S. Multi-Hazard, namely HAZUS®-MH (FEMA,2003), was created by the Department of Homeland Security for the Federal Emergency Management Agency in the Mitigation Division in Washington, D.C under a contract with the National Institute of Building Sciences (FEMA, 2003). As a part of the Natural Hazards Risk Assessment Program, its mission is to provide risk assessment data, tools, and analyses to support the development of risk communication tools for all phases of emergency management. HAZUS®-MH utilizes Geographic Information Systems (GIS) technology to estimate physical, economic, and social impact losses from earthquakes, floods, and hurricanes. Government planners, GIS specialists, and emergency managers use HAZUS to define losses and valuable mitigation tactics to take to reduce them. Microsoft SQL Server is used to organize the extensive amount of data generated for a given regional loss estimate (FEMA, 2003).

In the HAZUS Flood Model, the study region is evaluated through a county level region aggregation. Harlan County was selected from downloaded Kentucky state data updated to RSMeans (construction cost database) 2018 values and reflecting Census 2010 data. A flood hazard generation and flood loss estimation analysis will be performed for riverine flooding. In order to accurately estimate flood depth, elevation, and velocity, frequency, discharge, and ground elevation features are used in this process. The Flood Model uses a dasymetric, a method using areal symbols to spatially classify volumetric data, version of the Census Block data which attempts to clip out the unpopulated areas of the Census Block in order to focus on generating an analysis for the built environment (FEMA, 2003).

An extensive array of databases are used in the HAZUS Flood Model including, but not limited to, the 2013 National Land Cover Database products by the US Army Corps of Engineers, the article "Compilation of GIS Data Layers for Flash Flood Forecasting" published by the Michigan Technological University for the National Weather Service (2000), the article "Water-Resources Investigations Report 94-4002" for soil permeability predictability, the *National Operational Hydrologic Remote Sensing Center* data, and the *NWISWeb* Database (FEMA, 2003).

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Analysis of Results

The output from the HAZUS flood scenario performed on Harlan County can be found in the HAZUS: Flood Global Risk Report Summary in Appendix 2. The geographical size of the region is approximately 468 square miles and contains 2,421 census blocks. The region contains over 12 thousand households and has a total population of 29,278 people (2010 Census Bureau data). The distribution of population by State and County for the study region is provided in Appendix 2 of the HAZUS: Flood Global Risk Report Summary. There are an estimated 13,557 buildings in the region with a total building replacement value of $2.17 billion. Approximately 93.37% of the buildings (and 72.23% of the building value) are associated with residential housing.

For essential facilities, there is one hospital in the region with a total bed capacity of 150 beds. Physician access was assumed to have one physician per three beds, therefore having a total of 50 physicians. Since there was no impact to the number of hospital beds, assumptions are made for the same no impact to the number of physician access. There are 18 schools, 19 fire stations, eight police stations and one emergency operation center. HAZUS estimates that about 757 buildings will be at least moderately damaged. This is over 15% of the total number of buildings in the scenario. There are an estimated 565 buildings that will lose complete functionality. On the day of the scenario flood event, the model estimates that 150 hospital beds are to remain available in the region. The total economic loss estimated for the flood is $744.64 million.

The building losses are broken into two categories: direct building losses and business interruption losses. The direct building losses are the estimated costs to repair or replace the damage caused to the building and its contents. The business interruption losses are the losses associated with inability to operate a business because of the damage sustained during the flood. Business interruption losses also include the temporary living expenses for those people displaced from their homes because of the flood. The total building-related losses were $469.66 million. This represents 51.35% of the aggregate replacement value of the scenario buildings. 37% of the estimated losses were related to the business interruption of the region. The residential occupancies made up 44.67% of the total loss.

The following seven dimensions, PEOPLES, 1.) population and demographics, 2.) environmental and ecosystem, 3.) organized governmental services, 4.) physical infrastructure, 5.) lifestyle and community competence, 6.) economic development, and 7.) social and cultural capital, are individually discussed. For every serviceability curve, the x-axis is recovery time in days, the y-axis is the serviceability percentage measure, and the area under the curve equates to the resilience index. The average restoration times reported by HAZUS were for schools, fire station facilities, and police station facilities as 480 days, 693 days, and 727 days as seen in Table A3.1, Table A3.2 and Table A3.3 in the Appendix 3. According to Eq. 1, the maximum restoration time will be used in the loss of resilience calculations for all dimensions, therefore 727 days. Although the maximum restoration period must be used for the overall LOR of each dimension, if fire station facilities or schools pertain to any indicator measures, those restoration periods were used.

4.1.1 P: Population and Demographics

The population and demographics dimension measures the social vulnerability within the impacted community (Cimellaro et al. 2016). Social vulnerability is the characteristic that defines the society's ability to prepare for and recover from an unexpected event. In order to accurately portray the social vulnerability within a community, many indicators are used. Speciallfically for Harlan County its important to account for a smaller population, larger percentage population of people over 65 years, and a majorly white population. Some of the indicators used to measure the social vulnerability are population density, place attachment, equity, population stability, educational attainment equality, and homeownership. For example, the eduactional attainment equality indicator in the socio-economic status components is attained using Eq. 8 (Cimellaro et al. 2016).

$$\beta_1 = \frac{\%\, population\ with\ a\ college\ education}{\%\, population\ with\ less\ than\ a\ high\ school\ education} \tag{8}$$

where β_1 is the educational attainment equality measurement. The population and demographics dimension consists of three components: (1.) distribution/density, (2.) composition, and (3.) socio-economic status. Figure 4.1 displays the serviceability curve for the dimension for Harlan County.

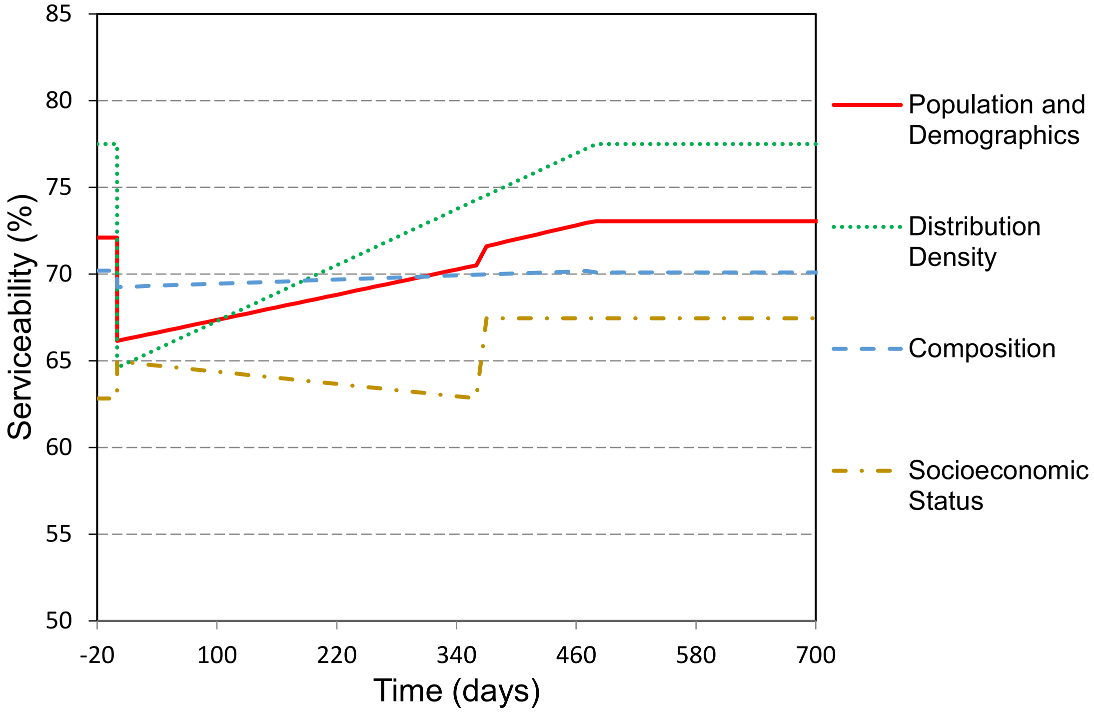


Figure 4.1 Serviceability of Population and Demographics Dimension

The distribution density, composition, and socioeconomic status components had a loss of resilience of 27.20%, 30.574%, and 35.82%, respectively. The overall population and demographic dimension equated to a loss of resilience of 29.872%. Eq. 9 mathematically interprets the loss of resilience for the population and demographics dimension.

$$LOR_{Pop.\&\,Demo.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 29.872\% \tag{9}$$

The recovery period for the socioeconomic status component displays a sudden increase at 365 days because the educational attainment equality indicator measurement was reliant on the schools' restoration time.

4.1.2 E: Environmental and Ecosystem

The environmental and ecosystem dimension measures the capability of the community's ecological system to be able to bounce back to its original form after a disturbance and its degree of absorbance without varying its environmental developments and configurations (Cimellaro et al. 2016). For example, the density of green vegetation across an area indicator of the biomass (vegetation) component is measured through a Normalized Difference Vegetation Index (NDVI), an index that defines the green vegetation density across an area through satellite remote sensing images (Rouse et al. 1973). Eq. 10 shows how the NDVI is computed per Cimellaro et al. (2016) as:

$$\beta_2 = NDVI = \frac{NIR - RED}{NIR + RED} \tag{10}$$

where β_2 represents the normalized difference vegetation with NIR expressing the near infrared absorption bands, and RED as the visible red infrared absorption bands. The NDVI is used to compare the before and after images following a natural disaster. The environmental and ecosystem dimension consists of six subcategories: (1.) water, (2.) air, (3.) soil, (4.) biodiversity, (5.) biomass (vegetation), and (6.) sustainability. Figure 4.2 displays the serviceability curve for the dimension.

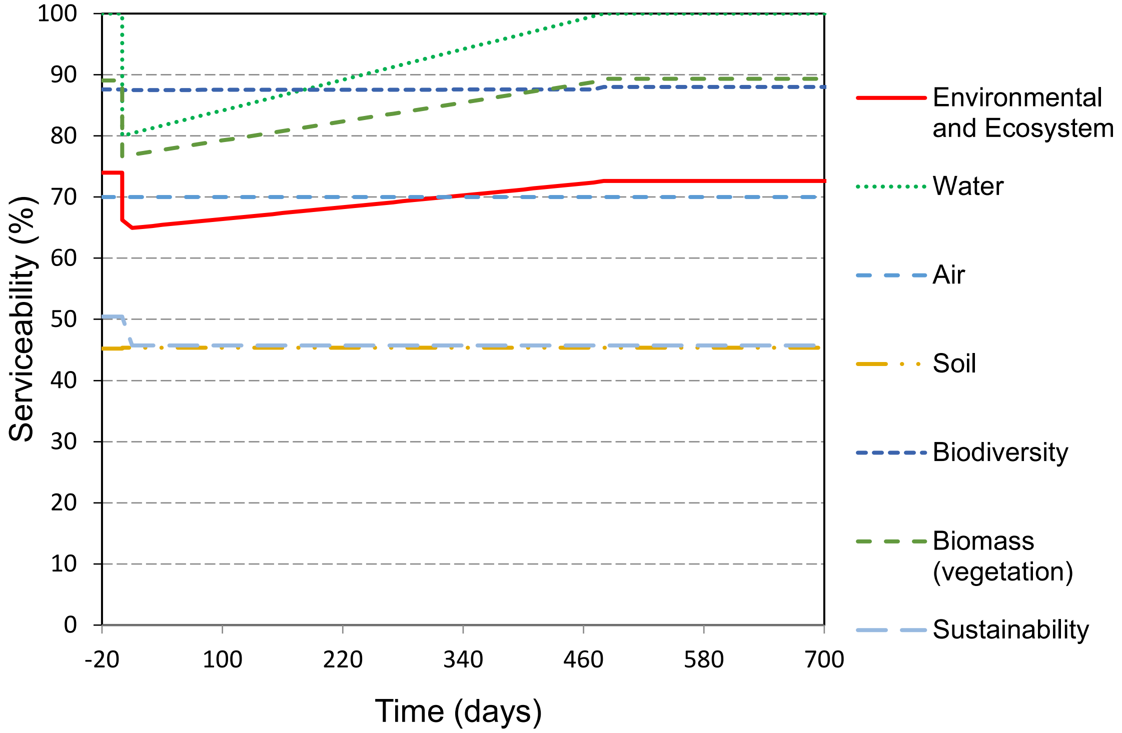


Figure 4.2 Serviceability of Environmental and Ecosystem Dimension

The water, air, soil, biodiversity, biomass (vegetation), and sustainability components had a loss of resilience of 6.81%, 30.42%, 56.98%, 12.47%, 15.65%, and

54.96%, respectively. The overall environmental and ecosystem dimension equated to a loss of resilience of 30.438%. Eq. 11 mathematically interprets the loss of resilience for the environmental and ecosystem dimension.

$$LOR_{Env.\&Eco.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 30.438\% \tag{11}$$

The water component saw the fastest recovery because of its priority within a community. The direct economic losses for utilities was heavily influenced by its impact on potable water and wastewater as seen in Table A3.5 in the Appendix 3.

4.1.3 O: Organized Governmental Services

The organized governmental services dimension measures the sustainability of the community's society before and after an extreme event. Emergency response teams are taken into account as well as legal and security services, police, fire departments, the military, and hospital emergency departments within this dimension. For example, in the executive/administrative component, the emergency response services indicator is measured by Eq. 12 (Cimellaro et al. 2016):

$$\beta_3 = \frac{\%\ \omega}{SV} \tag{12}$$

where β_3 is the emergency response services indicator with $\%\ \omega$ representing the percent of firefighting and law enforcement protection, and SV signifying the standard value acceptable in another community. Mitigation and recovery funding efforts are also addressed in this dimension. The organized governmental services dimension consists of five components: (1.) executive/administrative, (2.) judicial, (3.) legal/security, (4.) mitigation/preparedness, and (5.) recovery/response. Figure 4.3 displays the serviceability of the dimension with subplots Figure 4.4, Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8 for each component.

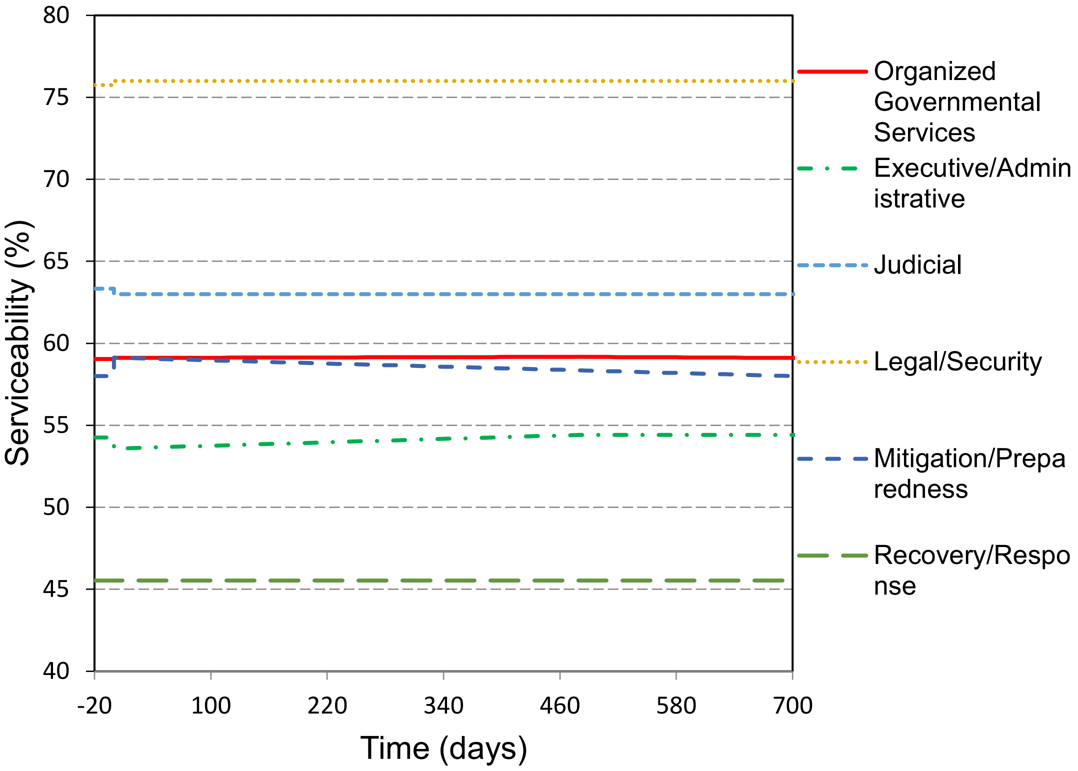


Figure 4.3 Serviceability of Organized Governmental Services Dimension

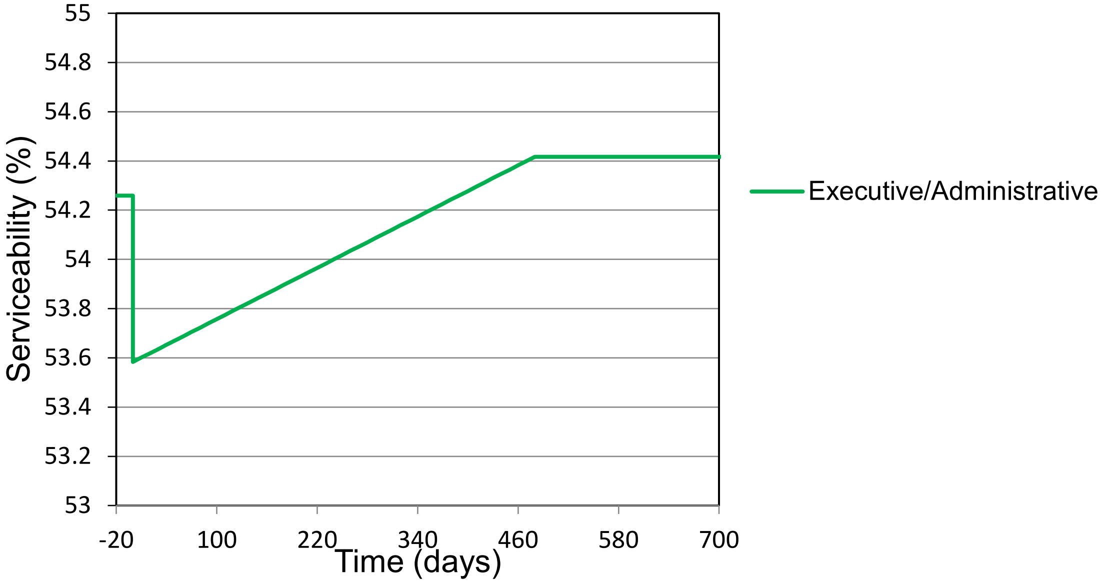


Figure 4.4 Serviceability of executive/administrative component

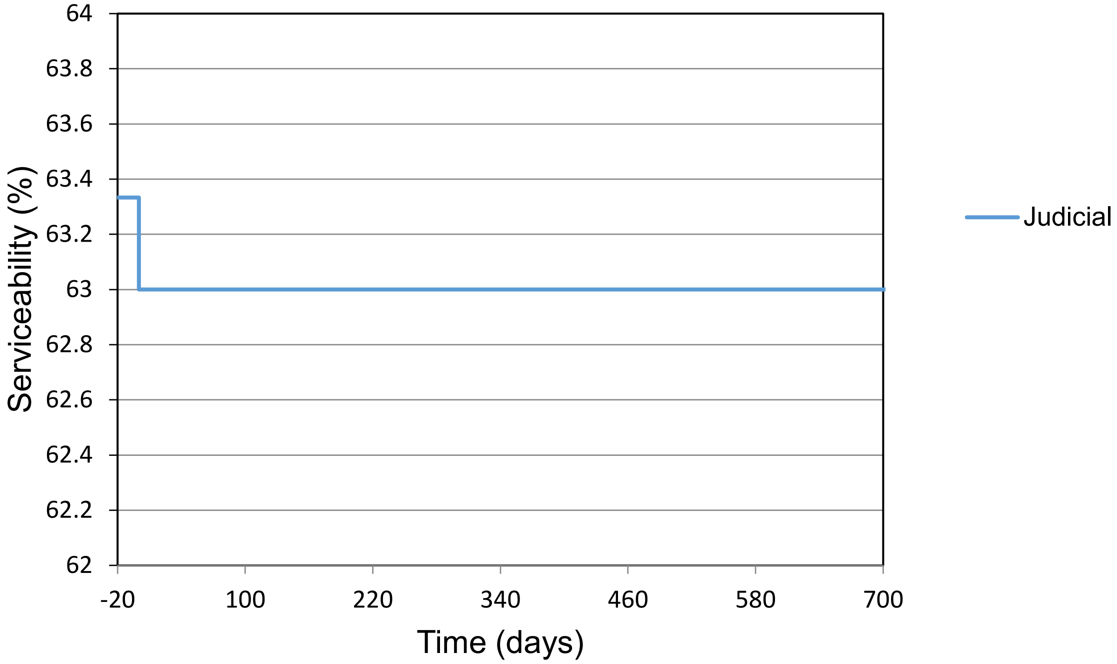


Figure 4.5 Serviceability of judicial component

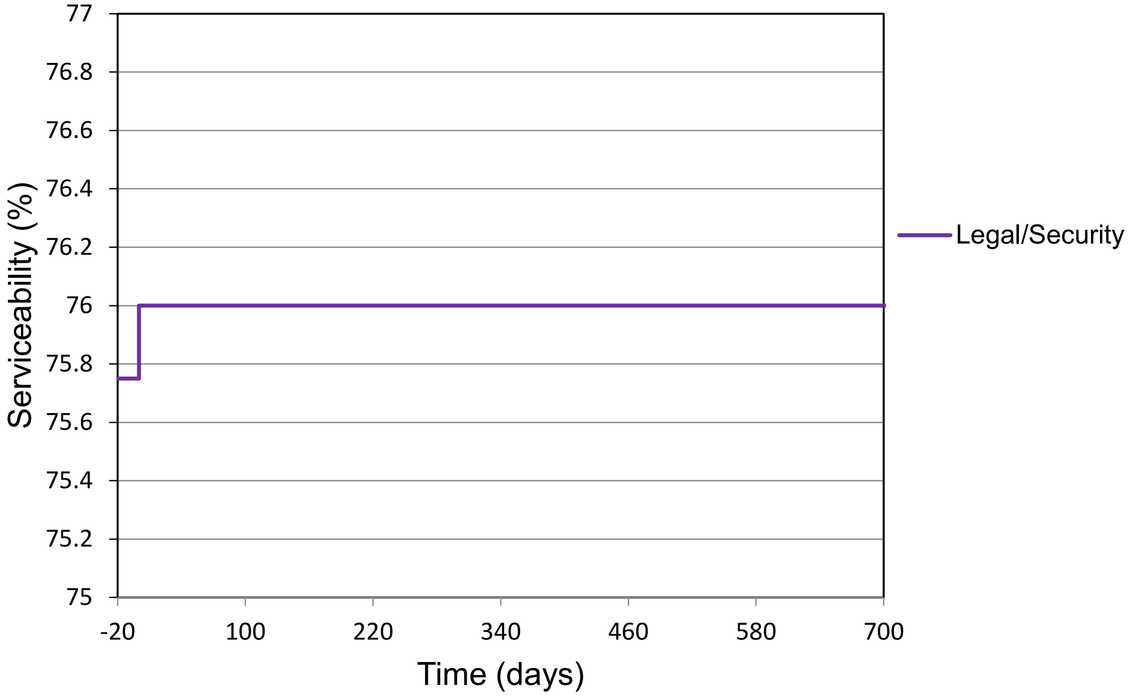


Figure 4.6 Serviceability of legal/security component

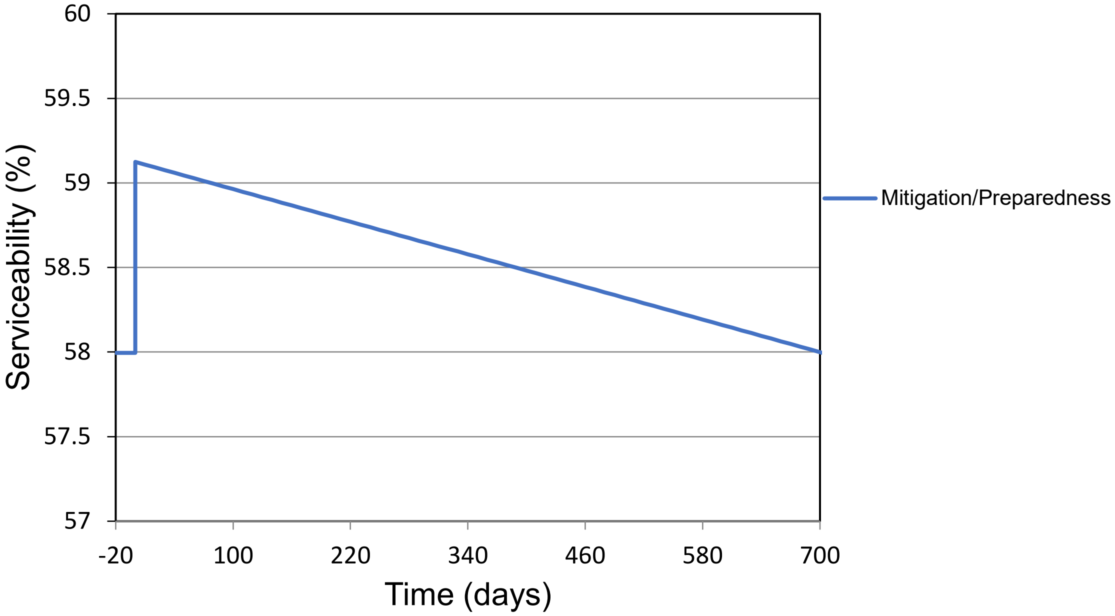


Figure 4.7 Serviceability of mitigation/preparedness component

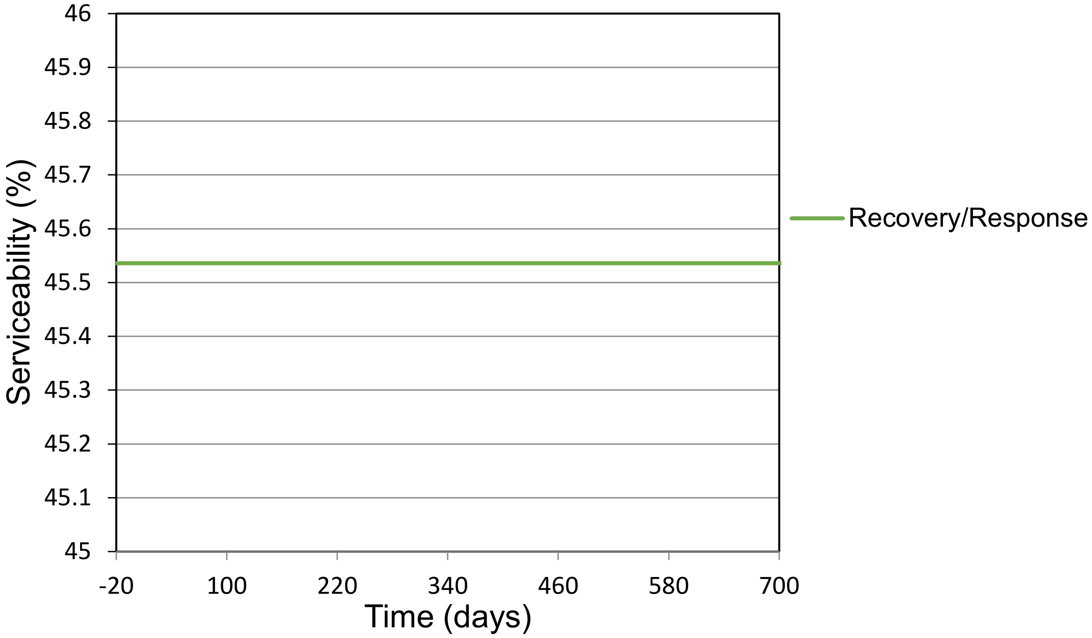


Figure 4.8 Serviceability of recovery/response component

The executive/administrative, judicial, legal/security, mitigation/preparedness, and recovery/response components had a loss of resilience of 46.50%, 37.51%, 24.33%, 42.03%, and 56.80%, respectively. The overall organized governmental services dimension equated to a loss of resilience of 41.423%. Eq. 13 mathematically interprets the loss of resilience for the organized governmental services dimension.

$$LOR_{organized\ gov.services} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 41.423\% \tag{13}$$

The subplots of the dimension demonstrate the large increase in the executive/administrative component, but declining efforts in the mitigation/preparedness component. Not enough funding options for mitigation efforts are given to the community, therefore, even before the impact strikes, the community is already suffering. Specifically, for Harlan County, the advancement in optimizing the damage assessment reports after a flood have made little progress. Recovery measures are still strongly needed. Through the unity of both components, the organized governmental services dimension could reduce its loss of resilience. Recovery/response in Figure 4.8 is shown as constant since, without the proper mitigation strategies set in place, recovery rates will remain the same. The recovery/response and legal/security components are heavily reliant on the mitigation/preparedness component.

4.1.4 P: Physical Infrastructure

The physical infrastructure dimension measures stability and resilience of facilities and lifelines within a built environment (Cimellaro et al. 2016). Serviceable schools, consistent transportation, and operable power and gas networks are evaluated in this dimension. For example, the high-speed internet infrastructure indicator in the lifelines component can be evaluated through Eq. 14 (Cimellaro et al. 2016) represented by β_4.

$$\beta_4 = Q_{Ph}(t) = \frac{\sum_{t_{0E}}^{t} n(t)}{n_{TOT}} \tag{14}$$

where $n(t)$ represents the number of households without service at a given time, t, from the time the impactful event struck, t_{0E}, and n_{tot} represents the total number of households with service before the emergency. The physical infrastructure dimension also relies heavily on the interdependencies between the different types of lifelines, e.g. water, wastewater, telecommunication, and electrical lines. The functionality of the community in totality is extremely weighed on this dimension due to these vital linkages. The physical infrastructure dimension consists of two subcategories: (1.) facilities, and (2.) lifelines. Figure 4.9 displays the serviceability curve for the dimension.

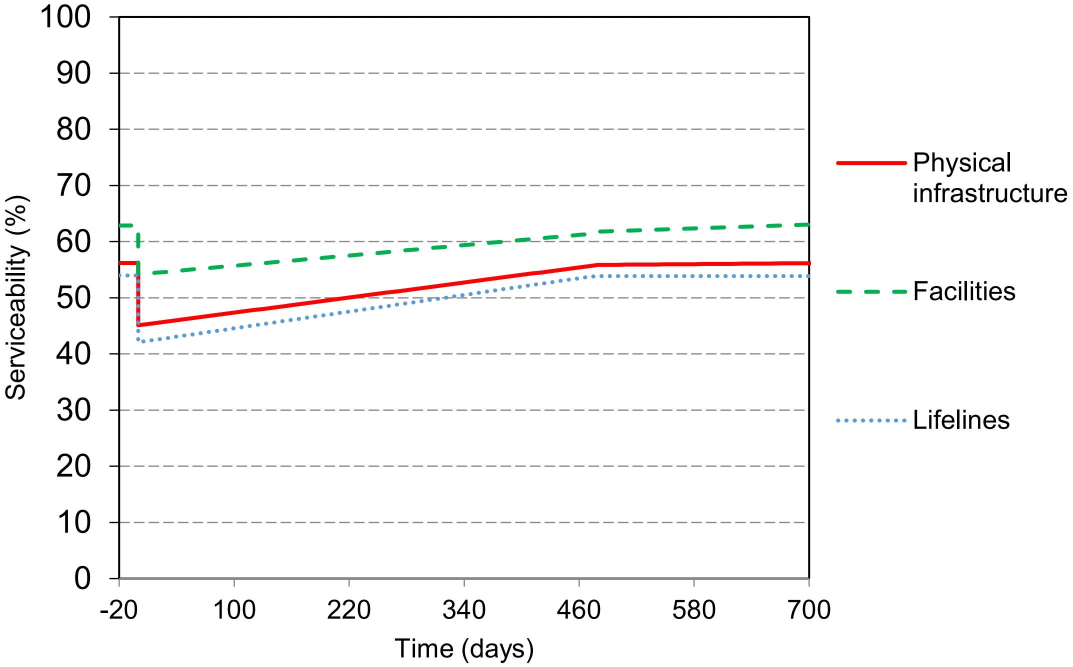


Figure 4. 9 Serviceability of Physical Infrastructure Dimension

The loss of resilience, using Eq. 1, of facilities was 42.38%, the loss of resilience of lifelines was 52.20%, and the loss of resilience of the entire dimension was 48.359%. Eq. 15 mathematically interprets the loss of resilience for the physical infrastructure dimension.

$$LOR_{Phys.\ infr.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 48.359\% \tag{15}$$

The lifelines component's loss of resilience is the deciding factor in fund allocation for the community within the dimension. The medical care capacity indicator was not affected by the flood, but the transportation indicator measure performed poorly.

4.1.5 L: Lifestyle and Community Competence

The lifestyle and community competence dimension measures the raw abilities and perceptions of the community (Cimellaro et al. 2016). This dimension measures the degree of mental competence a community has in problem solving through creativity and flexibility. Political partnerships are also evaluated in this sector. The community's competence can be measured through life survey questions such as the number of citizens involved in organizational disaster training programs, the number of immigrants, or the number of citizens involved in politics. The lifestyle and community competence dimension includes three components: (1.) collective actions and decision making, (2.) collective efficacy and empowerment, and (3.) quality of life. For example, a Eq. 16 *(Cimellaro et al. 2016)* explains the quality of life component through the means of transport, safety, quality of homes, and quality of neighborhood indicators.

$$\beta_5 = \varepsilon_{1 \ldots i_5} \tag{16}$$

where β_5 represents the quality of life component measures based on the indicator measures of household percentage with a minimum of one car, crime rate, and sustainability ratings for homes and neighborhoods. ε embodies the indicator within the 5th dimension, lifestyle and community competence, with the 1 to i subscript representing the different indicators pertaining to that dimension. Figure 4.10 displays the serviceability curve for the dimension.

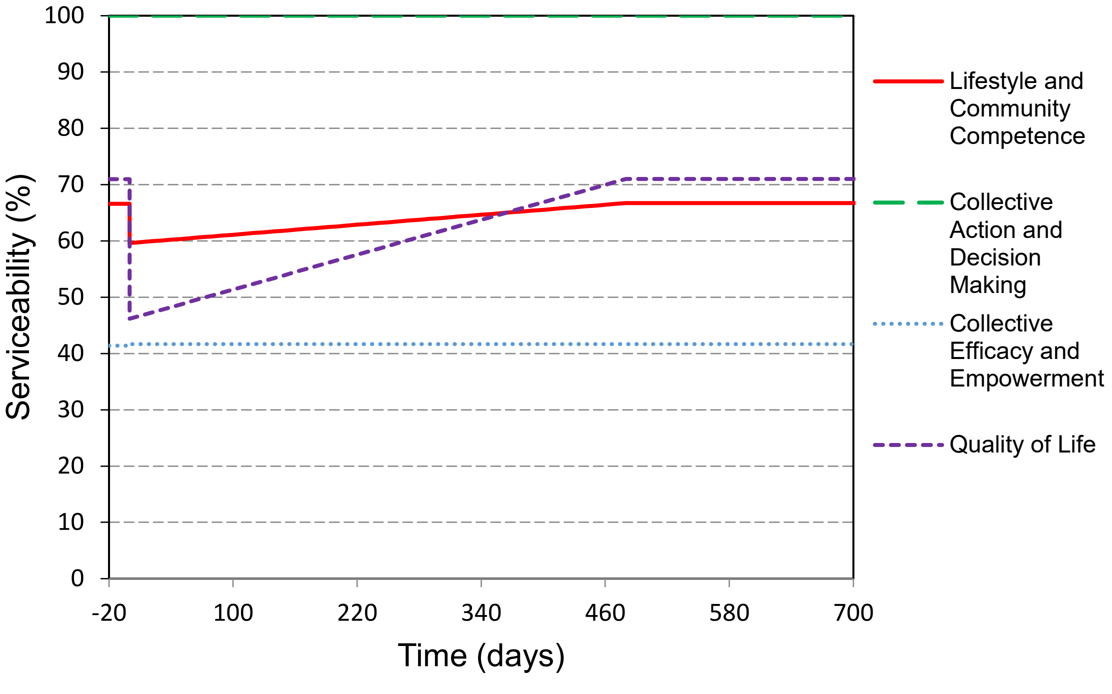


Figure 4. 10 Serviceability of Lifestyle and Community Competence Dimension

The collective action and decision making, collective efficacy and empowerment, and quality of life components had a loss of resilience of 0%, 59.14%, and 37.85%, respectively. The overall lifestyle and community competence dimension equated to a loss of resilience of 36.162%. Eq. 17 mathematically interprets the loss of resilience for the lifestyle and community competence dimension.

$$LOR_{lifestyle\&Com.Comp.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 36.162\% \tag{17}$$

The 0% LOR for the collective action and decision-making component means that this component was not affected, therefore, generating an 100% serviceability over time, as seen in Figure 4.10. The component has only one indicator, authorities interdependency, and the measure states that if there are less than three parties involved in the decision-making process then there will be no loss of resilience, but if there is more, then it would be excluded from the dimension loss of resilience quantification. Harlan County is a small rural community that has less than three parties involved. The more parties involved in decision-making, the more time it will take to reach a decision in the event of a flood. The fewer number of parties needing to be in agreement will enable decisions to be made easier and plans to be implemented quicker.

4.1.6 E: Economic Development

The economic development dimension measures the community's aptitude of replacing resources, services, and shift employment patterns when struck by an unexpected event through a static and dynamic assessment (Cimellaro et al., 2016). The static assessment evaluates the current economic activity within the community, while the dynamic assessment gauges the community's competence in maintaining the economic growth. For example, Eq. 18 (Cimellaro et al., 2016) calculates the economic diversity indicator within the industry-employment services component

$$\beta_6 = \frac{\%\, population\ not\ employed\ in\ primary\ industries}{Total\ employed\ population} \tag{18}$$

with β_6 representing the economic diversity indicator. The economic development dimension consists of three components: (1.) financial services, (2.) industry-employment services, and (3.) industry-production. Figure 4.11 displays the serviceability curve for the dimension.

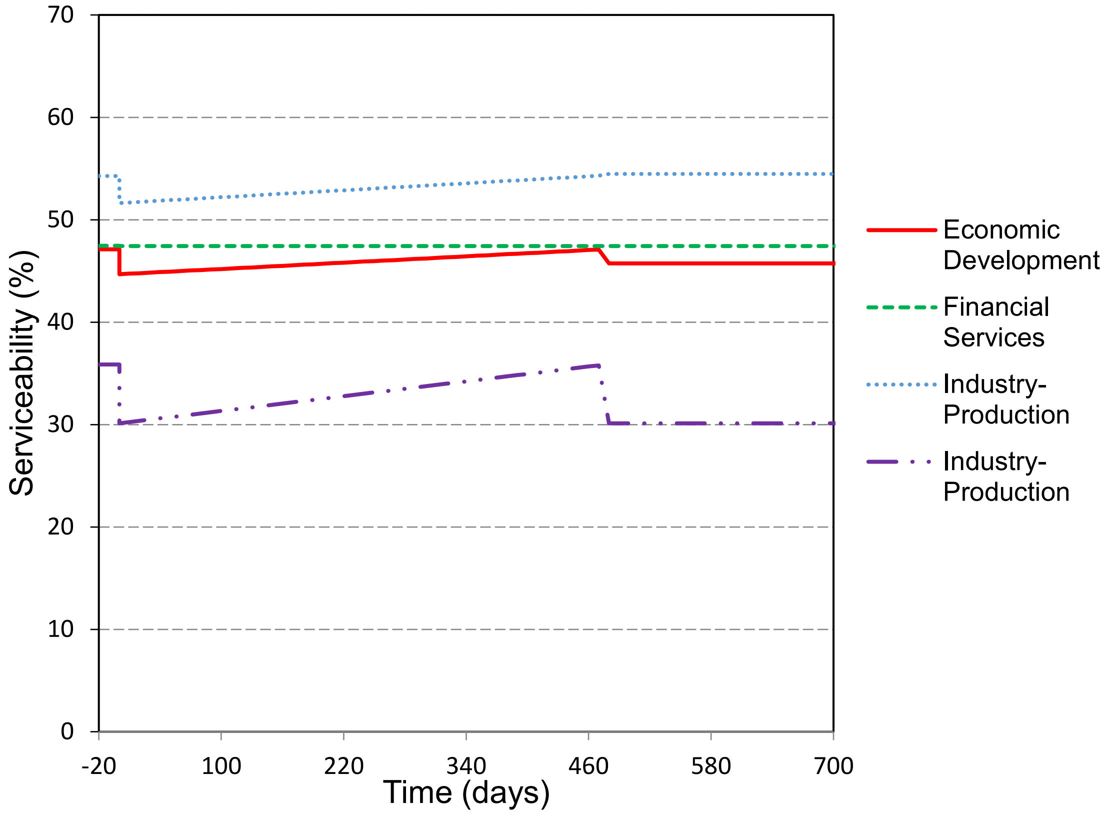


Figure 4. 11 Serviceability of Economic Development Dimension

The financial services, industry employment services, and industry-production components had a loss of resilience of 53.30%, 47.17%, and 68.97%, respectively. The overall economic development dimension equated to a loss of resilience of 59.917%. Figure 4.11 displays the serviceability curve for the dimension. Eq. 19 mathematically interprets the loss of resilience for the economic development dimension.

$$LOR_{Economic\ Develop.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 59.917\% \tag{19}$$

The serviceability of the economic development dimension is crippled once the flood passes. Most often, after the flood event occurred, the components of other dimensions would return back to their original serviceability states, but it is different for the economic development case. Economic stability is shaken, therefore inhibiting the possibility of economic growth. Economic stability will eventually return back to its original state, but the economic growth will take an extensive amount of time. The industry-production component includes two notable drops in its serviceability plot signifying the economic loss when first affected by the flood and the economic decline after the flood.

4.1.7 S: Social-Cultural Capital

The social and cultural capital dimension is a measure of the community's social connectivity (Cimellaro et al. 2016). This is measured through the number of citizens who participate in civic, religious, and political partaking, the amount of community engagement, and the residents' immersion in social groups. The social and cultural capital dimension consists of seven components: (1.) child and elderly services, (2.) commercial centers, (3.) community participation, (4.) cultural and heritage services, (5.) education services/disaster awareness, (6.) non-profit organization, and (7.) place attachment. Eq. 20 (Cimellaro et al. 2016), represented by β_7, characterizes the dimension's multiple indicator measures based on number of cultural resources, population percentage of people under 65 years old, and number of Red Cross volunteers per 10,000 persons.

$$\beta_7 = \varepsilon_{1_7 \ldots i_7} \tag{20}$$

where ε embodies the indicator within the 7th dimension, social and cultural capital, with 1 to i subscript representing the different indicators pertaining to that dimension. Figure 4.12 displays the serviceability curve for the dimension.

The child and elderly services, commercial centers, community participation, cultural and heritage services, education services/disaster awareness, non-profit, and place attachment components had a loss of resilience of 0%, 76.04%, 20.56%, 51.32%, 42.42%, 43.89%, and 52.14%, respectively. The overall social-cultural capital dimension equated to a loss of resilience of 34.326%. Eq. 21 mathematically interprets the loss of resilience for the social-cultural capital dimension.

$$LOR_{SocialCult.Cap.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 34.326\% \tag{21}$$

The 0% LOR for the child and elderly services components signifies that the component has an 100% serviceability over time, as seen in Figure 4.12. There is only one indicator for the component, child and elderly care programs. If the community has at least one program, then there is no loss of resilience, if not, it is excluded from the dimension's loss of resilience quantification.

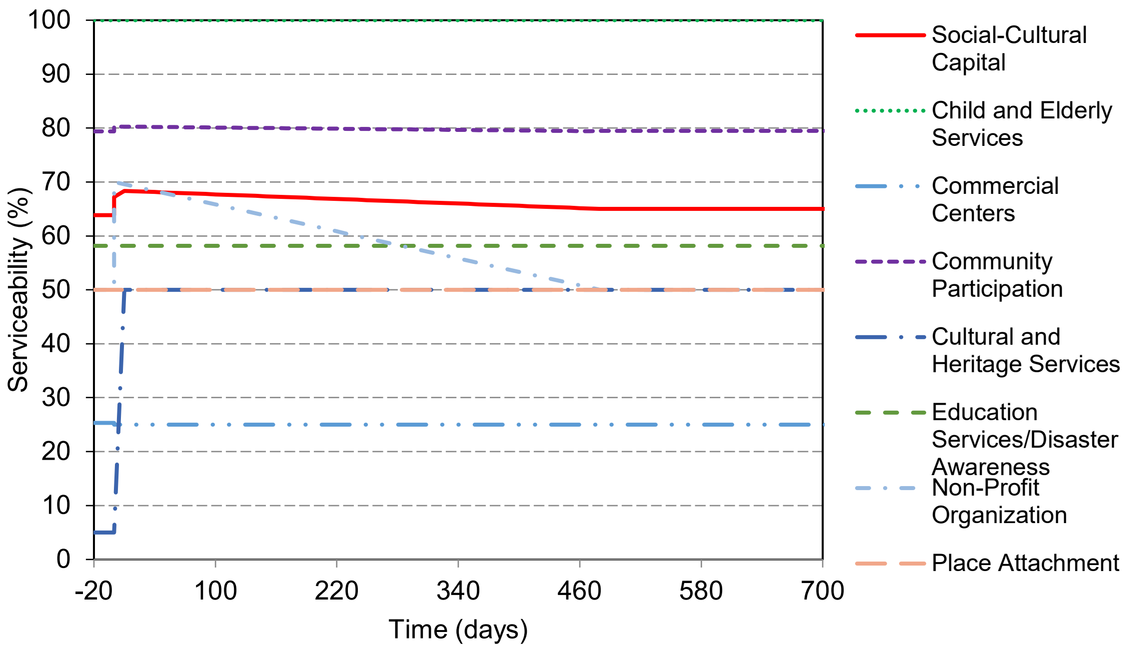


Figure 4. 12 Serviceability of Social-Cultural Capital Dimension

Harlan County has a total of 227 people in nursing facilities/skilled-nursing facilities according to 2010 data (city-data).

4.2 The Community Resilience Curve

The loss of resilience of the entire community including all seven dimensions equated to 37.395%. The economic development dimension was the dimension most affected by the flood impact. The loss of resilience was the highest with the physical infrastructure and organized governmental services following after with more than a 40% loss of resilience. Figure 4.13 displays the serviceability of the total community. All seven dimensions were aggregated to create a single *community total* serviceability curve.

The least affected dimension was the population and demographics dimension at 29.872% and the environmental and ecosystem dimension close at 30.438%. It can be inferred that due to a small population, the social vulnerability is less affected, therefore not impacting the population and demographics dimension as severely. The environmental and ecosystem's resistance exhibits the environment's adaptability.

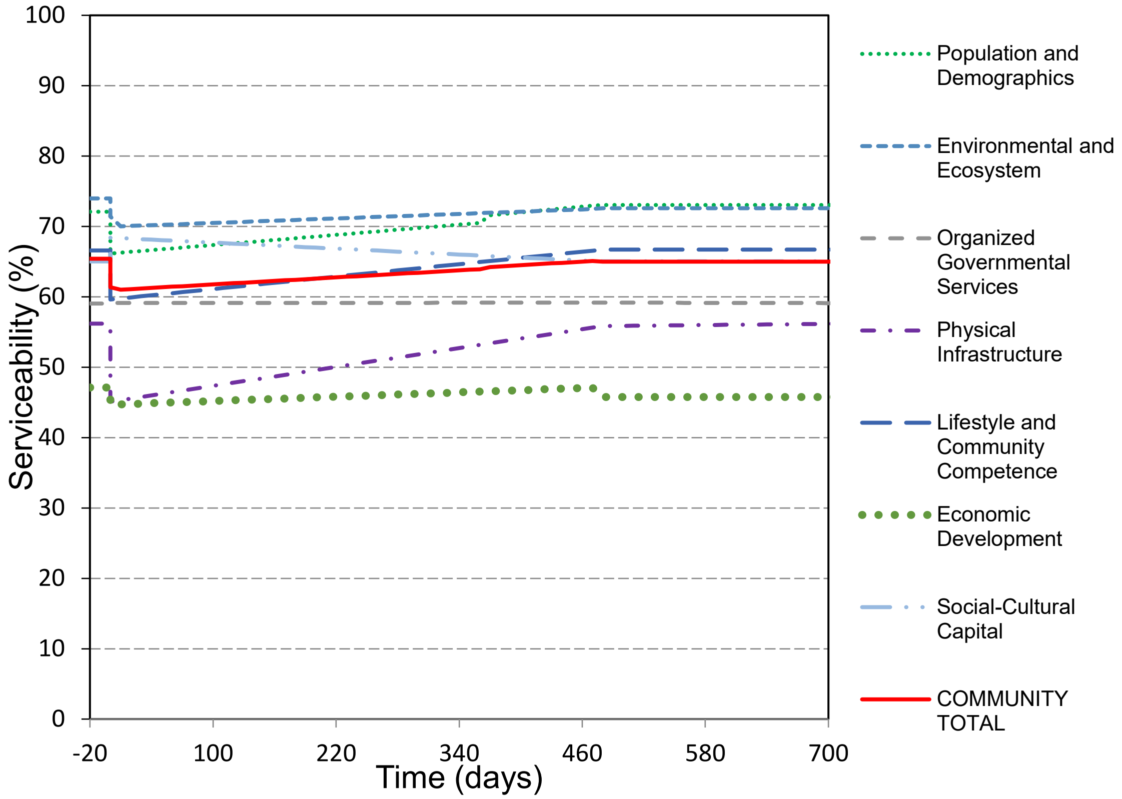


Figure 4. 13 Serviceability of the Community in Harlan County, KY

This adaptability can also be understood as the ecosystem and environment's forfeit to flood events. Harlan County has been exposed to flooding for many years and for that reason, the environment has unfortunately changed significantly compared to how it used to be.

The lifestyle and community competence dimension reveal the people's commitment to their community and their willingness to keep the community running, before or after the flood event (Cimellaro et al. 2016). The social-cultural capital dimension offers a similar approach, but on a more individualistic standpoint. Harlan County has a total of 54 abandoned/occupied coal camps (Appalachian Center & Appalachian Studies Program). The towns in which these camps were instituted into, in the early twentieth century, were considered coal towns where the extraction of coal shaped the social and economic life of the residents at the time (Appalachian Center & Appalachian Studies Program). These coal towns brought in multicultural and multilingual communities that still come together today for reunions in honor of their descendants. Place attachment is the driving factor. Regardless of the catastrophic events that occur, the social capital remains. These dimensions were in range of the overall loss of resilience of the community. Eq. 22 mathematically interprets the loss of resilience for the community in total.

$$LOR_{TOTAL} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 37.395\% \qquad (22)$$

The lifestyle and community competence dimension was 1.2% away, and the social-cultural capital dimension had a 3.09% difference.

4.3 Kentucky State Budget Allocation

By using this pre-decision disaster resilience framework, time and money can be spared for rural communities similar to Harlan County. Local emergency management teams can prepare more effective disaster preparation plans, and politicians can prioritize the allocation of funds to certain facilities and lifelines prior to the catastrophe.

Based on the PEOPLES results, the research advises Harlan County local officials to allocate additional funds to economic development, physical infrastructure, and organized governmental services. The indicators within the lifelines component are telecommunication, mental health support, physician access, medical care capacity, evacuation routes, industrial re-supply potential, high-speed internet infrastructure, efficient energy use, efficient water use, gas, access and evacuation, transportation, and wastewater treatment. Results showed 32.4% damage of the wastewater facilities and 40% of the potable water systems with $13,054,000 worth in damage.

The Kentucky State Budget runs on a biennial budget cycle with the fiscal year starting July 1st. The state budget is split into several categories, but the main categories within Kentucky are pensions, health care, education, defense, welfare, protection, transportation, general government, and other spending. Figure 4.14 demonstrates the funding allocation through a pie chart for the 2020 fiscal year. Compared to the 2018 State budget (Commonwealth of Kentucky, 2018), there was a 5.4% increase in healthcare funding, 4.7% increase in funding for education, and an 11% decrease in transportation funding.

Television – Public Safety Emergency Warning and Alert Capacity to ensure critical localized weather alerts for improvement in safety and preparedness around the state (Commonwealth of Kentucky, 2020).

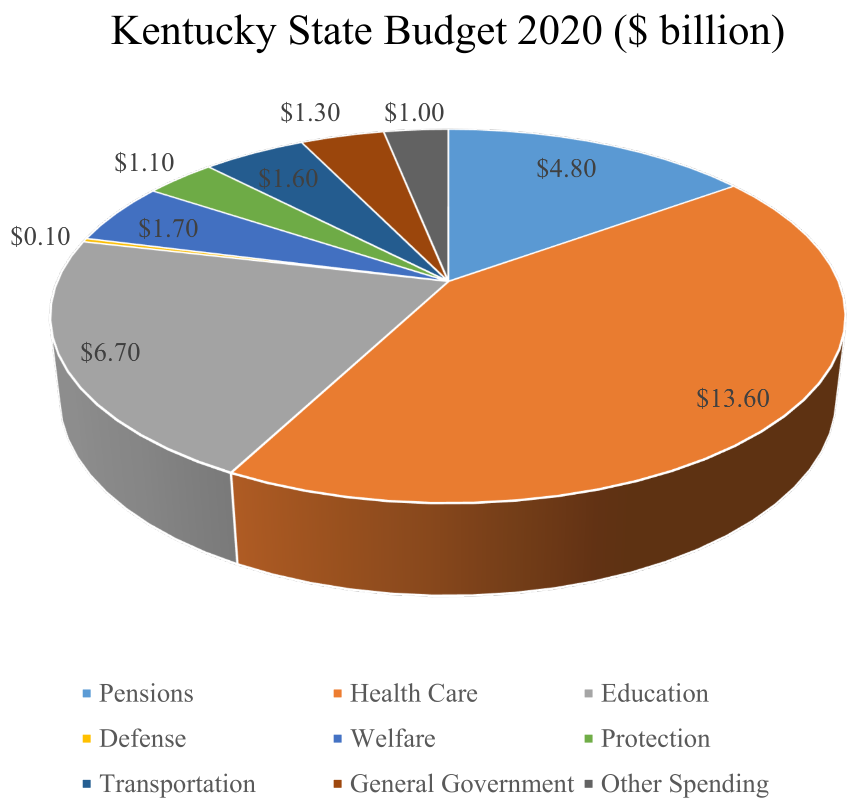


Figure 4. 14 Kentucky State Budget for the 2020 fiscal year

(Source: usgovernmentspending.com Last accessed: April 2020)

For the 2020-2022 cycle, $1,000,000,000 was allocated for the Kentucky Education Emergency warning is the first step but without enough funds for transportation, evacuation and recovery processes are compromised. Within the physical infrastructure dimension, it is suggested that the authorities should focus more on enhancing lifelines as the obtained benefits would be greater. When more money is put apart for transportation, which falls under the lifelines category, the loss of resilience for lifelines decreases to 31.6%, allowing a more resilient Harlan County. The overall physical infrastructure loss of resilience decreases to 33%. This is due to the dependability of the measurements for access and evacuation, industrial re-supply potential, and transportation on road and rail miles. Eq. 23 shows the new serviceability curve for the physical infrastructure dimension.

$$LOR_{Phys.\ inf.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 33.99\% \quad (23)$$

Within the economic development dimension, it is suggested that the authorities should focus more on enhancing industry-production as the obtained benefits would be greater. When more money is put apart for manufacturing, agriculture, and the development of more businesses, the overall economic development loss of resilience decreases to 37.68%, allowing a more resilient Harlan County.

$$LOR_{Economic\ devlopt.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 37.68\% \quad (24)$$

Within the organized governmental services dimension, it is suggested that the authorities should focus more on enhancing recovery/response as the obtained benefits would be greater. When more money is put apart for other services including disaster risk reduction measures integrated into post-disaster recovery and rehabilitation activities, local contingency plan degree including an outline strategy for post-disaster recovery and reconstruction, and ecosystem support plans, the overall organized governmental services loss of resilience decreases to 30.38%, allowing a more resilient Harlan County.

$$LOR_{Orgd.gov.} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 30.38\% \quad (25)$$

By adjusting these changes to each component within each of these three dimensions, the overall loss of resilience of the community reduces to 31.88%, roughly by a 5% difference.

$$LOR_{TOTAL} = \int_{t_0}^{t_1} \frac{100 - Q(t)}{T_c} dt = \int_{0}^{720} \frac{100 - Q(t)}{720} dt = 31.88\% \quad (26)$$

By strengthening and enhancing a system’s resilience though the proper risk reduction measures, a community can accrue a substantial amount of savings. The proposed modified PEOPLES framework allows a useful quantifiable assessment of a rural community’s vulnerabilities. Through this assessment, prioritization is applied to areas of the community that would most benefit from it. A holistic approach includes all characteristics of a community, which can help distinguish the vital relationship of dependability to consider. By doing so, local government officials in the community can take the proper steps in applying this information to mitigation, recovery, and response plans.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Summary of Conclusions

Community resilience is still under investigation in finding the best solution for a community to achieve it. A renowned resilience framework, namely PEOPLES, was investigated to quantify and evaluate the measurement of the overall community resilience of Harlan County, KY, part of Rural Appalachia. To gather data that can be used as input, a scenario flood was applied to Harlan County through the flood model of FEMA HAZUS-MH (FEMA, 2003). The flood was set in February, reflecting the February 2018 flood that caused immense damage to the county two years before.

This approach evaluates the scenario hazard on the community through a layered framework based off the dimensions: population and demographics, environmental and ecosystem, organized governmental services, physical infrastructure, lifestyle and community competence, economic development, and social and cultural capital. Within each of the seven dimensions, lies multiple components with a characteristic associated with the theme of the specified dimension, and within each component lies various indicators which take the qualitative measures and interpret them as quantitative measures. Weighting factors are assigned to each variable. After applying a modified PEOPLES resilience framework to Harlan County, KY, the level of resilience and serviceability curves were computed for each component, dimension, and the overall community.

The loss of resilience of the entire community including all seven dimensions equated to 36.85%. The economic development dimension was the dimension most affected by the flood impact. The loss of resilience was the highest with the physical infrastructure and organized governmental services following after with more than a 40% loss of resilience. It is suggested that the authorities should focus more on economic development, the physical infrastructure, and organized governmental services as the obtained benefits would be greater. By applying such modifications, the overall loss of resilience can decrease to 31.88%. The results show the validity of the proposed approach as a decision-support mechanism to assess and enhance the resilience of rural communities.

5.2 Recommendations for Further Research

When distinguishing rural communities versus urban communities, a prioritization to urban areas during a state of emergency is more prevalent than in rural areas. Between the years 2010 and 2016, a tremendous drop in rural population has occurred along with higher poverty and unemployment rates (USDA, 2017). By applying and investigating the resilience of rural Appalachia, this can open a door to international goals for evaluating resilience elsewhere. This layered resilience framework can be applied to more geographical regions of larger or smaller sizes impacted by other natural hazards such as flood, tornado, hurricane, and/or earthquake. Understanding the losses of one natural disaster can support decisions toward better preparedness and mitigation plans. A closer step towards flood resilience benefits the resilience research community to continue its investigations in finding new ways to build stronger infrastructure, urging to maintain rural facilities and lifelines, and incorporating interdependencies within the community for a well-rounded solution.

Another potential research direction can be by the modeling of decision-making in rural communities in terms of the adoption of technology considering the exogeneous and endogenous factors (Nejat, 2012). The synergy of cyber technology and physical infrastructure has allowed advancement in the various fields of political science, economics, management science, and engineering. Planned collaborations among multiple decision makers, diverse ranks of government, private entities, and nonprofit establishments are needed for disaster management therefore making game theory appropriate to study (Seaberg et al., 2017). It has been used in the application of natural disasters through many strategies. When determining the proper steps to take in the response phase of disaster management, methods such as the stochastic fictitious play model, Smyrnakis and Leslie (2010), proposed can make a difference. Coles and Zhuang (2011) introduced a method to provide and aid decision makers in emergency surroundings on how to choose and sustain relationships to advance resource utilization in a disaster., and Nagurney et al. (2019) introduced an integrated financial and logistical game theory model for humanitarian organizations or non-governmental organizations.

Future research directions in preexisting methodologies studying community resilience could try implementing computational models, particularly multiagent systems-based ones, and work in game theory, agent-based modeling, and system dynamics for the community resilience analysis applications. Future game-theory implementations can be explored such as using a goal-based, utility-based, or learning agent instead of the BDI agent to the community resilience frameworks as introduced in Chapter 1.

Further research is recommended to improve resilience frameworks and suggest the following future directions:

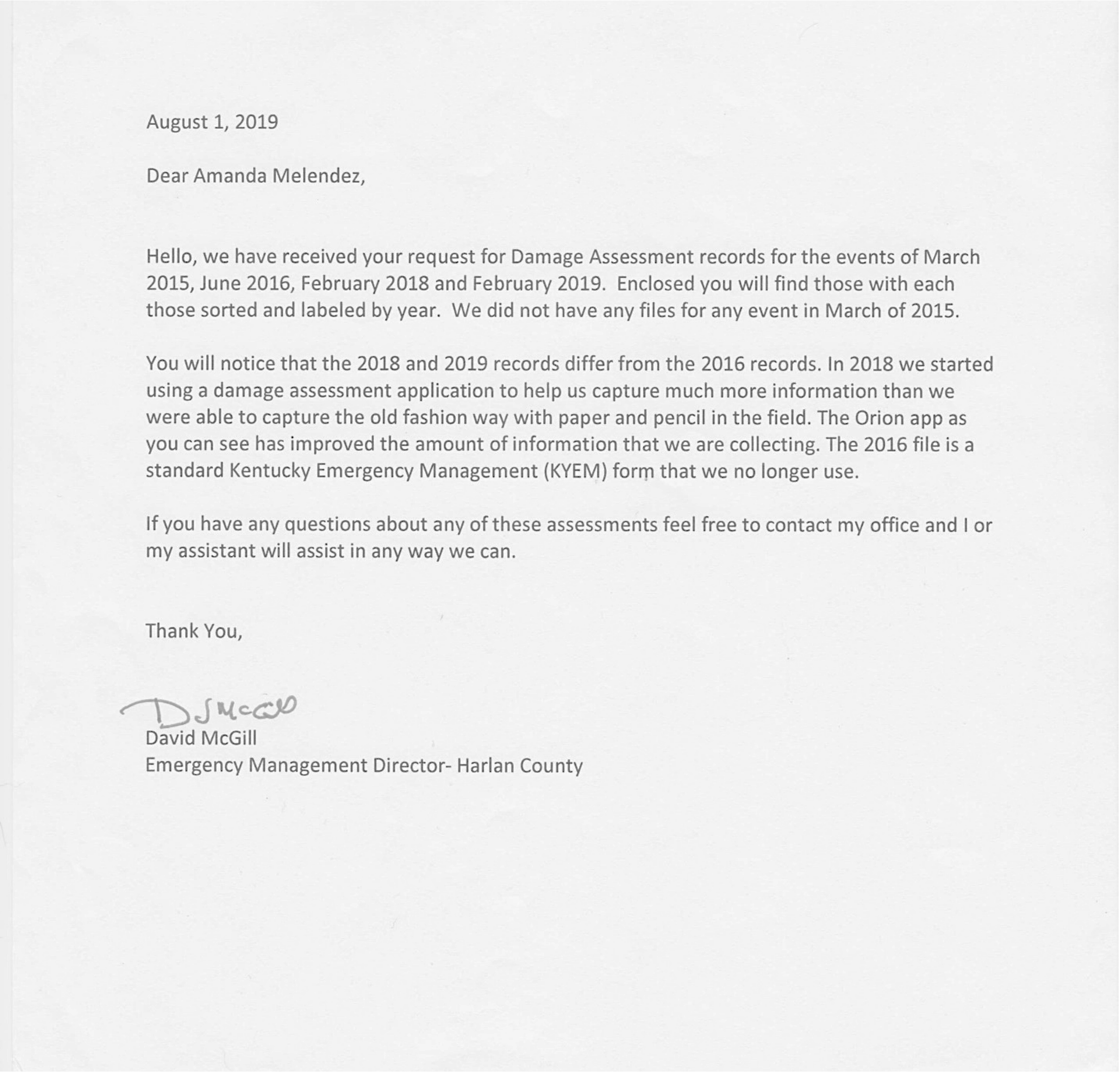
- Comparisons between other game theory applications integrated to community resilience frameworks
- The study of poverty models for dictating the degree of resiliency within a community to assign discrete measures appropriately to the community under evaluation
- Incorporating endogenous or direct attributes to an agent in agent-based models (i.e. age, health and socioeconomic status) (Nejat, 2012)
- Incorporating exogenous or indirect attributes to an agent in agent-based models (i.e. signals from policy makers for community commitment, or climate change) (Nejat, 2012)
- Investigating robustness of advanced mitigation strategies into community resilience (Javadinasab Hormozabad and Zahrai, 2019; Palacio Betancur and Gutierrez Soto, 2019).

As a result, the resilience framework could enable faster disaster planning for communities after a natural disaster making multiagent systems transform the understanding on individual and systems’ decisions affecting community resilience subjected to multiple hazard events.

Another potential future research direction is incorporating the results from structural extreme event reconnaissance network on different hazard events such as the Nashville Tornadoes (Wood et al. 2020), the Hurricanes Michael (Alipour et al. 2018) and Dorian (Kijewski-Correa et al. 2019) and the Palu Earthquake and Tsunami (Robertson and Kijewski-Correa, 2020).

APPENDICES

APPENDIX 1. Harlan County Damage Assessment Reports



August 1, 2019

Dear Amanda Melendez,

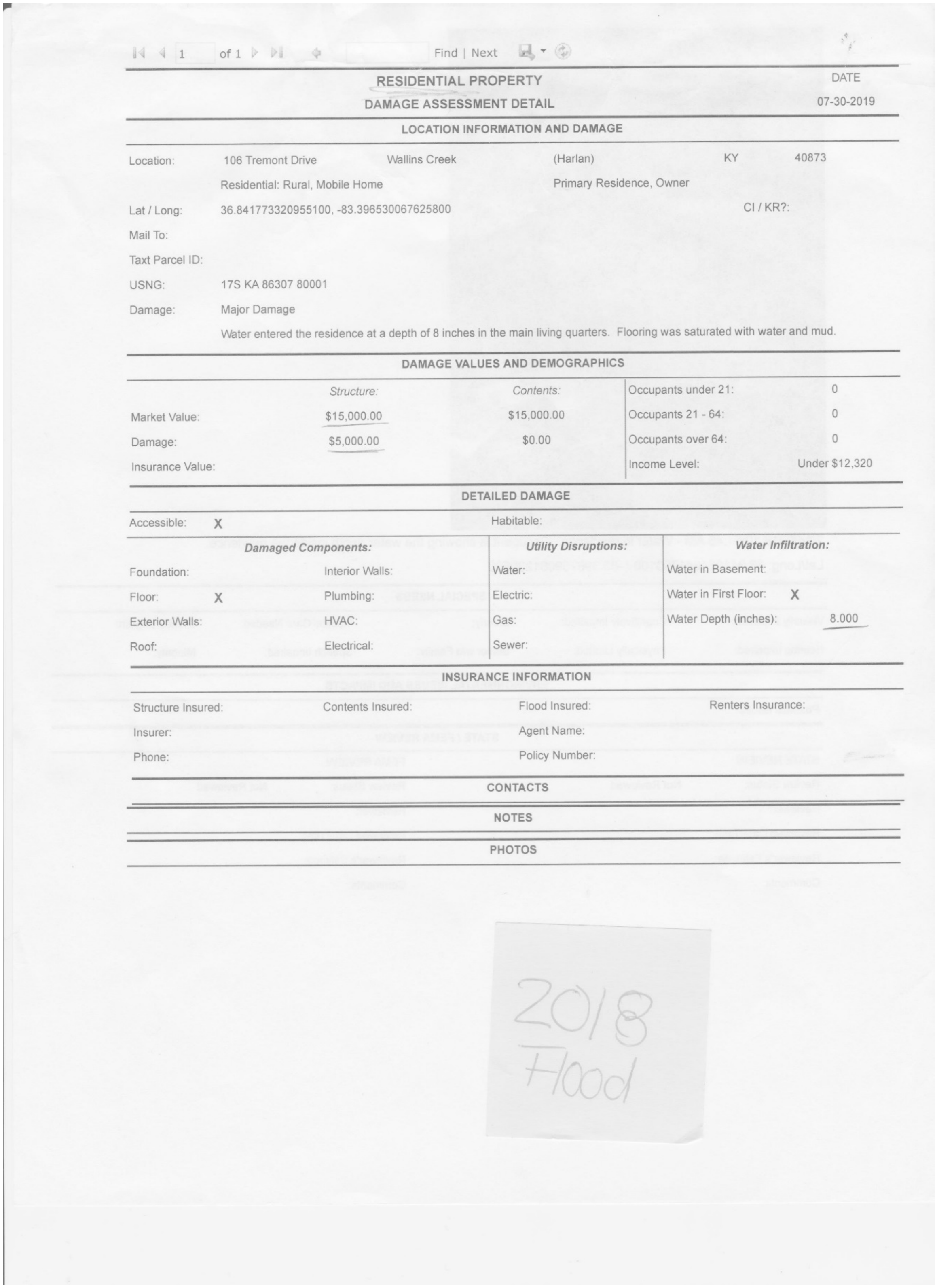
Hello, we have received your request for Damage Assessment records for the events of March 2015, June 2016, February 2018 and February 2019. Enclosed you will find those with each those sorted and labeled by year. We did not have any files for any event in March of 2015.

You will notice that the 2018 and 2019 records differ from the 2016 records. In 2018 we started using a damage assessment application to help us capture much more information than we were able to capture the old fashion way with paper and pencil in the field. The Orion app as you can see has improved the amount of information that we are collecting. The 2016 file is a standard Kentucky Emergency Management (KYEM) form that we no longer use.

If you have any questions about any of these assessments feel free to contact my office and I or my assistant will assist in any way we can.

Thank You,

D J McGill
David McGill
Emergency Management Director- Harlan County



RESIDENTIAL PROPERTY
DAMAGE ASSESSMENT DETAIL

DATE
07-30-2019

LOCATION INFORMATION AND DAMAGE

Location:	106 Tremont Drive	Wallins Creek	(Harlan)	KY	40873
	Residential: Rural, Mobile Home		Primary Residence, Owner		
Lat / Long:	36.841773320955100, -83.396530067625800			CI / KR?:	
Mail To:					
Taxt Parcel ID:					
USNG:	17S KA 86307 80001				
Damage:	Major Damage				

Water entered the residence at a depth of 8 inches in the main living quarters. Flooring was saturated with water and mud.

DAMAGE VALUES AND DEMOGRAPHICS

	Structure:	*Contents:*		
Market Value:	$15,000.00	$15,000.00	Occupants under 21:	0
Damage:	$5,000.00	$0.00	Occupants 21 - 64:	0
Insurance Value:			Occupants over 64:	0
			Income Level:	Under $12,320

DETAILED DAMAGE

Accessible: X
Habitable:

Damaged Components:				*Utility Disruptions:*	*Water Infiltration:*	
Foundation:		Interior Walls:		Water:	Water in Basement:	
Floor:	X	Plumbing:		Electric:	Water in First Floor:	X
Exterior Walls:		HVAC:		Gas:	Water Depth (inches):	8.000
Roof:		Electrical:		Sewer:		

INSURANCE INFORMATION

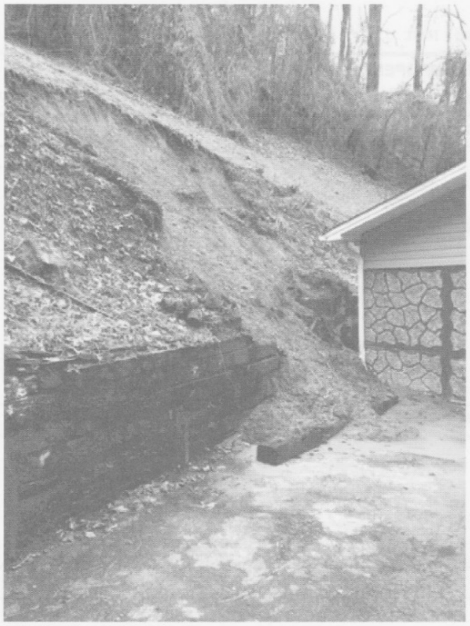
Structure Insured:	Contents Insured:	Flood Insured:	Renters Insurance:
Insurer:		Agent Name:	
Phone:		Policy Number:	

CONTACTS

NOTES

PHOTOS

2018
Flood



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SPECIAL NEEDS

Visiually Impaired:	Cognitively Impaired:	Elderly:	Medical Care Needed:	Limited English:
Hearing Impaired:	Physically Limited:	Senior w/o Family:	Speech Impaired:	Minority:

ENVIRONMENTAL ISSUES AND IMPACTS

Potential Issues:

STATE / FEMA REVIEW

STATE REVIEW		FEMA REVIEW	
Review Status:	Not Reviewed	Review Status:	Not Reviewed
Reviewer:		Reviewer:	
Reviewed Date/Time:		Reviewed Date/Time:	
Reviewer's Estimate:		Reviewer's Estimate:	
Comments:		Comments:	


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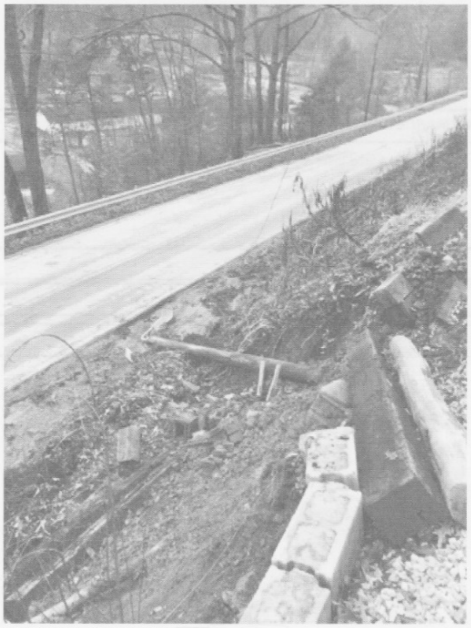
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2/11/2018 1:20:28 PM -

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SPECIAL NEEDS

Visiually Impaired:	Cognitively Impaired:	Elderly:	Medical Care Needed:	Limited English:
Hearing Impaired:	Physically Limited:	Senior w/o Family:	Speech Impaired:	Minority:

ENVIRONMENTAL ISSUES AND IMPACTS

Potential Issues:

STATE / FEMA REVIEW

STATE REVIEW		FEMA REVIEW	
Review Status:	Not Reviewed	Review Status:	Not Reviewed
Reviewer:		Reviewer:	
Reviewed Date/Time:		Reviewed Date/Time:	
Reviewer's Estimate:		Reviewer's Estimate:	
Comments:		Comments:	

3/1/2019 1:12:50 PM -

Lat/Long: 36.817351485657300 / -83.314811483161900

3/1/2019 1:13:22 PM -

Lat/Long: 36.817256863497800 / -83.314653196980000

77

INDIVIDUAL ASSISTANCE
DAMAGE SURVEY REPORT

City: ____________ County: Harlan Date: 6-27-16

Type of Damage: ☐ Tornado ☑ Flood ☐ Earthquake ☐ Other: ____________

Damage Survey Team: Rhonda + Willie

Street, Road or Area	Name of Family	Home		Type			Status		Affected Habitable	Uninhabitable				Water Depth			Est. Income			% Insured
		Prin.	Sec.	SF	MF	MH	Own	Rent		Min.	Maj.	Dest.	Isolated No Util.	Base-ment	1st Floor	2nd Floor	Low	Med	High	
118 Metcalfe Lane	[redacted]	✓					✓			–							–			
116 " "	[redacted]	✓					✓										✓			

2000 [illegible]

[illegible] Flood

June 2016
records

MH's (built before 1977)

- Affected: Received some damage but living unit is still habitable (0 - 6 inches).
- Minor: Damaged and uninhabitable but may be made habitable with minimal repairs (6 inches – 1 foot).
- Major: Damaged and uninhabitable, extensive repairs needed (2 - 4 feet).
- Destroyed: Total loss or damaged to such an extent that repairs are not feasible (over 4 feet).

Homes or (MH's built after 1977)

- Affected: Received some damage but living unit is still habitable (0 - 1 foot).
- Minor: Damaged and uninhabitable but may be made habitable with minimal repairs (1 – 3 feet).
- Major: Damaged and uninhabitable, extensive repairs needed (3 - 4 feet).
- Destroyed: Total loss or damaged to such an extent that repairs are not feasible (over 5 feet).

KyEM Form 551
(Revised December 1999)

APPENDIX 2. HAZUS: Flood Global Risk Report

HAZUS

EARTHQUAKE · WIND · FLOOD · TSUNAMI

Hazus: Flood Global Risk Report

Region Name: HarlanCountyKY

Flood Scenario: 100-yr

Print Date: Friday, October 18, 2019

Disclaimer:
This version of Hazus utilizes 2010 Census Data.
Totals only reflect data for those census tracts/blocks included in the user's study region.

The estimates of social and economic impacts contained in this report were produced using Hazus loss estimation methodology software which is based on current scientific and engineering knowledge. There are uncertainties inherent in any loss estimation technique. Therefore, there may be significant differences between the modeled results contained in this report and the actual social and economic losses following a specific Flood. These results can be improved by using enhanced inventory data and flood hazard information.

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Table of Contents

General Description of the Region

Hazus is a regional multi-hazard loss estimation model that was developed by the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS). The primary purpose of Hazus is to provide a methodology and software application to develop multi-hazard losses at a regional scale. These loss estimates would be used primarily by local, state and regional officials to plan and stimulate efforts to reduce risks from multi-hazards and to prepare for emergency response and recovery.

The flood loss estimates provided in this report were based on a region that included 1 county(ies) from the following state(s):

- Kentucky

Note:
Appendix A contains a complete listing of the counties contained in the region.

The geographical size of the region is approximately 468 square miles and contains 2,421 census blocks. The region contains over 12 thousand households and has a total population of 29,278 people (2010 Census Bureau data). The distribution of population by State and County for the study region is provided in Appendix B.

There are an estimated 13,557 buildings in the region with a total building replacement value (excluding contents) of 2,170 million dollars. Approximately 93.37% of the buildings (and 72.23% of the building value) are associated with residential housing.

Building Inventory

General Building Stock

Hazus estimates that there are 13,557 buildings in the region which have an aggregate total replacement value of 2,170 million dollars. Table 1 and Table 2 present the relative distribution of the value with respect to the general occupancies by Study Region and Scenario respectively. Appendix B provides a general distribution of the building value by State and County.

Table 1
Building Exposure by Occupancy Type for the Study Region

Occupancy	Exposure ($1000)	Percent of Total
Residential	1,567,249	72.2%
Commercial	381,265	17.6%
Industrial	63,031	2.9%
Agricultural	5,948	0.3%
Religion	68,250	3.1%
Government	20,115	0.9%
Education	63,853	2.9%
Total	**2,169,711**	**100%**

Building Exposure by Occupancy Type for the Study Region ($1000's)

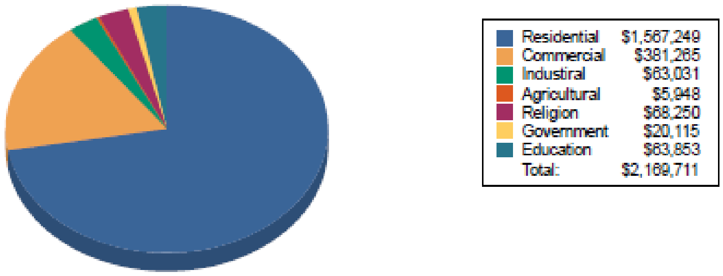
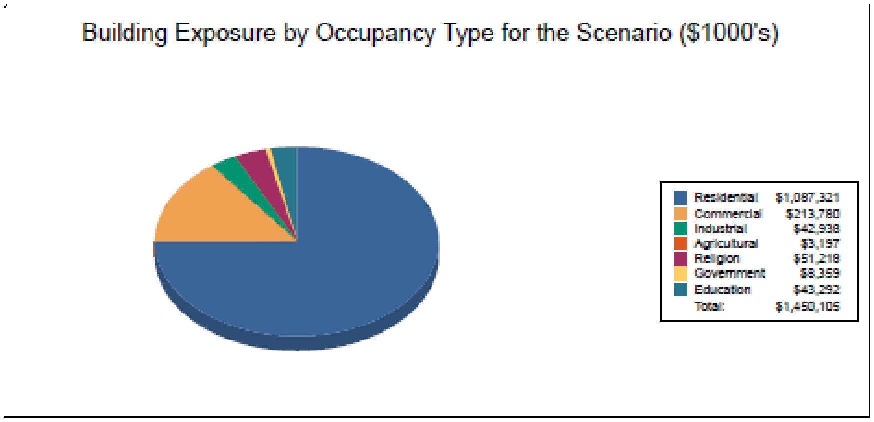


Table 2
Building Exposure by Occupancy Type for the Scenario

Occupancy	Exposure ($1000)	Percent of Total
Residential	1,087,321	75.0%
Commercial	213,780	14.7%
Industrial	42,938	3.0%
Agricultural	3,197	0.2%
Religion	51,218	3.5%
Government	8,359	0.6%
Education	43,292	3.0%
Total	**1,450,105**	**100%**


Building Exposure by Occupancy Type for the Scenario ($1000's)

Essential Facility Inventory

For essential facilities, there are 1 hospitals in the region with a total bed capacity of 150 beds. There are 18 schools, 19 fire stations, 8 police stations and 1 emergency operation center.

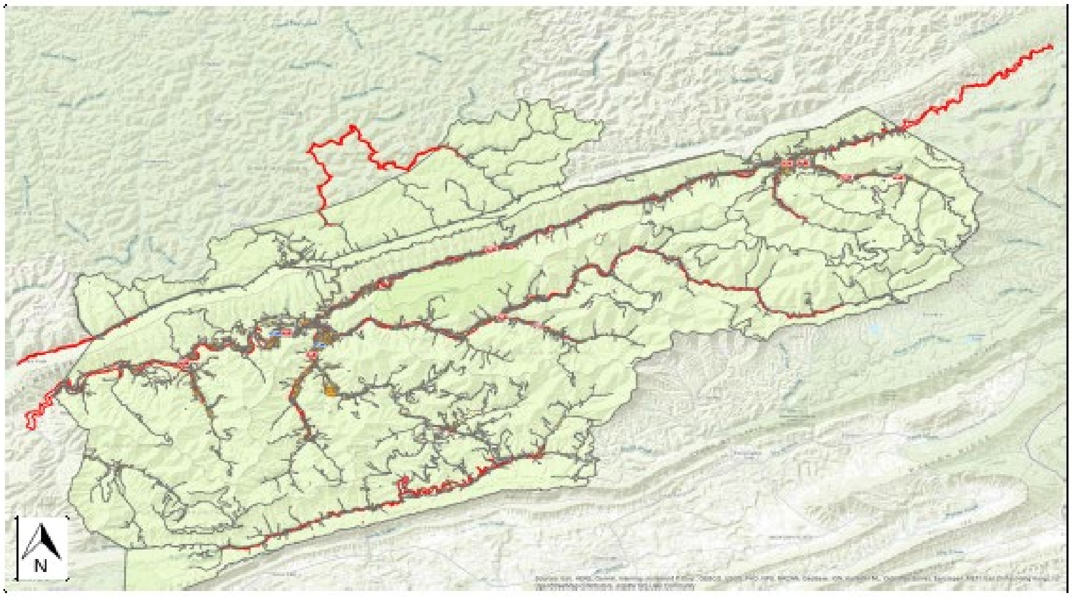
Flood Scenario Parameters

Hazus used the following set of information to define the flood parameters for the flood loss estimate provided in this report.

Study Region Name:	HarlanCountyKY
Scenario Name:	100-yr
Return Period Analyzed:	100
Analysis Options Analyzed:	No What-Ifs

Study Region Overview Map

Illustrating scenario flood extent, as well as exposed essential facilities and total exposure



Building Damage

General Building Stock Damage

Hazus estimates that about 757 buildings will be at least moderately damaged. This is over 15% of the total number of buildings in the scenario. There are an estimated 565 buildings that will be completely destroyed. The definition of the 'damage states' is provided in the Hazus Flood Technical Manual. Table 3 below summarizes the expected damage by general occupancy for the buildings in the region. Table 4 summarizes the expected damage by general building type.

Total Economic Loss (1 dot = $300K) Overview Map

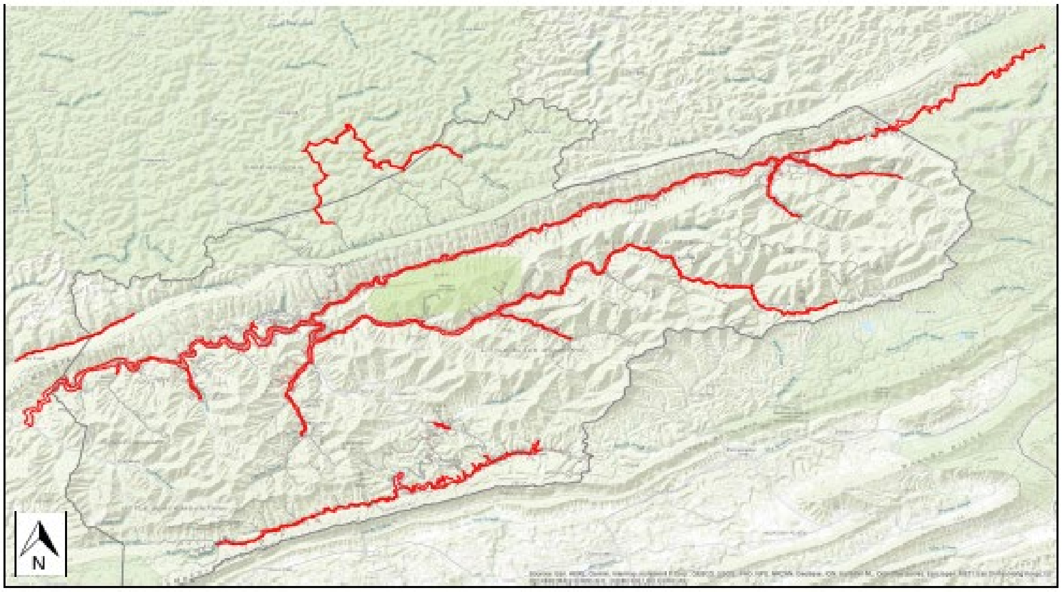
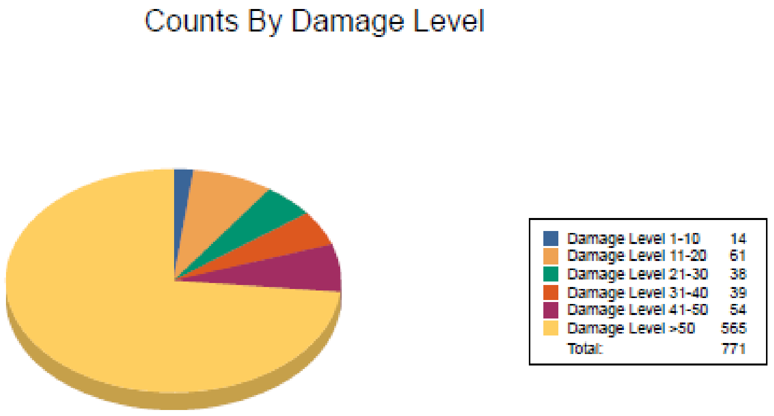


Table 3: Expected Building Damage by Occupancy

	1-10		11-20		21-30		31-40		41-50		>50	
Occupancy	Count	(%)	Count	(%)	Count	(%)	Count	(%)	Count	(%)	Count	(%)
Agriculture	0	0	0	0	0	0	0	0	0	0	0	0
Commercial	0	0	4	80	0	0	1	20	0	0	0	0
Education	0	0	0	0	0	0	0	0	0	0	0	0
Government	0	0	0	0	0	0	0	0	0	0	0	0
Industrial	0	0	0	0	0	0	0	0	0	0	0	0
Religion	0	0	0	0	0	0	0	0	0	0	0	0
Residential	14	2	57	7	38	5	38	5	54	7	565	74
Total	**14**		**61**		**38**		**39**		**54**		**565**	



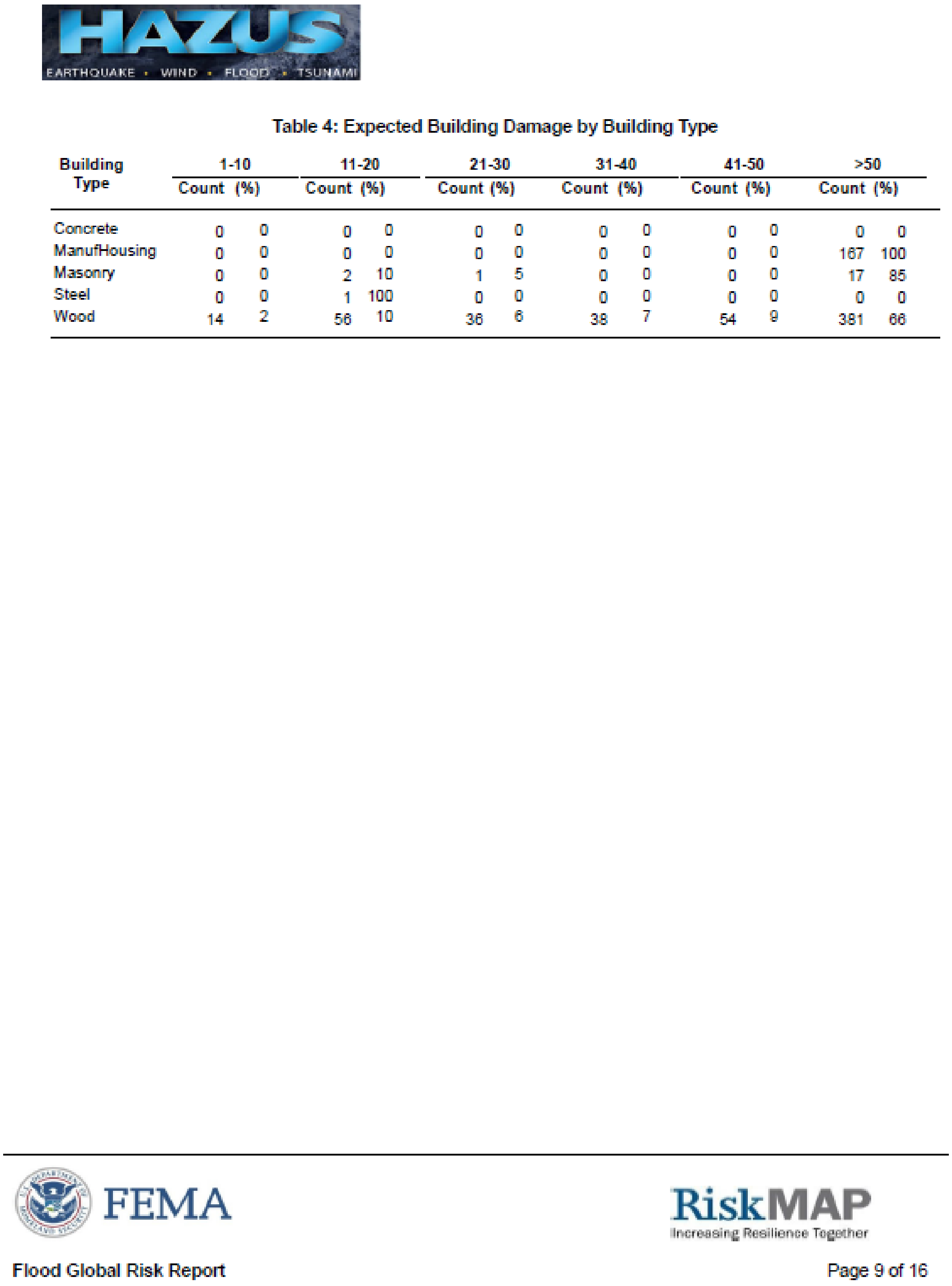


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Table 4: Expected Building Damage by Building Type

Building Type	1-10		11-20		21-30		31-40		41-50		>50	
	Count	(%)	Count	(%)	Count	(%)	Count	(%)	Count	(%)	Count	(%)
Concrete	0	0	0	0	0	0	0	0	0	0	0	0
ManufHousing	0	0	0	0	0	0	0	0	0	0	167	100
Masonry	0	0	2	10	1	5	0	0	0	0	17	85
Steel	0	0	1	100	0	0	0	0	0	0	0	0
Wood	14	2	56	10	36	6	38	7	54	9	381	66

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Flood Global Risk Report

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Essential Facility Damage

Before the flood analyzed in this scenario, the region had 150 hospital beds available for use. On the day of the scenario flood event, the model estimates that 150 hospital beds are available in the region.

Table 5: Expected Damage to Essential Facilities

		# Facilities		
Classification	Total	At Least Moderate	At Least Substantial	Loss of Use
Emergency Operation Centers	1	0	0	0
Fire Stations	19	7	2	9
Hospitals	1	0	0	0
Police Stations	8	2	2	4
Schools	18	1	0	1

If this report displays all zeros or is blank, two possibilities can explain this.

(1) None of your facilities were flooded. This can be checked by mapping the inventory data on the depth grid.

(2) The analysis was not run. This can be tested by checking the run box on the Analysis Menu and seeing if a message box asks you to replace the existing results.

Induced Flood Damage

Debris Generation

Hazus estimates the amount of debris that will be generated by the flood. The model breaks debris into three general categories: 1) Finishes (dry wall, insulation, etc.), 2) Structural (wood, brick, etc.) and 3) Foundations (concrete slab, concrete block, rebar, etc.). This distinction is made because of the different types of material handling equipment required to handle the debris.

Analysis has not been performed for this Scenario.

Social Impact

Shelter Requirements

Analysis has not been performed for this Scenario.

Economic Loss

The total economic loss estimated for the flood is 744.64 million dollars, which represents 51.35 % of the total replacement value of the scenario buildings.

Building-Related Losses

The building losses are broken into two categories: direct building losses and business interruption losses. The direct building losses are the estimated costs to repair or replace the damage caused to the building and its contents. The business interruption losses are the losses associated with inability to operate a business because of the damage sustained during the flood. Business interruption losses also include the temporary living expenses for those people displaced from their homes because of the flood.

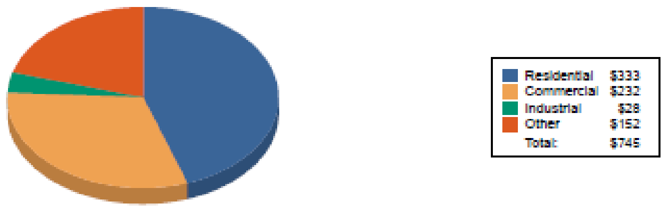
The total building-related losses were 469.66 million dollars. 37% of the estimated losses were related to the business interruption of the region. The residential occupancies made up 44.67% of the total loss. Table 6 below provides a summary of the losses associated with the building damage.

Table 6: Building-Related Economic Loss Estimates

(Millions of dollars)

Category	Area	Residential	Commercial	Industrial	Others	Total
Building Loss						
	Building	179.89	35.98	8.31	14.24	238.42
	Content	91.24	77.93	16.42	40.86	226.45
	Inventory	0.00	2.53	2.00	0.27	4.80
	Subtotal	**271.13**	**116.45**	**26.72**	**55.36**	**469.66**
Business Interruption						
	Income	1.06	40.65	0.36	13.23	55.29
	Relocation	43.74	14.13	0.38	6.84	65.08
	Rental Income	14.19	10.50	0.06	0.64	25.39
	Wage	2.51	49.95	0.50	76.27	129.22
	Subtotal	**61.49**	**115.22**	**1.29**	**96.97**	**274.98**
ALL	**Total**	**332.63**	**231.66**	**28.01**	**152.34**	**744.64**

Losses by Occupancy Types ($M)



Appendix A: County Listing for the Region

Kentucky

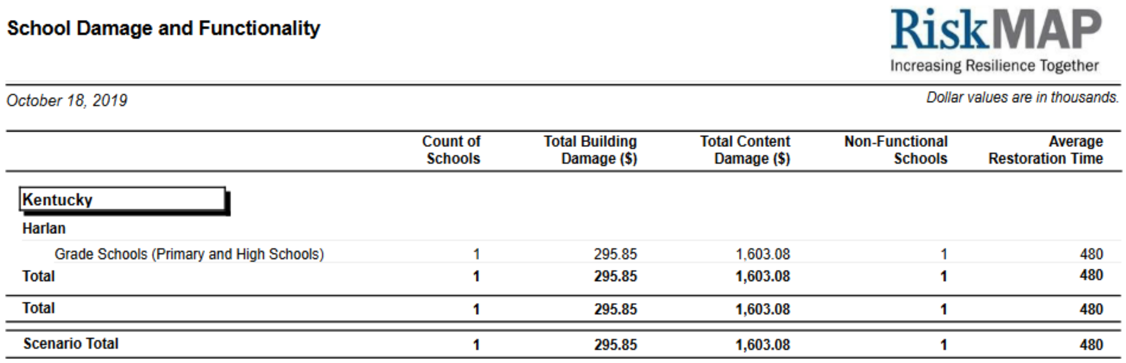
- Harlan

Appendix B: Regional Population and Building Value Data

		Building Value (thousands of dollars)		
	Population	Residential	Non-Residential	Total
Kentucky				
Harlan	29,278	1,567,249	602,462	2,169,711
Total	**29,278**	**1,567,249**	**602,462**	**2,169,711**
Total Study Region	**29,278**	**1,567,249**	**602,462**	**2,169,711**

APPENDIX 3. HAZUS Data Tables

Table A3. 1 School Damage Functionality



School Damage and Functionality

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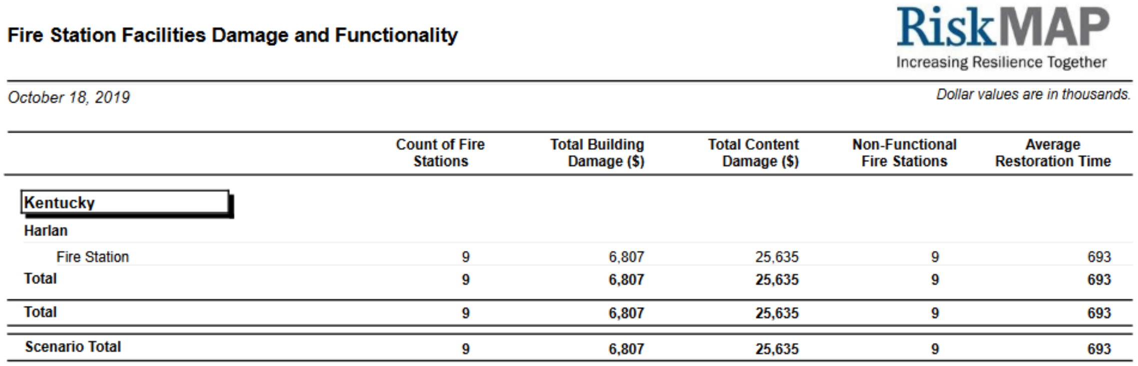
Dollar values are in thousands.

	Count of Schools	Total Building Damage ($)	Total Content Damage ($)	Non-Functional Schools	Average Restoration Time
Kentucky					
Harlan					
Grade Schools (Primary and High Schools)	1	295.85	1,603.08	1	480
Total	**1**	**295.85**	**1,603.08**	**1**	**480**
Total	**1**	**295.85**	**1,603.08**	**1**	**480**
Scenario Total	**1**	**295.85**	**1,603.08**	**1**	**480**

Table A3. 2 Fire Station Facilities Damage and Functionality



Fire Station Facilities Damage and Functionality

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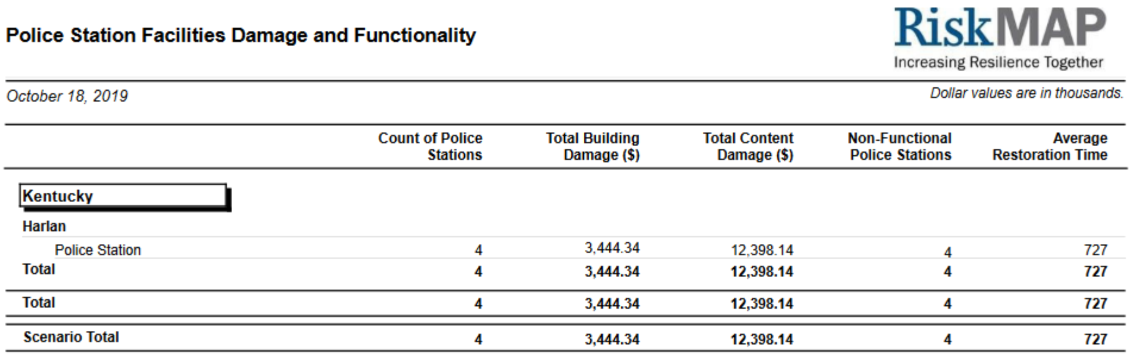
Dollar values are in thousands.

	Count of Fire Stations	Total Building Damage ($)	Total Content Damage ($)	Non-Functional Fire Stations	Average Restoration Time
Kentucky					
Harlan					
Fire Station	9	6,807	25,635	9	693
Total	**9**	**6,807**	**25,635**	**9**	**693**
Total	**9**	**6,807**	**25,635**	**9**	**693**
Scenario Total	**9**	**6,807**	**25,635**	**9**	**693**

Table A3. 3 Police Station Facilities Damage and Functionality



Police Station Facilities Damage and Functionality

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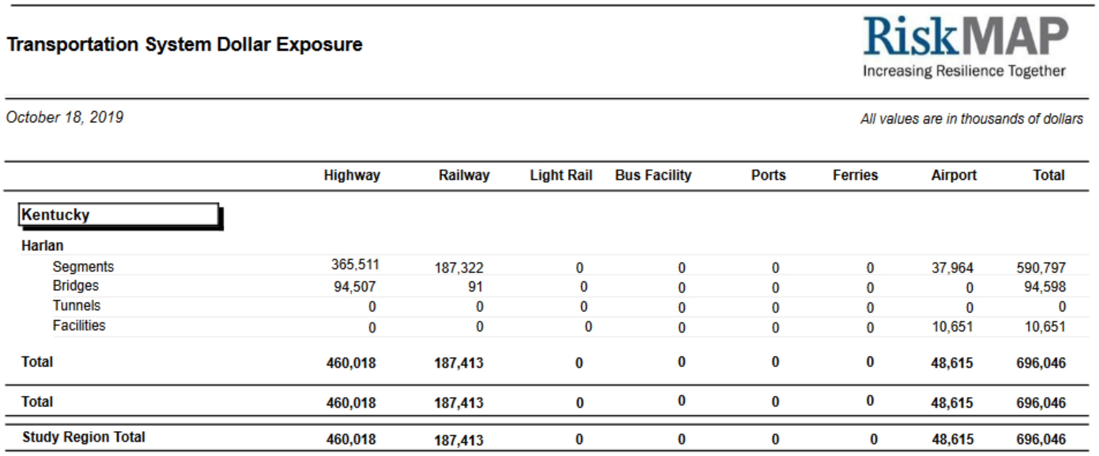
Dollar values are in thousands.

	Count of Police Stations	Total Building Damage ($)	Total Content Damage ($)	Non-Functional Police Stations	Average Restoration Time
Kentucky					
Harlan					
Police Station	4	3,444.34	12,398.14	4	727
Total	**4**	**3,444.34**	**12,398.14**	**4**	**727**
Total	**4**	**3,444.34**	**12,398.14**	**4**	**727**
Scenario Total	**4**	**3,444.34**	**12,398.14**	**4**	**727**

Table A3. 4 Transportation System Dollar Exposure



Transportation System Dollar Exposure

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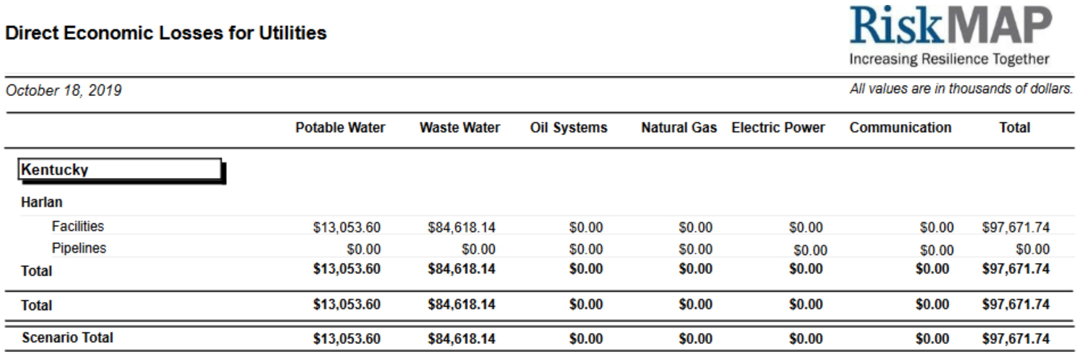
All values are in thousands of dollars

	Highway	Railway	Light Rail	Bus Facility	Ports	Ferries	Airport	Total
Kentucky								
Harlan								
Segments	365,511	187,322	0	0	0	0	37,964	590,797
Bridges	94,507	91	0	0	0	0	0	94,598
Tunnels	0	0	0	0	0	0	0	0
Facilities	0	0	0	0	0	0	10,651	10,651
Total	**460,018**	**187,413**	**0**	**0**	**0**	**0**	**48,615**	**696,046**
Total	**460,018**	**187,413**	**0**	**0**	**0**	**0**	**48,615**	**696,046**
Study Region Total	**460,018**	**187,413**	**0**	**0**	**0**	**0**	**48,615**	**696,046**

Table A3. 5 Direct Economic Losses for Utilities



Direct Economic Losses for Utilities

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All values are in thousands of dollars.

	Potable Water	Waste Water	Oil Systems	Natural Gas	Electric Power	Communication	Total
Kentucky							
Harlan							
Facilities	$13,053.60	$84,618.14	$0.00	$0.00	$0.00	$0.00	$97,671.74
Pipelines	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Total	**$13,053.60**	**$84,618.14**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$97,671.74**
Total	**$13,053.60**	**$84,618.14**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$97,671.74**
Scenario Total	**$13,053.60**	**$84,618.14**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$97,671.74**

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