## New Madrid Seismic Zone
## Catastrophic Earthquake Response Planning Project

# Impact of New Madrid Seismic Zone Earthquakes on the Central USA

## - Volume I -

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## Disclaimer

The assessments, comments and opinions in this report are those of the authors and do not necessarily represent the opinions of the Federal Emergency Management Agency or the US Army Corps of Engineers.

# Scenario Disclaimer

The scenario employed in this report has been selected following discussions with regional experts and recommendations from the United States Geological Survey (USGS). Final confirmation from USGS was obtained in support of the scenario. This scenario is intended to provide credible impacts for the New Madrid Seismic Zone (NMSZ) that is suitable for planning at the national level. The scenario represents one series of possible earthquakes and consequential impacts for the eight states and four FEMA regions that are affected by the NMSZ. Other studies may use different scenario components and hence lead to different results. The Project Team and the project consultants and advisors believe that the estimates given in this report are the most rigorous and plausible possible at the time of publication of the report in November 2009.

# Executive Summary

The information presented in this report has been developed to support the Catastrophic Earthquake Planning Scenario workshops held by the Federal Emergency Management Agency. Four FEMA Regions (Regions IV, V, VI and VII) were involved in the New Madrid Seismic Zone (NMSZ) scenario workshops. The four FEMA Regions include eight states, namely Illinois, Indiana, Kentucky, Tennessee, Alabama, Mississippi, Arkansas and Missouri.

The earthquake impact assessment presented hereafter employs an analysis methodology comprising three major components: hazard, inventory and fragility (or vulnerability). The hazard characterizes not only the shaking of the ground but also the consequential transient and permanent deformation of the ground due to strong ground shaking as well as fire and flooding. The inventory comprises all assets in a specific region, including the built environment and population data. Fragility or vulnerability functions relate the severity of shaking to the likelihood of reaching or exceeding damage states (light, moderate, extensive and near-collapse, for example). Social impact models are also included and employ physical infrastructure damage results to estimate the effects on exposed communities. Whereas the modeling software packages used (HAZUS MR3; FEMA, 2008; and MAEviz, Mid-America Earthquake Center, 2008) provide default values for all of the above, most of these default values were replaced by components of traceable provenance and higher reliability than the default data, as described below.

The hazard employed in this investigation includes ground shaking for a single scenario event representing the rupture of all three New Madrid fault segments. The NMSZ consists of three fault segments: the northeast segment, the reelfoot thrust or central segment, and the southwest segment. Each segment is assumed to generate a deterministic magnitude 7.7 ($M_w$7.7) earthquake caused by a rupture over the entire length of the segment. US Geological Survey (USGS) approved the employed magnitude and hazard approach. The combined rupture of all three segments simultaneously is designed to approximate the sequential rupture of all three segments over time. The magnitude of $M_w$7.7 is retained for the combined rupture. Full liquefaction susceptibility maps for the entire region have been developed and are used in this study.

Inventory is enhanced through the use of the Homeland Security Infrastructure Program (HSIP) 2007 and 2008 Gold Datasets (NGA Office of America, 2007). These datasets contain various types of critical infrastructure that are key inventory components for earthquake impact assessment. Transportation and utility facility inventories are improved while regional natural gas and oil pipelines are added to the inventory, alongside high potential loss facility inventories. The National Bridge Inventory (NBI, 2008) and other state and independent data sources are utilized to improve the inventory. New fragility functions derived by the MAE Center are employed in this study for both buildings and bridges providing more regionally-applicable estimations of damage for these infrastructure components. Default fragility values are used to determine damage likelihoods for all other infrastructure components.

The study reports new analysis using MAE Center-developed transportation network flow models that estimate changes in traffic flow and travel time due to earthquake damage. Utility network modeling was also undertaken to provide damage estimates for facilities and pipelines. An approximate flood risk model was assembled to identify areas that are likely to be flooded as a result of dam or levee failure. Social vulnerability identifies portions of the eight-state study region that are especially vulnerable due to various factors such as age, income, disability, and language proficiency. Social impact models include estimates of displaced and shelter-seeking populations as well as commodities and medical requirements. Lastly, search and rescue requirements quantify the number of teams and personnel required to clear debris and search for trapped victims.

The results indicate that Tennessee, Arkansas, and Missouri are most severely impacted. Illinois and Kentucky are also impacted, though not as severely as the previous three states. Nearly **715,000 buildings are damaged** in the eight-state study region. About **42,000 search and rescue personnel** working in 1,500 teams are required to respond to the earthquakes. Damage to critical infrastructure (essential facilities, transportation and utility lifelines) is substantial in the **140 impacted counties** near the rupture zone, including **3,500 damaged bridges** and nearly **425,000 breaks and leaks** to both local and interstate pipelines. Approximately **2.6 million households are without power** after the earthquake. Nearly **86,000 injuries and fatalities** result from damage to infrastructure. Nearly **130 hospitals are damaged** and most are located in the impacted counties near the rupture zone. There is extensive damage and substantial travel delays in both Memphis, Tennessee, and St. Louis, Missouri, thus hampering search and rescue as well as evacuation. Moreover roughly **15 major bridges are unusable**. Three days after the earthquake, **7.2 million people are still displaced** and **2 million people seek temporary shelter**. Direct economic losses for the eight states total **nearly $300 billion**, while indirect losses may be at least twice this amount.

The contents of this report provide the various assumptions used to arrive at the impact estimates, detailed background on the above quantitative consequences, and a breakdown of the figures per sector at the FEMA region and state levels. The information is presented in a manner suitable for personnel and agencies responsible for establishing response plans based on likely impacts of plausible earthquakes in the central USA.

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For more information on the earthquake impact assessment presented in this report please refer to Volume II. Additionally, both volumes I and II are posted on the Mid-America Earthquake Center website: http://mae.cee.uiuc.edu/.

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# Introduction

Catastrophic events, particularly natural disasters, have had devastating consequences on society not only in terms of damaged infrastructure but also in terms of impacts on citizens and economic stability in the affected region. Current initiatives by the Federal Emergency Management Agency (FEMA) seek to plan for potential natural disasters in an effort to minimize its negative impacts. The development of a response plan requires emergency managers to understand the potential impacts in terms of location, direct and secondary consequences, the needs of society both short- and long-term, as well as economic ramifications. Analytical impact assessments for natural disasters provide the potential to inform emergency managers and support the development of appropriate and effective response plans for catastrophic events. Furthermore, the disaster operations community finds great value in the analytical impact assessment results to gain situational awareness prior to on-the-ground reports. Such prior preparedness permits the rapid deployment of resources to heavily impacted areas.

In the case of analytical earthquake impact assessment, models and data are used to provide estimates of damage to infrastructure and network performance, as well as secondary damage due to cascading affects, social impacts and uncertainty quantifications. The three primary components required for analytical impact modeling are: *hazard*, *inventory*, and *fragility*. *Hazard* describes the intensity of ground shaking and ground deformation caused by an earthquake. The *inventory* utilized in an impact assessment model is characterized by a database of all assets in the region of interest. Numerous types of infrastructure are included in the inventory, as well as the population demographics of the region. *Fragility* relationships relate the intensity of ground shaking (hazard), or in some cases ground deformation, to the likelihood of different damage levels inflicted on various types of infrastructure. The outcome of the analytical model drives all other consequence algorithms for social impact, response requirements, cascading effects, and network analysis. Social impact models address numbers of displaced individuals and shelter population requirements, as well as their commodity and medical needs. Response requirements include search and rescue needs for impacted areas. Cascading effects address potential flood risk from damage to dams and levees. Network models provide estimates of post-event network performance in terms of road network congestion and travel time, as well as utility network damage and expected repair effort. Uncertainty quantification, undertaken for the first time in large-scale earthquake impact assessment, focuses on assigning ranges of impact values to infrastructure damage and economic loss parameters determined during primary modeling. The quantified levels of uncertainty are important for emergency management so that decisions can be facilitated by estimating the level of risk associated with assigned response and recovery effort. A combination of all these models produces a broad range of results, all of which are based on the most current and scientifically-defensible models and input information in an effort to assist local, state, regional, and national emergency managers and disaster operations personnel in their efforts to plan for response and recovery following major earthquakes.

The earthquake impact assessment presented in this report employs two analytical platforms, HAZUS (FEMA, 2008) and MAEviz (MAEC, 2009). HAZUS is a nationally applicable, analytical impact assessment software package that estimates impacts to numerous types of infrastructure, as well as society and the economy. MAEviz is the impact assessment software package developed by the Mid-America Earthquake Center and funded by the National Science Foundation. The program was developed jointly with the National Center for Supercomputing Applications at the University of Illinois and is described later in this report.

# Model Overview and Component Characteristics

## Regional Seismicity

Though not typically considered a seismically active region, numerous earthquakes occur in the Central US every year, primarily due to the activity of the New Madrid Seismic Zone (NMSZ) and the Wabash Valley Seismic Zone (WVSZ). The NMSZ stretches from northeast Arkansas to southern Illinois, passing through Missouri, western Tennessee, and western Kentucky. The New Madrid earthquake series that occurred in 1811 and 1812 includes some of the largest earthquakes in U.S. history, with estimated main shock moment magnitudes of 7 to 8 and several hundreds of aftershocks. According to the United States Geological Survey (USGS), the perception of strong shaking during this earthquake series was estimated to be two to three times larger than the 1964 Alaska earthquake and about 10 times larger than the 1906 San Francisco earthquake (USGS, 2009a). The seismic history of the NMSZ, however, precedes the 1811-1812 earthquake series. An increased number of geologic investigations since the 1970s have helped define historic seismic activity in the Central US. In addition to geological features, archeological evidence, such as the evidence obtained by Tuttle and Schweig (1995), verifies the occurrence of prehistoric earthquakes in the NMSZ from liquefaction feature studies focused on sand blows. A series of major earthquakes with moment magnitude equal to or greater than 7, including the 1811-1812 series, have occurred through a period of approximately 2,400 years, with intervals of 400 to 1,200 years (USGS, 2007).

As mentioned above, there is earthquake activity nucleating from the Wabash Valley Seismic Zone (WVSZ) located along the Wabash River between southeastern Illinois and Indiana. Geological evidence shows seismic activity of more than 20,000 years in that portion of the country. Though the magnitudes do not reach the maximum values of NMSZ events, it is evident that this fault poses a high risk of damage with magnitudes that could reach up to 7. The Wabash Valley Fault produced an earthquake as recently as April 2008, when a magnitude 5.2 earthquake occurred near Mt. Carmel, Illinois.

Structural damage was not significant during the 1811-1812 NMSZ earthquake series due to the dearth of settlements at the time. However, significant topological changes and ground deformation took place, including landslides, liquefaction, ground uplift and collapse. If similar events were to take place in the region today, the consequences would be much more significant and damage would be much more severe in terms of injuries and fatalities, structural damage, and economic and social impacts. According to USGS (2007), 150 to 200 earthquakes are recorded every year in the region. Today, the area is highly populated and densely covered with critical infrastructure, industry, commerce and residences. Furthermore, damage to certain facilities such as the Memphis airport, which hosts the largest FedEx hub in the U.S., would cause service interruption and negatively affect the regional, national, and global economies. Disastrous consequences would also result from the interruption of oil and gas services due to severely damaged pipelines. Events similar to the 1811-1812 New Madrid series would be catastrophic. Therefore, it is essential to accurately model and provide consequence assessment results that could be used to plan for and execute measures of mitigation, response and recovery on all levels.

## Overview of HAZUS Modeling

### Hazard

Earthquake hazards include ground shaking and deformation, as well as ground failure, surface faulting, and landslides. There are several methods available to define earthquake hazard. At a minimum, levels of shaking such as peak ground motion parameters or peak spectral values are required throughout the study region. Attenuation relationships are a common way to define earthquake hazard. Attenuation relationships describe the shaking propagation of an event from the seismic point source (epicenter) to a specific site. Other more advanced models include line source and area source modeling. However, in order to apply these more advanced models, extensive knowledge of the tectonic environment, mapping of fault geometry, and rupture mechanisms are required. Additional geotechnical features that significantly affect the earthquake hazard are soil amplification, especially in soft soils, liquefaction susceptibility, and the potential for landslides.

In HAZUS, ground motion is defined using one of two approaches: deterministic scenario analysis or probabilistic scenario analysis. In the case of deterministic ground motion analysis, the user can specify the hazard scenario by supplying ground shaking information that may or may not include soil data, which is used to apply the necessary amplification factors and modify the standard ground motion.

There are three levels of analysis in HAZUS: Level I, Level II, and Level III. Level I analysis uses HAZUS default settings without any improvements. Level II analysis allows for additional user-specified improvements, such as advanced source mechanism modeling (line source, area source), liquefaction susceptibility, as well as inventory and fragility updates. Level III involves advanced analysis, which also requires extensive effort and enormous time requirements. In the case of a Level III analysis, HAZUS models are modified to fit specific geographic locations, particularly economic factors pertaining to infrastructure value and loss. Additional models are also used to address impacts beyond the scope of the basic HAZUS program.

### Inventory

Inventory, or assets, consists of two major groups: population and infrastructure. Population includes demographic data, specifically classifications regarding age, income, gender, etc. Infrastructure is subdivided into buildings, transportation, utilities, and other critical infrastructure, referred to as high potential-loss facilities, primarily. The main inventory categories in HAZUS are classified into general buildings, essential facilities, high potential-loss facilities, transportation lifelines, and utility lifelines. The general building stock includes residential, commercial, industrial, agricultural, religious, government, and educational buildings (FEMA, 2008), while the systematic inventory classification utilized by HAZUS for the remainder of infrastructure inventory is shown below:

| | |
|---|---|
| **Essential Facilities** | |
| Medical Care Centers | Police Stations |
| Schools | Fire Stations |
| Emergency Operation Centers (EOCs) | |
| **High Potential-Loss Facilities** | |
| Nuclear Power Facilities | Dams |
| Hazardous Materials Facilities | Levees |
| **Transportation Lifelines** | |
| Airport Facilities | Highway Bridges |
| Bus Facilities | Railway Bridges |
| Ferry Facilities | Port Facilities |
| **Utility Lifelines** | |
| Communication Facilities | Oil Facilities |
| Electric Power Facilities | Potable Water Facilities |
| Natural Gas Facilities | Waste Water Facilities |
| Natural Gas Major Transmission Pipelines | Oil Major Transmission Pipelines |

A comprehensive inventory, both in terms of accuracy and detail, significantly increases the reliability of an impact assessment. Information like building type, construction materials, and age are extremely important when assessing the level of damage resulting from an earthquake event. Also, additional factors such as replacement values are necessary to predict economic losses. HAZUS default inventory has a basic inventory database; however, it is necessary to improve upon the initial HAZUS-provided inventory with additional sources that include the latest and most advanced infrastructure data currently available. Unique or irregular infrastructure must also be considered during the loss assessment. Unique structures do not fit the generalized structure types in HAZUS, thus requiring independent damage assessments. This provides the opportunity to include structures such as high rise buildings or long-span bridges that are not as common, but exceedingly important nonetheless. Other critical infrastructure includes cell phone towers and antennas, stadiums, and historic landmarks. Furthermore, in order to reduce inventory uncertainty, frequent inventory updates are necessary to assure the most scientifically sound model components.

### Fragility

Fragility, or vulnerability, functions relate the severity of shaking to the probability of a structure reaching or exceeding a specific damage limit state. A shaking intensity measure, such as a peak ground parameter or spectral response value, is applied to a fragility curve in order to estimate the probability of the given structure experiencing a certain level of damage. HAZUS defines four damage levels: slight, moderate, extensive, and complete; therefore, there are four fragility curves for each structure type. Furthermore, the intensity parameter that each set of fragility curves is based on depends upon the structure type assessed. For example, structures with long natural periods, such as long span bridges, are generally more sensitive to long-period spectral acceleration or displacement due to liquefaction. Intensity measures may include permanent ground displacement or long-period spectral values. Conversely, structures with short periods of vibration such as low rise masonry buildings are more sensitive to acceleration, thus peak ground acceleration is an acceptable parameter to represent the ground shaking intensity parameter.

The most common methods to derive fragilities can be categorized into three groups: observational, analytical, and hybrid. The observational method is based on professional experience, while the analytical method uses mathematical regression relationships to derive fragilities. Intuitively, the hybrid method is a combination of both analytical and observational methods. Many of the default fragility relationships in HAZUS are based on the observational method. These relationships are far less technically rigorous than analytical or hybrid fragilities. The use of more technically rigorous fragility relationships leads to more accurate assessments of structural performance and associated damage. Moreover, HAZUS default fragilities are applied to the entire U.S. though the observational data used to develop the fragilities is heavily based on California earthquake damage data. The resulting fragilities are applied to the entire U.S. even though they are not specific to the Central US; therefore, the uncertainty of default fragilities is high. In order to reduce the uncertainty and provide more accurate and structure-specific fragilities, new fragilities derived by the Mid-America Earthquake (MAE) Center are implemented in the earthquake impact assessment conducted in this study.

## Overview of MAEViz Modeling

MAEviz is an advanced seismic loss assessment and risk management software which stands on the Consequence-based Risk Management (CRM) methodology. CRM was first required for the complex nature of high-consequence earthquakes in the Central U.S. The MAE Center has pioneered the development and application of a holistic approach towards seismic risk assessment and mitigation, termed Consequence-based Risk Management (Elnashai and Hajjar, 2006). CRM provides the philosophical and practical bond between the cause and effect of the disastrous event and mitigation options. MAEviz follows the CRM methodology using a visually-based, menu-driven system to generate damage estimates from scientific and engineering principles and data, test multiple mitigation strategies, and support modeling efforts to estimate higher level impacts of earthquake hazards, such as impacts on transportation networks, social, or economic systems.  It enables policy-makers and decision-makers to ultimately develop risk reduction strategies and implement mitigation actions.

**Transportation Network Modeling**

The failure of transportation infrastructure following an earthquake not only hinders everyday activities, but also impairs the post-disaster response and recovery, resulting in substantial socio-economic losses and other negative social impacts. This section provides a general description of the transportation systems performance model for earthquake impact assessment. The network loss analysis (NLA) module of MAEViz, was developed to address the detailed modeling requirements of transportation networks that are not available in HAZUS. The NLA module is useful to evaluate system performance of transportation systems for emergency management. The results of traffic flow and travel delays provide useful information for emergency managers and relevant government agencies to develop emergency response plans for ingress and egress of impacted areas (e.g. disaster relief dispatch and evacuation), and to identify emergency routes and evaluate their performance under extreme events.

The key concept of the NLA module employs traffic assignment models to evaluate the performance of the transportation network. This study employs widely-used static traffic assignment models to simulate the traffic over the network. A static model assumes the model parameters (e.g. traffic demand and travel cost) do not vary over time, that is, the model parameters are static. The static models give steady-state traffic flow in user (traveler) equilibrium (UE), in which no traveler in the network can unilaterally change routes and improve individual travel time as a result (Wardrop, 1952; Sheffi, 1985). The static assignment models provide a fairly accurate and efficient prediction of the average travel time, have been employed elsewhere and are still widely accepted by many transportation agencies and practitioners (Kim et al., 2008).

**Utility Network Modeling**

The Interdependent Network Analysis (INA) tool provided in MAEViz is employed to provide utility system performance estimates in addition to seismic damage estimations provided by other models and software packages. The analysis addresses lifeline utility service changes that result from an earthquake, as well as damage of interdependent networks, and flow reductions following an earthquake. Rinaldi et al. (2001) defined network dependency as a linkage between two systems, through which the state of one is influenced by the other.

The INA tool combines inventory, hazard, and fragility parameters to determine the structural impact of earthquakes on topologically modeled utility lifeline systems. The damage assessment obtained from the structural model is then used for the determination of failed components in the network of the topological model. Network performance is assessed via two performance measures obtained from the interdependency model, utilizing Monte Carlo Simulations. The measures are applied to quantify the estimated loss of connectivity within the network, and the reduction in the network flow reaching the demand locations. The INA model is the result of past MAE Center research on interdependent utility network modeling and is based on algorithms developed by Duenas-Osorio (2005) and Kim (2007).

The results may be used directly to determine physical damage to the utility networks or they can be interpreted along with various other parameters to improve resilience of network systems, retrofitting of components to prevent major damage and disruptions, and estimating the repair effort and necessary resources for repairing. Additionally, impacts to the utility networks are vital components of earthquake response planning and provide necessary data for emergency managers.

## Modeling Components and Characteristics

### Hazard

Building upon previous hazard data in the region, additional substantial improvements pertaining to ground motion definition are implemented in this study. The Central United States Earthquake Consortium (CUSEC) State Geologists created a regionally comprehensive set of soil maps for the eight states included in this impact assessment study. New maps include extensive characterizations of soil site class based on the National Earthquake Hazard Reduction Program (NEHRP) soil classification scheme and liquefaction susceptibility maps based on the procedure outlined in Youd and Perkins (1978). Each of the eight state geological surveys produced its own state maps detailing soil site class and liquefaction susceptibility which were subsequently compiled into a single regional map.

The soil site class map development process followed the procedures outlined in the NEHRP provisions (Building Seismic Safety Council, 2004) and the 2003 International Building Codes (International Code Council, 2002). The map development initiated with the identification of liquefiable soils, thin soils, and thick soft soils. In order to identify liquefiable soils (Site Class F), thick soft soils (Site Class E), and thin soils several requirements needed to be satisfied. CUSEC State Geologists used the entire column of soil material down to bedrock and did not include any bedrock in the calculation of the average shear wave velocity for the column, since it is the soil column and the difference in shear wave velocity of the soils in comparison to the bedrock which influences much of the amplification (CUSEC, 2008). Using these procedures along with Fullerton et al. (2003), soil site class maps were produced for the eight states, and are shown in Figure 1.

Development of the liquefaction susceptibility maps utilized the procedure outlined in Youd and Perkins (1978). The map created was further matched with information in Fullerton et al. (2003) and the additional expertise of state geologists. The new liquefaction map was then formatted to meet HAZUS requirements and classifications. Figure 2 illustrates the liquefaction susceptibility of the eight states.

All of the ground motion maps are intended to represent a sequential rupture of the three NMSZ segments, meaning that the ground motion maps represent the combined ground motion caused by the rupture of all three segments. The constraints of HAZUS do not permit the modeling of three events in sequence, thus the single, simultaneous rupture of all three segments is used as the best available approximation of the three segment sequential rupture. Figure 3 illustrates the proposed three segments of the New Madrid Fault utilized in the scenario event.

The HAZUS computer program uses the soil site class map along with an earthquake magnitude and location to calculate the surface ground motions based on amplifications assigned to each soil site class; however, the HAZUS program does not perform the analysis outside a radius of 200 km from the earthquake source. This poses a significant problem as the affected region is much larger. As a solution, the CUSEC State Geologists soil site class map was incorporated into new ground motion maps developed by Chris Cramer which followed procedures in Cramer (2006). The ground motion was horizontally propagated through the rock layer and vertically propagated through soil layers above the bedrock. The ground motion maps were developed for a $M_w$7.7 earthquake. Figure 4 thru Figure 7 illustrate the hazard maps used in this study. Extensive calculations provided ground motion values, which account for soil amplification, at many grid points throughout the eight-state study region.

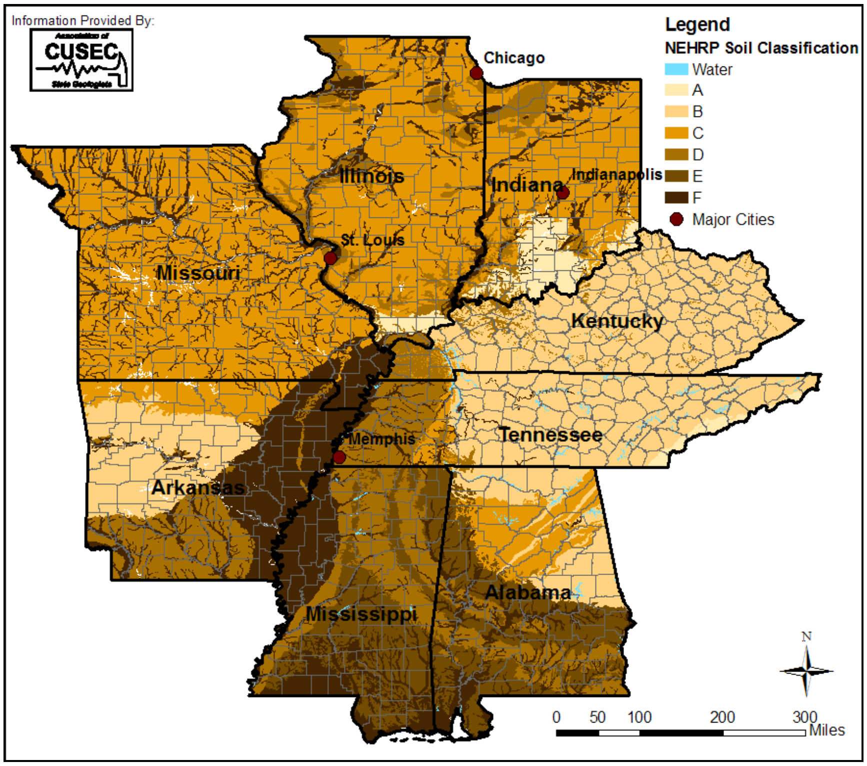


**Figure 1: Soil Site Class Map (CUSEC, 2008)**

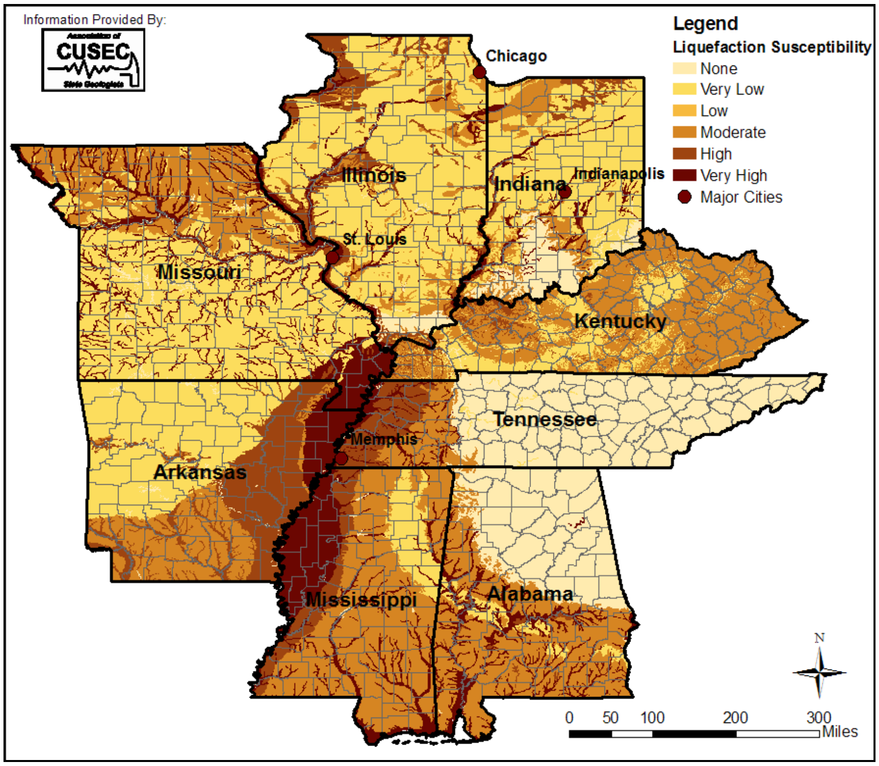


**Figure 2: NMSZ Liquefaction Susceptibility (CUSEC, 2008)**

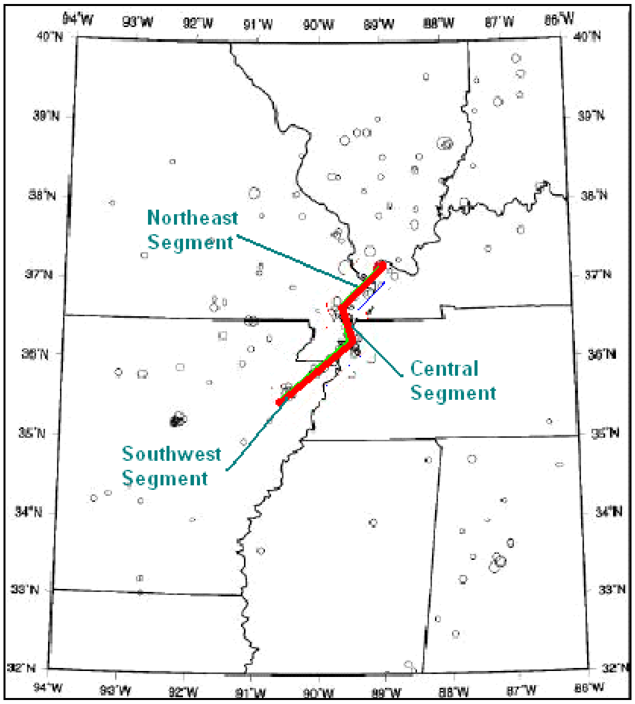


**Figure 3: Proposed Segments of New Madrid Fault**

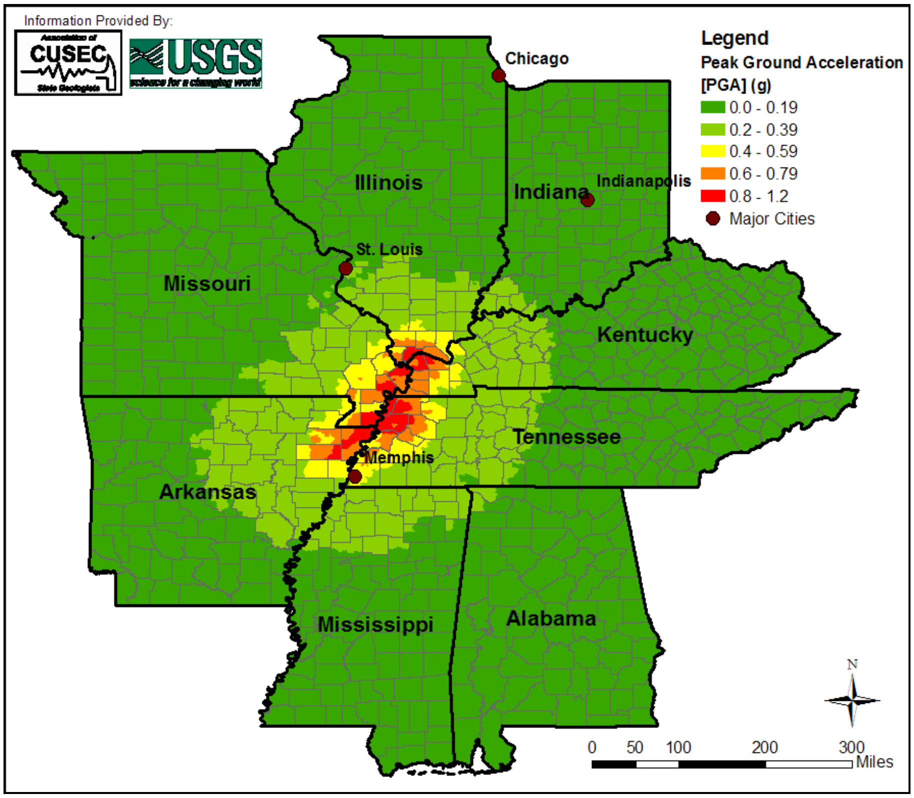


**Figure 4: NMSZ Scenario Event - Peak Ground Acceleration**

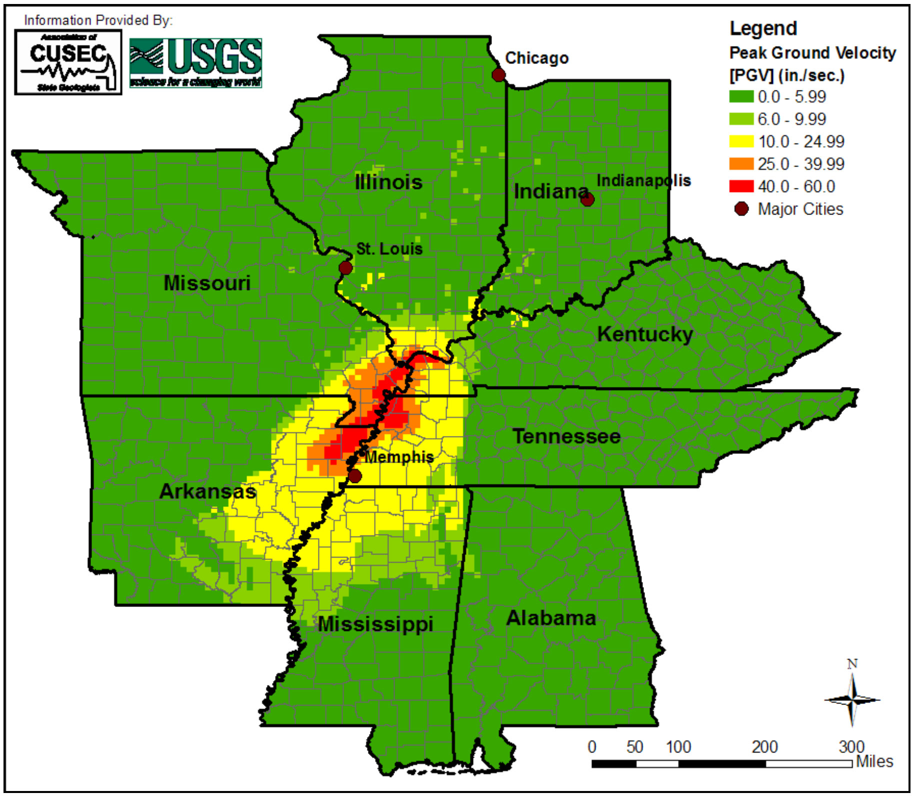


**Figure 5: NMSZ Scenario Event - Peak Ground Velocity**

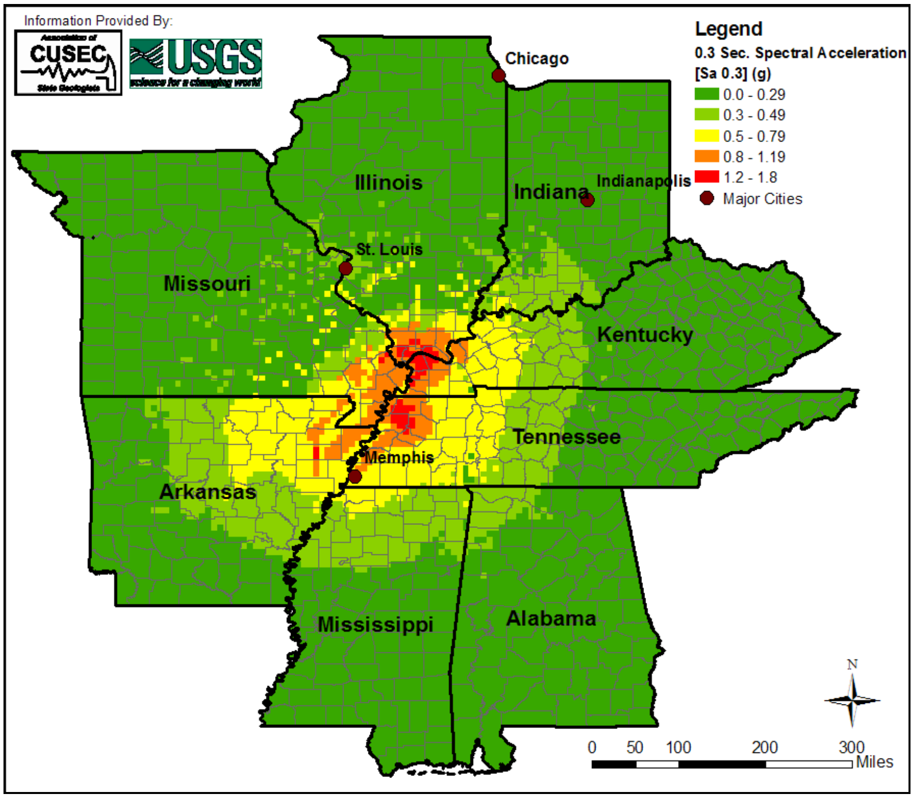


Figure 6: NMSZ Scenario Event - Spectral Acceleration at 0.3 Sec.

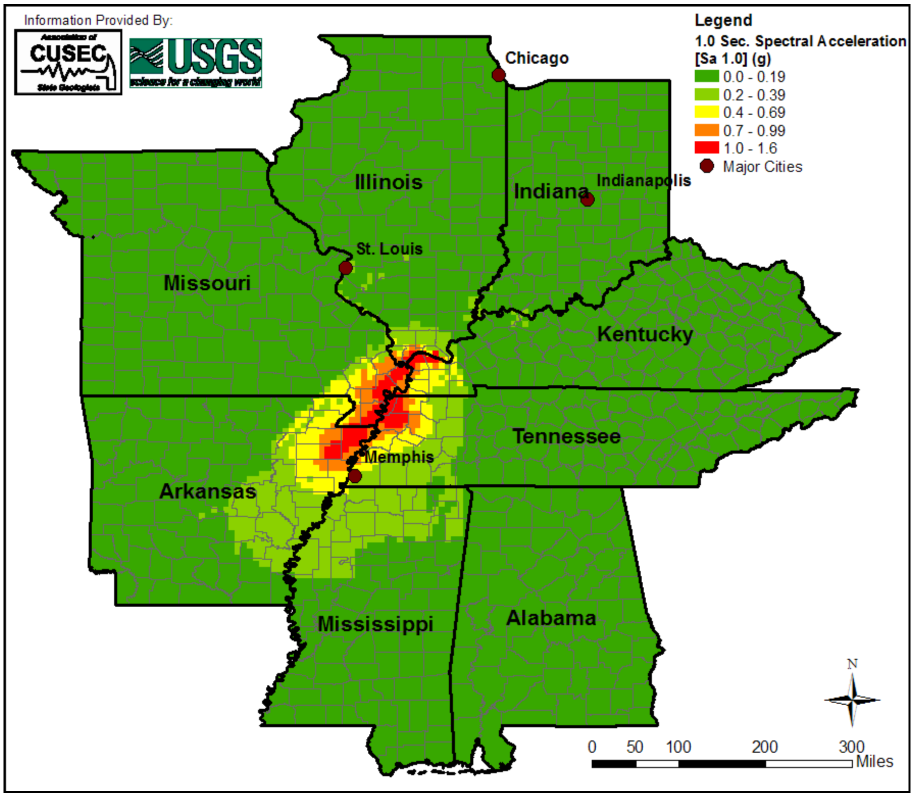


Figure 7: NMSZ Scenario Event - Spectral Acceleration at 1.0 Sec.

**Inventory**

Two major categories of inventory, or regional assets, are required to perform an analytical earthquake impact assessment, namely infrastructure and population characterizations. Population data includes the overall population as well as demographic groups which are delineated based on income, ethnicity, age, education, visitors and several other categories. Population demographic data is provided by HAZUS and includes data from the year 2000 census (FEMA, 2008). This baseline data is utilized in all assessments of NMSZ impacts. Figure 8 illustrates the population distribution from the year 2000 census that is used in this study.

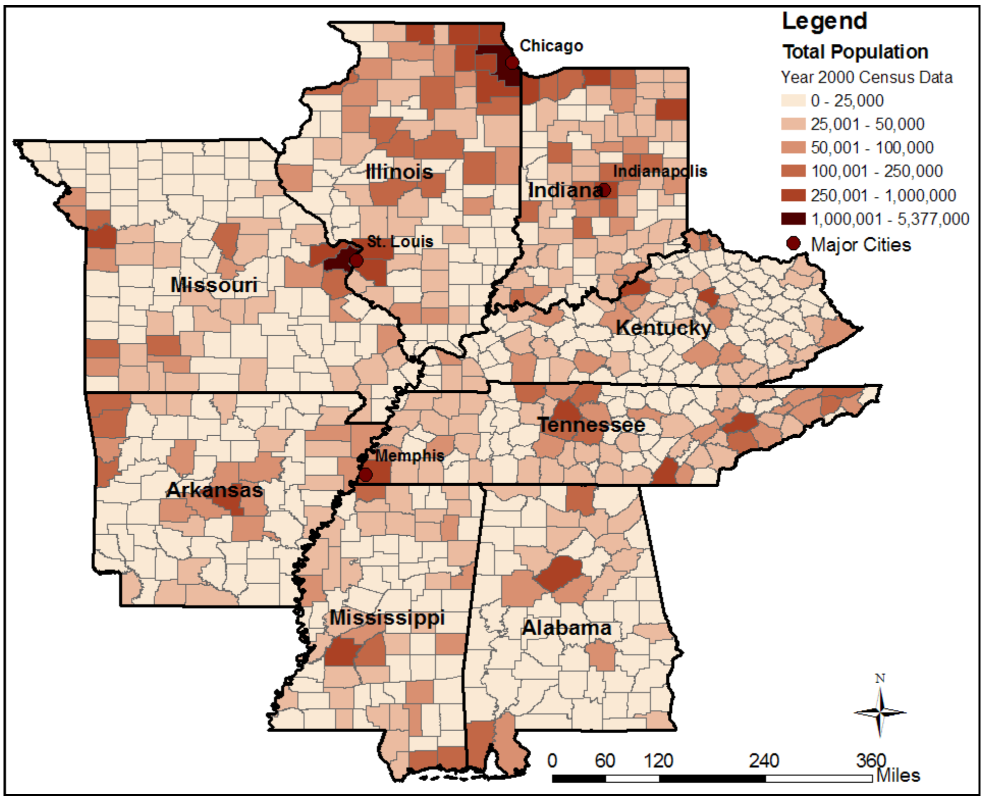

**Figure 8: Total Population of Eight-State Region Based on Year 2000 Census Data**

The HAZUS software also provides baseline data for various infrastructure, though this data is updated substantially to improve the accuracy of impact assessments. There are two primary methods used to represent infrastructure in HAZUS, aggregated data and point-wise data. Aggregated data provides structure totals at a specified level of granularity which is typically the census-tract level. All general buildings and local pipeline distribution networks use this form of data representation. General buildings include residential, commercial, industrial, education, government, agriculture, and religious use groups. Buildings are also divided into structure types: wood, steel, cast-in-place concrete, precast concrete, reinforced masonry, unreinforced masonry, and manufactured housing. Local distribution pipelines are quantified for potable water, waste water, and natural gas networks. These types of inventory are not updated due to the complexity of updates required and the limited amount of time available to acquire and implement the needed information. Thus, all aggregated infrastructure types utilize HAZUS baseline data from the MR3 release (FEMA, 2008).

Point-wise infrastructure inventory is employed for critical infrastructure, namely essential facilities, transportation lifelines, utility lifelines and other high-potential loss facilities. Numerous datasets are available to augment the baseline critical infrastructure data in HAZUS and many are utilized to improve the inventory characterization within the study region. Specific types of critical infrastructure that are improved include:

**Essential Facilities**

| | |
|---|---|
| Medical Care Centers | Police Stations |
| Schools | Fire Stations |
| Emergency Operation Centers (EOCs) | |

**High Potential-Loss Facilities**

| | |
|---|---|
| Nuclear Power Facilities | Dams |
| Hazardous Materials Facilities | Levees |

**Transportation Lifelines**

| | |
|---|---|
| Highway Bridges and Roads | Railway Bridges, Tracks, and Facilities |
| Airport Facilities | Bus Facilities |
| Port Facilities | Ferry Facilities |

**Utility Lifelines**

| | |
|---|---|
| Communication Facilities | Potable Water Facilities |
| Electric Power Facilities | Waste Water Facilities |
| Natural Gas Facilities and Interstate Pipelines | Oil Facilities and Interstate Pipelines |

Improvements to these critical infrastructure datasets employ data from national and state datasets as well as independent searches conducted by the MAE Center. National datasets include the Homeland Security Infrastructure Program (HSIP) Gold Datasets from both 2007 and 2008 (NGA, 2007 & 2008), the National Bridge Inventory (NBI) from 2008 (US Dept. of Transportation, 2008), and US Army Corps of Engineers Levee Data acquired by the MAE Center in 2008. The HSIP data includes more than 200 datasets for various types of infrastructure while the NBI and US Army Corps data only refers to bridge and levee data, respectively. Some state-specific data is also used, namely in Illinois and Indiana. A previous impact assessment project at the MAE Center cataloged essential facilities in southern Illinois and these facilities are added to the inventory for the state. Additionally, extensive datasets were compiled by the POLIS Center at Purdue University for the State of Indiana. Most types of critical infrastructure were included in this study and thus incorporated in this impact assessment project. Lastly, MAE Center independent searches are used to identify major river crossings in the study region. A total of 127 major river crossings are identified on the Arkansas, Illinois, Ohio, Mississippi, and Missouri Rivers within the eight-state study region. Various sources are utilized to develop this set of bridges.

The incorporation of numerous datasets presents challenges when attempting to develop a single, comprehensive dataset for the study region, specifically eliminating duplicate data.

In many cases, several datasets, including the HAZUS baseline data, share many common facilities though the geo-spatial data used to locate these facilities differ slightly in each dataset. These small differences necessitate a location-based filter which is offered in geographic information systems (GIS) software. When location, or coordinate, differences are larger other metadata is used to filter the datasets. Such metadata include facility name and street address. All efforts are made to remove duplicate facilities in the short timeframe allowed by this project.

**Table 1: Inventory Statistics for FEMA Regional Impact Assessments**

| Infrastructure Category | Baseline Inventory (Project Yr. 1) | Regional Modeling Inventory (Project Yr. 3) | Additional Infrastructure from Baseline |
|---|---|---|---|
| **Essential Facilities** | | | |
| Hospitals | 1,074 | 2,825 | 1,751 |
| Schools | 18,455 | 20,291 | 1,836 |
| Fire Stations | 5,032 | 10,346 | 5,314 |
| Police Stations | 3,982 | 4,480 | 498 |
| Emergency Operation Centers | 353 | 1,182 | 829 |
| **Essential Facilties Total** | **28,896** | **39,124** | **10,228** |
| **Transportation Facilities** | | | |
| Highway Bridges | 104,048 | 165,771 | 61,723 |
| Highway Tunnels | 11 | 11 | 0 |
| Railway Bridges | 1,663 | 1,888 | 225 |
| Railway Facilities | 990 | 1,118 | 128 |
| Railway Tunnel | 2 | 72 | 70 |
| Bus Facilities | 310 | 405 | 95 |
| Port Facilities | 1,738 | 1,904 | 166 |
| Ferry Facilities | 6 | 52 | 46 |
| Airports | 2,435 | 3,773 | 1,338 |
| Light Rail Facilities | 0 | 537 | 537 |
| Light Rail Bridges | 38 | 38 | 0 |
| **Transportation Facilities Total** | **111,241** | **175,569** | **64,328** |
| **Utility Facilities** | | | |
| Communication Facilities | 3,160 | 145,722 | 142,562 |
| Electric Power Facilities | 554 | 10,893 | 10,339 |
| Natural Gas Facilities | 464 | 34,339 | 33,875 |
| Oil Facilities | 138 | 89,621 | 89,483 |
| Potable Water Facilities | 918 | 1,195 | 277 |
| Waste Water Facilities | 4,518 | 48,430 | 43,912 |
| **Utility Facilities Total** | **9,752** | **330,200** | **320,448** |
| **High Potential-Loss Facilities** | | | |
| Dams | 15,098 | 17,573 | 2,475 |
| Hazardous Materials Facilities | 20,153 | 39,939 | 19,786 |
| Levees | 0 | 1,326 | 1,326 |
| Nuclear Power Facilities | 15 | 25 | 10 |
| **High Potential-Loss Facilities Total** | **35,266** | **58,863** | **23,597** |
| **Total Number of Facilities** | **185,155** | **603,756** | **418,601** |

Substantial improvements are made in the characterization of infrastructure inventory in the study region through the incorporation of the aforementioned data. Baseline HAZUS inventory includes roughly 185,000 critical facilities and upon completion of all inventory improvements for the FEMA Regional Workshop analysis there are over 600,000 critical facilities. Several infrastructure types show significantly improved infrastructure characterizations. Infrastructure types showing the greatest improvements are utility facilities, though some transportation and high potential-loss facilities show substantial increases in facility counts. Specifically, over 140,000 communication facilities are added, plus nearly 34,000 natural gas facilities, nearly 90,000 oil facilities, and 44,000 waste water facilities. Furthermore, almost 62,000 bridges and 20,000 hazardous materials facilities are added. More moderate improvements are made to essential facilities and many other transportation facility datasets. Overall, however, the updates to regional inventory over the entire course of the impact assessment project are substantial and greatly improve the accuracy and reliability of the impact assessment results. Table 1 details the initial and final inventory counts for critical infrastructure in the eight-state study region.

An independent inventory collection process was also undertaken for the transportation network modeling in MAEViz. The road network data for the two metropolitan areas of St. Louis, Missouri, and Memphis, Tennessee, include locations of nodes and links, road characteristics, and travel demand are all collected from the local metropolitan planning organizations (MPOs) (i.e., the East-West Gateway Council of Governments at St. Louis, MO, and the Memphis Urban Area MPO at Memphis, TN). The road network databases contain over 100 fields with descriptive characteristics for each link that are used to estimate capacity and speed setting for traffic modeling.

The East-West Gateway Council of Governments (EWGCOG) consists of the City of St. Louis, and also Franklin, Jefferson, St. Charles, and St. Louis Counties in Missouri, and Madison, Monroe, and St. Clair Counties in Illinois. The Memphis Urban Area MPO consists of Shelby, Fayette, and Tipton Counties in Tennessee, as well as Desoto and Marshall Counties in Mississippi. The road network database and the associated travel demand are extracted from the 2004 highway network model from the Memphis MPO. The St. Louis MPO road network and travel demand are extracted from the 2002 loaded highway network product from the EWGCOG's TransEval transportation model.

Utility network models also require additional inventory investigations. As with transportation network modeling, advanced utility network modeling is completed for St. Louis and Memphis only, since these are the two primary metropolitan areas significantly impacted by a NMSZ event. Water network data was obtained from The City of St. Louis Water Division. The MAE Center was not permitted to retain any of the inventory data, so researchers completed all analyses at the St. Louis Water Division headquarters. The aforementioned HSIP 2008 data provided the basis for electric power network data in the St. Louis area.

St. Louis Natural Gas data was provided by Laclede Gas Company. Due to the confidential nature of this proprietary data, the MAE Center is not in a position to display the pipeline inventory, though results are included in subsequent sections and are represented in an aggregated form. All data for Memphis, Tennessee, utility network analyses was obtained from Memphis Light, Gas, and Water (MLGW). Network datasets included natural gas, potable water and sewage pipelines as well as electric network data.

**Fragility**

Several types of fragility relationships are improved in this Central US earthquake impact assessment and reflect the unique demand, capacity, or both, of infrastructure in this region. New fragilities are incorporated for all 36 building types and as well as all HAZUS bridge types applicable in the Central US.

*Fragility Relationships for Buildings*

A new way to derive fragilities is used to improve upon the HAZUS default fragility functions. The methodology employed to develop the new building fragilities allows for a more accurate damage assessment and was used to derive sets of fragility curves for all building types. The HAZUS fragility derivation methodology developed by Genctürk (2007) consists of three main components: capacity, demand, and methodology.

The capacity of structures is defined by yield and ultimate points and is represented through either analytical or expert opinion pushover curves. Demand refers to the earthquake event a structure is subjected to and represented earthquake ground motions. HAZUS provides default capacity and demand curves for all infrastructure types, though the demand curves are adjusted to represent Central US event during the development of new building fragilities. Also, HAZUS default capacity curves were used to generate new building fragilities. With regard to demand, synthetic records are often used in the Central US for large magnitude earthquakes due to lack of adequate existing earthquake records for events with magnitudes large enough to generate catastrophic impacts. Synthetic, site-specific ground motions were generated in order to capture site-specific factors such as frequency distribution, duration, and site conditions (Genctürk et al., 2008). Finally, structural assessment is completed by applying an advanced Capacity Spectrum Method (CSM), and fragilities are derived and presented in two different forms: conventional and HAZUS compatible. Only the HAZUS compatible fragility relationships are used in this study.

Conventional fragilities differ from HAZUS fragilities in terms of intensity measures. The majority of conventional fragilities utilize peak ground parameters (acceleration [PGA], velocity [PGV], or displacement [PGD]) or spectral values to represent the ground shaking intensity used to determine specific damage level probabilities. HAZUS fragilities are presented differently. In HAZUS, the fragility relationships are expressed by damage state exceedance probabilities related to structural response and the only parameter required to derive the HAZUS compatible fragility curves is the combined uncertainty of capacity and demand, which is obtained through the "convolution" process (Genctürk, 2007). The spectral displacement ground motion parameter is employed in HAZUS building fragility curves and thus is the basis for all new HAZUS-compatible fragility relationships incorporated in this study. Building demand curves for all building types included in the HAZUS program were not modified for these HAZUS-compatible fragilities, instead the HAZUS default capacity curves were employed during the creation of new building fragilities. Using this process, four median probabilities are obtained, corresponding to each damage state: slight, moderate, extensive, and complete damage. Subsequently, a lognormal distribution is applied to create the fragility curves.

*Fragility Relationships for Bridges*

Only 19 of the 36 bridge types in HAZUS are applicable to bridges in the Central US, and 16 of those are updated with new fragilities specific to the study region. These 16 HAZUS bridge types are mapped onto the five of the nine bridge types specified in Nielson and DesRoches (2004, 2006a, 2006b). Only five bridge types considered by Nielson and DesRoches correlate well with HAZUS bridge types. Some new bridge fragilities are applied to two HAZUS bridge types based on structural characteristics. The three remaining HAZUS bridges types are reserved for bridges over 500-ft. (HWB1 and HWB2) or all other bridges that do not fit the general bridge classes outlined in the Technical Manual (HWB 28). For these three bridge types, the HAZUS default fragility values are retained.

New bridge fragility relationships consider several bridge components individually, unlike the HAZUS default fragility functions. Such individually analyzed components include columns, fixed bearings, expansion bearings, and both lateral and transverse abutments. Three-dimensional analytical models are created for each component in the bridge structure and non-linear time histories are applied to determine component behavior. As with building fragilities, synthetic ground motion records are used in the time history analysis for all bridge components. Component performance is used to determine the overall performance of the bridge. The capacity of the bridge system is compared with the demand established by the synthetic records. The combination of regionally-appropriate earthquake records and individual bridge component generated fragility curves provide the best available representation of bridge performance in the Central US.

**Transportation Network Analysis**

The Central US is an important "hub" of the national transportation system. According to the 2002 Commodity Flow Survey by the Bureau of Transportation Statistics (BTS), more than 968 billion ton-miles, or about 31% of the total US commodities originate, pass through, or arrive in the Central US region (BTS, 2005).

The greater metropolitan areas of Memphis and St. Louis are of particular significance. With regard to freight, the Federal Express Corporation (FedEx) worldwide headquarters and world hub are located in Memphis. The third largest U.S. cargo facility of the United Parcel Service, Inc. (UPS), and also the only UPS facility capable of processing both air and ground cargo, is located in Memphis (Hanson, 2007). The Memphis International Airport has been the world's busiest airport in terms of cargo traffic volume. St. Louis is also the home of the nation's second-largest inland port by trip ton-miles and the nation's third-largest rail center (St. Louis RCGA, n.d.).With regard to general travel, the Central US is home to millions of people, including two major population centers in the St. Louis and Memphis metropolitan areas. In order to determine impacts to the transportation network in these major urban centers, the aforementioned $M_W7.7$ scenario earthquake is used to estimate the damage to bridges and subsequent impact on the road network.

The Memphis network consists of 12,399 nodes and 29,308 links, and travel demand of the network are represented by 1,605,289 origin-destination (OD) pairs (See Figure 9). The St. Louis network is considerably larger, containing 17,352 nodes, 40,432 links, and 7,263,025 OD pairs (See Figure 10).

Bridge information is extracted from the 2002 National Bridge Inventory (NBI) database from the Federal Highway Administration (FHWA). The 2002 version of the NBI database is compatible with the road network information provided by the local MPOs. Though the 2008 NBI was incorporated in the aforementioned HAZUS inventory, the 2002 NBI must be used in the transportation model since it corresponds to the data provided by the MPO. In this case, using the most current NBI would hinder the modeling process as MPO and NBI datasets would be incompatible. From the NBI database, a total number of 3,095 and 615 bridges within the MPO boundaries are filtered in GIS for the St. Louis and Memphis MPO networks, respectively.

The key components and procedures of the MAEViz Network Loss Analysis module for transportation network performance and system functionality assessment are presented. Figure 11 summarizes the major components of the overall methodological framework, including input data, major analysis procedures, and outputs. Three groups of input data are required for the model, including hazard, transportation infrastructure inventory, and network operations information. Hazard definition includes information on ground shaking and ground deformations such as those due to liquefaction and landslides. The bridge and network inventory consists of essential network configuration of topology, link properties, and bridge information. Network components are assumed to be independent when estimating the physical damage to bridges. The inventory, hazard, and damage information are integrated in the geographic information systems (GIS) and provide an efficient means of data manipulation and visualization. The baseline analyses estimate the pre-event system performance as a reference point. The post-event network status is determined by evaluating bridge functionalities resulting from the scenario earthquake. The post-event system performance with damaged bridges is assessed with traffic assignment models and recommendations are made based on the system functionality losses. Traffic modeling provides essential information on traffic flow changes, and travel delays that result from particular route closure due to excessive damage to key infrastructure elements, or from the reduced traffic carrying capacity because of less severe damage (e.g., lane closure for repair or imposed lower speed limit).

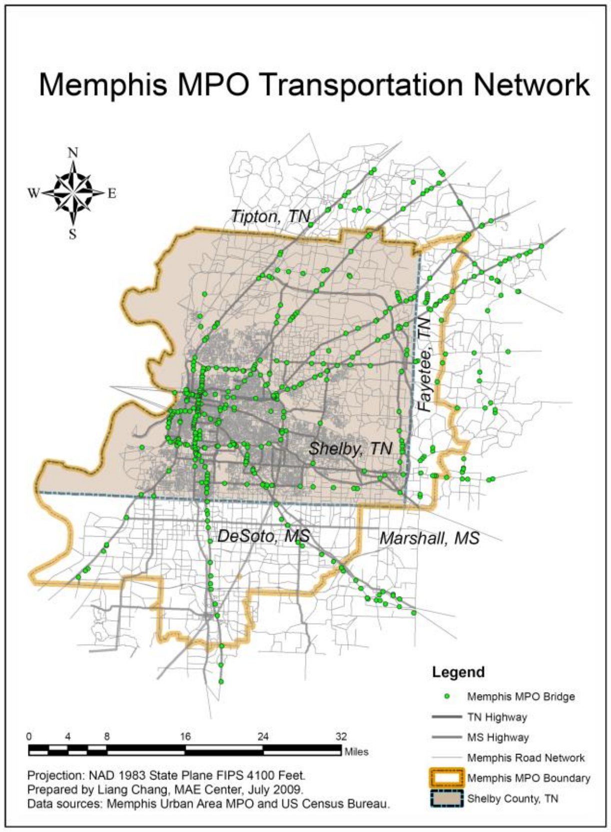


**Figure 9: Memphis MPO Transportation Network**

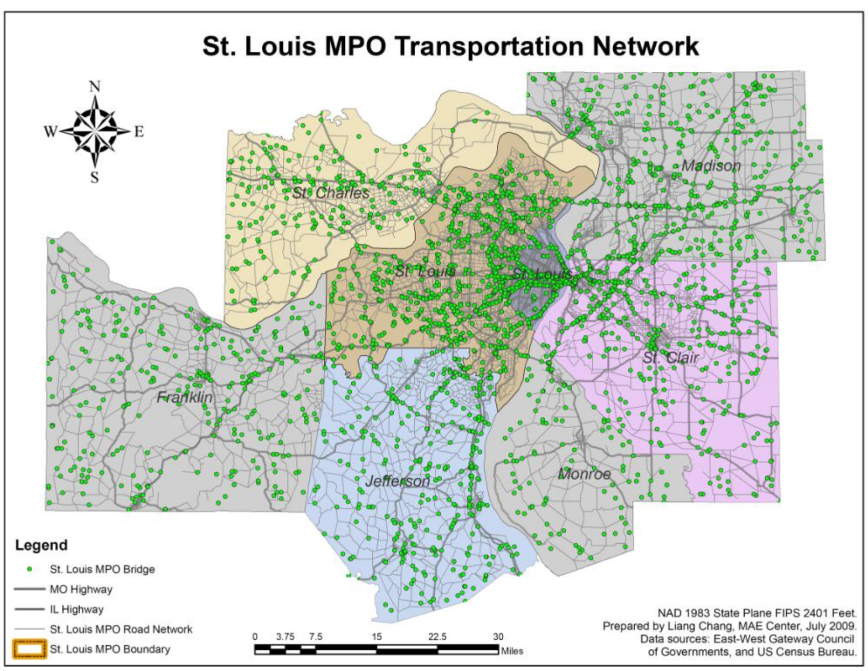


**Figure 10: Transportation Network in St. Louis Area**

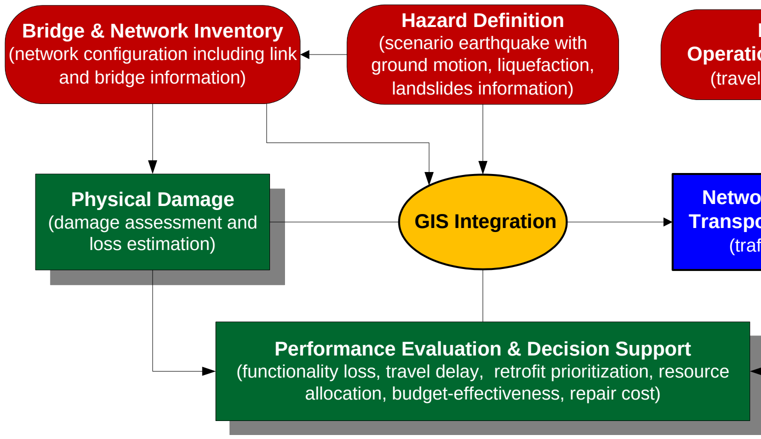


**Figure 11: Transportation Modeling Methodological Framework**

**Utility Network Analysis**

In addition to the default analysis of major interstate transmission lines, structures, and generalized pipeline information per census tract in HAZUS, lifeline utility networks of St. Louis, Missouri, and Memphis, Tennessee, are assessed in detail with MAEViz. The two major metropolitan areas in the NMSZ (Figure 12) house populations of 2,817,000 and 1,286,000 people, respectively, according to U.S. Census Bureau (2008). The MAEViz analysis covers the structural damage assessment and interdependent network performance analysis of the electric power, potable water, and natural gas networks in St. Louis and Memphis.

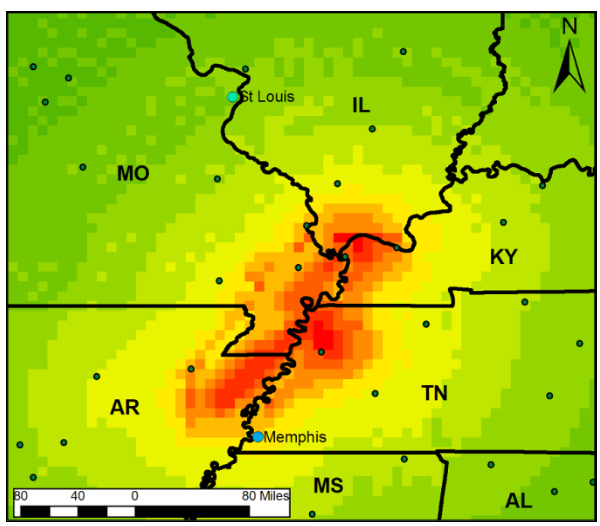


**Figure 12: St. Louis, MO and Memphis, TN in the New Madrid Seismic Zone**

The network analysis methodology suggests the examination of the network systems using two separate models comprised of two phases: structural analysis and interdependent network modeling. The network analysis phase requires the topological modeling of the utility networks.

In the structural analysis phase, structural damage estimates of network pipelines and network facilities caused by ground shaking and liquefaction-induced ground deformations are obtained via fragility relationships. Individual buried pipeline segments are defined by pipe material, joint type, diameter, segment length, and soil corrosivity information. Network facilities are defined by facility type, capacity, and availability of a backup power generator (for water and natural gas network facilities). Fragility curves and damage functions are matched to individual components based on the above characteristics in order to estimate the expected damage properly.

The interdependent network modeling phase requires topological modeling of the lifeline utility networks upon the completion of initial damage estimations. Physical arrangements and connections of each component with other components in the network are defined in order to model the connectivity and flow patterns in the networks. Monte Carlo simulations are utilized to assess the network performance. Failures of components are determined probabilistically in each simulation based on the structural damage estimated in the first analysis. Structurally damaged or topologically isolated components are considered to have 'failed' and are removed from the network. A network facility may also be removed from the network if it relies on the operability of a failed utility facility in another network. Damaged networks are re-structured in each Monte Carlo simulation to assess the performance by applying two system-wide performance measures that are represented as percentages: connectivity loss (CL) and service flow reduction (SFR). CL quantifies the ability of every distribution node to receive flow from the generation nodes; whereas SFR quantifies the loss in supply that cannot meet the demand at distribution nodes (Kim et al., 2007). The latter indicates system capacity and the effect of the earthquake on the end users.

**Threshold Values**

The Mississippi River divides the Central US into two parts, namely the eastern and western parts. There are many different long-span bridges, major dams, and levees built on this river and other major rivers in the Central US. Moreover, thousands of storage tanks that frequently hold hazardous materials are located in cities and towns in this part of the country. The Central US is considered a low probability, high consequence earthquake zone, which leads to the assumption that a repeat of the 1811-1812 earthquake series would likely generate some form of damage in these major structures. The infrastructure systems described above, however, are not amenable to analytical fragility assessments due to their diversity of types and complexity. Developing analytical fragility relationships for each unique infrastructure item is time-prohibitive. An alternative method of damage approximation is employed in the form of rapid damage assessment with threshold values. Threshold values are basic pass-fail values, above which a structure is likely damaged, and below which a structure is not likely to incur damage. A comparison of a threshold value and a typical fragility relationship is illustrated in Figure 13.

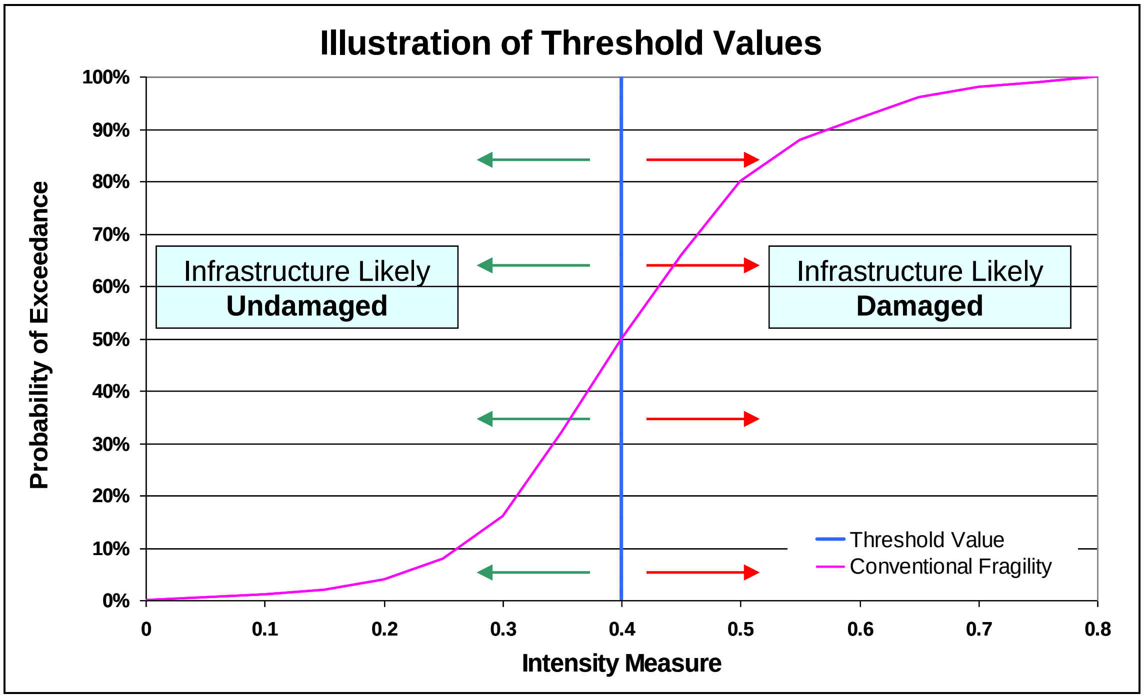


**Figure 13: Comparison of Threshold Value and Typical Fragility Relationship**

This study presents a procedure for rapid damage assessment of major river crossings (MRCs), dams, levees, and hazardous material storage tanks. Broad classifications are required for rapid assessment and include six groups of MRCs, two classes of dams, a single levee type, and several types of storage tanks. Using peak ground acceleration (PGA) as the intensity measure, threshold values have been established for rapid damage assessment of the aforementioned infrastructure components.

Previous research conducted on bridge fragility curve development and damage evaluation of the infrastructure systems subjected to various earthquakes has been reviewed extensively not only to reduce the uncertainties but also to provide a more realistic vulnerability assessment. The engineering judgment-based methodology that is used to generate the approximate threshold values is summarized in the following:

- The peak ground acceleration (PGA) is used as the intensity measure since it is readily available from earthquake records and is already part of the scenario event hazard definition
- Fragility curves (only pertaining to the infrastructure that exemplifies the identified infrastructure groups) are considered to minimize the uncertainties and provide a more realistic vulnerability assessment
- When fragility curves are unavailable, previous research containing bridge damage data collected via field-surveys after earthquakes is taken into consideration
- Reasonable lower bounds are defined as the threshold values for each infrastructure category

Damage limit states described in HAZUS are considered in the damage evaluation of the infrastructure components. Damage state definitions are primarily based on qualitative descriptions in HAZUS and recommendations from previous studies made by experts after field-survey.

The classification of bridges is based on respective construction type and construction material, whereas dams and storage tanks are classified based on building material only, i.e. earth or concrete. In addition, broad classifications of storage tanks are employed based on the identification of common structural features. There are 127 major river crossings located on five major rivers in Central US (Mississippi, Missouri, Arkansas, Ohio, and Illinois). Some of the bridges are vertical lift or side- or center-mounted swing bridges. Vertical lift bridges lift without tilting to provide sufficient clearance over the navigation channel for marine traffic. The majority of the bridges fall into the 'multispan simply supported and continuous steel truss bridges', while most dams are classified as 'earth and concrete gravity dams'.

The values of pass-fail peak ground accelerations presented in Table 2 are ready for use in regional impact assessment in the Central US. The methodology is applicable to other situations where detailed analytical modeling approaches are not feasible. Though these threshold values are not as technically robust as more conventional fragility relationships they do provide basic estimations of damage to critical infrastructure that are extremely helpful for emergency planning and disaster operations.

**Table 2: Threshold Values for New Critical Infrastructure**

| Structure Type | Slight (g) | Moderate (g) | Extensive (g) | Complete (g) |
|---|---|---|---|---|
| **Bridges** | | | | |
| Cable-Stayed & Suspension | N/A | 0.15 | N/A | N/A |
| Multispan Continuous Steel Truss | 0.18 | 0.31 | 0.39 | 0.5 |
| Multispan Simply Supported Steel Truss | 0.2 | 0.33 | 0.47 | 0.61 |
| Multispan Continuous Steel Girder | 0.18 | 0.31 | 0.39 | 0.5 |
| Multispan Simply Supported Steel Girder | 0.2 | 0.33 | 0.47 | 0.61 |
| Multispan Simply Supported Concrete Girder | 0.28 | 0.61 | 0.73 | 1 |
| **Dams & Levees** | | | | |
| Earth Dams | 0.5 | 0.63 | 1.25 | N/A |
| Concrete Gravity & Arch Dams | 0.63 | 1.25 | N/A | N/A |
| Levees | 0.33 | N/A | N/A | N/A |
| **Hazardous Materials Facilities (Tanks)** | 0.7 | 1.1 | 1.29 | 1.35 |

**Flood Risk Modeling**

The flood risk model utilizes the previously discussed threshold methodology to determine dam damage. The two categories are defined as "damaged" or "not damaged" and the threshold limit is based on the assumption that any dam expected to release water after an earthquake must incur at least a moderate level of damage which generates significant cracks for water seepage or substantial displacement of the structure.

Once the dams are classified into the two aforementioned categories, the selected flood risk methodology is applied to determine areas at risk. According to the selected model, parameters such as dam height, elevation, and maximum storage capacity can be used to determine the danger zones by determining a danger reach length (relevant distance that water travels after the dam fails) and width of the overflowing water. By combining the two, an area or surface is created to define a potential flood risk zone. Respective elevations are then assigned to each potential flood risk zone created for each damaged dam, based on dam elevation information. The elevation at the bottom of the dam is assigned as the elevation of the respective potential flood risk zone.

Danger reach length is a very important parameter, since it determines how far downstream the flood analysis should continue, thus defining the extent of flood risk considered. Commonly, the height and maximum storage capacity of the dam are utilized to determine the danger reach length. The method implemented in this study was adapted from information contained in the Soil Conservation Service TSC Engineering-UD-16, 1969 (Johnson, 1998). According to the methodology, the dam is assumed to fail at maximum capacity. The water height, the maximum storage capacity, and 100-year flood plain valley width are utilized to approximate the danger length from a derived graph.

The second essential parameter in determining danger zones is the water width. First the breach width is established. In this analysis, the valley width is used as the initial width. Subsequently, a slope of 1:3 is used to progress the lateral water flow until the danger reach length limit is attained. The selected slope is implemented as the average of two slopes; a 1:2 slope used for an area populated by houses, and a 1:4 slope used for open areas such as roadways (Johnson, 1998).

After the potential flood risk zones are drawn and respective elevations are assigned, the flood surfaces are intersected with a 3D elevation map of the study region, and a cut-fill analysis is performed to determine which areas are at risk. Based on the analysis results, areas from the elevation map that lie below the potential flood risk zone elevations are considered ‘at risk’. Once the areas that exhibit flood risk potential are determined, the ‘at risk’ infrastructure in these areas are identified. The uncertainty of the methodology is significant, especially in identifying the danger zones and the pass-fail criteria that are implemented when determining dam damage. Future improvements to both damage and flood risk procedures are recommended, though the basic estimates provided by this methodology are extremely useful when addressing secondary hazard in the emergency planning and response process.

**Uncertainty Modeling**

Two independent uncertainty characterization methods are utilized in this study. Each method details an approach to quantify the uncertainties in impacts by examining various model parameters. Neither method should be considered the definitive approach to uncertainty characterization, but rather a sampling of model parameters and impacts to be considered when determining the potential variation in impacts estimated by earthquake impact assessment software.

*Uncertainty Characterization Approach 1*

Due to the random nature of seismic hazards and the lack of complete knowledge or data, various types of uncertainties are inherent in regional seismic loss estimation. Therefore, the deterministic loss assessment by use of computer software such as HAZUS and MAEViz may cause unquantified risk of making risk-management decisions based on significant under- or over-estimation of the losses. As a result, it is important for regional loss estimation software to quantify the uncertainty for risk-informed decision making. However, there have been not many research efforts to quantify the uncertainties in regional loss estimation in a systematic manner. In this study, an efficient uncertainty quantification framework was developed for HAZUS loss estimation and the feasibility of the approach was tested by example analysis of eight states in the Central US.

Regional loss estimation contains various types of uncertainties, such as:

- Intrinsic randomness in seismic intensity (SI) measures such as spectral acceleration ($S_a$), peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD)
- Uncertainty in predicting the seismic performance of structures (e.g. exceedance of prescribed limit states) and the number of damaged items (ND)
- Variations of damage-related measures (DM) such as damage factors, repair cost ratios, and reduced traffic capacities
- Statistical uncertainties of parameters that appear in socio-economic loss models
- Erroneous or outdated data in inventory databases
- Existence of multiple competing models

This study, for preliminary research purposes, deals with three types of uncertainties only: (1) the randomness in the seismic intensity, (2) the uncertainty in the number of damaged items, and (3) the variations of damaged measures such as damage factors, repair cost ratios, and casualty ratios. The developed method quantifies the uncertainties propagated to three types of HAZUS regional loss measures for building stocks: number of damaged buildings (five damage states: none, slight, moderate, extensive, and complete), capital stock loss (four types), and number of displaced households. Table 3 shows uncertainties considered for these HAZUS regional seismic loss measures.

For intuitive interpretation of the results, the uncertainty in the estimated losses is presented by a confidence interval, which is the interval around the expectation (mean) value for a given level of confidence. A semi-automated computing tool was developed using Matlab® to import HAZUS data and to quantify the propagated uncertainties using the framework developed in this study.

**Table 3: Regional Seismic Loss Measures and Uncertainties Considered in This Study**

| *Regional Seismic Loss Measures* | *Uncertainty Type* | | |
|---|---|---|---|
| | *Seismic Intensity* (SI) | *Number of Damaged Items* (ND) | *Damage Measures* (DM) |
| ***Physical Loss*** | | | |
| • Number of damaged building | X | X | |
| ***Direct Economic Loss*** | | | |
| • Structural | X | X | X |
| • Non-structural | X | X | X |
| • Contents | X | X | X |
| • Inventory | X | X | X |
| ***Social Loss*** | | | |
| • Displaced households | X | X | X |

*Uncertainty Characterization Approach 2*

The current uncertainty propagation methods may require a large amount of computation time for nationwide earthquake loss estimation because its framework involves large vectors of dependent random variables. The Monte Carlo method, which has been generally used for uncertainty analyses, requires an extremely large number of samples and abundant computing time to obtain acceptable accuracy in its approximations. Thus, this study proposes an applicable framework for probabilistic loss estimation by using the HAZUS logic trees and a fast and reliable approximation method for uncertainty propagation by modifying the quantile arithmetic method. The important advantages of the proposed approach are its simplicity and applicability by using a powerful numerical method to combine random variables instead of Monte Carlo method and by using information and data given by the HAZUS Technical Manual (FEMA, 2008).

A simple framework for probabilistic assessment is developed based on the HAZUS methodology as follows:

$$C_R = \int_p \int_q \int_r \int_s f_{RC}(p) f_{IN}(q) f_{SF}(r) h_{IM}(s)\, dp\, dq\, dr\, ds \qquad (1)$$

where, $C_R$ is the expected repair cost (i.e., direct economic loss), $f_{RC}(p)$ is the probability density function of repair costs given by damage states, $f_{IN}(q)$is the probability density function of inventory data, $f_{SF}(r)$ is the probability density function of mean seismic fragility given by damage states, and $h_{IM}(s)$ is the probability density function of the seismic intensity.

For an analysis of uncertainty propagation, this study proposes a modified quantile arithmetic method. In the quantile arithmetic method, the continuous probability density functions are approximated by equivalent discrete probability density functions with equal probability intervals. The proposed method uses two different values of probability interval for converting a continuous probability density function into a discrete probability density function. By fitting a cumulative distribution function curve with a steep slope change near the 20$^{th}$ and 80$^{th}$ percentiles, a probability interval equal to half that at the 50th percentile results at the two high and low ends of the probability density function. This modification significantly reduces computation errors near the tails of a probability density function curve.

Uncertainties are included in all steps of the earthquake impact assessment procedure, from seismic hazard analysis to social and economic impact. Seismic hazard is generally modeled as lognormal. For the NMSZ, the coefficient of variation representing the epistemic uncertainty about PGA and $S_a$ at 0.3 and 1.0 seconds can exceed 0.6 (Cramer, 2001). The inventory databases may include uncertainty due to incomplete or dated demographic, infrastructure, and economic parameter data. The uncertainty embedded in inventory data can be represented by the standard deviations of a normal distribution. All methods for constructing fragility curves contain uncertainties in the assessment procedures and data used. Seismic fragility is usually modeled by lognormal distribution. Replacement costs of buildings depend upon many variables such as size, shape, design features, materials, quality, heating, cooling, and geographic condition of the building prior to the damage occurring. The replacement and repair cost can be modeled by lognormal distribution. The coefficient of variation for total repair costs is assumed to be in the range of 0.15 to 0.20 (RS Means Corp., 1997).

The proposed framework gives the cumulative distributions about the number of damaged buildings and the direct economic loss by building model type and by occupancy class. Uncertainty about the earthquake loss is represented by the lower and upper bounds for a certain confidence interval and by a mean value and standard deviation.

## Social Impact Assessment and Response Requirements

### Social Vulnerability

Social vulnerability is defined as the characteristics of a person or group, along with their situation, that influences their capacity to anticipate, cope with, resist, and recover from the impact of disasters (Wisner et al., 2004). It is not just concerned with the present or the future but is equally, and intimately, a product of the pre-existing conditions (UNDP, 2004; Hilhorst and Bankoff, 2004). Thus, social vulnerability is a by-product of social inequalities (Cutter and Emrich, 2006) and marginalities (Bankoff, 2004).

*Importance of Social Vulnerability Analysis*

People are not equally able to access resources, nor are they equally exposed to the hazards. People's exposure to risk differs according to their class which affects their income, and determines how and where they live. Characteristics such as gender, ethnicity, disabilities, and immigration status, etc., all affect one's level of risk and resiliency when dealing with natural and man-made hazards (Wisner et al., 2004).

Despite this reality, when planning for emergencies, little attention has been paid to social vulnerability. Cutter (2006a) argues that among all factors that contribute to vulnerability, those that we know least about are social factors. Since social factors significantly influence the needs of communities in the aftermath of large scale disasters, planning efforts that only take into account the physical or economic vulnerabilities give an incomplete picture for determining response activities and performing requirement assessments. In addition to the sheer number of people at risk, emergency managers have the additional task of identifying those residents who may be the most vulnerable (Cutter, 2006b). Comprehensive disaster preparedness plans must take into consideration the impact of social factors, and disaster planners should use this critical piece of information as they identify preparedness actions to be taken (Yeletaysi et al., 2009).

*Factors Influencing Social Vulnerability*

An individual's social vulnerability to disasters is based on a variety of different factors such us gender, class, race, culture, nationality, age, and other power relationships (Enarson et al., 2006). The quality of human settlements (housing type and construction, infrastructure and lifelines) (Dwyer et al., 2004; Cutter et al., 2003; Bolin and Stanford, 1998); tenure type (Dwyer et al., 2004; Cutter et al., 2003); built environment; family structure (Cutter et al., 2003; Buckle et al., 2000; Morrow, 1999); population growth (Cutter et al, 2003); commercial and industrial development (Cutter et al., 2003); medical services (Cutter et al., 2003); and special needs population (Cutter et al., 2003) are also important in understanding social vulnerability, especially as these characteristics influence potential economic losses, injuries and fatalities from natural hazards (Cutter et al., 2003).

*Methodology to Bridge the Gap Between Social Vulnerability and Selection of Preparedness Action*

In order to identify differing levels of social vulnerability at the county level, Cutter et al. (2003) developed the Social Vulnerability Index (SOVI). The SOVI provides a county-level comparative metric of social vulnerability to natural hazards based on the underlying socio-economic, demographic, and built environment profile. SOVI helps determine which places may require special attention in terms of post-event needs planning based on their existing level of social vulnerability. It also helps assess where additional resources may be needed to facilitate longer term recovery after an event. As an objective quantitative metric, the SOVI allows emergency managers, planners, and individuals to identify the relative social vulnerability of places of interest. This is a critical step in determining actions that decrease overall vulnerability and to increase future resilience (Cutter et al., 2003; Cutter and Emrich; 2006; Cutter and Finch, 2008). SOVI's reductionist nature and standardized scoring allow for comparisons across multiple locations, thus making it very suitable for decision processes where a single standardized quantitative metric for social vulnerability may be necessary. However, based on recent work with state and regional disaster planners, the social vulnerability index – while very useful to obtain a general understanding of the spatial distribution of social vulnerabilities – may not provide sufficient information to drive the selection of specific preparedness actions within a planning unit (Yeletaysi et al., 2009).

As the main focus of planning is to establish priorities and to identify the most realistic, beneficial, and plausible set of preparedness activities. It makes sense to focus on the vulnerability criteria that translate easily into preparedness actions. Furthermore, while planning for preparedness, it is beneficial to determine an optimal number of informative social vulnerability criteria to be selected and measured quantitatively. To facilitate the planning and preparation for potential large scale earthquake disasters within the NMSZ, a set of vulnerability criteria was selected through the process of consensus building within the planning group. More specifically, the following four vulnerability criteria were selected for this study:

- Poverty level (measured by the percentage of population living in poverty)
- Lack of proficiency in English (measured by the percentage of population not proficient in English)
- Vulnerable age groups (measured by the percentage of population under five and above 65 years old)
- Disabled population (measured by the number of disabled residents)

The poverty data used in this report is based on the 2007 poverty data estimates published by the Small Area Income and Poverty Estimates (SAIPE) program of the U.S. Census Bureau (U.S. Census 2008). The estimates published by SAIPE are neither direct counts from enumerations or administrative records, nor direct estimates from sample surveys. Instead county level estimates are calculated by combining survey data with population estimates and administrative records. To determine the poverty status, the U.S. Census Bureau uses thresholds (income cutoffs) arranged in a two-dimensional matrix. The matrix consists of family size (from one person to nine or more people) cross-classified by presence and number of family members under 18 years old (from no children present to eight or more children present). The threshold matrix can be found in Table 4. The income includes all earnings before taxes and does not include non-cash benefits such as food stamps and housing subsidies. If a person lives with a family, the income of all family members is used to determine the family income. The same thresholds are used throughout the United States and do not vary geographically. To determine a person's poverty status, one compares the person’s total family income in the last 12 months with the poverty threshold appropriate for that person's family size and composition. If the total income of that person's family is less than the threshold appropriate for that family, then the person is considered “below the poverty level”, together with every member of his or her family.

**Table 4**: **Poverty Thresholds**

| Poverty Thresholds for 2007 by Size of Family and Number of Related Children Under 18 Years | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Size of Family Unit | Weighted Average Thresholds | Related children under 18 years | | | | | | | | |
| | | None | One | Two | Three | Four | Five | Six | Seven | 8 or more |
| One person (unrelated individual) | 10,590 | | | | | | | | | |
| Under 65 years | 10,787 | 10,787 | | | | | | | | |
| 65 years and over | 9,944 | 9,944 | | | | | | | | |
| Two people | 13,540 | | | | | | | | | |
| Householder under 65 years | 13,954 | 13,884 | 14,291 | | | | | | | |
| Householder 65 years and over | 12,550 | 12,533 | 14,237 | | | | | | | |
| Three people | 16,530 | 16,218 | 16,689 | 16,705 | | | | | | |
| Four people | 21,203 | 21,386 | 21,736 | 21,027 | 21,100 | | | | | |
| Five people | 25,080 | 25,791 | 26,166 | 25,364 | 24,744 | 24,366 | | | | |
| Six people | 28,323 | 29,664 | 29,782 | 29,168 | 28,579 | 27,705 | 27,187 | | | |
| Seven people | 32,233 | 34,132 | 34,345 | 33,610 | 33,098 | 32,144 | 31,031 | 29,810 | | |
| Eight people | 35,816 | 38,174 | 38,511 | 37,818 | 37,210 | 36,348 | 35,255 | 34,116 | 33,827 | |
| Nine people or more | 42,739 | 45,921 | 46,143 | 45,529 | 45,014 | 44,168 | 43,004 | 41,952 | 41,691 | 40,085 |
| Source: U.S. Census Bureau | | | | | | | | | | |

The data for proficiency in English is based on the county-level census data from the 2000 census (U.S. Census 2001a). This data set provides the most current data on this topic. Table P19 of the Summary file 3 (SF3), 2000 census data provides information on the ability to speak English for the population that is 5 years or older. In this study all persons who are classified as speaking English “less than well” or “not at all” are considered non-proficient in English. Furthermore the data is broken down into the primary language spoken by this subset of the population. Languages include Spanish, other Indo-European languages, Asian and Pacific Island languages and other languages.

Young (under five years old) and elderly population (above 65 years old) may also require special assistance during disasters. The most current county level data is provided by the 2007 population estimates published by the Census Bureau (U.S. Census 2007).

The Census Bureau defines disability as a long-lasting physical, mental, or emotional condition. This condition makes it difficult for a person to do activities such as walking, climbing stairs, dressing, bathing, learning, or remembering. This condition also prevents a person from being able to go outside the home alone or to work at a job or business. Census 2000 included two questions with a total of six subparts with which to identify people with disabilities. The resulting disability data was published in the Census 2000 data files (U.S. Census 2001b).

Data for all four social vulnerability indicators (poverty, English proficiency, age, and disabilities) were collected on the county level and also aggregated on a planning area level. To facilitate the interpretation of the data, maps have been created. These maps use color codes for different vulnerability levels and include scenario information (see Figure 14). This overlay of social vulnerability data with the earthquake scenario allows emergency managers to identify planning needs.

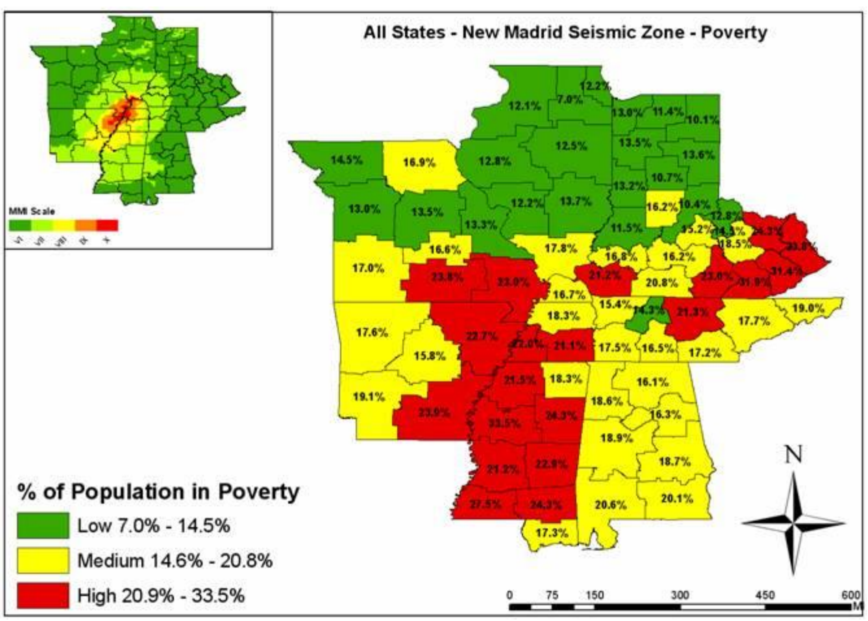


**Figure 14: Sample Social Vulnerability Map**

**SWEAT (Security, Water, Energy, Accessibility, Transportation) Analysis**

SWEAT analysis is the primary tool used to prioritize issues related to critical infrastructure assessment and restoration during the response and recovery phases following a disaster. The SWEAT doctrine was originally developed by the Army and later modified and used by the Army Corps of Engineers in civil disasters. This assessment tool offers data that is relevant, easy to use, and provided in a timely manner. It does not supply all data required for restoration activities but rather provides an excellent high-level starting point for developing a prioritization scheme for infrastructure recovery. It does not, however, replace some of the sector specific assessments that must occur.

SWEAT categorizes the infrastructure into following categories:

- S-Security
- W-Water
- E-Energy
- A-Accessibility
- T-Telecommunications

Each category is a collimation of the related infrastructure sector. Table 5 represents the breakdown of these categories:

**Table 5: SWEAT Categories**

| Legend | S - Security | W - Water | E - Energy | A- Accessibility | T - Telecom |
|---|---|---|---|---|---|
| | · EOC<br>· Police<br>· Fire<br>· Hospitals | · Potable Water<br>· Waste Water Facilities | · Electricity<br>· Natural Gas Facilities | · Major River Crossings<br>· Highway Bridges<br>· Roads<br>· Schools | · Communications Facilities |

The damage in each sector is analyzed at the county level and is presented in the form of a color coded matrix. Where:

| G | Full Capacity/Capability (80-100%) | Y | Reduced Capacity/Capability (79-40%) | R | No Capacity/Capability (0-39%) |
|---|---|---|---|---|---|

The matrix helps emergency managers at the regional level by identifying counties as per their colors in the following manner: counties which are color-coded red identify those which require external assistance. These counties are severely impacted and have either little or no capacity to deal with the damage. Counties in yellow are those which have sufficient capacity to respond to and recover from the incident. However, these counties will not be able to provide any assistance to neighboring counties, i.e. these counties do not require external assistance and also cannot provide assistance. Green counties are better prepared either because the impact is much less in their area or they have more than sufficient capability to deal with the damage. From the planning perspective, these counties are identified as the ones which will be readily able to provide assistance.

| Impacted Counties (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossing | Hwy Bridges | Schools | Telecom |
| Ballard | R | R | R | G | R | R | R | R | R | R | R | R |
| Caldwell | G | G | G | G | G | R | R | R | G | G | G | R |
| Calloway | R | R | R | R | Y | R | R | R | G | G | R | R |
| Carlisle | R | R | R | G | R | R | R | R | G | G | R | R |
| Crittenden | G | G | G | G | G | R | R | R | G | G | G | R |
| Daviess | G | G | G | R | G | G | Y | G | G | G | G | G |
| Fulton | R | R | R | R | R | R | R | R | G | G | R | R |
| Graves | R | R | R | R | R | R | R | R | G | G | R | R |
| Henderson | G | G | G | G | G | G | Y | G | G | G | G | G |
| Hickman | R | R | R | G | R | R | R | R | G | G | R | R |
| Hopkins | G | G | G | G | G | G | R | G | G | G | G | G |
| Livingston | R | R | Y | G | G | R | R | R | G | G | R | R |
| Lyon | G | G | G | G | G | R | R | R | G | G | G | R |
| Marshall | R | R | Y | R | R | R | R | R | G | G | R | R |
| McCracken | R | R | R | R | R | R | R | G | R | Y | R | R |
| Muhlenberg | G | G | G | G | G | G | Y | G | G | G | G | G |
| Trigg | G | G | G | G | G | R | R | R | G | G | G | R |
| Union | G | G | G | G | G | Y | Y | R | G | G | G | Y |
| Webster | G | G | G | G | G | Y | R | G | G | G | G | G |

**Figure 15: Sample SWEAT Analysis**

It is recommended that emergency managers focus more on the red labeled counties, and that efforts be made to strengthen the preparedness level in these counties. Within this study, the SWEAT analysis is conducted for the immediate aftermath (e.g. day 1) of an earthquake event and, therefore, provides an initial assessment for the planning areas. The results are calculated for all eight states and reported for impacted counties only. An example of the SWEAT analysis is illustrated in Figure 15.

### Medical Response Requirements

#### *Medical Needs/Fatalities*

'Medical Needs Requirement' presents two sets of data to planners, the number and type of casualties, and the status of hospital facilities. Casualties include both injuries and fatalities. The type and number of injuries that are expected immediately after the incident are presented on a county level. This estimate assists planners in determining the resources required to deal with the increased surge in the patients. For example, a large portion of injuries that occur during an earthquake are crushing injuries. This type of injury often affects the victim's kidneys and in some cases requires dialysis as part of the medical treatment. The casualty estimates only take into account the injuries/fatalities due to structural building and bridge damage. It does not include the injuries/fatalities due to transportation accidents, fire following events, hazmat exposure and injuries to those assisting in the response effort. The injured persons are categorized into four levels (see Table 6); the categorization follows the same principal of triage as practiced by the first responders after an incident. Level 1 patients are those who require some basic medical attentions but do not require hospitalization, Level 2 patients require hospital care, Level 3 patients have life threatening injuries, and Level 4 represents the number of people killed.

**Table 6: Injury Classification Scale (FEMA, 2008)**

| Injury Severity Level | Injury Description |
|---|---|
| Severity 1 | Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self treated are not estimated by HAZUS. |
| Severity 2 | Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration or exposure. |
| Severity 3 | Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome. |
| Severity 4 | Instantaneously killed or mortally injured |

The number of injuries/fatalities is provided by HAZUS (FEMA, 2008). HAZUS methodology assumes that there is a strong correlation between building damage (both structural and nonstructural) and the number and severity of casualties. This methodology excludes casualties caused by heart attacks, car accidents, falls, and power failure which lead to failures of medical equipment such as respirators, incidents during post-earthquake search and rescue or post-earthquake clean-up and construction activities, electrocution, tsunami, landslides, liquefaction, fault rupture, dam failures, fires, and hazardous materials releases. Therefore, the number provided should be interpreted as a lower bound. The following relevant issues in casualty estimation are included in the methodology: occupancy potential, collapse and non-collapse vulnerability of the building stock, time of the earthquake occurrence, and spatial distribution of the damage.

The model requires three types of input data for casualty estimation:

- Scenario time definition
- Data supplied by other modules
- Data specific to the casualty module

Although the methodology provides information necessary to produce casualty estimates for three times of a day (2 AM, 2 PM and 5 PM), in this study, 2 AM was chosen as the scenario to be modeled. Generally, casualty estimates for 2 AM are higher than both 2 PM and 5 PM, as most of the population is inside their homes during this time period. For a more in-depth description of the HAZUS methodology, refer to the HAZUS Technical Manual (FEMA, 2008).

The second set of data provides information on the operating status of ‘Hospitals’. The number of “Hospitals” includes urgent care facilities as well as hospitals, but does not include long-term care facilities such as nursing homes. Table 7 shows a sample of the information provided for Medical Response Requirements at the county level.

**Table 7: Sample Output of Medical Needs Requirements**

| Injuries (2 AM) | | | | | | | | | | Fatalities (2 AM) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Impacted Counties (IC) | Level 1 | Level 2 | Level 3 | Total | Hospital Damage | # Facilities | # Beds | Power Outages | Water Outages | Impacted Counties (IC) | Fatalities |
| Benton | 19 | 5 | - | 24 | None (0%) | 1 | 93 | Reduced (45%) | None (0%) | Benton | 1 |
| Carroll | 149 | 33 | 3 | 185 | Complete (100%) | 2 | 135 | Complete (65%) | None (13%) | Carroll | 6 |
| Chester | 127 | 33 | 4 | 164 | No Data | | | Complete (65%) | Reduced (32%) | Chester | 7 |
| Crockett | 337 | 90 | 10 | 437 | No Data | | | Complete (88%) | Complete (100%) | Crockett | 18 |
| Dyer | 1,559 | 430 | 47 | 2,036 | Complete (100%) | 2 | 225 | Complete (96%) | Complete (100%) | Dyer | 88 |
| Fayette | 349 | 90 | 8 | 447 | Complete (100%) | 2 | 50 | Complete (65%) | Complete (93%) | Fayette | 15 |
| Gibson | 1,103 | 295 | 32 | 1,430 | Complete (100%) | 3 | 235 | Complete (75%) | Complete (100%) | Gibson | 59 |
| Hardeman | 235 | 60 | 6 | 302 | Complete (100%) | 2 | 308 | Complete (69%) | Complete (80%) | Hardeman | 11 |

‘Hospital’ structural damage is presented in a color-coded format where red represents critical damage to the facility, yellow represents moderate damage, and green represent minor damage. Planners should pay special attention to the ‘Hospitals’ in the red category as these facilities are not only be unable to respond but most likely need to be evacuated. It is recognized that hospitals without power and water are severely affected. Therefore, county level water and power outages are provided along with structural damage.

The hospital-related data reported in this section is output directly from the HAZUS model. HAZUS recognizes the following medical care facilities based on the number of beds:

**Table 8: Classification of Medical Care Facilities**

| **Medical Care Facility** | **Description** |
|---|---|
| Small Hospital | Hospital with less than 50 beds |
| Medium Hospital | Hospital with beds between 50 & 150 |
| Large hospital | Hospital with greater than 150 beds |
| Medical Clinics | Clinics, Labs ad Blood banks |

The output (damage assessment of hospitals) is based on the model building type and the response spectrum at the building’s location. In order to support planning on various levels, results are reported for impacted counties, as well as at the state and regional level.

*Chronic Illnesses*

During a disaster, access to health care, personal support, and medication is reduced. This leaves people with chronic medical conditions at risk for serious medical complications - even to the point of death. Following Hurricane Katrina, there were more than 200,000 people with chronic medical conditions displaced by the storm or isolated by the flooding. These individuals were left without access to their usual medications and sources of care (World Bank, 2006)**.** It is important for planners to take into account the needs of this vulnerable population.

**Table 9: Estimate of Chronic Illnesses (County Level)**

| Impacted Counties (IC) | Cancers | Diabetes | Heart Disease | Hyper-tension | Stroke | Mental Disorders | Pulmonary Conditions |
|---|---|---|---|---|---|---|---|
| Benton | 90 | 120 | 159 | 306 | 20 | 218 | 408 |
| Carroll | 240 | 322 | 426 | 820 | 55 | 585 | 1,093 |
| Chester | 141 | 189 | 250 | 481 | 32 | 343 | 641 |
| Crockett | 191 | 255 | 338 | 650 | 43 | 463 | 866 |
| Dyer | 452 | 606 | 801 | 1,540 | 103 | 1,099 | 2,054 |
| Fayette | 321 | 431 | 569 | 1,095 | 73 | 781 | 1,460 |
| Gibson | 609 | 817 | 1,080 | 2,076 | 138 | 1,481 | 2,768 |

Estimates of the number of displaced people with chronic illnesses were calculated on both a county and state level. The chronic illnesses reported in the study include the number of cases of cancer, diabetes, heart disease, hypertension, stroke, mental disorder, and pulmonary conditions. An example is provided in Table 9. This data assists mass care providers in determining the special medical needs of the shelter-seeking population and also in determining strategies for gaining access to necessary medical supplies. Estimates of the number of cases of chronic illnesses utilized information collected by the Milken Institute (DeVol and Bedroussian 2007). This information provided the percentage of the aforementioned chronic illnesses as a percentage of total population for each of the eight states. Using these percentages along with the estimate of shelter-seeking population it is possible to calculate the number of cases of chronic illnesses in the shelter-seeking population. In many cases, people suffer from more than one illness. It is recommended that planners consider the types of medication typically used for the various illnesses along with the method of administration (ingested, injected, etc.) when developing procedures to care for this vulnerable population.

When stockpiling medications, it is relevant to note that some medications become obsolete as new medications are introduced and also that certain medications have a relatively short shelf life. It is also useful to estimate the demand for medical needs other than medications, such as walkers, eyeglasses, dentures, smoking cessation, etc. Finally, the planners need to prepare for the care of those with chronic illnesses not only during the response phase, but until the local healthcare providers are able to support the increased demand in both the impacted area as well as locations receiving evacuees.

**Mass Care and Emergency Assistance Requirements**

Mass care and emergency assistance requirements comprise the commodities (water, ice, food) and shelter requirements of the ‘At Risk’ population. ‘At Risk’ population is defined as displaced households (due to structural damage) and those without water and/or power for at least 72 hours. Shelter-seeking population is a subset of the displaced population based on socio-economic characteristics such as ethnicity and income level.

*Displaced/'At Risk' Population Estimation*

This report incorporates and extends the HAZUS methodology for displaced and shelter-seeking populations. The HAZUS methodology calculates displaced and shelter-seeking populations solely for displacement due to structural damage. It is assumed that all people residing in collapsed buildings and 90% of the population residing in extensively damaged multi-family homes are displaced (FEMA, 2008). The displaced population then requires alternative shelter elsewhere though many stay with friends and family or rent motel rooms or apartments. When other options do not exist, people turn to public shelters provided by the Red Cross or others. The decision to utilize public shelter is correlated with a variety of social and demographic factors. The HAZUS methodology uses a multi-attribute utility model which considers ethnicity and income as major factors contributing to demand for public shelters. The parameters for this model were originally developed by the American Red Cross and were based on expert opinion along with historical data (Harrald et al. 1992). Data from over 200 victims of the 1994 Northridge earthquake were analyzed and used in finalizing these parameters.

Severe and long term damage to lifeline systems such as water and electricity also forces people to leave their homes. This often leads to increases in the shelter population. For this study, it is assumed that all people without proper access to utilities remain in their homes for the first 72 hours and do not seek external support immediately following the event. If the outage continues beyond this period, these people require support in terms of commodities and/or housing. People without power and water are considered "at risk". An example is shown in Table 10.

The following method is used to calculate the "at risk" and shelter-seeking populations (the shelter-seeking population is a subset of the "at risk" population):

- "At risk" population at day 1: HAZUS estimates for displaced people
- "At risk" population at day 3: HAZUS estimates for displaced people plus those without water and/or electric power at day 3
- Shelter-seeking population at day 1: HAZUS estimates for short-term shelter-seeking population
- Shelter-seeking population at day 3: "At risk" population at day 3 multiplied by a factor for the shelter-seeking population (this factor is calculated at the census tract level and is equal to the factor employed in HAZUS)

**Table 10: Estimate of "At Risk" and Shelter Seeking Populations (State and Regional Level)**

| FEMA Region | State Total | Total Population | Day 1 # at risk | Day 1 # shelter seeking | Day 3 # at risk | Day 3 # shelter seeking |
|---|---|---|---|---|---|---|
| Region IV | Alabama | 4,447,100 | 9,645 | 3,081 | 601,561 | 173,412 |
| | Kentucky | 4,041,769 | 53,860 | 14,952 | 850,615 | 233,909 |
| | Mississippi | 2,844,658 | 61,997 | 18,345 | 705,032 | 205,507 |
| | Tennessee | 5,689,283 | 316,681 | 91,103 | 2,072,942 | 562,468 |
| | Total RIV | 17,022,810 | 442,183 | 127,481 | 4,230,150 | 1,175,296 |
| Region V | Illinois | 12,419,293 | 50,285 | 15,588 | 650,247 | 185,139 |
| | Indiana | 6,080,485 | 9,932 | 2,701 | 579,627 | 153,570 |
| | Total RV | 18,499,778 | 60,217 | 18,289 | 1,229,874 | 338,709 |
| Region VI | Arkansas | 2,673,400 | 124,730 | 38,827 | 937,518 | 285,865 |
| | Total RVI | 2,673,400 | 124,730 | 38,827 | 937,518 | 285,865 |
| Region VII | Missouri | 5,595,211 | 103,665 | 30,074 | 842,002 | 237,991 |
| | Total RVIi | 5,595,211 | 103,665 | 30,074 | 842,002 | 237,991 |
| Total | | 43,791,199 | 730,795 | 214,671 | 7,239,544 | 2,037,861 |

*Shelter and Commodity Requirements*

Shelter capacity, space, resources, and staffing requirements provide a high-level needs assessment regarding the essential components of short-term accommodation and commodities for the "At Risk" population. Commodities considered in this study include drinking water, food (provided as MRE – Meals Ready to Eat), and ice. Ice is generally a necessity following a disaster due to water and electrical outages as well as contaminated water supplies. It is recognized that access to ice is not as critical during the winter (the current scenario is set at February 7th), nonetheless it is important to include these estimates in the planning process.

The parameters for commodity and shelter requirement estimations are detailed in Table 11. The requirements are based on various research endeavors (National Research Council, 1989; Sphere Project, 2004; State of Florida, 2005; American Red Cross, 2007).

Staffing requirements for shelters depend upon the size of the shelters used during the response. Staffing estimates are provided using an average shelter capacity of 200 people. Larger shelters, in general, require fewer personnel per shelter-seeking person, while smaller shelters require a comparatively higher number.

In addition to the shelter and commodity requirement estimation, a shelter gap analysis is performed using the National Shelter System (NSS) database (FEMA, 2007) along with estimates of the shelter-seeking population to determine gaps. The NSS provides information on many attributes of available shelters, including address and, most importantly, the sheltering capacity. Shelters for all eight states have been extracted from the NSS and geo-coded for use in a GIS environment. Unfortunately, the NSS database is somewhat incomplete with many data entries incomplete and/or incorrect. It is recommended that improvements to the current NSS data be made and that an accurate database be maintained for all potential public shelters.

**Table 11: Estimations for Commodity and Shelter Requirements**

| | |
|---|---|
| **Shelter space total**<br>• 480 square foot per person (this includes space for all shelter related infrastructure)<br>• Source: Sphere<br><br>**Sleeping space**<br>• 60 square foot per person<br>• Source: Sphere, ARC<br><br>**Cots and Blankets**<br>• 1 per person<br>• Source: Sphere, ARC<br><br>**Toilets**<br>Toilets<br>• 1 toilet per 40 persons<br>• Source: Sphere<br><br>**Sinks**<br>• 1 per 80 persons<br>• Source: Sphere<br><br>**Garbage**<br>Refuse Containers (30 gallon containers)<br>• 1 for every 50 persons<br>• Source: ARC, Sphere<br><br>**Ice**<br>• 8 pounds of ice per person (1 bag)<br>• Source: USACE<br>Calculation of truck loads<br>• 5,000 bags / 40,000 pounds per truck<br>• Source: USACE | **Water**<br>Drinking water:<br>• 1 gallon per person per day<br>• Source: Sphere, ARC, USACE<br>Water for washing and personal hygiene:<br>• 2 gallon per person per day<br>• Source: Sphere<br>Other water requirements (e.g. cooking, etc.):<br>• 2 gallon per person per day<br>• Source: Sphere<br>Calculation of truck loads<br>• 4750 gallons per truck load<br>• Source: USACE<br><br>**Food**<br>Estimated Calories<br>• 2,000 Calories per person day<br>• Source: NRC<br>Fresh Food (if calories are provided by fresh food)<br>• 3 pound per person per day<br>• Source: Sphere<br>MRE:<br>• 2 MRE per person per day<br>• Source: USACE<br>Truck loads for MRE<br>• 21744 MRE per truck load<br>• Source: USACE<br><br>**Staffing**<br>Dependent on size of shelter and other planning numbers – assume average shelter size of 200 people<br>• Staff to run shelters: 10 people<br>• Staff to feed people: 4 people<br>• Staff for bulk distribution: 8 people<br>• Source: ARC |

## Search and Rescue Requirements

This section describes the methodology used to calculate the number and type of search and rescue teams and personnel that are required to respond immediately following an event. It is based on the methodology developed by D. Bausch (Physical Scientist, FEMA Region VIII) with contributions by D. Webb (USAR, FEMA HQ).

The total number of completely damaged buildings in each area provides the basis for search and rescue requirements. The number of collapsed buildings is calculated using the collapse rates of completely damaged buildings. The collapse rates depend on the structural building types and are given in Table 12.

**Table 12: Collapse Rates for Completely Damaged Buildings**

| Structural Building Type | Collapse Rate for Completely Damaged Buildings |
|---|---|
| Wood | 6% |
| Steel | 12% |
| Concrete | 20% |
| Precast | 26% |
| Reinforced Masonry | 20% |
| Unreinforced Masonry | 30% |
| Manufactured Housing | 6% |

The number of search and rescue teams required is directly proportional to the estimated number of collapsed buildings. The following four types of search and rescue task forces are used for search and rescue activities and are dependent on construction type damaged:

- US&R Type I Task Forces
  Task force trained & equipped for light frame, heavy wall, heavy floor and concrete-steel construction (heavy reinforced concrete)
- US&R Type II Task Forces
  Task force trained & equipped for light frame, heavy wall, heavy floor and concrete-steel construction
- Collapse S&R Type III Teams
  Task force trained & equipped for unreinforced masonry construction
- Collapse S&R Type IV Teams
  Task force trained & equipped for light frame construction

Table 13 details the requirements for each type of S&R team including team size, deployment time, work load, etc.

**Table 13: Search and Rescue Team Specifications**

| | Type I | Type II | Type III | Type IV |
|---|---|---|---|---|
| Personnel per Team or Task Force | 70 | 32 | 22 | 6 |
| | | | | |
| Hours Allowed for Mission Accomplishment | 72 | 72 | 72 | 72 |
| Hours Deployment Time | 24 | 24 | 6 | 6 |
| Hours Available for Mission Accomplishment | 48 | 48 | 66 | 66 |
| | | | | |
| Structures per Team/Task Force per Op Period | 2 | 4 | 8 | 16 |
| Hours per Day | 12 | 12 | 12 | 12 |
| Structures per Team/Task Force per Day | 2 | 4 | 8 | 16 |

Both the collapse rates (Table 12) and clearance rates (Table 13) could be highly variable. For example, based on time of day, there may be many collapsed structures that are unoccupied and cleared quickly, or major rescue sites that require multiple teams. The team capabilities and collapse estimates are used to determine the team and personnel requirements for the given scenario. Table 14 provides an example of the information calculated for search and rescue requirements at the state level.

**Table 14: Search and Rescue Team and Personnel Requirements (Example Tennessee)**

| | Type I | | Type II | | Type III | | Type IV | |
|---|---|---|---|---|---|---|---|---|
| | Teams | Personnel | Teams | Personnel | Teams | Personnel | Teams | Personnel |
| **Total for Tennessee** | 89 | 6,213 | 25 | 804 | 226 | 4,972 | 119 | 714 |

The model assumes the standard deployment times given in Table 13. Due to the catastrophic nature of the earthquake, and the resulting infrastructure and road network damage, deployment / transportation delays need to be taken into consideration.

**Mortuary Services**

HAZUS estimates the number of fatalities solely based on the injuries due to structural building and bridge damage. It does not include deaths due to transportation accidents, fire following events, hazmat exposure and those of first responders, therefore this number should be taken as a lower bound. The number of fatalities is provided on both a county and state level.

**Other Relevant Populations**

HAZUS estimates for displaced and shelter-seeking population only account for populations in residential buildings. For planning purposes it is essential to include other relevant populations since they also require extra support in the areas of transportation, medical care, communication, etc. Other relevant populations include:

- People in dormitories, including school dormitories, military quarters, and homeless shelters
- People in nursing homes
- People in institutions, such as correctional facilities, juvenile facilities, hospitals and other institutions
- Visiting populations, including business and leisure travelers

Data has been collected from a variety of sources. The population data for dormitories, nursing homes and institutions was derived from (U.S. Census, 2001c). Business travelers and tourist information was estimated from data published by the following resources:

- Alabama: Alabama Department of Tourism (Alabama, 2008)
- Arkansas: The Arkansas Department of Parks and Tourism (Arkansas, 2008)
- Indiana:
  - 2004 Travel and Tourism in Indiana (Shifflet, 2006a)
  - D.K. Shifflet County Rankings (Shifflet, 2006b)
  - Indiana Hotel & Lodging Association (Indiana, 2008)
- Illinois: Illinois 2006 Visitor Profile October 2007 (Shifflet, 2007)
- Kentucky:
  - Economic Impact of Travel on Kentucky counties 2003-2004 (Kentucky, 2005)
  - Tourism Tracker (Tourism Tracker, 2006)
- Mississippi: State Visitors Bureau (Mississippi, 2008)
- Missouri:
  - Missouri Division of Tourism (Missouri, 2008)

    - Missouri University (Missouri University, 2008)
- Tennessee: Tennessee Department of Tourist Development (Tennessee, 2008)

**Security Needs**

Since jails and prison populations are also affected by earthquakes planners must consider specific security needs. For example, it may become necessary to relocate inmates to other facilities or to reinforce structures to minimize the risk of structural failure. For this report the following data has been collected:

- Federal prison population: Data was collected from the weekly population reports published by the Federal Bureau of Prisons (U.S. Department of Justice, 2009).
- State prison population: Data was collected from the eight State Departments of Correction. Where available, the most current data for the actual prison population was collected. If this data was not available, prison capacity data was used instead.
- Local jails: Jail data is based on the 2005 jail census data collected by the Department of Justice (U.S. Dept. of Justice, 2007).

Dependent on the jurisdictional affiliation of the facilities, different laws and guidelines must be considered. It is recommended that planners contact and collaborate with the appropriate authorities to determine a strategy concerning inmates and corresponding facilities.

# Overview of Results from Impact Assessment

This section provides selected results of various impact assessment models included in the New Madrid Catastrophic Event Planning project. Individual sections address HAZUS modeling which includes direct damage to infrastructure, induced damage, casualty estimation and direct economic losses. Potential flood risk from dam failure is included and ‘at risk’ infrastructure identified. Network models for utility and transportation networks in major metropolitan areas are presented and impacts discussed. A characterization of uncertainty is incorporated and addresses uncertainties in various HAZUS model results. Social impact modeling includes mass care needs for displaced, shelter, and special needs populations. Commodities and search and rescue requirements are also included. Additional shelter requirements and regional capacities are presented as well. The results of all models create a comprehensive representation of the post-event environment and provide the necessary data for regional and national response planning for a catastrophic New Madrid earthquake.

## Direct Damage to Infrastructure, Induced Damage, Casualties, and Economic Loss

All direct damage, debris generation (induced damage), casualty, and direct economic loss estimations are determined via HAZUS models. As discussed previously a single, nationally-catastrophic scenario event is used for all HAZUS models. Results are presented by state with an eight-state summary of results following all state results discussions. A list of ‘impacted counties’ is listed for each state, with the exception of Alabama. Each state’s list was compiled based on a cumulative review of direct damage and functionality of infrastructure, social impacts, and direct economic losses. Impacts are most severe in the impacted counties listed in this section, though it is important to remember that all counties in each state are impacted at some level be the NMSZ scenario event. A set of ‘socially impacted’ counties is provided for Alabama. All counties in Alabama failed to meet the criteria for damage infrastructure that is required for ‘impacted counties’ though social impacts were prominent in several. As a result a list of ‘socially impacted’ counties is used for Alabama only.

**Impact Assessment Results for Alabama**

The *socially* impacted counties identified in Alabama are listed below:

- Autauga
- Baldwin
- Bibb
- Bullock
- Choctaw
- Clarke
- Dallas
- Elmore
- Escambia
- Etowah
- Fayette
- Geneva
- Hale
- Lamar
- Lowndes
- Macon
- Marengo
- Mobile
- Pickens
- Russell
- Tuscaloosa

There are nearly 1.76 million buildings in the State of Alabama, roughly 1.73 million of which are residences. A large portion of damaged buildings are residential structures which is inline with their relative frequency in the state's building inventory. Over 14,500 at least moderately damaged structures are residences, either single family or multiple family (also called 'other residential') dwellings. Table 15 also shows that residential structures comprise a large percentage of all completely damaged structures. Complete damage does not necessarily mean collapse, though complete damage does indicate that the buildings are uninhabitable. In many cases, collapse may occur as the result of an aftershock. Conversely, wood structures comprise a large portion of the building inventory by building type, but a much smaller fraction of actual building damage. As shown in Table 16 only 3,000 at least moderately damaged structures are wood construction, while 11,100 are manufactured housing. A large portion of complete damage, however, is attributed to wood structures. Estimates show a large portion of damage occurs in Mobile County which is along the Gulf Coast and very far from the fault rupture. This seemingly disproportionate distribution is due to the high density of infrastructure in the Mobile metropolitan area. The percentage of buildings damaged in Mobile County is similar to the remainder of the state, though this percentage equates to a larger number of damaged buildings in this highly populated and developed area.

**Table 15: Building Damage by Occupancy Type for Alabama**[1]

| General Building Damage by Occupancy Type for Alabama | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 1,342,900 | 3,200 | 3,000 |
| **Other Residential** | 368,400 | 11,400 | 700 |
| **Commercial** | 29,100 | 500 | 60 |
| **Industrial** | 8,100 | 200 | 20 |
| **Other** | 9,800 | 100 | 40 |
| **Total** | 1,758,300 | 15,400 | 3,820 |

[1] Building damage estimates are rounded in an effort to avoid providing highly specific numbers that often reflect high levels of certainty, when actual impacts are likely to vary from the exact model outputs.

**Table 16: Building Damage by Building Type for Alabama**[2]

| General Building Damage by Building Type For Alabama | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 1,315,900 | 3,000 | 2,960 |
| **Steel** | 23,000 | 700 | 50 |
| **Concrete** | 5,500 | 200 | < 20 |
| **Precast** | 1,800 | < 100 | < 20 |
| **Reinforced Masonry** | 8,600 | < 100 | 20 |
| **Unreinforced Masonry** | 88,100 | 400 | 200 |
| **Manufactured Housing** | 315,500 | 11,100 | 570 |
| **Total** | 1,758,400 | 15,400 | 3,820 |

Damage to various types of critical infrastructure, including essential facilities, transportation lifelines, utility lifelines, dams, levees, and hazardous materials facilities are assessed at the facility location as oppose to the aggregated damage evaluation used for general building damage, shown previously. The low levels of ground shaking throughout Alabama do not cause significant structural damage to critical infrastructure. As shown in Table 17, there are no moderately damaged essential facilities. These damage estimations include structural damage only, thus it is possible that non-structural damage, or even minor structural damage, occurs. Though minor forms of damage are possible, the lack of significant structural damage likely indicates that the majority of Alabama's essential facilities are operational immediately after the earthquake event.

**Table 17: Essential Facilities Damage for Alabama**[3]

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 1,903 | 0 | 0 |
| **Fire Stations** | 1,388 | 0 | 0 |
| **Police Stations** | 496 | 0 | 0 |
| **Hospitals** | 210 | 0 | 0 |
| **EOCs** | 124 | 0 | 0 |

**Table 18: Transportation Lifeline Damage for Alabama**[4]

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 17,491 | 0 | 0 |
| **Railway Bridges** | 118 | 0 | 0 |
| **Railway Facilities** | 115 | 0 | 0 |
| **Bus Facilities** | 24 | 0 | 0 |
| **Port Facilities** | 327 | 0 | 0 |
| **Airport Facilities** | 469 | 0 | 0 |

[2] Please reference footnote 1.
[3] For tables in this section the following method is used to determine the number of facilities in a damage category. HAZUS assigns each facility a probability of reaching a specific damage level (at least moderate, complete, etc.). In order to provide quantities of facilities at various damage levels, all those facilities that experience a damage probability of 50% or greater for a given damage level are counted as 'damaged.' Therefore, the facilities that are not 50% likely to incur damage at a specific damage level are deemed 'undamaged.'
[4] Please reference footnote 3.

Transportation and utility lifeline facilities show similar damage trends. Table 18 illustrates the lack of moderate or more severe structural damage to transportation infrastructure in Alabama. Minor structural damage may occur, such as surface cracking of bridge abutments and minor movements of structural connections in bridges and other facilities, though these forms of damage do not compromise a structure significantly. Most transportation lifelines are operational immediately after the event and movement within Alabama should not be restricted due to transportation infrastructure damage. Utility facilities present similar damage trends, in so far as moderate structural damage is unlikely, though minor structural damage is possible. Additionally, minor permanent deformations of support structures may render some equipment at utility facilities inoperable. Table 19 shows the lack of moderate structural damage to utility facilities in Alabama. At this time there is no method to gather information regarding equipment at these facilities or method to determine damage to such equipment, thus these estimations are not included in this series of models for the NMSZ scenario event.

The combination of minor shaking and ground deformation causes roughly 2,000 breaks and leaks to utility pipelines in Alabama. Local distribution lines are most common and thus incur the greatest amounts of damage. Interstate pipelines carry natural gas and oil through Alabama to other major commerce centers and portions of the Central and Eastern US. As Table 20 shows, there are very few repairs required in these major transmission pipelines. Damage to utility infrastructure leads to utility services losses throughout the state. Though potable water service is retained throughout Alabama, approximately 230,000 households are without electric power immediately after the event. These estimates are likely conservative, particularly power outages estimates. A major failure on the power grid could generate significantly larger numbers of power outages.

**Table 19: Utility Facilities Damage for Alabama**[5]

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 30 | 0 | 0 |
| **Waste Water Facilities** | 9,315 | 0 | 0 |
| **Natural Gas Facilities** | 458 | 0 | 0 |
| **Oil Facilities** | 425 | 0 | 0 |
| **Electric Facilities** | 1,629 | 0 | 0 |
| **Communication Facilities** | 15,895 | 0 | 0 |

**Table 20: Utility Pipeline Damage for Alabama**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 124,800 | 460 | 292 | 752 |
| **Waste Water Local** | 74,900 | 364 | 231 | 595 |
| **Natural Gas Local** | 49,900 | 389 | 247 | 636 |
| **Natural Gas Interstate** | 5,300 | 5 | 11 | 16 |
| **Oil Interstate** | 1,800 | 2 | 5 | 7 |

[5] Please reference footnote 3.

**Table 21: Other Critical Facilities Damage for Alabama**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 2,233 | 0 |
| **Levees** | 5 | 0 |
| **Hazardous Materials** | 3,656 | 0 |

Damage to infrastructure, both buildings and critical infrastructure[6], generate debris which must be removed. In some cases, debris must be removed to reach impacted areas and earthquake victims. More commonly, however, debris is removed during the recovery phase as homes and businesses are rebuilt or critical infrastructure is repaired. A total of 560,000 tons of debris is generated in Alabama. Roughly 260,000 tons is steel and concrete, while the remaining 300,000 tons is brick, wood, and other building materials. Nearly 22,400 truckloads[7] are required to remove all the debris resulting from the scenario event.

Casualties are considered a social impact, though they are the direct result of structural damage to buildings and other infrastructure as determined in HAZUS. As a result, casualty estimates are presented following the direct damage estimations for each state. Casualties are estimated at three times throughout the day in order to represent the difference in building use in the afternoon, evening, and night. Estimates at 2:00 AM reflect expected casualties when the population is home, 2:00 PM estimates reflect the majority of the population in office buildings while at work, and 5:00 PM estimates reflect a large portion of the population commuting from work to home. The number of casualties at 2:00AM is detailed here since the scenario event occurs at 2:00AM. Furthermore, several severity levels are defined within the impact estimation tool. Descriptions of the four HAZUS casualty severity levels are provided below:

- Severity Level 1: Injuries will require rudimentary medical attention but hospitalization is not needed, though injuries should be rechecked frequently
- Severity Level 2: Injuries will require hospitalization but are not considered life-threatening
- Severity Level 3: Injuries will require hospitalization and can become life threatening if not promptly treated
- Severity Level 4: Victims are killed as a result of the earthquake

Please note that a Level 4 casualty is a fatality and is included in the overall estimation of casualties for the scenario event.

The scenario event causes nearly 1,000 total casualties in Alabama, many of which are minor injuries. Table 22 shows that roughly 75% of all casualties are minor injuries which do not require hospitalization. Nearly 200 people require hospitalization for their injuries (Levels 2 & 3) while nearly 30 fatalities are expected.

[6] In this report critical infrastructure refers to essential facilities, transportation lifelines, utility lifelines, and 'other' critical infrastructure including dams, levees, and hazardous materials facilities.
[7] All truck for debris removal are assumed to be 25-ton trucks for state results and regional summary results.

Total assets in Alabama include more than $290 billion in building value, approximately $125 billion in transportation infrastructure value, nearly $700 billion in utility infrastructure value. This equates to $1.1 trillion in total infrastructure value throughout the state. Table 23 details the economic losses expected based on infrastructure group. Utility losses comprise a large portion of the $14 billion of total economic loss in Alabama. Building and transportation losses comprise substantially lesser portions of economic loss in the state.

**Table 22: Total Casualties for 2:00AM Event in Alabama**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 726 | 179 | 16 | 28 | 949 |

**Table 23: Direct Economic Loss for Alabama ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $1,758 | $274 | $11,626 | $13,658 |

**Impact Assessment Results for Arkansas**

The impacted counties, or those impacted most severely, in Arkansas are:

- Arkansas
- Clay
- Craighead
- Crittenden
- Cross
- Greene
- Independence
- Jackson
- Lawrence
- Lee
- Mississippi
- Monroe
- Phillips
- Poinsett
- Prairie
- Randolph
- Saint Francis
- White
- Woodruff

There are approximately 1.3 million buildings in the State of Arkansas, with approximately 1.2 million residences for either a single family or multiple families (other residential). Over 162,000 buildings are damaged in Arkansas though a large portion of damage occurs in the northeast portion of the state. Nearly 145,000 at least moderately damaged buildings are residential construction, as is shown in Table 24. Residential construction also incurs substantial amounts of complete damage which renders many homes unusable.

Additionally, over 900,000 buildings are wood frame structures, while another 180,000 are unreinforced masonry (URM) structures. Steel, precast, and cast-in-place concrete buildings comprise a much smaller portion of the state building inventory. Table 25 shows that a significant portion of at least moderate damage occurs in woodframe construction, over 40%, and manufactured housing, over 30%. Approximately half of all complete damage is attributed to wood structures, though both URMs and manufactured housing each account for 20% of all complete damage in Arkansas. Several counties experience more damage than the remainder of the state. Greene, Craighead, Poinsett, Crittenden, and Mississippi Counties are each estimated to incur at least 10,000 damaged buildings.

**Table 24: Building Damage by Occupancy Type for Arkansas**[8]

| General Building Damage by Occupancy Type for Arkansas | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 833,500 | 69,700 | 35,800 |
| **Other Residential** | 408,500 | 75,000 | 27,400 |
| **Commercial** | 53,200 | 11,000 | 4,700 |
| **Industrial** | 14,600 | 2,800 | 1,100 |
| **Other** | 15,600 | 3,700 | 1,700 |
| **Total** | 1,325,400 | 162,200 | 70,700 |

**Table 25: Building Damage by Building Type for Arkansas**[9]

| General Building Damage by Building Type For Arkansas | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 902,100 | 68,800 | 35,000 |
| **Steel** | 25,300 | 7,300 | 2,700 |
| **Concrete** | 6,600 | 1,500 | 700 |
| **Precast** | 6,700 | 1,600 | 700 |
| **Reinforced Masonry** | 5,200 | 1,100 | 500 |
| **Unreinforced Masonry** | 181,900 | 29,100 | 15,500 |
| **Manufactured Housing** | 197,600 | 52,800 | 15,600 |
| **Total** | 1,325,400 | 162,200 | 70,700 |

Critical infrastructure is severely damaged and operational capabilities are substantially reduced in northeastern Arkansas. Well over 200 schools, 100 police stations, nearly 180 fire stations and 25 hospitals are damaged by the scenario event and a large portion of that damage is complete, rendering many facilities useless after the event. Table 26 details damage estimates for essential facilities in Arkansas. The impacted counties are catastrophically impacted, particularly Clay, Craighead, Crittenden, Cross, Greene, Jackson, Lee, Mississippi, Monroe, Phillips, Poinsett, Prairie, Saint Francis, and Woodruff Counties where most essential facilities, medical services, law enforcement and fire fighting services are nearly non-existent immediately after the event.

**Table 26: Essential Facilities Damage for Arkansas**[10]

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 1,328 | 219 | 56 |
| **Fire Stations** | 1,330 | 179 | 65 |
| **Police Stations** | 515 | 107 | 48 |
| **Hospitals** | 125 | 24 | 18 |
| **EOCs** | 113 | 25 | 8 |

[8] Please reference footnote 1.
[9] Please reference footnote 1.
[10] Please reference footnote 3.

**Table 27: Transportation Lifeline Damage for Arkansas**[11]

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 14,060 | 1,083 | 336 |
| **Railway Bridges** | 68 | 11 | 0 |
| **Railway Facilities** | 69 | 14 | 0 |
| **Bus Facilities** | 18 | 1 | 0 |
| **Port Facilities** | 103 | 17 | 0 |
| **Airport Facilities** | 335 | 37 | 0 |

Significant damage to transportation lifelines is generally confined to the impacted counties. Craighead, Crittenden, Mississippi, and Poinsett Counties incur the largest numbers of damaged bridges. Furthermore, several major river bridges are damaged effectively separating major sections of Arkansas from neighboring states. The Harahan, Frisco, and Memphis/Arkansas bridges are damaged and impassible after the event. Nearly 40 airports and 15 railway facilities are damaged in the state, as shown in Table 27. Most damage to rail, air and water transport facilities is located in Clay, Crittenden, Craighead, Cross, Greene, Mississippi, and Poinsett Counties.

Impacts on utility infrastructure are most prominent in the impacted counties, though pipeline repairs are required throughout the entire state. Table 28 details expected utility facility damage for Arkansas, and shows that hundreds of waste water and communication facilities are damaged. Clay, Crittenden, Craighead, Cross, Greene, Independence, Jackson, Lawrence, Lee, Mississippi, Phillips, Poinsett, Randolph, St. Francis, White, and Woodruff Counties incur the majority of damage to waste water, communication, and other utility facilities.

**Table 28: Utility Facilities Damage for Arkansas**[12]

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 69 | 6 | 0 |
| **Waste Water Facilities** | 2,107 | 349 | 0 |
| **Natural Gas Facilities** | 422 | 47 | 0 |
| **Oil Facilities** | 96 | 14 | 0 |
| **Electric Facilities** | 800 | 147 | 0 |
| **Communication Facilities** | 4,626 | 633 | 0 |

**Table 29: Utility Pipeline Damage for Arkansas**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 118,700 | 19,532 | 27,649 | 47,181 |
| **Waste Water Local** | 71,200 | 15,448 | 21,868 | 37,316 |
| **Natural Gas Local** | 47,500 | 16,513 | 23,376 | 39,889 |
| **Natural Gas Interstate** | 9,700 | 340 | 1,092 | 1,432 |
| **Oil Interstate** | 2,200 | 62 | 214 | 276 |

[11] Please reference footnote 3.
[12] Please reference footnote 3.

Utility pipelines carry much-needed commodities to other parts of the country as well as individual homes in Arkansas. Both local distribution and major interstate pipeline repairs are quantified in Table 29. Local distribution networks for potable water, waste water, and natural gas require a combined 124,000 repairs. Restoring the networks to their pre-event status will take weeks or months depending on the availability of spare parts and accessibility of damaged pipelines. In addition, over 1,700 repairs are needed on interstate pipelines which transport vital commodities to the upper Midwest and east coast. Without timely restoration these portions of the country that are not directly impacted by the earthquake will experience significant indirect affects as natural gas and oil are unavailable, or in scarce supply. Damage to utility infrastructure also leaves hundreds of thousands without power or water immediately after the event. Approximately 330,000 households are without power and 190,000 households without water after the event. Over 80% of all households in Craighead, Poinsett, Mississippi, Cross, and Crittenden Counties are without power immediately after the event.

There are over 3,000 other critical facilities in Arkansas and over 100 are damaged by the scenario earthquake. Table 30 shows that nearly 60 dams are damaged, all of which are located in Poinsett County. The 20 damaged levees are located in Craighead, Greene, Mississippi, and Poinsett Counties. Very intense ground shaking is required to damage hazardous materials facilities and such levels of shaking occur in small portions of northeast Arkansas. All damaged hazardous materials facilities are located in Mississippi County.

**Table 30: Other Critical Facilities Damage for Arkansas**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 1,228 | 55 |
| **Levees** | 124 | 20 |
| **Hazardous Materials** | 1,834 | 69 |

Infrastructure damage generates 9.4 million tons of debris in Arkansas. Approximately 4.1 million tons are attributed to steel and concrete, while the remaining 5.3 million tons is comprised of wood, brick, and other building materials. Nearly two million tons of debris is created in Craighead County, with another 1.5 million tons in Mississippi County and one million tons in Crittenden County. Poinsett, Pulaski, and Greene Counties also have debris estimates between 650,000 and 750,000 tons. Over 375,000 truckloads[13] are required to remove all the debris generated by the scenario event.

**Table 31: Casualties at 2:00AM for Arkansas**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 11,245 | 3,075 | 344 | 641 | 15,305 |

**Table 32: Direct Economic Loss for Arkansas ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $18,167 | $2,347 | $18,515 | $39,029 |

[13] Please reference footnote 7.

Damage from the scenario event causes 15,300 total casualties throughout the state. As illustrated in Table 31, nearly 75% of all casualties are minor injuries that do not require hospitalization. Nearly 650 deaths are expected as well and nearly all are estimated to occur in the impacted counties. Crittenden, Mississippi, and Craighead Counties are most severely impacted as each county is estimated to incur 2,000 to 3,000 total casualties for the 2:00 AM scenario earthquake.

Total assets in Arkansas include more than $180 billion in building value, nearly $75 billion in transportation infrastructure value, and approximately $210 billion in utility infrastructure value. This equates to more than $465 billion in total infrastructure value throughout the state. Table 32 illustrates losses by infrastructure group which shows that buildings and utility lifelines experience nearly identical economic losses, about $18 billion. Transportation lifelines constitute a smaller portion of state economic loss at nearly $2.5 billion. With total economic losses reaching nearly $40 billion Arkansas will require substantial assistance to rebuild after the disaster.

**Impact Assessment Results for Illinois**

The impacted counties, or those impacted most severely, in Illinois are:

- Alexander
- Bond
- Clinton
- Fayette
- Franklin
- Gallatin
- Hamilton
- Hardin
- Jackson
- Jefferson
- Johnson
- Lawrence
- Madison
- Marion
- Massac
- Monroe
- Perry
- Pope
- Pulaski
- Randolph
- Saint Clair
- Saline
- Union
- Washington
- Wayne
- White
- Williamson

There are approximately 3.7 million buildings in the State of Illinois, of which approximately 3.5 million are residences. Of the 44,500 at least moderately damaged buildings over 95% are residences. Building damage by occupancy type is illustrated in Table 33. Nearly 50% of all moderate and more severe damage is complete damage. Furthermore, 20,700 completely damaged buildings are residences. Over 2.6 million buildings are wood frame structures and another 780,000 are URM structures. Steel, precast, and cast-in-place concrete buildings comprise a much smaller portion of the state building inventory. Table 34 details damage by building type and shows that wood structures, URMs, and manufactured housing experience the most cases damage across all building types. Approximately 60% of all complete damage occurs in wood structures, though only 40% of all moderate and more severe damage occurs with this building type. St. Clair and Madison Counties incur the greatest number of damaged buildings largely due to the high density of buildings in these more urban areas. The percentage of buildings damaged in these counties is less than in the southernmost counties where more 80% of all buildings are damaged, such as Alexander, Massac, and Pulaski.

**Table 33: Building Damage by Occupancy Type for Illinois**[14]

| General Building Damage by Occupancy Type for Illinois | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 3,079,900 | 26,700 | 16,600 |
| **Other Residential** | 455,900 | 15,900 | 4,100 |
| **Commercial** | 78,300 | 1,200 | 400 |
| **Industrial** | 22,500 | 300 | 100 |
| **Other** | 19,200 | 400 | 100 |
| **Total** | 3,655,800 | 44,500 | 21,300 |

**Table 34: Building Damage by Building Type for Illinois**[15]

| General Building Damage by Building Type For Illinois | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 2,626,400 | 17,700 | 12,600 |
| **Steel** | 38,100 | 1,000 | 200 |
| **Concrete** | 41,800 | 900 | 300 |
| **Precast** | 11,300 | 200 | < 50 |
| **Reinforced Masonry** | 8,300 | 100 | < 50 |
| **Unreinforced Masonry** | 783,300 | 10,100 | 5,000 |
| **Manufactured Housing** | 146,600 | 14,500 | 3,200 |
| **Total** | 3,655,800 | 44,500 | 21,300 |

Southern Illinois medical and fire fighting services, as well as law enforcement capabilities are drastically reduced after the scenario event. Over 100 fire and police stations are moderately or more severely damaged. Several hospitals and over 100 schools are damaged in southern Illinois, many are completely damaged. Table 35 details essential facilities damage for Illinois. It is expected that essential facilities in Alexander, Johnson, Massac, Pope, Pulaski, Saline, and Union Counties are severely damaged while facilities in Gallatin, Jackson, and Williamson Counties are damaged but some may remain functional after the event.

Road, rail, air and water transportation are heavily damaged in southern Illinois as well. The airports in Alexander, Johnson, Massac, Pulaski, and Union Counties experience severe damage, leaving these counties without many functioning facilities. Over 150 bridges are damaged in southern Illinois, and almost 70 bridges are completely damaged, as shown in Table 36. Most bridges along Interstate 57 in Alexander and Pulaski Counties are heavily damaged and likely impassible the day after the earthquake. Also, the Interstate 24 bridge in Massac County is damaged and not functioning immediately after the earthquake. Roughly 10 major bridges are damaged in southern Illinois, limiting traffic between Illinois and the neighboring states of Kentucky and Missouri. Most damaged major bridges are located in Alexander and Massac Counties, though a major bridge in Jackson County is damaged as well. Among the damaged bridges are the

[14] Please reference footnote 1.
[15] Please reference footnote 1.

Mississippi and Ohio River bridges in Cairo, Illinois, the I-57 bridge at Cairo, Illinois, and the I-24 bridge at Metropolis, Illinois.

**Table 35: Essential Facilities Damage for Illinois**[16]

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 5,795 | 114 | 47 |
| **Fire Stations** | 1,822 | 60 | 17 |
| **Police Stations** | 1,082 | 34 | 14 |
| **Hospitals** | 413 | 7 | 1 |
| **EOCs** | 221 | 8 | 3 |

**Table 36: Transportation Lifeline Damage for Illinois**[17]

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 29,967 | 157 | 66 |
| **Railway Bridges** | 1,030 | 11 | 0 |
| **Railway Facilities** | 304 | 7 | 0 |
| **Bus Facilities** | 120 | 2 | 0 |
| **Port Facilities** | 517 | 20 | 0 |
| **Airport Facilities** | 935 | 20 | 0 |

Though most utility facilities in Illinois are not completely damaged, moderate damage is common and affects the operational capabilities of these damaged facilities. Table 37 shows that over 1,700 communication facilities and 600 wastewater facilities are damaged in southern Illinois. The majority of these damaged facilities, and all other types of utility facilities, are located in Alexander, Johnson, Massac, Pope, Pulaski, Union, Gallatin, Hardin, Jackson, Saline, and Williamson Counties. Local pipelines for potable water, waste water, and natural gas require nearly 26,000 repairs, most in southern Illinois. In addition, interstate pipelines that carry natural gas and oil require roughly 1,500 repairs. Table 38 details pipeline damage by pipe type for Illinois.

**Table 37: Utility Facilities Damage for Illinois**[18]

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 242 | 14 | 0 |
| **Waste Water Facilities** | 9,807 | 616 | 5 |
| **Natural Gas Facilities** | 3,778 | 150 | 3 |
| **Oil Facilities** | 41,105 | 755 | 0 |
| **Electric Facilities** | 2,231 | 75 | 0 |
| **Communication Facilities** | 36,436 | 1,715 | 30 |

Damage to utility infrastructure leaves hundreds of thousands of Illinois households without utility services. Nearly 100,000 households in southern Illinois are without water immediately after the event. Over 90% of households in Alexander, Pulaski, Massac, and Jackson Counties are without water after the event, though services outages may last

[16] Please reference footnote 3.
[17] Please reference footnote 3.
[18] Please reference footnote 3.

several days to weeks. Additionally, 235,000 households are without power as a result of damage from the scenario event. Union, Johnson, Alexander, Pulaski, and Massac Counties experience the greatest percentages of power loss with over 80% of households without power immediately after the event.

**Table 38: Utility Pipeline Damage for Illinois**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 164,800 | 4,396 | 5,372 | 9,768 |
| **Waste Water Local** | 98,900 | 3,480 | 4,252 | 7,732 |
| **Natural Gas Local** | 74,200 | 3,651 | 4,516 | 8,167 |
| **Natural Gas Interstate** | 15,000 | 371 | 955 | 1,326 |
| **Oil Interstate** | 8,400 | 37 | 111 | 148 |

Damage to other critical infrastructure is most common in the southernmost counties of Illinois. All damaged dams are located in Johnson, Massac, Union, Pope, and Pulaski Counties. Additionally, damage to levees occurs in Union, Pope, Alexander, Massac, and Pulaski Counties. Hazardous materials facilities require substantially more intense ground shaking than dams and levees for damage to occur, levels of ground shaking that occur only in the southernmost parts of Illinois. Nearly 40 hazardous materials facilities are damaged in Alexander, Massac, and Pulaski Counties. Table 39 details the state inventory and damage to other critical infrastructure.

**Table 39: Other Critical Facilities Damage for Illinois**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 1,562 | 31 |
| **Levees** | 576 | 34 |
| **Hazardous Materials** | 17,130 | 36 |

**Table 40: Casualties at 2:00AM for Illinois**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 4,597 | 1,270 | 146 | 271 | 6,284 |

**Table 41: Direct Economic Loss for Illinois ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $8,105 | $1,303 | $34,764 | $44,172 |

Infrastructure damage generates nearly 2.8 million tons of debris in Illinois. Steel and concrete account for 1.3 million tons of debris, while 1.5 million tons is attributed to brick, wood, and other building materials. St. Clair County produces more debris than any single county, roughly 850,000 tons. Massac and Madison Counties produce roughly 300,000 tons of total debris each. Three additional counties generate more than 100,000 tons each: Alexander, Jackson and Pulaski Counties. These six counties alone generate a total of 2 million tons of debris, or more than 70% of all debris in the state. Over 110,000 truckloads[19] are required to remove all the debris created by the earthquake event.

[19] Please reference footnote 7.

Damage from the scenario event causes nearly 6,300 total casualties. Table 40 shows that nearly 300 are fatalities and over 1,400 casualties are injuries that require hospitalization (Levels 2 & 3). The largest number of casualties, 2,500 in total, occurs in St. Clair County. Massac, Madison, Pulaski, and Alexander Counties also incur large numbers of casualties at 500 to 600.

Total assets in Illinois include more than $1 trillion in building value, nearly $170 billion in transportation infrastructure value, and approximately $1 trillion in utility infrastructure value. This equates to more than $2.2 trillion in total infrastructure value throughout the state. As Table 41 shows, utility lifelines losses account for just under 80% of all economic losses in Illinois. Building losses comprise a little less than 20%, while the remaining 3% are attributed to transportation losses. Total economic losses of more than $44 billion are among the largest in the eight-state study region.

**Impact Assessment Results for Indiana**

The impacted counties, or those impacted most severely, in Indiana are:

- Crawford
- Dubois
- Gibson
- Harrison
- Knox
- Lawrence
- Martin
- Orange
- Perry
- Pike
- Posey
- Spencer
- Vanderburgh
- Warrick

There are approximately 2.2 million buildings in the State of Indiana, of which approximately 2.1 million are residences. Only 14,200 buildings are expected to incur damage throughout the state. Approximately half of all at least moderate damage is attributed to single family homes and 45% is attributed to other residential structures. Nearly all building damage is experienced by residential structures, both moderate and complete, as shown in Table 42. Nearly 1.6 million of all Indiana buildings are wood frame structures and another 420,000 are URM structures. Steel, precast, and cast-in-place concrete buildings comprise a much smaller portion of the state building inventory.
Table 43 shows that manufactured housing incurs the most cases of moderate damage, though very few cases of complete damage. Wood structures experience nearly 70% of all complete damage. Vanderburgh, Gibson, Marion, and Posey Counties incur the greatest numbers of damaged buildings of all counties in Indiana. Marion County shows a higher number of damage buildings than the surrounding counties, though the 1,400 damaged buildings in this county are a very small portion of the total inventory of 290,000 buildings.

Damage to essential facilities is confined to southwestern Indiana. Ground shaking throughout the remainder of the state is not sufficient to cause measurable structural damage. Table 44 details damage to essential facilities throughout the state and it is evident that very few facilities are damaged. Most damage is moderate and confined to

Posey, Vanderburgh, Gibson, Pike, Warrick, Dubois, Spencer, Perry, Crawford, Harrison, Orange, and Lawrence Counties.

**Table 42: Building Damage by Occupancy Type for Indiana**[20]

| General Building Damage by Occupancy Type for Indiana | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 1,883,300 | 6,800 | 5,600 |
| **Other Residential** | 251,700 | 6,400 | 1,000 |
| **Commercial** | 41,200 | 600 | 100 |
| **Industrial** | 13,600 | 200 | < 50 |
| **Other** | 12,200 | 200 | 100 |
| **Total** | 2,202,000 | 14,200 | 6,800 |

**Table 43: Building Damage by Building Type for Indiana**[21]

| General Building Damage by Building Type For Indiana | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 1,587,800 | 4,800 | 4,700 |
| **Steel** | 21,800 | 600 | 100 |
| **Concrete** | 6,200 | 100 | < 50 |
| **Precast** | 6,300 | 100 | < 50 |
| **Reinforced Masonry** | 3,200 | < 50 | < 50 |
| **Unreinforced Masonry** | 416,500 | 2,600 | 1,300 |
| **Manufactured Housing** | 160,200 | 6,000 | 600 |
| **Total** | 2,202,000 | 14,200 | 6,800 |

**Table 44: Essential Facilities Damage for Indiana**[22]

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 2,874 | 6 | 0 |
| **Fire Stations** | 1,247 | 4 | 0 |
| **Police Stations** | 537 | 2 | 0 |
| **Hospitals** | 1,285 | 5 | 0 |
| **EOCs** | 113 | 1 | 0 |

Both transportation and utility lifelines are largely undamaged throughout Indiana. Moderate or more severe structural damage is not expected, though minor structural damage to transportation infrastructure, utility facilities and facility equipment. In some cases equipment at some facilities may be inoperable due to small deformations of supports or other structural components. Table 45 and Table 46 indicate that the thousands of bridges, transportation and utility facilities do not incur significant structural damage.

[20] Please reference footnote 1.
[21] Please reference footnote 1.
[22] Please reference footnote 3.

**Table 45: Transportation Lifeline Damage for Indiana**[23]

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 20,387 | 0 | 0 |
| **Railway Bridges** | 92 | 0 | 0 |
| **Railway Facilities** | 149 | 0 | 0 |
| **Bus Facilities** | 46 | 0 | 0 |
| **Port Facilities** | 100 | 0 | 0 |
| **Airport Facilities** | 675 | 0 | 0 |

**Table 46: Utility Facilities Damage for Indiana**[24]

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 203 | 0 | 0 |
| **Waste Water Facilities** | 4,531 | 0 | 0 |
| **Natural Gas Facilities** | 3,556 | 0 | 0 |
| **Oil Facilities** | 5,771 | 0 | 0 |
| **Electric Facilities** | 975 | 0 | 0 |
| **Communication Facilities** | 22,806 | 0 | 0 |

Pipeline repairs for the entire state of Indiana are detailed in Table 47. Local pipelines require nearly 4,800 repairs, mostly in southwestern Indiana or major metropolitan areas where distribution pipelines are most dense. Table 47 also shows that over 150 repairs are needed to restore major natural gas and oil pipelines. Without these critical repairs the flow of commodities to the east coast will be severely reduced. Additionally, 15,000 households are without water immediately after the event. All water outages occur in Gibson, Posey, and Vanderburgh Counties. Approximately 220,000 households are without power as a result of the scenario earthquake. Marion and Vanderburgh Counties show the greatest number of households without power at roughly 50,000 and 32,000 households, respectively. Additionally, Clark, Delaware, Hamilton, Hendricks, Madison, Monroe, Tippecanoe, Vigo, and Warrick Counties each report between 5,000 and 10,000 households without power at Day 1.

**Table 47: Utility Pipeline Damage for Indiana**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 111,400 | 727 | 1,080 | 1,807 |
| **Waste Water Local** | 66,800 | 575 | 854 | 1,429 |
| **Natural Gas Local** | 44,600 | 615 | 913 | 1,528 |
| **Natural Gas Interstate** | 10,200 | 9 | 24 | 33 |
| **Oil Interstate** | 4,600 | 28 | 102 | 130 |

Damage to dams, levees, and hazardous materials facilities is unlikely in Indiana. Ground shaking is not intense enough to cause significant structural damage and thus no release of water or hazardous material is expected. Table 48 shows that none of the several thousand critical facilities incur damage, though minor cracking or damage may occur.

[23] Please reference footnote 3.
[24] Please reference footnote 3.

**Table 48: Other Critical Facilities Damage for Indiana**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 1,187 | 0 |
| **Levees** | 101 | 0 |
| **Hazardous Materials** | 5,112 | 0 |

Infrastructure damage generates over one million tons of debris in Indiana. Nearly 500,000 tons is attributed to steel and concrete while the remaining 550,000 tons is attributed to brick, wood, and other building materials. Nearly 50% of all debris is generated in three counties: Gibson, Marion, and Vanderburgh Counties. Marion County alone, where Indianapolis is located, generates nearly 230,000 tons of debris. Though the shaking beneath Marion County, and Indianapolis, is relatively low, small amounts of debris generated by minor damage are amplified due to the density of housing and infrastructure. Nearly 42,000 truckloads[25] are required to remove all the debris generated from the event.

**Table 49: Casualties at 2:00AM for Indiana**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 1,458 | 395 | 43 | 80 | 1,976 |

**Table 50: Direct Economic Loss for Indiana ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $3,472 | $464 | $8,355 | $12,291 |

Approximately 2,000 total casualties are expected in Indiana. Table 49 shows that less than 100 casualties are fatalities and nearly 1,500 casualties do not require hospitalization. A large number of casualties occur in Gibson, Vanderburgh, Marion and Tippecanoe Counties. Nearly all casualties in Tippecanoe and Marion Counties are minor injuries that do not require hospitalization while the other two counties have greater numbers of serious injuries.

Total assets in Indiana include nearly $500 billion in building value, nearly $115 billion in transportation infrastructure value, and approximately $430 billion in utility infrastructure value. This equates to more than $1 trillion in total infrastructure value throughout the state. Total direct economic losses are roughly $12 billion for the entire state, as shown in Table 50. Utility losses are a large portion of all state economic losses accounting for nearly 70% of all economic losses. Building losses comprise nearly 30% of all losses and the remaining losses are attributed to transportation lifelines. Losses in Indiana are far less than many states included in the NMSZ study region.

[25] Please reference footnote 7.

**Impact Assessment Results for Kentucky**

The impacted counties, or those impacted most severely, in Kentucky are:

- Ballard
- Caldwell
- Calloway
- Carlisle
- Crittenden
- Daviess
- Fulton
- Graves
- Henderson
- Hickman
- Hopkins
- Livingston
- Lyon
- McCracken
- Marshall
- Muhlenberg
- Trigg
- Union
- Webster

There are approximately 1.54 million buildings in the State of Kentucky, with approximately 1.52 million residences. Table 51 shows that nearly 95% of all moderate and more severe damage is incurred by residential structures, many being single family homes. Moreover, 65% of all complete damage is attributed to single family homes. There are also over 1.1 million wood frame structures in Kentucky, while another 170,000 are URM structures. Steel, precast, and cast-in-place concrete buildings comprise a much smaller portion of the state building inventory. Table 52 details damage by building type. Wood structures experience the greatest amount of damage at both moderate and complete damage levels. Manufactured housing and URMs also incur significant amounts of damage. The largest number of damaged buildings occurs in McCracken County where 24,100 structures are damaged. Graves and Marshall Counties also incur substantial building damage at 9,000 and 5,100 buildings, respectively. Conversely, over 90% of all buildings in Ballard and Hickman Counties are expected to experience damage. Additionally, 80% to 90% of buildings in McCracken and Carlisle Counties are damaged.

**Table 51: Building Damage by Occupancy Type for Kentucky[26]**

| General Building Damage by Occupancy Type for Kentucky | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 1,194,800 | 42,100 | 16,100 |
| **Other Residential** | 305,100 | 22,800 | 7,100 |
| **Commercial** | 28,100 | 2,200 | 900 |
| **Industrial** | 7,900 | 700 | 200 |
| **Other** | 8,000 | 600 | 200 |
| **Total** | 1,543,900 | 68,400 | 24,500 |

Substantial structural damage occurs in hundreds of essential facilities in western Kentucky. As Table 53 shows, nearly 100 schools, over 70 fire stations, 20 police stations and several hospitals experience moderate or more severe structural damage. A significant portion of that damage is complete damage which renders many facilities non-operational. Ballard, Calloway, Carlisle, Daviess, Fulton, Graves, Hickman, Livingston, Marshall, and McCracken Counties comprise the majority of damaged essential facilities.

[26] Please reference footnote 1.

These counties will likely require assistance from other counties in Kentucky or neighboring states.

**Table 52: Building Damage by Building Type for Kentucky**[27]

| General Building Damage by Building Type For Kentucky | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 1,106,000 | 36,100 | 12,700 |
| **Steel** | 14,100 | 1,700 | 500 |
| **Concrete** | 3,900 | 300 | 100 |
| **Precast** | 4,000 | 300 | 100 |
| **Reinforced Masonry** | 2,000 | 100 | < 50 |
| **Unreinforced Masonry** | 170,100 | 9,400 | 5,000 |
| **Manufactured Housing** | 243,800 | 20,500 | 6,100 |
| **Total** | 1,543,900 | 68,400 | 24,500 |

Various modes of transportation are also compromised in western Kentucky following the NMSZ scenario event. Over 250 bridges are damaged; numerous airports and port facilities are also heavily damaged. Table 54 details the estimate of damaged transportation infrastructure in Kentucky. Many damaged bridges are located in Ballard and McCracken Counties. Numerous bridges along US-51, US-60, and US-45 are heavily damaged and likely impassible the day after the earthquake. Additionally, damage to major river bridges during the event severely limits traffic between Kentucky and Illinois, Tennessee, and Missouri. It is estimated that several bridges from Cairo, Illinois, to Kentucky are damaged as well as the I-24 Bridge from Metropolis, Illinois, and the Irvin S. Cobb Bridge at Paducah, Kentucky, are substantially damaged and unusable after the event. Extensive damage to many infrastructure types occurs in Ballard, Carlisle, Fulton, Hickman, Livingston, and McCracken Counties.

**Table 53: Essential Facilities Damage for Kentucky**[28]

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 1,871 | 99 | 40 |
| **Fire Stations** | 1,066 | 71 | 25 |
| **Police Stations** | 407 | 22 | 10 |
| **Hospitals** | 189 | 9 | 3 |
| **EOCs** | 146 | 10 | 5 |

Utility infrastructure in heavily damaged and limits the flow of commodities and availability of critical utility services throughout the state. Of the thousands of damaged facilities highlighted in Table 55, most are located in Ballard, Caldwell, Calloway, Carlisle, Crittenden, Fulton, Graves, Hickman, Hopkins, Livingston, Lyon, Marshall, McCracken, Union and Trigg Counties. Damage to pipelines in Kentucky also limits the availability of key services. Local distribution networks for water and natural gas require 30,000 repairs, many of which are needed in western Kentucky where gaining access to damaged pipes may be extremely difficult. In addition, major interstate transmission lines

[27] Please reference footnote 1.
[28] Please reference footnote 3.

may be down for an extended period of time while the over required 400 repairs are completed. Table 56 details the type and extent of damage to various pipelines in Kentucky. Over 75,000 of the 1.6 million households in Kentucky are without water immediately after the event. Furthermore, 330,000 households are without power. Western Kentucky is most severely impacted and may remain without these utility services for days or weeks depending upon how rapidly damaged infrastructure is repaired.

**Table 54: Transportation Lifeline Damage for Kentucky[29]**

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 15,418 | 262 | 64 |
| **Railway Bridges** | 166 | 3 | 0 |
| **Railway Facilities** | 125 | 17 | 0 |
| **Bus Facilities** | 26 | 1 | 0 |
| **Port Facilities** | 301 | 61 | 0 |
| **Airport Facilities** | 222 | 13 | 0 |

**Table 55: Utility Facilities Damage for Kentucky[30]**

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 179 | 17 | 0 |
| **Waste Water Facilities** | 9,447 | 650 | 5 |
| **Natural Gas Facilities** | 22,146 | 77 | 0 |
| **Oil Facilities** | 34,492 | 175 | 0 |
| **Electric Facilities** | 1,976 | 202 | 2 |
| **Communication Facilities** | 17,099 | 1,373 | 24 |

**Table 56: Utility Pipeline Damage for Kentucky**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 120,800 | 5,834 | 5,572 | 11,406 |
| **Waste Water Local** | 61,600 | 4,614 | 4,408 | 9,022 |
| **Natural Gas Local** | 41,100 | 4,932 | 4,712 | 9,644 |
| **Natural Gas Interstate** | 7,400 | 72 | 214 | 286 |
| **Oil Interstate** | 1,200 | 37 | 105 | 142 |

**Table 57: Other Critical Facilities Damage for Kentucky**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 1,196 | 53 |
| **Levees** | 90 | 10 |
| **Hazardous Materials** | 2,865 | 43 |

Over 50 dams are damaged and all are located in Carlisle, Ballard, Hickman, McCracken, and Graves Counties. Fulton and McCracken County are expected to incur damage to levees, while most hazardous materials facilities damage is confined to Ballard and

[29] Please reference footnote 3.
[30] Please reference footnote 3.

McCracken Counties. Many of these counties are at risk of flooding from dam and levee failure or hazardous materials release. Table 57 shows critical infrastructure damage estimates for Kentucky.

Over 4.8 million tons of debris is generated in Kentucky due to infrastructure damage. Two million tons is attributed to steel and concrete and the remaining 2.8 million to brick, wood, and other building materials. Specifically, McCracken County generates nearly 2.1 million tons of total debris. Nearly 550,000 tons of debris is generated in Graves County and roughly 350,000 tons are generated in both Marshall and Daviess Counties. A total of 193,000 truckloads (using 25-ton trucks) are required to remove all debris.

**Table 58: Casualties at 2:00AM for Kentucky**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 5,042 | 1,358 | 153 | 287 | 6,840 |

**Table 59: Direct Economic Loss for Kentucky ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $11,369 | $1,131 | $40,261 | $52,761 |

Nearly 7,000 total casualties are expected in Kentucky. Table 58 shows that roughly 5,000 are minor injuries, approximately 1,500 casualties require hospitalization, and nearly 300 fatalities are expected. The largest number of total casualties, approximately 2,750, occurs in McCracken County. Graves, Ballard, Daviess, and Marshall Counties each incur roughly 500 total casualties as a result of building and infrastructure damage.

Total assets in Kentucky include nearly $290 billion in building value, approximately $135 billion in transportation infrastructure value, and nearly $875 billion in utility infrastructure value. This equates to approximately $1.3 trillion in total infrastructure value throughout the state. Direct economic losses, as shown in Table 59, are nearly $53 billion for the NMSZ scenario event. Utility losses of $40 billion comprise 75% of state economic losses, while the $11 billion in building losses is roughly 20% of all economic loss in Kentucky.

### Impact Assessment Results for Mississippi

The impacted counties, or those impacted most severely, in Mississippi are:

- Alcorn
- Benton
- Bolivar
- Coahoma
- Desoto
- Lafayette
- Marshall
- Panola
- Pontotoc
- Prentiss
- Quitman
- Sunflower
- Tallahatchie
- Tate
- Tippah
- Tishomingo
- Tunica
- Union
- Yalobusha

There are approximately 1.06 million buildings in the State of Mississippi, with approximately 1.03 million residences. Approximately 57,400 buildings are at least moderately damaged throughout the state and over half of them are multi-family dwellings (other residential). Also, Table 60 shows that single family homes experience more complete damage than any other occupancy type. Furthermore, Table 61 shows that over half of all at least moderately damaged buildings are manufactured housing. Only 35% of this type of damage is attributed to woodframe structures. The majority or complete damage, however, occurs with this building type. Desoto, Marshall, Tate, Lafayette, Panola, and Coahoma Counties experience the largest numbers of damaged buildings.

**Table 60: Building Damage by Occupancy Type for Mississippi[31]**

| General Building Damage by Occupancy Type for Mississippi | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 814,000 | 22,700 | 17,400 |
| **Other Residential** | 222,000 | 31,500 | 4,200 |
| **Commercial** | 17,400 | 1,900 | 500 |
| **Industrial** | 4,600 | 700 | 100 |
| **Other** | 6,000 | 600 | 100 |
| **Total** | 1,064,000 | 57,400 | 22,300 |

**Table 61: Building Damage by Building Type for Mississippi[32]**

| General Building Damage by Building Type For Mississippi | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 794,700 | 19,900 | 16,800 |
| **Steel** | 8,600 | 1,500 | 200 |
| **Concrete** | 2,600 | 300 | 100 |
| **Precast** | 2,600 | 400 | 100 |
| **Reinforced Masonry** | 1,200 | 100 | < 50 |
| **Unreinforced Masonry** | 64,500 | 5,000 | 1,500 |
| **Manufactured Housing** | 189,800 | 30,200 | 3,600 |
| **Total** | 1,064,000 | 57,400 | 22,300 |

Essential facilities in northern Mississippi are severely damaged and unable to provide key services to local victims. Over 100 schools and fire stations are damaged, as well as several police stations and hospitals (see Table 62). The majority damage occurs in Alcorn, Benton, Bolivar, Coahoma, Desoto, Lafayette, Marshall, Panola, Pontotoc, Prentiss, Quitman, Tallahatchie, Tate, Tippah, Tunica, Union, and Yalobusha Counties. Local fire and law enforcement services are limited or non-existent. Medical services are largely unavailable in the impacted counties and most patients and earthquake victims must be transported out of northern Mississippi for any sort of prolonged medical care.

[31] Please reference footnote 1.
[32] Please reference footnote 1.

Levels of ground shaking and deformation are not sufficient, even in northern Mississippi, to cause widespread structural damage to transportation infrastructure. As shown in Table 63, only a few bridges are damaged in Mississippi. All other transportation infrastructure are not expected to incur significant structural damage. Minor structural damage and equipment damage is possible, though these types of damage are not included herein. It is estimated, however, that the Charles W. Dean Bridge from Arkansas City, Arkansas, is damaged and unusable after the event. Transferring commodities and providing aid into the heavily impacted area of northern Mississippi via the highway/interstate systems is hindered by the severe damage to this major bridge in Bolivar County.

**Table 62: Essential Facilities Damage for Mississippi[33]**

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 1,297 | 140 | 0 |
| **Fire Stations** | 984 | 104 | 0 |
| **Police Stations** | 365 | 42 | 0 |
| **Hospitals** | 163 | 23 | 2 |
| **EOCs** | 121 | 15 | 2 |

**Table 63: Transportation Lifeline Damage for Mississippi[34]**

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 18,293 | 6 | 0 |
| **Railway Bridges** | 63 | 0 | 0 |
| **Railway Facilities** | 76 | 0 | 0 |
| **Bus Facilities** | 41 | 0 | 0 |
| **Port Facilities** | 222 | 0 | 0 |
| **Airport Facilities** | 257 | 0 | 0 |

Thousands of utility facilities are located in Mississippi's impacted counties and many are damaged by the scenario event. Nearly 150 waste water facilities and over 450 communication facilities are damaged.

[33] Please reference footnote 3.
[34] Please reference footnote 3.

Table 64 also shows that several natural gas, oil, and electric power facilities are damaged with most damage occurring in Desoto, Marshall, Tate, and Tunica Counties. Extensive pipeline damage is also a concern especially in northern Mississippi. Many of the 28,300 repairs required along local distribution pipelines are located in the northern portion of the state. Table 65 also details major transmission line damage for natural gas and oil. These pipelines carry product from processing centers along the Gulf Coast to the Midwest and east coast, and any downtime will impact states far from the rupture zone since these commodities will be in short supply. In addition, services outages on the order of 80,000 households without water and 230,000 households without power are expected immediately after the event. Many of the impacted counties are expected to have 60% or more of their population without power.

**Table 64: Utility Facilities Damage for Mississippi**[35]

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 17 | 0 | 0 |
| **Waste Water Facilities** | 3,406 | 145 | 0 |
| **Natural Gas Facilities** | 3,442 | 19 | 0 |
| **Oil Facilities** | 7,405 | 4 | 0 |
| **Electric Facilities** | 853 | 36 | 0 |
| **Communication Facilities** | 9,915 | 467 | 0 |

**Table 65: Utility Pipeline Damage for Mississippi**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 106,200 | 4,281 | 6,454 | 10,735 |
| **Waste Water Local** | 63,700 | 3,386 | 5,104 | 8,490 |
| **Natural Gas Local** | 42,500 | 3,620 | 5,456 | 9,076 |
| **Natural Gas Interstate** | 10,200 | 169 | 586 | 755 |
| **Oil Interstate** | 3,500 | 21 | 68 | 89 |

**Table 66: Other Critical Facilities Damage for Mississippi**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 3,544 | 0 |
| **Levees** | 50 | 0 |
| **Hazardous Materials** | 2,042 | 0 |

Table 66 shows that no facilities are damaged, mainly due to their location. The facilities do not experience significant ground shaking and thus are largely undamaged. Minor cracking of dams and levees may occur, though it is unlikely that flooding will occur. Furthermore, it is unlikely that hazardous materials are released in Mississippi.

Induced damage includes 3.4 million tons of debris in the State of Mississippi. Steel and concrete comprise 1.5 million tons of total debris while the remaining 1.9 million tons are attributed to brick, wood, and other building materials. Over 136,000 truckloads[36] are required to remove all the debris generated. Desoto County produces the most debris by far, generating roughly 1,256,000 tons of total debris. Coahoma, Tate, and Panola Counties produce 265,000, 184,000, and 161,000 tons of total debris, respectively. Additionally, Tunica and Harrison Counties produce roughly 125,000 tons each.

Casualty and economic loss estimates for Mississippi are significant, though not as severe as several other NMSZ states. As shown in Table 67, over 6,000 total casualties are expected, though nearly 4,600 are minor injuries. Less than 200 fatalities are estimated and many of those are expected to occur in the impacted counties where infrastructure damage is more common. Desoto County incurs the greatest number of total casualties, approximately 2,100. Coahoma and Tate Counties incur substantial casualties as well, with roughly 680 and 400 total casualties, respectively.

[35] Please reference footnote 3.
[36] Please reference footnote 7.

Total assets in Mississippi include nearly $160 billion in building value, approximately $72 billion in transportation infrastructure value, and more than $290 billion in utility infrastructure value. This equates to nearly $525 billion in total infrastructure value throughout the state. Table 68 details direct economic losses by infrastructure group. Losses total nearly $17 billion with building and utility losses comprising large portions of all state losses.

**Table 67: Casualties at 2:00AM for Mississippi**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 4,588 | 1,181 | 104 | 183 | 6,056 |

**Table 68: Direct Economic Loss for Mississippi ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $7,305 | $660 | $8,759 | $16,724 |

**Impact Assessment Results for Missouri**

The impacted counties, or those impacted most severely, in Missouri are:

- Bollinger
- Butler
- Cape Girardeau
- Carter
- Dunklin
- Iron
- Jefferson
- Madison
- Mississippi
- New Madrid
- Oregon
- Pemiscot
- Perry
- Reynolds
- Ripley
- St. Charles
- St. Francois
- St. Louis
- Ste. Genevieve
- Scott
- Stoddard
- Wayne
- City of St. Louis

Please note that the City of St. Louis is not a county, but rather a separate jurisdiction. It is included in the list of impacted counties, thus creating a list of 23 impacted areas, all of which are referred to as impacted counties in this report. There are approximately 2.1 million buildings in the State of Missouri, with approximately 2.0 million are residences. Nearly 87,000 buildings are moderately or more severely damaged, over 70% of which are single family homes. Table 69 also shows that nearly 44,000 buildings are completely damaged. Residential buildings, both single family homes and multi-family dwellings (other residential) comprise over 95% all complete building damage. Furthermore, roughly half of all damage is attributed to wood structures. Manufacture homes only account for 20% of damage at moderate and complete damage levels. URM buildings comprise another 30% of all building damage at both levels presented in Table 70. The largest number of damaged buildings, nearly 106,700, are damaged in Scott County. Nearly 10,000 buildings are damaged in Dunklin County, 8,200 in Stoddard County, and approximately 7,000 in Cape Girardeau and Pemiscot Counties. The largest building damage percentages occur in Mississippi, Pemiscot, and New Madrid Counties where 93%, 86%, and 83% are damaged, respectively.

**Table 69: Building Damage by Occupancy Type for Missouri**[37]

| General Building Damage by Occupancy Type for Missouri | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 1,753,400 | 61,700 | 31,800 |
| **Other Residential** | 292,600 | 21,900 | 10,400 |
| **Commercial** | 35,300 | 2,000 | 1,000 |
| **Industrial** | 9,600 | 600 | 300 |
| **Other** | 10,900 | 600 | 300 |
| **Total** | 2,101,800 | 86,800 | 43,800 |

**Table 70: Building Damage by Building Type for Missouri**[38]

| General Building Damage by Building Type For Missouri | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 1,418,000 | 40,200 | 20,300 |
| **Steel** | 17,500 | 1,200 | 500 |
| **Concrete** | 5,200 | 300 | 200 |
| **Precast** | 5,200 | 300 | 200 |
| **Reinforced Masonry** | 2,900 | 200 | 100 |
| **Unreinforced Masonry** | 460,200 | 26,800 | 14,300 |
| **Manufactured Housing** | 192,800 | 17,800 | 8,200 |
| **Total** | 2,101,800 | 86,800 | 43,800 |

**Table 71: Essential Facilities Damage for Missouri**[39]

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 2,871 | 136 | 90 |
| **Fire Stations** | 1,399 | 69 | 45 |
| **Police Stations** | 654 | 53 | 40 |
| **Hospitals** | 208 | 7 | 1 |
| **EOCs** | 84 | 13 | 11 |

Intense ground shaking and extensive liquefaction cause widespread damage to all types of critical infrastructure. Table 71 details essential facilities damage for Missouri. While a great number of facilities are moderately or more severely damaged, a large percentage of those facilities are completely damaged. This is mainly due to the highly liquefiable soils in southeastern Missouri where shaking is most severe. These soils liquefy during the earthquake and cause significant ground deformations that damage infrastructure. Most damaged facilities are confined to the impacted counties, specifically Dunklin, Pemiscot, New Madrid, Mississippi, Scott, Butler, Cape Girardeau, and Stoddard Counties. Transportation infrastructure experiences moderate damage though very few facilities are completely damaged. As Table 72 illustrates, over 1,000 highway bridges are damaged. In addition, it is estimated that several major bridges are damaged including, the

[37] Please reference footnote 1.
[38] Please reference footnote 1.
[39] Please reference footnote 3.

Caruthersville Bridge which is unusable after the event. The I-57 Bridge between Cairo, Illinois, and Mississippi County, Missouri, and the Bill Emerson Memorial Bridge in Cape Girardeau, Missouri, are also heavily damaged. Airports, ports and rail infrastructure are damaged and inoperable in Dunklin, Pemiscot, New Madrid, Pemiscot, Mississippi, Scott, and Cape Girardeau Counties.

**Table 72: Transportation Lifeline Damage for Missouri**[40]

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 27,258 | 1,004 | 545 |
| **Railway Bridges** | 200 | 2 | 0 |
| **Railway Facilities** | 139 | 23 | 0 |
| **Bus Facilities** | 72 | 5 | 0 |
| **Port Facilities** | 232 | 52 | 0 |
| **Airport Facilities** | 562 | 28 | 0 |

**Table 73: Utility Facilities Damage for Missouri**[41]

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 357 | 28 | 0 |
| **Waste Water Facilities** | 7,816 | 519 | 0 |
| **Natural Gas Facilities** | 354 | 64 | 0 |
| **Oil Facilities** | 167 | 7 | 0 |
| **Electric Facilities** | 1,855 | 117 | 0 |
| **Communication Facilities** | 21,789 | 1,536 | 0 |

Southeastern Missouri also experiences extensive utility infrastructure damage. Specifically, hundreds of facilities are damaged and inoperable as a result of the NMSZ earthquake. Most damaged facilities are confined to the impacted counties listed previously. Dunklin, Pemiscot, Butler, Stoddard, New Madrid, Mississippi, Scott, Bollinger, Cape Girardeau, and Perry Counties are the most heavily impacted counties in the state with regard to utility facility damage. In addition, widespread damage to pipeline networks limits the flow of commodities and services to customers. All local distribution networks require nearly 96,000 repairs which is far more than most other Central US states included in this study. Major transmission lines are heavily damaged and require nearly 1,200 repairs. Table 74 details damage estimates for various types of utility networks. Lastly, Over 310,000 households are without power and nearly 125,000 households are without water at Day 1 as the result of damage to utility infrastructure.

**Table 74: Utility Pipeline Damage for Missouri**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 165,900 | 14,964 | 21,624 | 36,588 |
| **Waste Water Local** | 99,500 | 11,842 | 17,098 | 28,940 |
| **Natural Gas Local** | 66,400 | 12,653 | 18,275 | 30,928 |
| **Natural Gas Interstate** | 4,100 | 217 | 727 | 944 |

[40] Please reference footnote 3.
[41] Please reference footnote 3.

| | | | | |
|---|---|---|---|---|
| **Oil Interstate** | 6,400 | 52 | 176 | 228 |

**Table 75: Other Critical Facilities Damage for Missouri**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 5,408 | 55 |
| **Levees** | 369 | 25 |
| **Hazardous Materials** | 3,040 | 32 |

Secondary flooding and hazardous materials release are likely in southeastern Missouri where dams, levees, and hazardous materials facilities are damaged. Most damage occurs in Pemiscot, New Madrid, and Mississippi Counties.

Debris resulting from infrastructure damage totals nearly 6.5 million tons. Approximately three million tons is comprised of steel and concrete while the remaining 3.5 million tons is attributed to brick, wood, and other building materials. Scott and Dunklin Counties produce the most debris, roughly 935,000 and 835,000 tons, respectively. New Madrid, Stoddard, and Pemiscot Counties, plus the City of St. Louis produce roughly 500,000 tons of total debris each. Nearly 260,000 truckloads[42] are required to remove all debris generated by the NMSZ scenario event.

**Table 76: Casualties at 2:00AM for Missouri**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 10,179 | 2,898 | 361 | 687 | 14,125 |

**Table 77: Direct Economic Loss for Missouri ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $13,512 | $1,789 | $33,700 | $49,001 |

Over 14,000 casualties are expected throughout Missouri. Nearly 700 fatalities are estimated to occur all in southeast Missouri. Table 76 details the number of casualties expected by severity level. Nearly 1,900 total casualties occur in both Dunklin and Scott Counties, while New Madrid and Pemiscot Counties are each estimated to incur 1,300 total casualties. Additionally, Jefferson and St. Louis Counties, along with the City of St. Louis, incur large numbers of casualties.

Total assets in Missouri include more than $400 billion in building value, nearly $125 billion in transportation infrastructure value, and approximately $770 billion in utility infrastructure value. This equates to more than $1.3 trillion in total infrastructure value throughout the state. Total direct economic losses are estimated at $49 billion and losses by infrastructure group are shown in Table 77. Nearly 70% of all losses are attributed to utility infrastructure, though buildings also comprise a sizeable portion of losses, over 25% of the state total.

[42] Please reference footnote 7.

**Impact Assessment Results for Tennessee**

The impacted counties, or those impacted most severely, in Tennessee are:

- Benton
- Carroll
- Chester
- Crockett
- Dyer
- Fayette
- Gibson
- Hardeman
- Hardin
- Haywood
- Henderson
- Henry
- Lake
- Lauderdale
- Madison
- McNairy
- Obion
- Shelby
- Tipton
- Weakley

There are approximately 2.1 million buildings in the State of Tennessee, with approximately 2.0 million residences. The number of damaged buildings in Tennessee is far greater than all other states in the eight-state study region. Over 264,000 buildings are moderately or more severely damaged and nearly 107,000 of those buildings are completely damaged. Table 78 details building damage by occupancy type. Approximately 75% of all building damage occurs in single family homes. It is evident in

Table 79 that wood structures incur more damage than other structure types, though they also comprise a large portion of the inventory. Conversely, URM buildings comprise a much smaller portion of the inventory, only 10%, though they account for nearly 20% of all at least moderate damage and 15% of all complete damage. Furthermore, Shelby County, Tennessee, comprises half of all building damage in the state primarily due to the major metropolitan area in and around Memphis. Additionally, substantial building damage occurs in Gibson, Dyer, Tipton, and Obion Counties.

**Table 78: Building Damage by Occupancy Type for Tennessee[43]**

| General Building Damage by Occupancy Type for Tennessee | | | |
|---|---|---|---|
| **General Occupancy Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Single Family** | 1,715,800 | 193,300 | 84,700 |
| **Other Residential** | 348,400 | 55,200 | 16,700 |
| **Commercial** | 40,500 | 10,100 | 3,500 |
| **Industrial** | 10,800 | 2,800 | 1,000 |
| **Other** | 11,100 | 2,800 | 1,000 |
| **Total** | 2,126,600 | 264,200 | 106,900 |

[43] Please reference footnote 1.

**Table 79: Building Damage by Building Type for Tennessee**[44]

| General Building Damage by Building Type For Tennessee | | | |
|---|---|---|---|
| **General Building Type** | **Total Buildings** | **At Least Moderate Damage** | **Complete Damage** |
| **Wood** | 1,619,800 | 163,600 | 75,400 |
| **Steel** | 19,500 | 5,700 | 2,100 |
| **Concrete** | 5,500 | 1,400 | 500 |
| **Precast** | 5,600 | 1,600 | 600 |
| **Reinforced Masonry** | 2,800 | 700 | 200 |
| **Unreinforced Masonry** | 209,000 | 48,900 | 16,600 |
| **Manufactured Housing** | 264,400 | 42,300 | 11,500 |
| **Total** | 2,126,600 | 264,200 | 106,900 |

**Table 80: Essential Facilities Damage for Tennessee**[45]

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 2,352 | 608 | 44 |
| **Fire Stations** | 1,110 | 242 | 25 |
| **Police Stations** | 424 | 119 | 24 |
| **Hospitals** | 232 | 54 | 7 |
| **EOCs** | 171 | 44 | 15 |

Hundreds of essential facilities are damaged in western Tennessee. Table 80 details damage for the entire State of Tennessee, though nearly all damaged facilities are located in the impacted counties. Many facilities in Carroll, Chester, Crockett, Dyer, Fayette, Gibson, Hardeman, Haywood, Henderson, Henry, Lake, Lauderdale, Madison, McNairy, Obion, Shelby, Tipton, and Weakley Counties are damaged and inoperable as a result of the scenario event. Many completely damaged facilities are located on counties along the western border of Tennessee.

Similarly, transportation infrastructure damage is focused in western Tennessee. There are approximately 23,000 bridges in the State of Tennessee and roughly 6,700 bridges in the 20 impacted counties. More than 1,000 bridges are damaged in western Tennessee, and almost 250 bridges are completely damaged. Numerous bridges along I-55, I-40, US-51, US-412, and US-45W are heavily damaged and likely impassible the day after the earthquake. Table 81 also shows that numerous airports, ports and railway facilities are damaged, primarily in Obion, Dyer, Lake, Lauderdale, Shelby, and Tipton Counties. Damage to major river crossings also inhibits travel across the Mississippi River to Arkansas and Missouri. It is estimated that the Harahan, Frisco, and Memphis/Arkansas bridges into Memphis, Tennessee, are substantially damaged and unusable after the event. The Caruthersville Bridge in Dyersburg is heavily damaged as well.

Substantial damage to utility infrastructure causes hundreds of thousands of service outages throughout the state. Over 4,000 communication facilities are damaged severely limiting cellular and landline communication in western Tennessee. Also, hundreds of

[44] Please reference footnote 1.
[45] Please reference footnote 3.

electric power facilities are damaged causing massive power outages throughout the state. Table 82 also details damage to other types of facilities in Tennessee. Nearly 104,000 repairs are required to fully restore the local potable water, waste water, and natural gas networks. Nearly 2,000 additional repairs are required for major interstate transmission lines. Completing all the repairs quantified in Table 83 will take several weeks or months depending upon the availability of parts and labor after the earthquake. The aforementioned damage leaves over 500,000 households without water and over 700,000 households without power immediately after the event. Service outages are more frequent in western Tennessee where direct infrastructure damage is most severe. Such extensive power and water service interruptions will also impede the response efforts in the state and region.

**Table 81: Transportation Lifeline Damage for Tennessee[46]**

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 22,897 | 1,035 | 244 |
| **Railway Bridges** | 151 | 2 | 0 |
| **Railway Facilities** | 141 | 58 | 0 |
| **Bus Facilities** | 58 | 7 | 0 |
| **Port Facilities** | 202 | 82 | 0 |
| **Airport Facilities** | 318 | 45 | 0 |

**Table 82: Utility Facilities Damage for Tennessee[47]**

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 98 | 11 | 1 |
| **Waste Water Facilities** | 2,001 | 453 | 7 |
| **Natural Gas Facilities** | 183 | 61 | 0 |
| **Oil Facilities** | 160 | 43 | 0 |
| **Electric Facilities** | 574 | 96 | 2 |
| **Communication Facilities** | 17,156 | 4,024 | 61 |

**Table 83: Utility Pipeline Damage for Tennessee**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 117,400 | 15,258 | 24,051 | 39,309 |
| **Waste Water Local** | 70,500 | 12,067 | 19,022 | 31,089 |
| **Natural Gas Local** | 47,000 | 12,900 | 20,334 | 33,234 |
| **Natural Gas Interstate** | 4,600 | 351 | 1,232 | 1,583 |
| **Oil Interstate** | 1,000 | 71 | 234 | 305 |

There is a larger inventory of dams than levees in western Tennessee thus the larger number of damaged facilities. The majority of dam damage occurs in Dyer and Obion Counties though a small number of dams in Gibson and Lake Counties are damaged as well. Most levee damage is confined to Dyer, Lake, and Shelby Counties. Some hazardous materials facilities in Dyer, Lake, Lauderdale, Gibson, Obion, and Tipton

[46] Please reference footnote 3.
[47] Please reference footnote 3.

Counties are likely to incur some damage to tank supports, widespread leakage of hazardous materials is unlikely though still possible in limited amounts.

**Table 84: Other Critical Facilities Damage for Tennessee**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 1,215 | 133 |
| **Levees** | 11 | 7 |
| **Hazardous Materials** | 4,080 | 73 |

The amount of debris generated in Tennessee far exceeds all other states mainly due to the density of infrastructure in the heavily damaged City of Memphis. Approximately 21.6 million tons of debris is generated statewide, though over 13 million tons is produced in Shelby County alone. Additionally, Dyer and Gibson Counties produce 1.5 and 1.1 million tons, respectively. Madison, Obion, and Tipton Counties produce between 775,000 and 975,000 tons of total debris each. Roughly 9.3 million tons of all debris is steel and concrete, while the remaining 12.3 million tons is brick, wood, and other building materials. More than 860,000 truckloads[48] are required to remove all debris generated in Tennessee.

Infrastructure damage and falling debris cause more than 34,200 total casualties. Over 1,300 of these casualties represent fatalities while another 7,500 are injuries requiring hospitalization. Shelby County experiences the greatest number of total casualties, nearly 21,500. Dyer, Tipton, and Gibson Counties incur substantial casualties as well, with 2,100, 1,500 and 1,500, respectively. Table 85 details total casualties by severity level for the entire state.

Total assets in Tennessee include nearly $400 billion in building value, approximately $95 billion in transportation infrastructure value, and nearly $185 billion in utility infrastructure value. This equates to more than $675 billion in total infrastructure value throughout the state. Table 86 illustrates direct economic losses for Tennessee by infrastructure group. Building losses comprise more than 70% of all economic losses with utility losses comprising less than 25% of the total direct economic loss estimate.

**Table 85: Casualties at 2:00AM for Tennessee**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 25,431 | 6,765 | 715 | 1,319 | 34,230 |

**Table 86: Direct Economic Loss for Tennessee ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $49,392 | $2,898 | $16,121 | $68,411 |

[48] Please reference footnote 7.

**Impact Assessment Results for the Eight-State Study Region**

The entirety of the eight-state region included in the NMSZ earthquake impact assessment is affected by the scenario earthquake. As previously mentioned in each state discussion there are numerous counties selected by researchers due to the severity of impacts in these specific counties. The most catastrophic damage to infrastructure, loss of facility functionality, social impacts and direct economic losses occur in these 140 impacted counties. These counties are listed previously in each state results section. A map of these impacted counties is provided in Figure 16. There are no impacted counties in Alabama, though a set of 'socially impacted' counties was outlined previously. These 'socially' impacted counties are not shown in Figure 16.

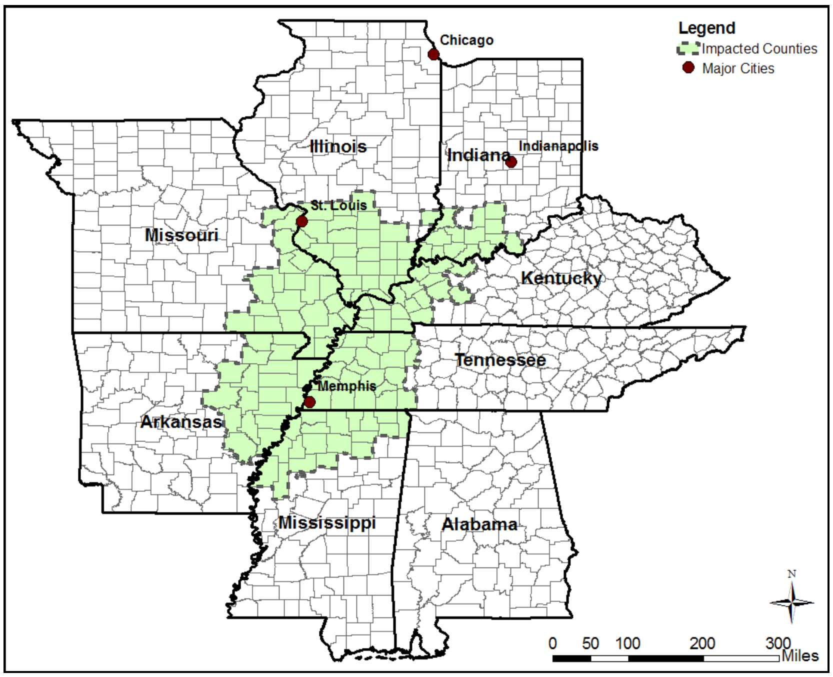


**Figure 16: Impacted Counties in Eight-State Study Region**

**Table 87: Building Damage by State for Eight-State Study Region**

| State | Total Buildings | Buildings Damaged | URM Damage | Wood Damage |
|---|---|---|---|---|
| **Alabama** | 1,758,300 | 15,400 | 400 | 3,000 |
| **Arkansas** | 1,325,400 | 162,200 | 29,100 | 68,800 |
| **Illinois** | 3,655,800 | 44,500 | 10,100 | 17,700 |
| **Indiana** | 2,202,000 | 14,200 | 2,600 | 4,800 |
| **Kentucky** | 1,543,900 | 68,400 | 9,400 | 36,100 |
| **Mississippi** | 1,064,000 | 57,400 | 5,000 | 19,900 |
| **Missouri** | 2,101,800 | 86,800 | 26,800 | 40,200 |
| **Tennessee** | 2,126,600 | 264,200 | 48,900 | 163,600 |
| **Total** | 15,777,800 | 713,100 | 132,300 | 354,100 |

Overall, there are more than 713,000 buildings moderately or severely damaged in the eight-state study region. Table 87 describes the distribution of damage by state. Arkansas and Tennessee experience the greatest amounts of damage while Alabama and Indiana incur relatively little damage in comparison. Additionally, more than 130,000 URMs and 354,000 woodframe structures are damaged in the eight-state region. Figure 17 illustrates the distribution of total building damage throughout the study region. It is evident that Shelby County, Tennessee, incurs the most damaged buildings by far, though numerous other counties in Arkansas and Tennessee, as well as some in Kentucky, Missouri and Illinois experience large numbers of damaged structures. It is also important to note that building damage counts are represented in Figure 17, which differ from percentages of buildings damaged per county. When considering damage percentages counties far from the rupture zone would not appear so heavily damaged since the building inventory in those counties is quite large.

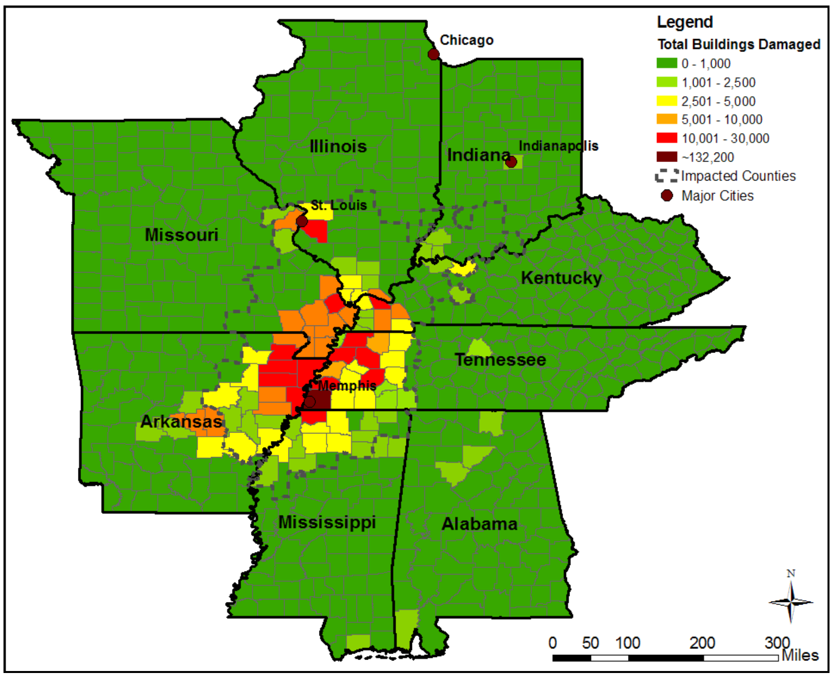


**Figure 17: General Building Damage in Eight-State Study Region (No. of Buildings Damaged)**

**Table 88: Essential Facilities Damage for Eight-State Study Region[49]**

| Essential Facility | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Schools** | 20,291 | 1,322 | 277 |
| **Fire Stations** | 10,346 | 729 | 177 |
| **Police Stations** | 4,480 | 379 | 136 |
| **Hospitals** | 2,825 | 129 | 32 |
| **EOCs** | 1,093 | 116 | 44 |

The scenario event leaves thousands of essential facilities damaged in the Central US. In addition, Table 88 shows that nearly 700 facilities are completely damaged in the study region. Many are schools, fire stations and police stations indicating that numerous potential shelters are unavailable and firefighting and law enforcement services are nearly non-existent close to the rupture zone. Figure 18 illustrates the likelihood of structural

[49] Please reference footnote 3.

damage to hospitals as a result of the NMSZ scenario event. It is evident that southeastern Missouri, northeastern Arkansas, western Kentucky, and western Tennessee are most critically impacted and most hospitals are severely damaged. These portions of the study region also incur the most severe damage to other essential facility types.

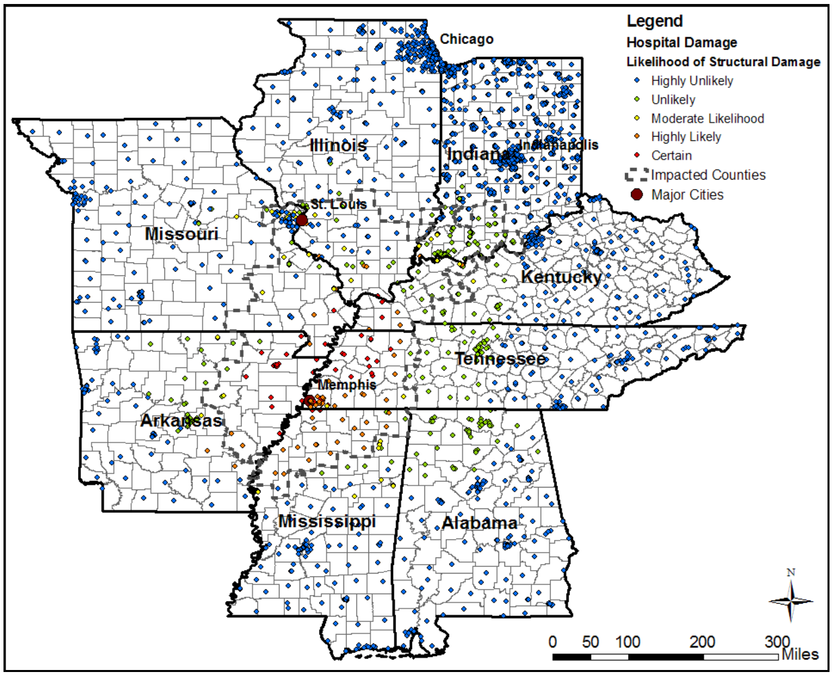


**Figure 18: Hospital Damage for Eight-State Study Region**

Major river crossings in the Central US are those that cross the Illinois, Mississippi, Missouri, Ohio, and Arkansas Rivers. These bridges are unique structures and carry high volumes of traffic as well as major pipelines and communication lines. It is estimated that roughly 15 major bridges are damaged and impassible. Figure 19 illustrates the locations of damaged major river crossings in the Central US. Numerous damaged bridges lie along the Mississippi River, effectively separating the eight-state study region into two individual sections along the river. It is unlikely that response workers, evacuees and supplies can be moved from across the river for several hundred miles south of St. Louis, Missouri, to south of Memphis, Tennessee .

**Table 89: Transportation Lifeline Damage for Eight-State Study Region[50]**

| Transportation Lifelines | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Highway Bridges** | 165,771 | 3,547 | 1,255 |
| **Railway Bridges** | 1,888 | 29 | 0 |
| **Railway Facilities** | 1,118 | 119 | 0 |
| **Bus Facilities** | 405 | 16 | 0 |
| **Port Facilities** | 2,004 | 232 | 0 |
| **Airport Facilities** | 3,773 | 143 | 0 |

[50] Please reference footnote 3.

Damage to highway bridges in general drastically limits transportation within the 140 impacted counties in the study region. Over 3,500 bridges are damaged moderately or more severely while roughly 1,250 bridges are completely damaged and almost certainly impassible. Table 89 also details damage to other transportation infrastructure. Hundreds of ports and airports are damaged in the impacted counties and limit water and air travel. A lack of functioning airports will impede the movement of response workers, relief supplies, and evacuation efforts. Furthermore, railway bridges and facilities are damaged in the impacted counties, limiting the movement of people and goods over rail lines.

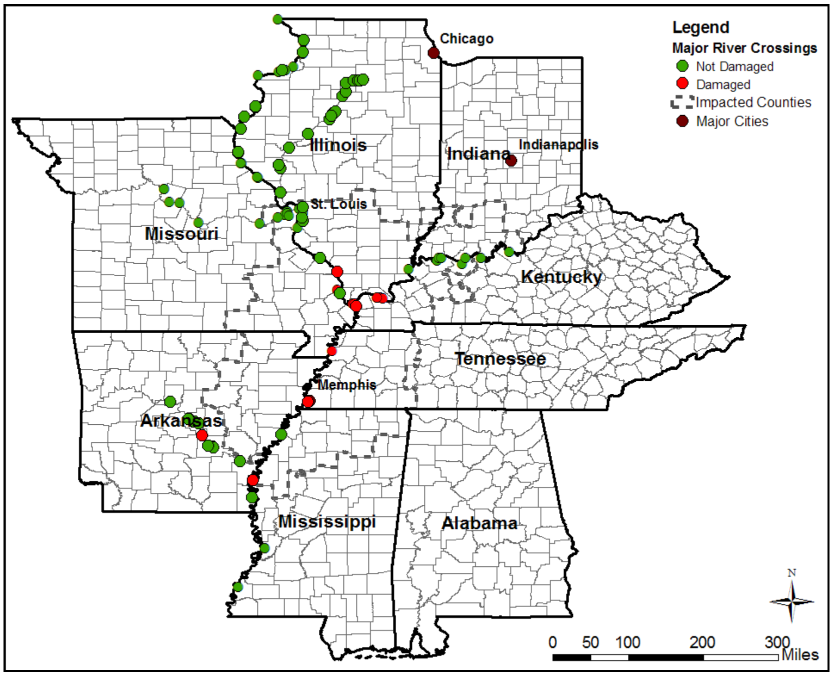

**Figure 19: Major River Crossing Damage for Eight-State Study Region**

Utility infrastructure is also compromised throughout the eight-state region. Table 90 details facility damage totals for all eight states. Well over 9,700 communication facilities are damaged leaving many in the impacted counties without communication services which includes aid workers attempting to coordinate response efforts. Moreover, thousands of water, oil, natural gas, and electric power facilities are damaged, mainly in the impacted counties of Illinois, Missouri, Kentucky, Tennessee, and Arkansas. Damage to utility pipelines also limits regional utility service capabilities post-event. As Table 91 details, local distribution lines for water alone require over 280,000 repairs. Additionally, local natural gas lines require over 130,000 repairs. Restoring local pipelines is vital though repairing the more than 7,500 breaks and leaks to interstate natural gas and oil pipelines severely impacts commodities distribution to other parts of the country. There will be limited availability of spare parts and labor to complete the necessary repairs and thus all repairs must be prioritized. Service outages are widespread as many facilities and pipelines are damage by the scenario event. Figure 20 illustrates the percentage of households in each county that are without electric power service. It is clear that numerous counties in Kentucky, Tennessee, Illinois, Missouri, and Arkansas have extensive electric service outages. A total of 2.6 million households in the eight-state study region are without power immediately after the event. Furthermore, 1.1 million households are without water. These outages may last several weeks or months depending upon the extent of damage to infrastructure.

**Table 90: Utility Facilities Damage for Eight-State Study Region**[51]

| Utility Facilities | Total Facilities | At Least Moderate Damage | Complete Damage |
|---|---|---|---|
| **Potable Water Facilities** | 1,195 | 76 | 1 |
| **Waste Water Facilities** | 48,430 | 2,732 | 17 |
| **Natural Gas Facilities** | 34,339 | 418 | 3 |
| **Oil Facilities** | 89,621 | 998 | 0 |
| **Electric Facilities** | 10,893 | 673 | 4 |
| **Communication Facilities** | 145,722 | 9,748 | 115 |

**Table 91: Utility Pipeline Damage for Eight-State Study Region**

| Pipeline System | Total Miles | Leaks | Breaks | Total Repairs |
|---|---|---|---|---|
| **Potable Water Local** | 1,030,000 | 65,452 | 92,094 | 157,546 |
| **Waste Water Local** | 607,100 | 51,776 | 72,837 | 124,613 |
| **Natural Gas Local** | 413,200 | 55,273 | 77,829 | 133,102 |
| **Natural Gas Interstate** | 66,500 | 1,534 | 4,841 | 6,375 |
| **Oil Interstate** | 29,100 | 310 | 1,015 | 1,325 |

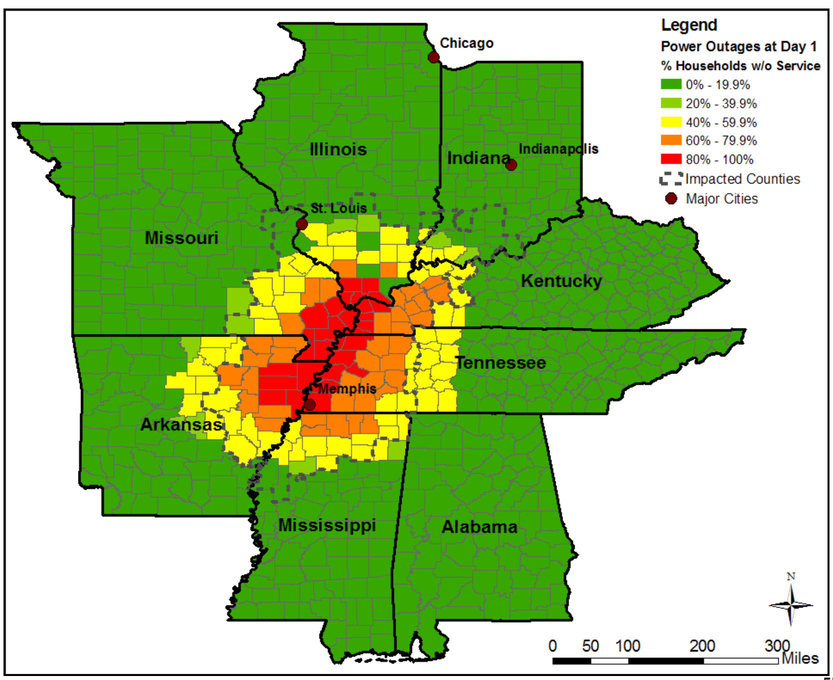


**Figure 20: Electric Power Outages at Day 1 for Eight-State Study Region**[52]

Damage to facilities that generate secondary hazards are of particular concern near the rupture zone. Though there are tens of thousands dams and levees in the eight-state

[51] Please reference footnote 3.

[52] Electric Power Outages are based solely on the likelihood of any structural damage to electric substations and do not include impact due to damage to electric power plants or distribution networks.

region roughly 400 are damaged by the scenario event. Not all of these damaged dams and levees are likely to cause flooding, though several along the Ohio, Mississippi, and other smaller rivers may incur damage severe enough to flood neighboring areas and damage other infrastructure and homes. Additionally, Table 92 shows that over 250 hazardous materials facilities are damaged. Only a small fraction of these facilities near the rupture zone are likely to release any hazardous materials.

**Table 92: Other Critical Facilities Damage for Eight-State Study Region**

| Facility Type | Total Facilities | Damaged |
|---|---|---|
| **Dams** | 17,573 | 327 |
| **Levees** | 1,326 | 96 |
| **Hazardous Materials** | 39,759 | 253 |

Damaged infrastructure generates roughly 50 million tons of debris throughout the region. Approximately 22 million tons are attributed to steel and concrete while the remaining 28 million tons are attributed to brick, wood, and other building materials. Over 40% of all debris occurs in Arkansas, roughly 30% is generated in Tennessee, and just over 20% in Kentucky. Most of this debris is located in the impacted counties within each state. Over two million truckloads[53] are required to remove all debris generated by the earthquake.

The catastrophic nature of this scenario earthquake event is depicted best by the number of casualties estimated in Table 93 and illustrated in Figure 21. Nearly 86,000 total casualties are expected for the 2:00AM event. A large portion of these casualties are minor injuries, approximately 63,300, though 3,500 fatalities are also expected. Most fatalities are confined to the impacted counties. Furthermore, emergency medical services must accommodate the 19,000 estimated injuries that require hospitalization. Many of these injuries occur in areas where hospitals and urgent care facilities are damaged so an evacuation plan must account for the transportation of these victims and their compromised health. A large number of total casualties, nearly 21,500, are expected in Shelby County, Tennessee, alone. Additional counties in Tennessee, Arkansas, and Missouri experience large numbers of casualties and will likely need substantial external assistance immediately after the event.

The eight-state study region includes $8.6 trillion in building, transportation lifeline, and utility lifeline assets. Over 25% of all study region assets are located in Illinois though only 15% of all economic losses occur there. Conversely, only 8% of regional asset value is located in Tennessee but nearly 25% of all economic losses occur there. Kentucky and Missouri each incur roughly 17% of all direct economic losses in the study region. The State of Arkansas comprises only 5% of all economic assets in the eight states, though 13% of all economic losses occur there. Overall, the NMSZ scenario event generates approximately $300 billion in direct economic losses. Table 94 describes economic losses by infrastructure type. Nearly 60% of all economic losses are attributed to utility lifelines and nearly 40% are attributed to buildings. Less than 4% of all economic losses are attributed to transportation lifelines.

[53] Please reference footnote 7.

**Table 93: Casualties at 2:00AM for Eight-State Study Region**

| | Level 1 | Level 2 | Level 3 | Level 4 | Total |
|---|---|---|---|---|---|
| **Casualties at 2:00AM** | 63,266 | 17,121 | 1,882 | 3,496 | 85,765 |

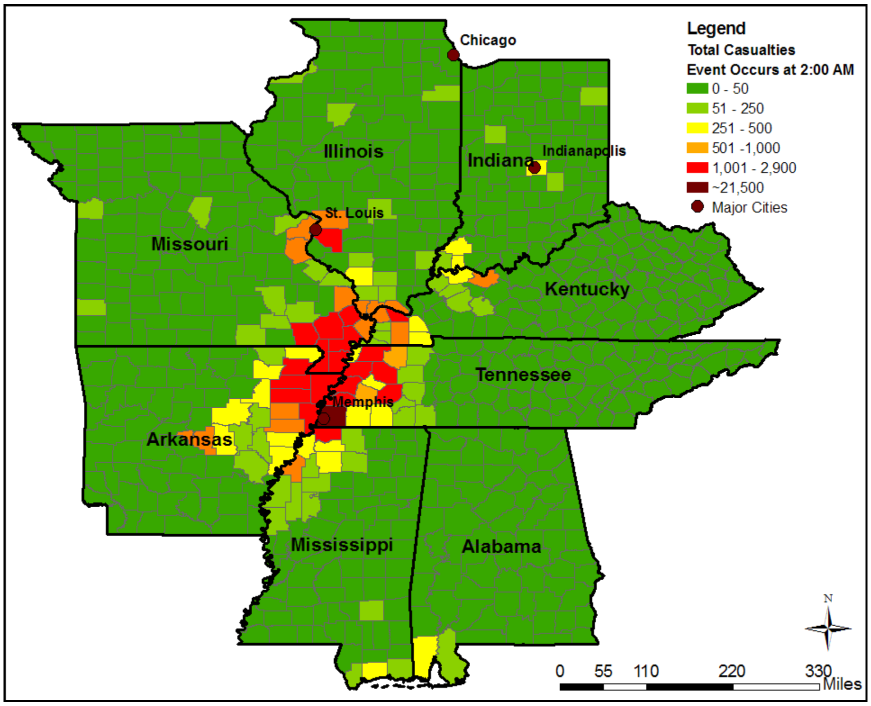


**Figure 21: Total Casualties for 2:00AM Event in Eight-State Study Region**

**Table 94: Direct Economic Loss for Eight-State Study Region ($ millions)**

| | Buildings | Transportation | Utilities | Total |
|---|---|---|---|---|
| **Direct Economic Loss** | $113,080 | $10,866 | $172,101 | $296,047 |

## Flood Risk Analysis

Flood risk modeling involved the identification of potential flood risk zones in the Central US. Based on direct damage results for dam infrastructure, there are five states that are potentially affected by floods including Arkansas, Illinois, Kentucky, Missouri, and Tennessee, while the three remaining states, Alabama, Indiana, and Mississippi, are not expected experience any secondary flooding. The following is a comprehensive list of counties at risk for flooding in each state, while the regional flood risk is presented in Figure 22.

- Arkansas: Poinsett County
- Illinois: Massac, Pope, and Pulaski Counties
- Kentucky: Ballard, Carlisle, and Hickman Counties
- Missouri: Scott County
- Tennessee: Dyer, Gibson, and Obion Counties

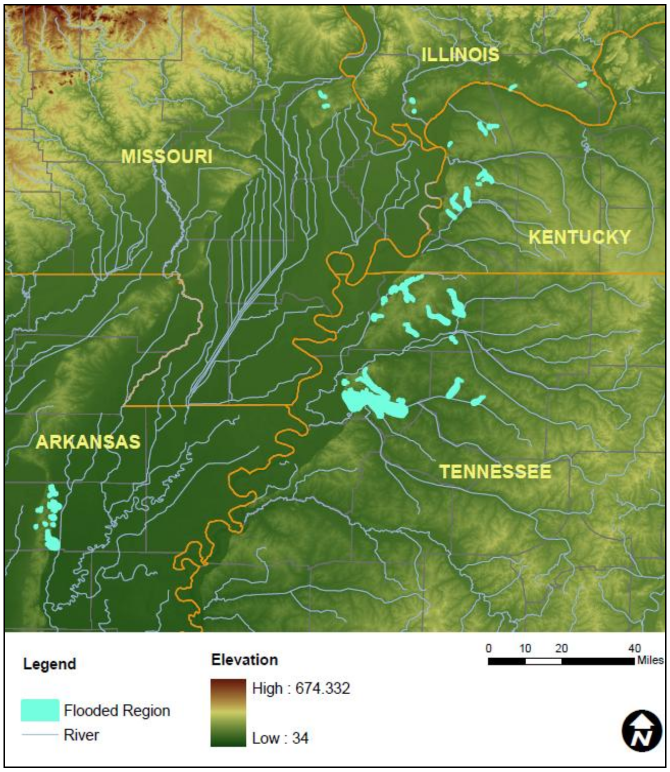


**Figure 22: NMSZ Flood Risk Due to Dam Damage**

Inventory that is located either completely or partially inside a flooded region boundary is considered at risk for secondary flooding. Overall, the most impacted facilities include communication facilities, fire stations, waste water facilities, and highway bridges. Tennessee has the largest amount of infrastructure in flood risk areas by a large margin when compared to the four other at risk states. The region summary regarding potentially flooded facilities is presented in Table 95, while Figure 23 illustrates the mapping of essential facilities flood potential for Tennessee. As illustrated, there is significant flood risk to police stations, fire stations, and schools.

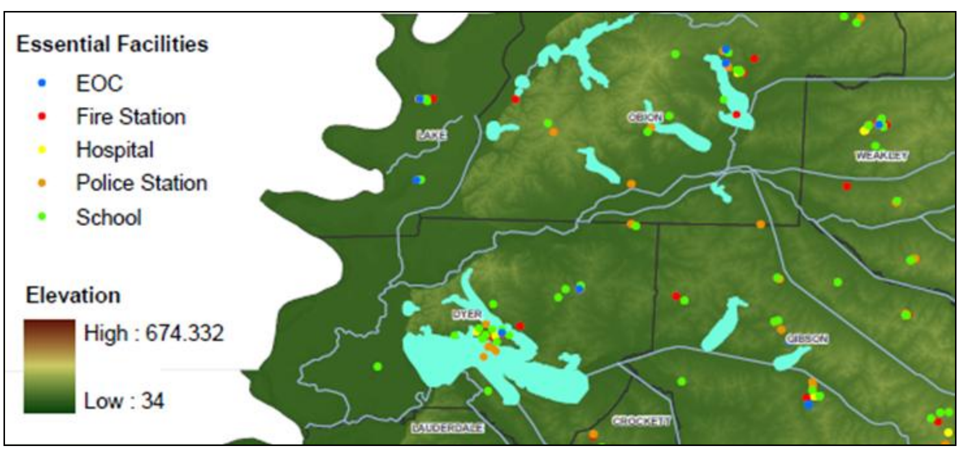


**Figure 23: Tennessee Essential Facilities Flood Risk**

**Table 95: Flood Risk Results - Region Summary**

| Inventory Category | Facility Type | Number of Potentially Flooded Facilities | | | | | Total by Facility Type |
|---|---|---|---|---|---|---|---|
| | | AR | IL | KY | MO | TN | |
| Essential Facilities | EOC | 0 | 0 | 0 | 0 | 2 | **2** |
| | Fire Stations | 2 | 1 | 1 | 0 | 7 | **11** |
| | Hospitals | 0 | 0 | 0 | 0 | 1 | **1** |
| | Police Stations | 0 | 0 | 0 | 0 | 7 | **7** |
| | Schools | 0 | 1 | 0 | 1 | 8 | **10** |
| | | | | | | | |
| Transportation | Airports | 0 | 0 | 0 | 0 | 2 | **2** |
| | Bus Facilities | 0 | 0 | 0 | 0 | 1 | **1** |
| | Highway Bridges | 25 | 2 | 23 | 2 | 132 | **184** |
| | Ports | 0 | 0 | 0 | 0 | 0 | **0** |
| | Railway Bridges | 0 | 0 | 0 | 0 | 0 | **0** |
| | Railway Facilities | 0 | 0 | 0 | 0 | 0 | **0** |
| | | | | | | | |
| Utilities | Communication Facilities | 0 | 0 | 4 | 1 | 59 | **64** |
| | Electric Power Facilities | 0 | 0 | 0 | 0 | 1 | **1** |
| | Natural Gas Facilities | 0 | 0 | 0 | 2 | 1 | **3** |
| | Oil Facilities | 0 | 0 | 0 | 0 | 1 | **1** |
| | Potable Water Facilities | 0 | 0 | 0 | 0 | 2 | **2** |
| | Waste Water Facilities | 0 | 2 | 3 | 0 | 15 | **20** |
| | | | | | | | |
| **Total Facilities by State** | | **27** | **6** | **31** | **6** | **239** | **309** |

## Network Models

### Transportation Network Model

The NLA module is implemented in the latest version of MAEViz and demonstrated over the transportation networks in the metropolitan areas of St. Louis, Missouri, and Memphis, Tennessee. For demonstration purposes, this section only gives the results of the traffic analysis of the networks before and after the scenario earthquake (day 0). Performance at other time frames such as day 3 and day 7 can be obtained by using time-dependent functionality restoration relationship (Padgett and DesRoches, 2007). Components of the MAEViz traffic model are illustrated in Figure 24 and Figure 25.

The changes of travel delays before and after earthquake are shown in Figure 26 and Figure 27 for the cities of St. Louis and Memphis, respectively. Travel delays on the segments of the interstate highways I-44, I-55, I-170, I-64, I-70, I-255, and I-270 in the City of St. Louis are estimated to increase significantly after the earthquake, while travel delays in other regions increase moderately or slightly. Model results indicate that many major arterials in St. Louis County and the City of St. Louis experience severe congestion. Highways and major arterials connecting St. Louis and surrounding counties also experience high density traffic and severe congestion.

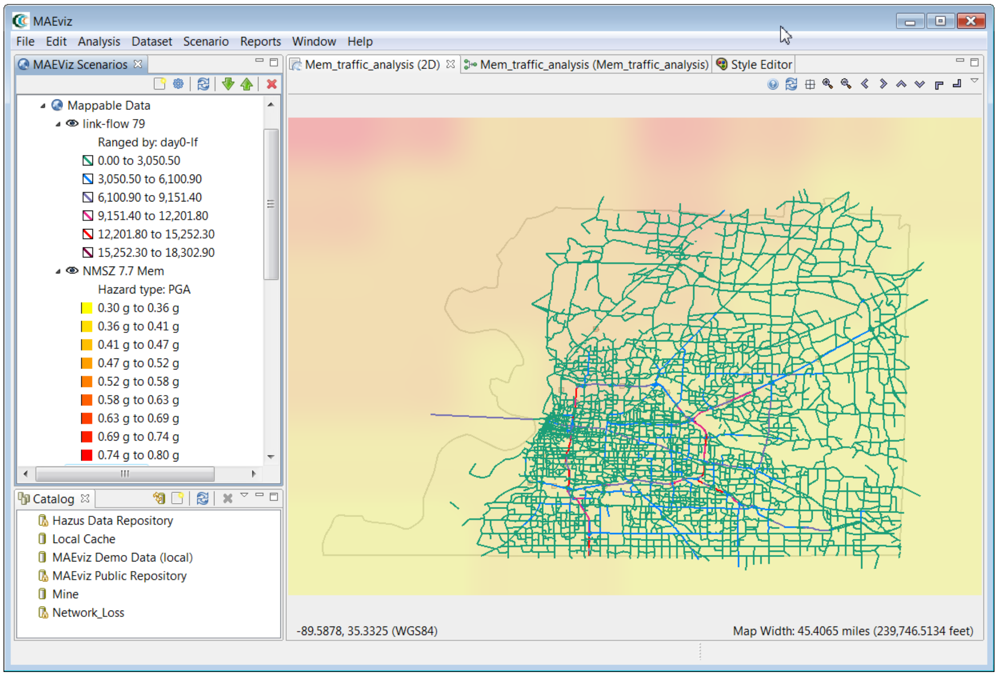


**Figure 24: MAEViz Traffic Modeling - User Interface**

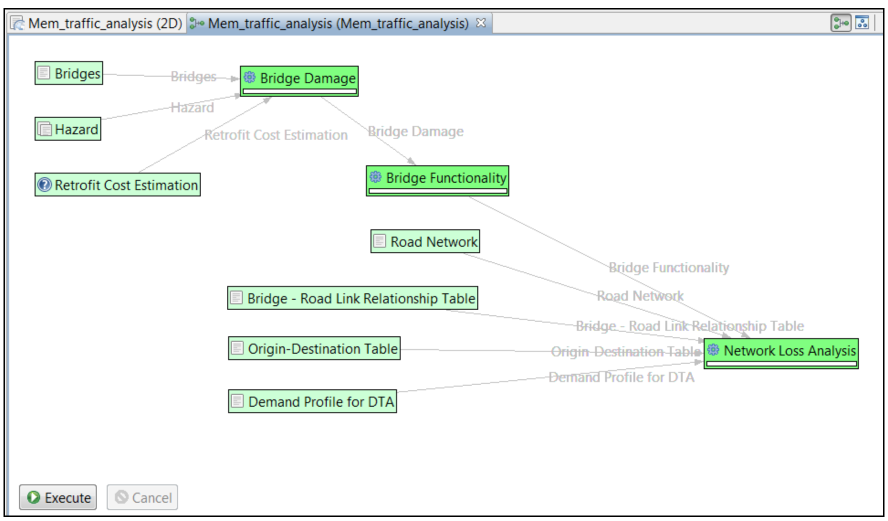


**Figure 25: MAEViz Traffic Modeling - Network Loss Analysis Module**

Figure 27 gives the post-earthquake level of service of the road segments in Memphis, Tennessee. Note that most major arterials in the Memphis area are predicted to experience minimal congestion. Only segments of I-240 and I-40 in the City of Memphis experience high density traffic and severe congestion. Several major and minor arterials in the City of Memphis and Shelby County are expected to have significantly increased travel times after the earthquake.

It is noted that the changes in travel delays in the St. Louis area are more severe than those in the Memphis area, though St. Louis is farther from the NMSZ ruptures and has a smaller percentage of significantly damaged bridges. One possible explanation for this is that the Memphis MPO includes the City of Memphis, the entirety Shelby County and other parts of adjacent counties only and is a much smaller region than the St. Louis MPO that contains of the City of St. Louis and entirety seven neighboring counties. The total travel demand in the Memphis area is much smaller and can only be used to reflect the local traffic within the MPO boundary. Unlike Memphis, the St. Louis MPO area is a much larger region with significantly higher travel demand. The travel demand data can be used to provide the travel pattern changes at a broader scale. The other possible reason is the static assumptions of travel behavior and demand are unrealistic. Dynamic traffic assignment (DTA) models which can provide much more realistic traffic simulation results will be utilized to address the issue in a future MAE Center study.

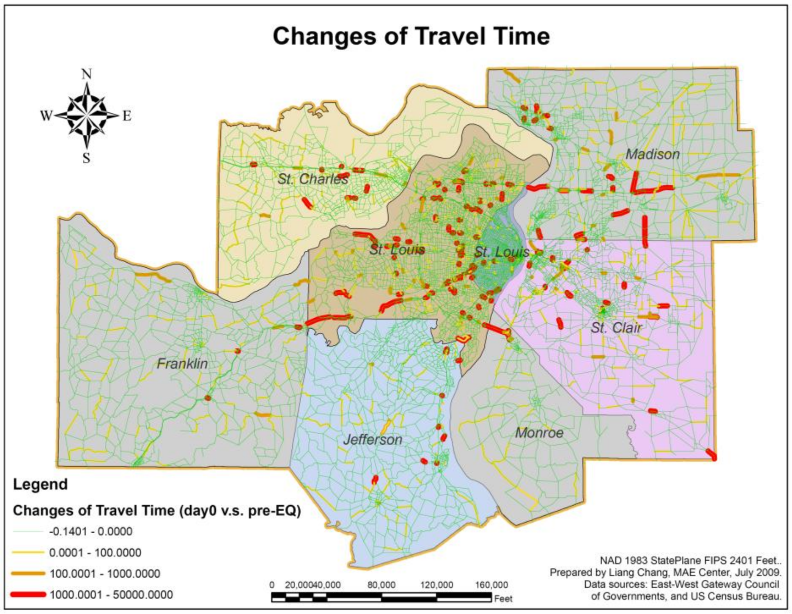


**Figure 26: Post-Earthquake Changes of Travel Delay (Day 0) (St. Louis MPO)**

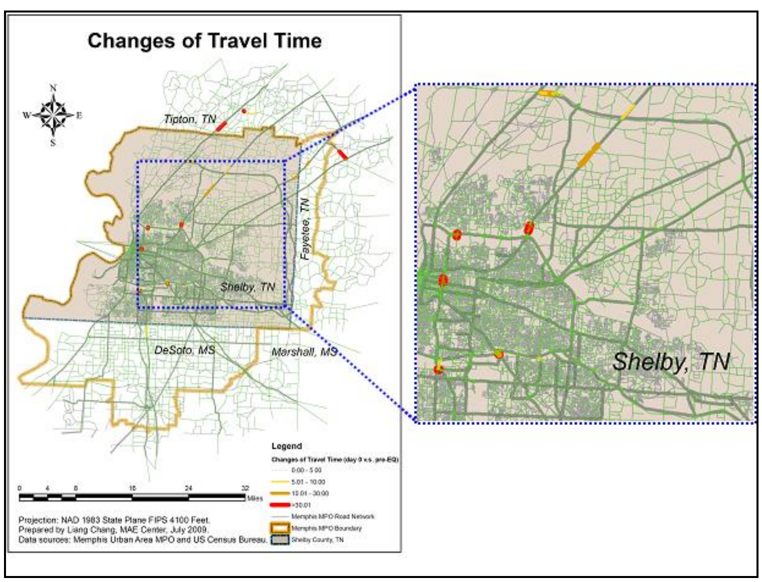


**Figure 27: Post-Earthquake Change of Travel Delay (Day 0) (Memphis MPO)**

## Utility Network Model

*Analysis of St. Louis, Missouri*

The St. Louis utility network inventory contains the natural gas pipelines and the electric power transmission network in the City of St. Louis, St. Louis, St. Charles, and Jefferson Counties; and the water network for the City of St. Louis. Natural gas pipelines consist of approximately 250,000 segments and total 8,622 miles in length. The water pipelines are 1,485 miles in total length and consist of 56,102 segments. There are two water treatment plants, two water reservoirs, six power plants, and 43 substations serving these St. Louis networks. The expected damage caused by the New Madrid Seismic Zone scenario totals approximately 480 repairs on both networks, with about 175 repairs caused by leaks, and 305 by pipe breaks (Table 96).

**Table 96: St. Louis, Missouri Pipeline Damage**

| St. Louis Inventory | Total pipe length (miles) | Ground Shaking Induced Pipeline Repairs | Liquefaction Induced Pipeline Repairs | Total Leaks | Total Breaks |
|---|---|---|---|---|---|
| New Madrid Seismic Zone Scenario (Mw=7.7) | | | | | |
| **Water Pipelines** | 1,485 | 27 | 138 | 49 | 116 |
| **Natural Gas Pipelines** | 8,622 | 102 | 211 | 124 | 189 |

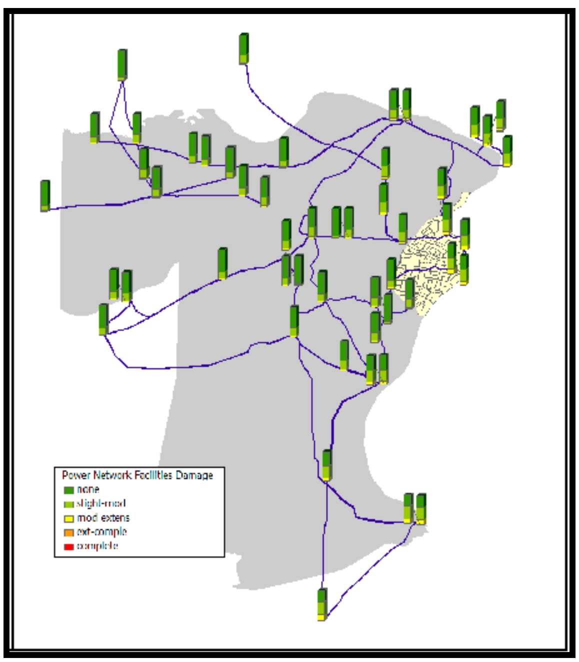


**Figure 28: St. Louis Power Network Damage for NMSZ Event**

Expected damage due to the New Madrid Seismic Zone earthquake scenario is relatively low for the water facilities. All water facilities are expected to experience approximately 10% probability of at least moderate damage in St. Louis. Power facilities of St. Louis are expected to experience relatively lower damage in the New Madrid Seismic Zone earthquake scenario. Damage due to New Madrid Seismic Zone scenario is higher in facilities in St. Louis City or south, along Mississippi River (Figure 28). Due to the New Madrid Seismic Zone earthquake, connectivity loss ($C_L$) in the electric power network is expected to be 2.5% and service flow reduction ($S_{FR}$) in the network is expected to be less than 1% for St. Louis power networks. The connectivity loss $C_L$ for the water network is expected to be 7.7%; the surface flow reduction $S_{FR}$ is expected to be 39.2%.

*Analysis of Memphis, Tennessee*

The analysis inventory consists of the entire electric power, natural gas, and water systems in Shelby County, Tennessee, where Memphis is located. The electric power network in Shelby County has 28 substations providing electric power. The natural gas network contains 3 gate stations, 120 pressure regulator stations, and 6,773 miles of main and service pipelines. Shelby County also has 192 water wells, 17 water tanks, 39 water pumps, and 27 booster stations in the potable water network. The water pipelines have a total length of 4,350 miles with 202,294 pipe segments.

As a result of the scenario earthquake, 13,500 repairs are required in the water pipeline system, and a total of 9,000 repairs to natural gas pipelines (Table 97). A total of 17,500 repairs in the water and natural gas systems are expected due to liquefaction effects, whereas approximately 5,000 repairs are expected as the result of pipe leaks.

**Table 97: Memphis, TN Pipeline Damage**

| Memphis Inventory | Total pipe length (miles) | Ground Shaking Induced Pipeline Repairs | Liquefaction Induced Pipeline Repairs | Total Leaks | Total Breaks |
|---|---|---|---|---|---|
| **New Madrid Seismic Zone Scenario (Mw=7.7)** | | | | | |
| **Water Pipelines** | 4350 | 452 | 13097 | 2981 | 10568 |
| **Natural Gas Pipelines** | 6773 | 435 | 8606 | 2069 | 6972 |

Network facilities are expected to experience significant damage from the New Madrid Seismic Zone earthquake as well. All facilities in the power, natural gas, and water network are expected to have at least 50% probability of moderate or more severe damage (Figure 29). Due to New Madrid scenario earthquake, Shelby County utility networks are expected to suffer extensive damage and disruptions. Reduction in the natural gas network performance is quantified with $C_L$ of 9.2% and $S_{FR}$ of 75.8%. $C_L$ for the water network is expected to be 99%; $S_{FR}$ to be 96%.

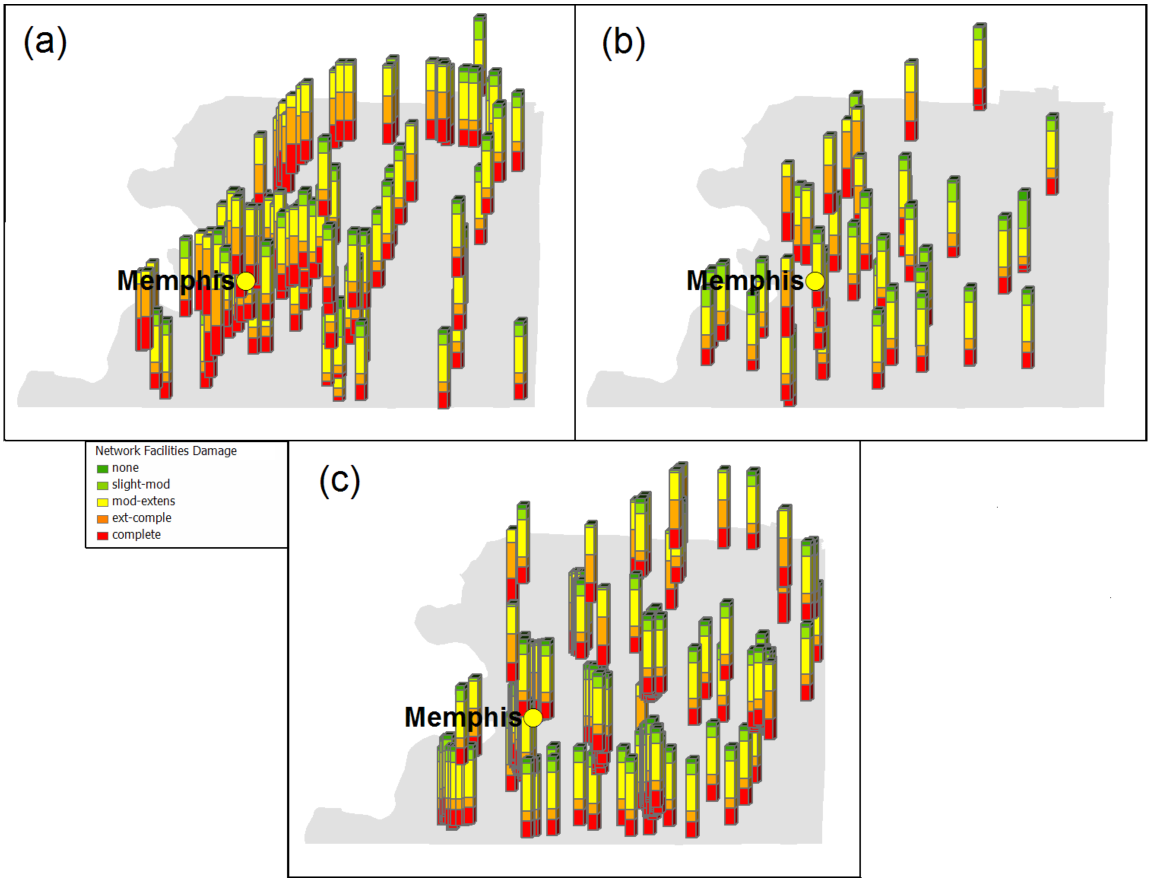


**Figure 29: Structural Damage Estimates for Shelby County**
**(a) Natural Gas, (b) Electric Power, (c) Potable Water Network Facilities**

## Uncertainty Analysis

### Uncertainty Characterization Approach 1

As a brief summary of the uncertainty analysis results, the total losses in the eight-state study region (i.e. the eight states combined) are given in Table 98 thru Table 100. "SI" and "No SI" respectively indicate the cases in which the uncertainty in the seismic intensity is considered and those in which it is not considered. "L/B" and "U/B" denote the lower and upper bounds of the confidence intervals, respectively. It is observed that some of the deterministic loss estimation results by HAZUS do not match with the average values calculated based on the methodology in the HAZUS Technical Manual. In this preliminary study, the quantified uncertainties in the number of damaged buildings (Table 98) are relatively small, compared with the other types of losses because this is not affected by the variations in damage measures. Table 99 and Table 100 show that the uncertainties from the variations of damage measures are dominant in this study.

Decision makers, intuitively or from experience, understand that any loss estimate is subjected to uncertainties and thus entails the risk of under- or over-estimation. Therefore, it is important for regional loss assessment software to provide the quantified uncertainty for risk-informed decision making. However, there have been not many research efforts to quantify the uncertainties in the regional loss estimation in a systematic manner, especially with the consideration of the implementation to loss assessment software such as HAZUS. The attempt in this study demonstrates that it is possible to quantify the uncertainties efficiently without repeated runs of HAZUS. More research efforts are needed for quantifying actual level of the uncertainties and for software implementations.

**Table 98: Number of Damaged Buildings**

| Damage State | No SI | | | *SI* | | |
|---|---|---|---|---|---|---|
| | Mean | L/B | U/B | Mean | L/B | **U** |
| None | 14,315,674 | 14,312,228 | 14,319,121 | 14,452,735 | 14,449,167 | **14,456,303** |
| Slight | 757,057 | 753,634 | 760,494 | 509,585 | 506,479 | **512,707** |
| Moderate | 314,080 | 311,954 | 316,220 | 439,955 | 437,299 | **442,625** |
| Extensive | 93,060 | 91,915 | 94,220 | 199,321 | 197,550 | **201,107** |
| Complete | 298,080 | 296,027 | 300,146 | 176,357 | 174,943 | **177,784** |
| **Total** | **15,777,951** | **15,765,758** | **15,790,202** | **15,777,952** | **15,765,439** | **15,790,527** |

**Table 99: Capital Stock Loss (in Thousands of Dollars)**

| Type | No SI | | | SI | | |
|---|---|---|---|---|---|---|
| | Mean | L/B | U/B | Mean | L/B | U/B |
| Structural | 16,358,686 | 13,798,067 | 19,348,000 | 13,830,992 | 12,093,246 | 15,764,180 |
| Non-Str. | 60,044,367 | 51,909,584 | 69,283,276 | 40,377,776 | 35,820,385 | 45,364,800 |
| Contents | 29,669,858 | 26,522,801 | 33,119,070 | 18,024,815 | 16,332,882 | 19,834,995 |
| Inventory | 905,229 | 753,495 | 1,085,617 | 480,642 | 397,525 | 576,213 |
| **Total** | **106,978,140** | **92,983,947** | **122,835,962** | **72,714,225** | **64,644,038** | **81,540,189** |

**Table 100: Number of Displaced Households**

| | No SI | | | SI | | |
|---|---|---|---|---|---|---|
| | Mean | L/B | U/B | Mean | L/B | U/B |
| Displaced HH | 250,312 | 170,643 | 355,279 | 128,476 | 78,184 | 199,837 |

**Uncertainty Characterization Approach 2**

The eight states in the Central US include more than fifteen structure types. However, a demonstration of the proposed framework considers three structural types of buildings only, i.e. wood for light frame (W1), unreinforced masonry bearing walls for low-rise buildings (URML), and mobile homes (MH), because they occupy more than 96 percents in the number of buildings. Also, it includes three occupancy classes of buildings, i.e. single-family dwelling (RES1), mobile home (RES2), and multi-family dwelling (RES3). Uncertainty propagation analysis was conducted for impacted counties in the eight states. Since only a select number of building types and occupancy types are included in this investigation impact estimates attributed to the HAZUS model are less than the estimates shown in earlier state and regional results sections since all building and occupancy types are included in those estimates.

**Table 101: Structural Damage of Buildings for the Eight States**

| State | Statistic | Damage State | | | | | Moderate to Complete Damage | Total No. Damaged Buildings |
|---|---|---|---|---|---|---|---|---|
| | | None | Slight | Moderate | Extensive | Complete | | |
| Alabama | Mean | 461,441 | 20,798 | 6,653 | 1,195 | 165 | 8,014 | 28,812 |
| | St. Dev. | 6,768 | 240 | 68 | 13 | 1 | 69 | 249 |
| | HAZUS* | 484,462 | 4,222 | 1,327 | 82 | 3,464 | 4,875 | 9,097 |
| Arkansas | Mean | 77,043 | 40,695 | 43,937 | 28,736 | 71,370 | 144,044 | 184,739 |
| | St. Dev. | 816 | 376 | 398 | 260 | 713 | 857 | 936 |
| | HAZUS* | 87,896 | 59,529 | 41,110 | 16,663 | 57,885 | 115,657 | 175,187 |
| Illinois | Mean | 259,680 | 58,969 | 45,883 | 22,668 | 21,188 | 89,739 | 148,708 |
| | St. Dev. | 4,095 | 643 | 410 | 187 | 180 | 485 | 805 |
| | HAZUS* | 323,594 | 50,253 | 15,615 | 4,817 | 18,880 | 39,303 | 89,561 |
| Indiana | Mean | 155,454 | 24,199 | 14,130 | 4,526 | 2,262 | 20,918 | 45,117 |
| | St. Dev. | 1,966 | 475 | 261 | 78 | 47 | 277 | 550 |
| | HAZUS* | 168,902 | 25,254 | 3,768 | 484 | 2,770 | 7,025 | 32,277 |
| Kentucky | Mean | 72,624 | 38,481 | 37,735 | 23,357 | 26,241 | 87,334 | 125,815 |
| | St. Dev. | 1,095 | 438 | 394 | 254 | 348 | 584 | 729 |
| | HAZUS* | 103,857 | 36,798 | 25,532 | 9,809 | 23,018 | 58,359 | 95,159 |
| Mississippi | Mean | 110,836 | 38,075 | 28,793 | 13,658 | 9,385 | 51,835 | 89,910 |
| | St. Dev. | 1,168 | 474 | 409 | 213 | 184 | 497 | 686 |
| | HAZUS* | 116,496 | 42,819 | 19,404 | 5,951 | 16,572 | 41,927 | 84,747 |
| Missouri | Mean | 618,117 | 57,881 | 43,068 | 22,921 | 42,164 | 108,153 | 166,034 |
| | St. Dev. | 13,356 | 612 | 373 | 199 | 433 | 605 | 861 |
| | HAZUS* | 640,381 | 69,176 | 30,259 | 7,624 | 39,044 | 76,930 | 146,110 |
| Tennessee | Mean | 106,942 | 101,151 | 119,465 | 78,082 | 100,247 | 297,794 | 398,945 |
| | St. Dev. | 2,488 | 2,600 | 2,964 | 1,784 | 2,088 | 4,041 | 4,805 |
| | HAZUS* | 79,351 | 191,196 | 103,227 | 32,191 | 101,343 | 236,766 | 427,959 |

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

**Table 102: Percentage of Building Damage for the Eight States**

| State | Mean | | HAZUS | |
|---|---|---|---|---|
| | Moderate to Complete | Damaged Building | Moderate to Complete | Damaged Building |
| Alabama | 1.6 | 5.9 | 1.0 | 1.8 |
| Arkansas | 55.0 | 70.6 | 44.0 | 66.6 |
| Illinois | 22.0 | 36.4 | 9.5 | 21.7 |
| Indiana | 10.4 | 22.5 | 3.5 | 16.0 |
| Kentucky | 44.0 | 63.4 | 29.3 | 47.8 |
| Mississippi | 25.8 | 44.8 | 20.8 | 42.1 |
| Missouri | 13.8 | 21.2 | 9.8 | 18.6 |
| Tennessee | 58.9 | 78.9 | 46.7 | 84.4 |

Table 101 and Table 102 summarize numbers of structurally damaged buildings and their ratios to total number of buildings for the eight states, respectively[54]. Table 103 shows the lower and upper bounds of the 90% confidence interval for direct economic loss due to structural damage. It can be seen that the proposed framework gives consistent and reasonable estimates comparing with the HAZUS results. For high-hazard states, such as

[54] Note that the 'HAZUS*'damage figures included in Table 101 through Table 102 represent damage and economic loss to building types W1, URML, and MH and occupancy types RES1, RES2, and RES3 only. The numbers in these tables are less than those presented previously in the state and eight-state region results sections. Previous sections include damage quantities for all HAZUS building and occupancy types.

Arkansas, Missouri, and Tennessee, the difference between the probabilistic estimates and the HAZUS results are not significant. This means that both approaches can give fairly reasonable estimates in a high-seismicity area.

**Table 103: Direct Economic Losses Due to Structural Damage of Buildings for the Eight States**
($ millions)

| State | Lower Bound | Upper Bound | HAZUS* |
|---|---|---|---|
| Alabama | 37.62 | 61.31 | 123.72 |
| Arkansas | 3,096.86 | 6,239.14 | 2,359.75 |
| Illinois | 1,053.12 | 1,957.62 | 868.47 |
| Indiana | 191.99 | 259.85 | 158.86 |
| Kentucky | 1,199.00 | 2,001.76 | 1,501.98 |
| Mississippi | 526.83 | 1,281.85 | 878.10 |
| Missouri | 1,699.67 | 3,488.51 | 1,801.92 |
| Tennessee | 4,766.44 | 7,170.25 | 7,251.58 |

* HAZUS results represent direct loss for all buildings.

## Social Impacts and Requirements Analysis

This section summarizes the findings of the study as it relates to potential social vulnerabilities of the NMSZ along with estimated impacts of the earthquake scenario on security, water, energy, accessibility, and telephone (SWEAT) in the region. Because social vulnerability and SWEAT analysis provide insight into the scope of the necessary disaster response, those metrics are used in the Response Requirements section to estimate the resource requirements and needs for the proper execution of a timely, organized, and efficient emergency operation.

### Social Vulnerability Analysis

The social vulnerability analysis focuses on the interpretation of four metrics that contribute to the overall social vulnerability. These four metrics are disability, age (i.e. people younger than 5 years and older than 65 years), poverty, and English proficiency. These criteria are important because they provide emergency planners information related to the geographical distributions of potential vulnerability hotspots, which could be mitigated with proper pre-positioning of equipment and resources.

*Disability*

Disability is an important indicator of social vulnerabilities. Disabled individuals are often at a disadvantage during emergencies and disasters, especially when the individuals are limited in their mobility, have special needs, or require ongoing care. The needs and expectations of the disabled population must be taken into consideration during disaster response planning and requirements analysis.

The natural breaks (Jenks) method is used to develop the eight-state vulnerability map in Figure 30. Planning areas with 13.9%-20.5% of the population having a disability are considered to have a low disability rate. Similarly, areas with a 20.6%-24.9% of the population having a disability are considered to have a medium disability rate, and areas with 25%-35% are considered to have a high disability rate. As shown in Figure 30, this region has a scattered distribution of disabled people. Disability is less of a problem in the northern portion of the region than it is in the southern areas. It is evident that most parts of northern Missouri, Illinois, and Indiana have a relatively low disability level, whereas Arkansas, Kentucky, Tennessee, southeast Missouri, and Alabama have a relatively medium to high percentage of disabled people.

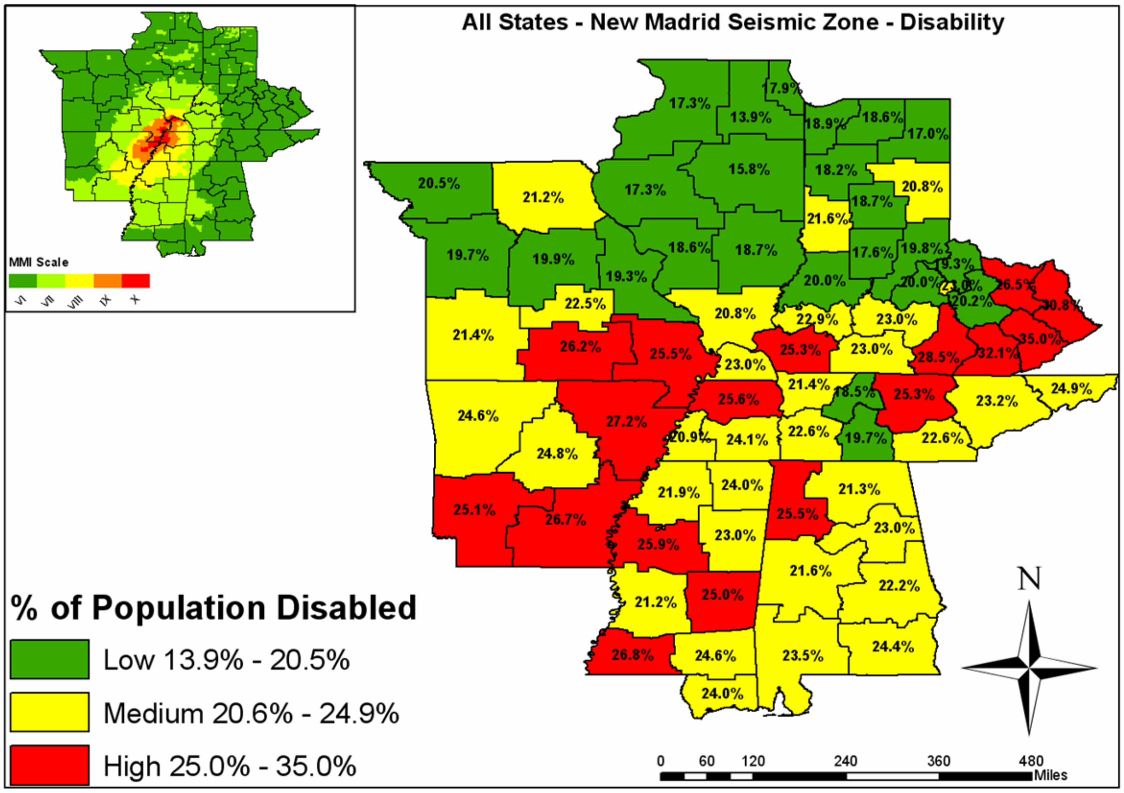


**Figure 30: Distribution of Disabled Population in NMSZ Planning Areas**

The natural breaks method is also used to examine the impacted counties. In these counties with 12.5%-20.2% of the population having a disability are considered to have a low disability rate. Similarly, areas with a 20.3%-25.6% of the population having a disability are considered to have a medium disability rate, and areas with 25.7%-32.7% are considered to have a high disability rate. Within the impacted counties, the southern Missouri counties of Iron, Madison, Carter, Reynolds, Oregon, Ripley, Butler, Wayne, Dunklin, and Pemiscot, and almost all Arkansas counties have relatively high disability levels. In the State of Mississippi, Coahoma, Tunica, Quitman, Tallahatchie, Panola, Yalobusha, Benton, Tippah, Alcorn, and Tishomingo Counties have a relatively high disability rate. In Tennessee, the counties of Dyer, Luke, Lauderdale, Crockett, Haywood, McNairy, Hardin, and Benton have relatively high disability levels. In Kentucky, Hickman, Lyon, Trigg, Webster, and Muhlenberg Counties have relatively high levels of disability (See Figure 31).

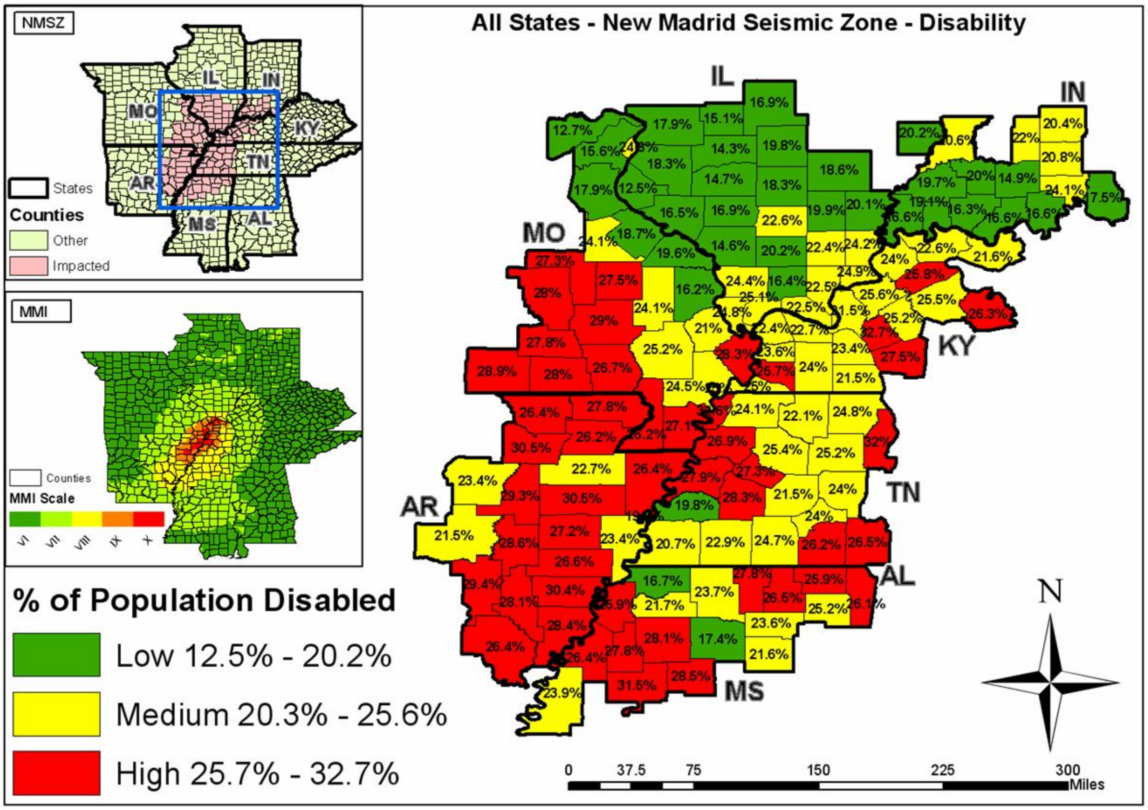


**Figure 31: Distribution of Disability in NMSZ Impacted Counties**

*Vulnerable Age Groups*

Vulnerable age groups include individuals younger than 5 years and older than 65 years. Children less than 5 years old are considered to be a vulnerable portion of the population because they are largely dependent on their parents, or other adults, to satisfy their immediate needs for food, shelter, security, and other care. The elderly are considered vulnerable because they carry a higher risk of diminished physical strength, mobility limitations, age-related diseases, and special prescription medication needs. Therefore, in locations with a significant presence of vulnerable people due to age, requirements and needs assessments must include the special needs associated with these groups.

The natural breaks (Jenks) method is used to develop the eight-state vulnerability map in Figure 32. Planning areas with 17.01%-19.22% of the population within the vulnerable age groups, are considered to have a low percentage of age vulnerability. Similarly, areas with a 19.23%-21.07% vulnerable age population are considered to have a medium vulnerability, and areas with 21.08%-23.83% vulnerable age population are considered to have a high vulnerable age population rate (See Figure 32).

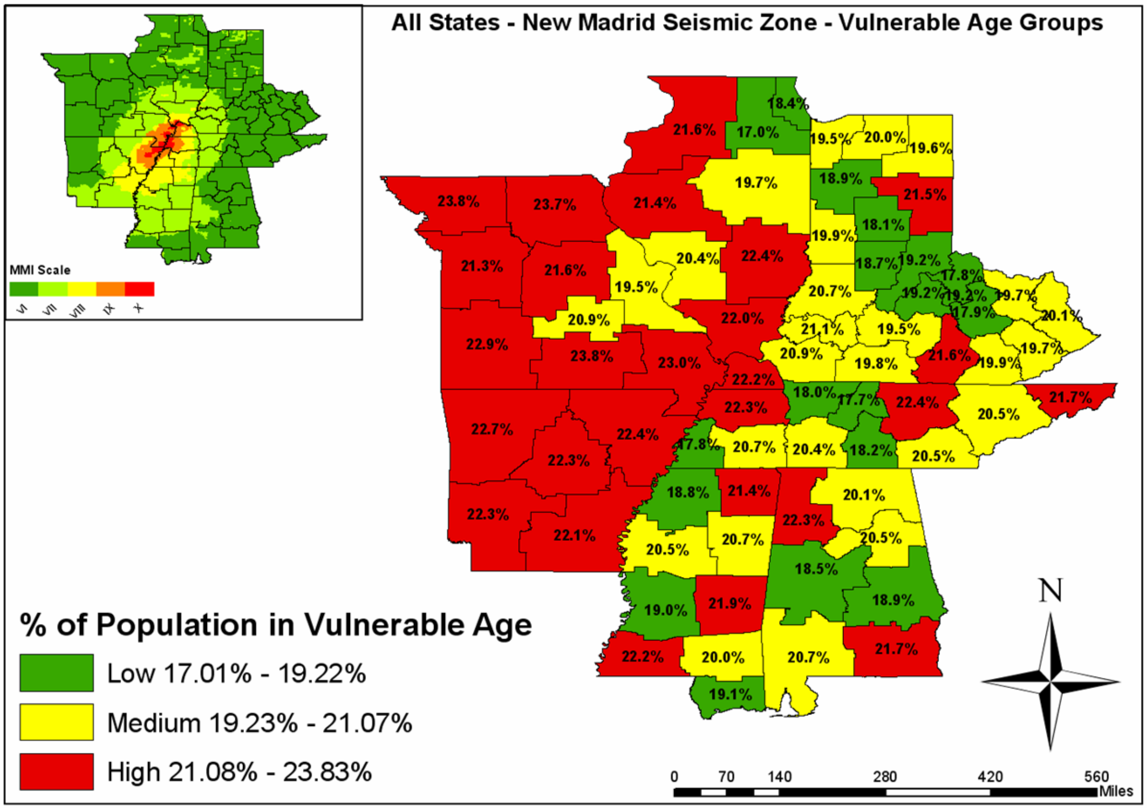

**Figure 32: Distribution of Vulnerable Age Groups in NMSZ Planning Areas**

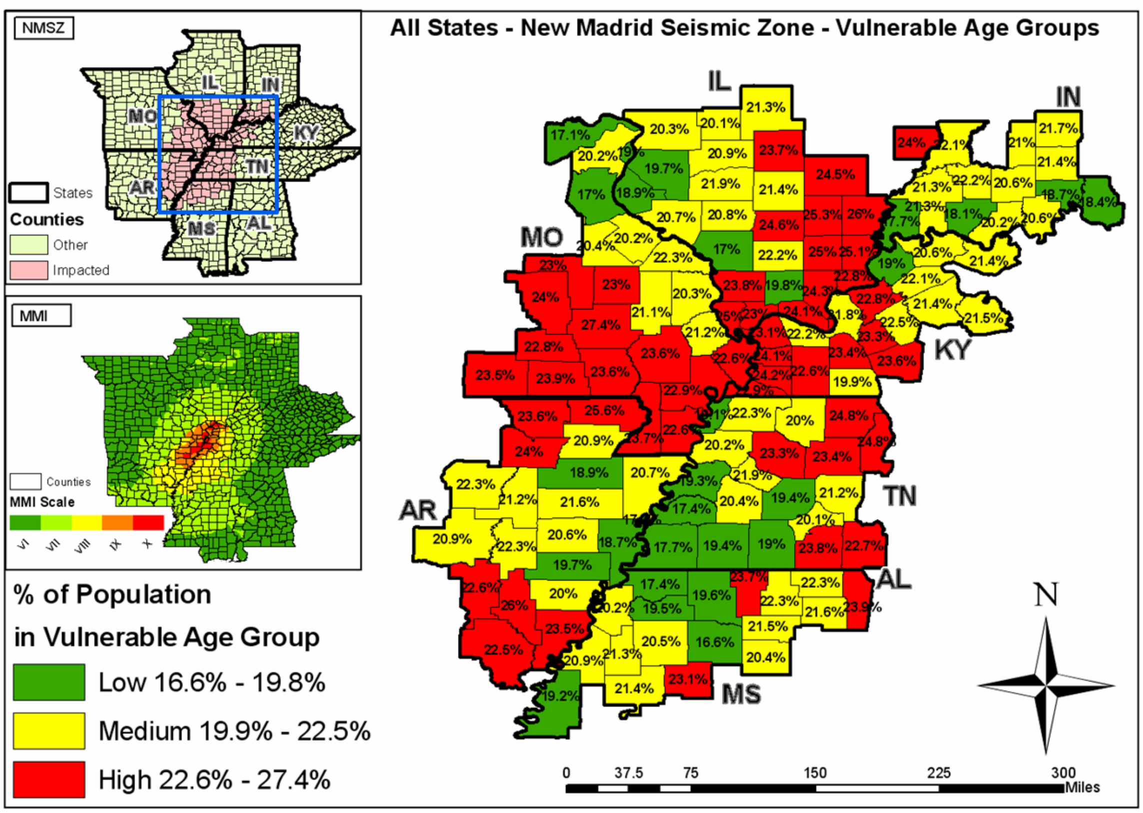

**Figure 33: Distribution of Vulnerable Age Groups in NMSZ Impacted Counties**

Again, the natural breaks (Jenks) method is employed to examine the impacted counties specifically. Counties with 16.6%-19.8% of the population within the vulnerable age ranges are considered to have a low percentage of age vulnerability. Similarly, impacted counties with a 19.9%-22.5% vulnerable age population are considered to have medium age vulnerability, and counties with 22.6%-27.4% vulnerable age population are considered to have high age vulnerability. An interesting overlap between highly vulnerable counties and those counties impacted by the earthquake scenario is shown. Figure 33 suggests that it is useful to determine a common strategy to deal with the special needs of the age vulnerable population in many adjacent counties near the intersection of Missouri, Illinois, and Kentucky. This strategy must also take into account the highly vulnerable counties of Prairie, Monroe, Phillips, and Arkansas in southern Arkansas, the impacted counties of Henry, Benton, Carroll, Gibson, McNairy and Hardin in Tennessee, and Yalobusha, Benton, and Tishomingo in Mississippi (See Figure 33).

*Poverty*

Poverty is an important indicator of social vulnerability. Research has shown that it is more difficult for economically disadvantaged communities to cope with the impacts of disasters when compared to communities with more stable economic conditions. This is partially explained by the strong correlation between poverty and the lack of resources for preparedness and recovery, as well as access to education, information, and awareness.

The natural breaks (Jenks) method is employed to construct the eight-state vulnerability map in Figure 34. Planning areas where 7%-14.5% of the population is living below poverty level are considered to have a low poverty rate. Areas with a 14.6%-20.8% poverty rate are classified as medium, and areas with 20.9%-33.5% poverty rate are high in terms of percent of population in poverty. Geographical distribution of poverty within the NMSZ is comprised of three distinct clusters. Nearly all of Indiana, Illinois, and Missouri (except the southern portion) have low poverty rates. Central and western Arkansas, Alabama, most of Tennessee, and the western part of Kentucky have medium levels of poverty. Conversely, southeastern Missouri, eastern Arkansas, nearly all of Mississippi, southwestern Tennessee and eastern Kentucky have high poverty rates (See Figure 34).

The natural breaks (Jenks) method is employed to examine the impacted counties here as well. Counties where 4.4%-14% of the population is living below poverty level are considered to have a low poverty rate. Impacted counties with a 14.1%-22.5% poverty rate are considered medium, and impacted counties with 22.6%-39.5% poverty rate are considered high in terms of percent of population in poverty. One interesting observation among impacted counties is that a significant number of relatively high poverty counties are located in areas where infrastructure damage and social impacts are severe. These counties include Jackson, Alexander and Pulaski Counties in Illinois; Mississippi, New Madrid, Pemiscot, and Dunklin Counties in Missouri: Mississippi, Poinsett, Jackson, Woodruff, Monroe, Phillips, Lee, St. Francis, and Crittenden Counties in Arkansas; Bolivar, Coahoma, Tunica, Quitman, Panola, Tallahatchie, and Yalobusha Counties in

Mississippi; Lauderdale, Haywood, Hardeman Counties in Tennessee; and Fulton County in Kentucky. There is also a separate cluster of impacted counties with relatively high poverty in Missouri, which includes Iron, Reynolds, Wayne, Carter, Ripley, and Oregon Counties (See Figure 35).

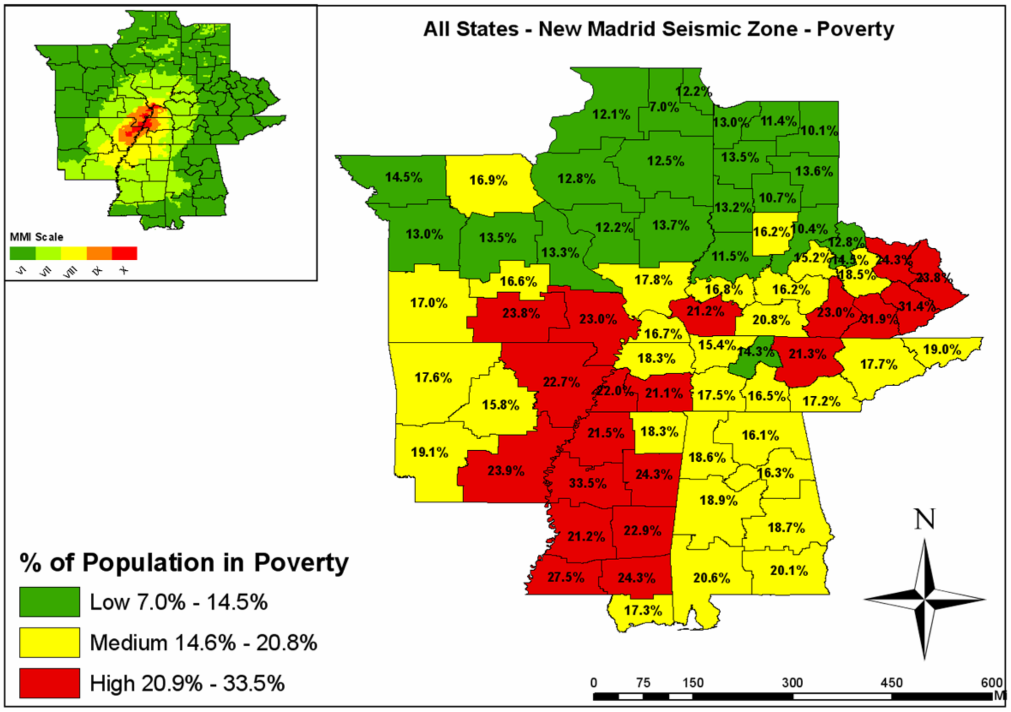


**Figure 34: Distribution of Poverty in NMSZ Planning Areas**

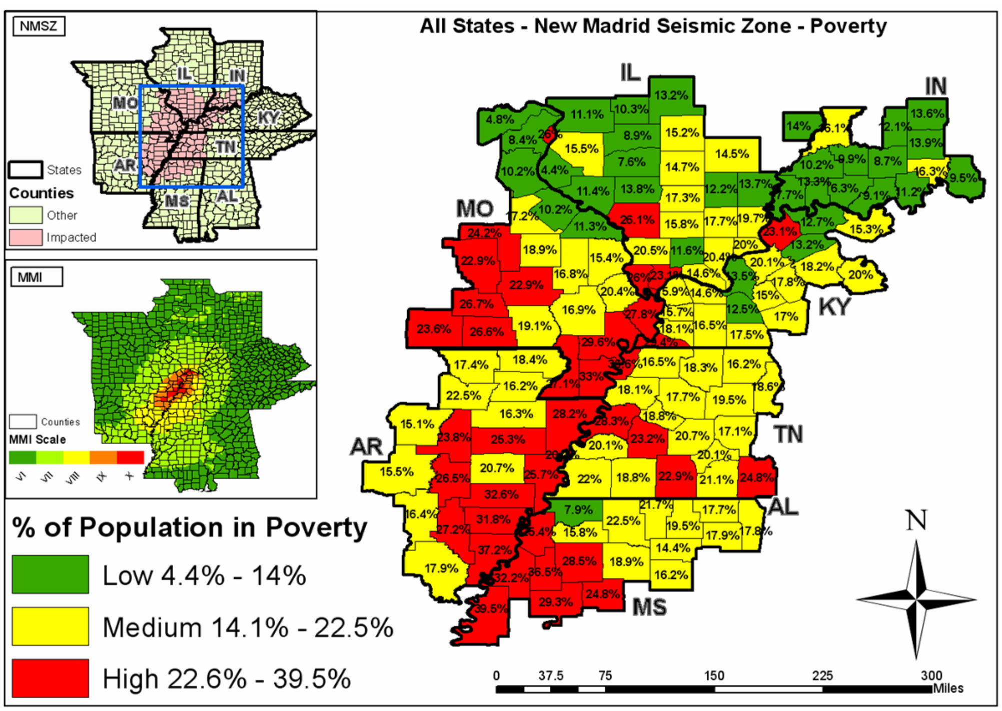


**Figure 35: Distribution of Poverty in NMSZ Impacted Counties**

*English Proficiency*

The last social vulnerability metric covered in this study is English Proficiency. Lack of proficiency in English is an indicator of potential social vulnerability, as lack of proficiency with the local language tends to cause difficulties in communicating with others and socialization issues, which lead to isolation from the community and its support networks. From an emergency response planning perspective, in areas where lack of proficiency in English is common, communication with those communities before, during, and after emergencies can be difficult. It is important that communications in such areas take into account the language barrier as well as the underlying cultural barriers. Close cooperation with the representatives of these communities during early stages of planning is critical to understanding needs, and to developing strategies that reduce this vulnerability.

The natural breaks (Jenks) method is used to define relative English proficiency levels in the eight-state region. Areas where 0.3%-1.1% of the population is not proficient in English are considered to have a low English Non-Proficiency rate. Areas with a 1.2%-3.7% English Non-Proficiency rate are considered medium, and areas with 3.8%-7.1% English Non-Proficiency rate are considered high in terms of percent of population that are not proficient in English. Most areas in the NMSZ area have a relatively low English Non-proficiency rate. The only exception is the Chicago Metropolitan Area in Illinois, which is not only the single highest English Non-Proficiency area in the region, but it has an English Non-Proficiency rate of 7.1% which is very high even on an absolute scale (See Figure 36). While the area surrounding Memphis, Tennessee, is only categorized as having a medium Non-Proficiency rate, planners must still pay attention to this area due to its high population density as well as the high level of physical impacts from NMSZ earthquake.

English proficiency in the impacted counties is delineated with the natural breaks (Jenks) method as with all other social vulnerability factors. Counties where 0%-0.5% of the population is not proficient in English are considered to have a low English Non-Proficiency rate. Counties with a 0.6%-1.2% English Non-Proficiency rate are considered medium, and counties with 1.3%-3.1% English Non-Proficiency rate are considered high in terms of percent of population that are not proficient in English. Most impacted counties in the NMSZ have a relatively low English Non-proficiency rate. Impacted counties with relatively higher English Non-Proficiency rate are scattered around the area without an apparent cluster pattern. Those impacted counties are Jackson County in Illinois, Dubois County in Indiana, Webster and Graves Counties in Kentucky, Union County in Mississippi, and Shelby and Crockett (with the highest value of all counties, 3.1%) Counties in Tennessee (See Figure 37).

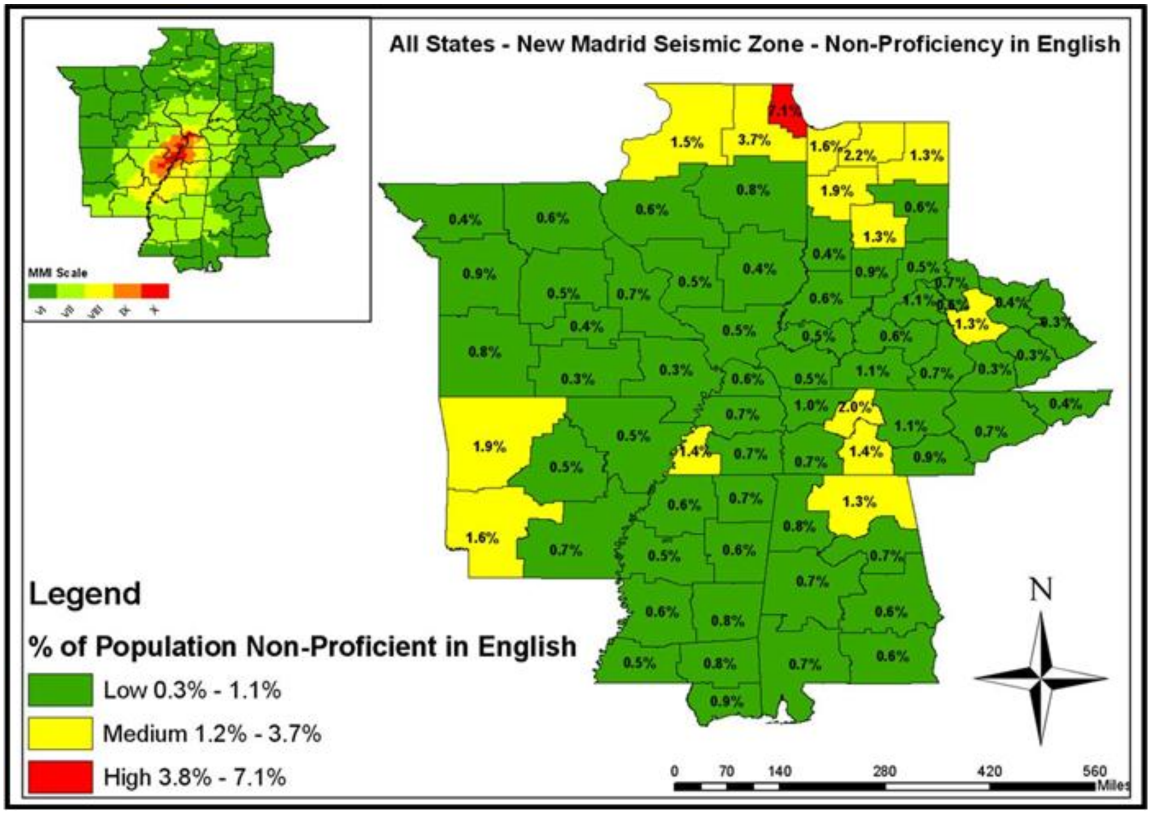


**Figure 36: Distribution of English Non-Proficiency in NMSZ Planning Areas**

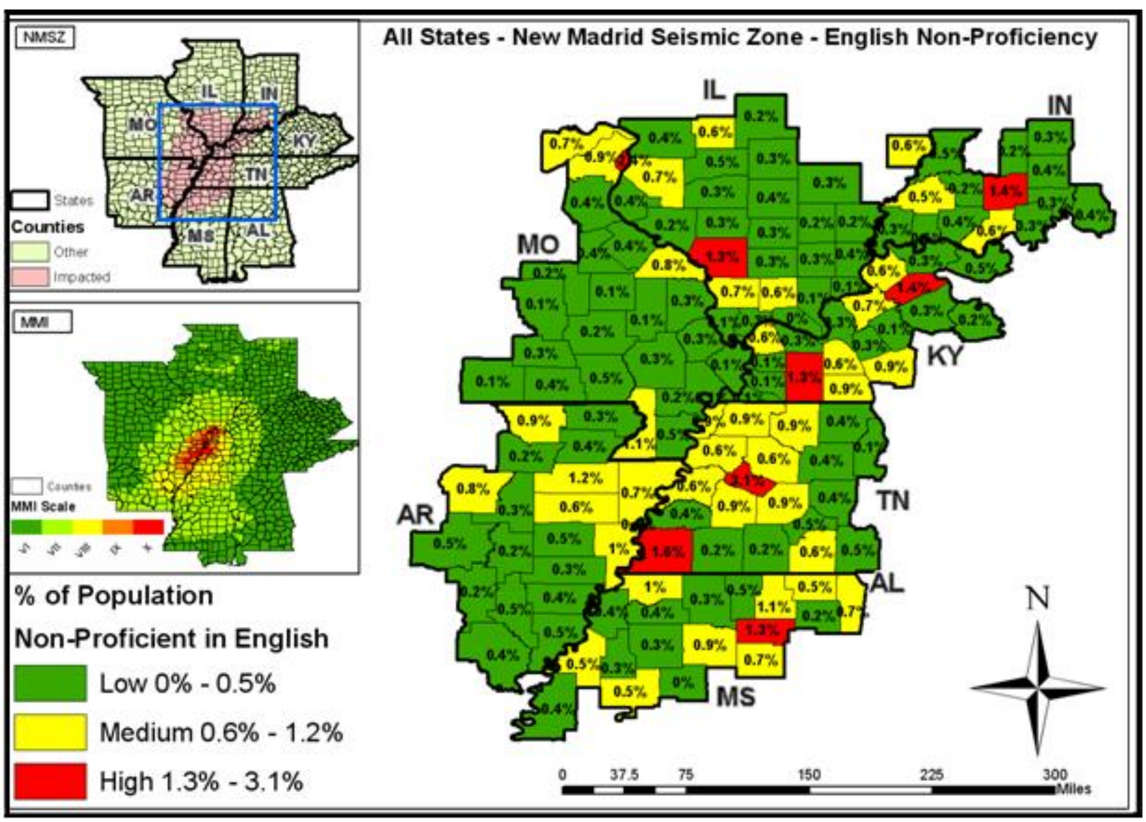


**Figure 37: Distribution of English Non-Proficiency in NMSZ Impacted Counties**

**SWEAT Analysis**

SWEAT is an abbreviation for: **S**ecurity, **W**ater, **E**nergy, **A**ccessibility, and **T**elecommunications. The aim of a SWEAT analysis is to estimate potential impacts of a hazardous event on the aforementioned services, commodities, and infrastructure. To further detail the analysis, security is analyzed in terms of damage to emergency operation centers (EOC) including 911 call centers, police facilities, fire facilities, and hospitals. Water is decomposed into impacts to potable water, and waste water facilities. Energy includes electricity and natural gas facilities. Accessibility includes major river crossings, highway bridges, and schools. Telephone includes the telecom infrastructure. The impact of the earthquake on the capacity of each of those resources has been estimated for each impacted county on a standardized scale. This color-coded scale uses the following three levels/colors to describe available capacity:

- Red: No Capacity/Capability (0%-39% of typical operating capacity)
- Yellow: Reduced Capacity/Capability (40%-79% of typical operating capacity)
- Green: Full capacity/Capability (80%-100% of typical operating capacity)

The SWEAT matrix for each state lists the impacted counties in a single column, each measured item in its own column, and each cell in the matrix is assigned a capacity/capability level based on the color-coded scale. The matrix can be interpreted twofold: (1) from the perspective of impact to counties and, (2) from the perspective of impact to each infrastructure/service type. A SWEAT diagram is provided for each of the NMSZ states with the exception of Alabama. None of the counties in Alabama qualified as highly impacted and all of the cells of the Alabama SWEAT diagram are green.

| Impacted Counties (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossing | Hwy Bridges | Schools | Telecom |
| Arkansas | G | Y | G | R | R | G | Y | G | G | G | G | G |
| Clay | R | R | R | R | R | R | R | R | G | G | R | R |
| Craighead | R | R | R | R | R | R | R | R | G | Y | R | R |
| Crittenden | R | R | R | R | R | R | R | R | R | R | R | R |
| Cross | R | R | R | R | R | R | R | G | G | Y | R | R |
| Greene | R | R | R | R | R | R | R | R | G | Y | R | R |
| Independence | G | G | G | G | G | R | R | G | G | G | G | Y |
| Jackson | R | R | R | R | R | R | R | R | G | G | R | R |
| Lawrence | R | R | Y | R | R | R | R | R | G | Y | Y | R |
| Lee | R | R | R | G | R | R | R | G | G | G | R | R |
| Mississippi | R | R | R | R | R | R | R | R | G | R | R | R |
| Monroe | R | R | R | G | R | G | Y | G | G | G | R | G |
| Phillips | R | R | R | R | G | Y | Y | G | G | G | R | G |
| Poinsett | R | R | R | G | R | R | R | G | G | Y | R | R |
| Prairie | R | R | R | G | R | G | Y | G | G | G | R | G |
| Randolph | R | R | Y | G | R | R | R | R | G | G | Y | R |
| Saint Francis | R | R | R | R | R | R | R | G | G | Y | R | R |
| White | G | G | G | G | Y | Y | Y | Y | G | G | G | Y |
| Woodruff | R | R | R | G | R | R | R | G | G | G | R | R |

**Figure 38: SWEAT Analysis for the Impacted Counties of Arkansas**

The Arkansas SWEAT analysis appears in Figure 38. The matrix illustrates that all Arkansas counties except White, Independence, and Arkansas County are significantly impacted by a lack of SWEAT resources and infrastructure. Crittenden County receives the highest impact, losing its entire capacity for services, resources, and infrastructure. From the perspective of resources and infrastructure, all SWEAT elements in Arkansas except major river crossings and highway bridges experience significant impacts from the earthquake. Most of those impacts occur in the form of full capacity loss, which generally takes longer to repair.

The Illinois SWEAT analysis is shown in Figure 39. It reveals that Alexander, Johnson, Pope, Pulaski, Union, and Williamson Counties receive more significant SWEAT impact than other counties. Similarly, the matrix reveals that waste water facilities, electricity infrastructure, natural gas facilities, and telecom infrastructure impacts are more severe when compared to the impacts experienced by other resources and services.

| Impacted Counties (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossing | Hwy Bridges | Schools | Telecom |
| Alexander | R | R | R | G | R | R | R | R | Y | Y | R | R |
| Bond | G | G | G | G | G | G | G | G | G | G | G | G |
| Clinton | G | G | G | G | G | G | Y | G | G | G | G | G |
| Fayette | G | G | G | G | Y | G | G | G | G | G | G | G |
| Franklin | G | G | G | G | G | Y | Y | Y | G | G | G | Y |
| Gallatin | G | G | G | G | G | R | Y | Y | G | G | G | R |
| Hamilton | G | G | G | G | G | G | Y | G | G | G | G | G |
| Hardin | G | G | G | G | G | R | G | R | G | G | G | R |
| Jackson | G | G | G | G | R | R | R | R | R | G | G | R |
| Jefferson | G | G | G | G | G | G | G | G | G | G | G | G |
| Johnson | R | R | R | G | G | R | R | R | G | G | R | R |
| Lawrence | G | G | G | G | G | G | G | G | G | G | G | G |
| Madison | G | G | G | G | G | G | G | G | G | G | G | G |
| Marion | G | G | G | G | G | G | Y | G | G | G | G | G |
| Massac | R | R | R | R | R | R | R | R | G | Y | R | R |
| Monroe | G | G | G | G | G | G | G | G | G | G | Y | G |
| Perry | G | G | G | G | R | G | Y | G | G | G | G | G |
| Pope | R | R | R | G | G | R | G | R | G | G | Y | R |
| Pulaski | R | R | R | G | R | R | R | R | G | Y | R | R |
| Randolph | G | G | G | Y | G | G | Y | G | G | G | G | G |
| Saint Clair | Y | G | G | G | Y | G | Y | G | G | G | G | G |
| Saline | G | G | G | G | G | R | R | R | G | G | G | R |
| Union | R | R | R | G | G | R | R | R | G | G | R | R |
| Washington | G | G | G | G | G | G | Y | G | G | G | G | G |
| Wayne | G | G | G | G | G | G | Y | G | G | G | G | G |
| White | G | G | G | G | G | G | Y | G | G | G | G | G |
| Williamson | R | G | Y | R | G | R | G | R | G | G | G | R |

**Figure 39: SWEAT Analysis for the Impacted Counties of Illinois**

The Indiana SWEAT analysis is illustrated in Figure 40. With the exception of the red capacity loss of EOC resources in Posey County, no other counties in Indiana are significantly impacted under the SWEAT assumptions.

| Impacted Counties (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossings | Hwy Bridges | Schools | Telecom |
| Crawford | G | G | G | G | G | G | G | G | G | G | G | G |
| Dubois | G | G | G | G | G | G | G | G | G | G | G | G |
| Harrison | G | G | G | G | G | G | G | G | G | G | G | G |
| Knox | G | G | G | G | G | G | G | G | G | G | G | G |
| Lawrence | G | G | G | G | G | G | G | G | G | G | G | G |
| Martin | G | G | G | G | G | G | G | G | G | G | G | G |
| Orange | G | G | G | G | G | G | G | G | G | G | G | G |
| Perry | G | G | G | G | G | G | G | G | G | G | G | G |
| Pike | G | G | G | G | G | G | G | G | G | G | G | G |
| Posey | R | Y | Y | Y | Y | G | Y | G | G | G | Y | G |
| Spencer | G | G | G | G | G | G | Y | G | G | G | G | G |
| Vanderburgh | G | G | G | G | G | G | Y | G | G | G | G | G |
| Warrick | G | G | G | G | G | G | Y | G | G | G | G | G |

**Figure 40: SWEAT Analysis for the Impacted Counties of Indiana**

The Kentucky SWEAT analysis appears in Figure 41. The matrix shows that Ballard, Calloway, Carlisle, Fulton, Graves, Hickman, Livingston, Marshall, and McCracken Counties incur significant SWEAT capacity losses in almost all services, resources, and infrastructure. Caldwell, Crittenden, Lyon, and Trigg Counties also receive significant impacts, but those impacts are limited to waste water facilities, electricity infrastructure, natural gas facilities, and telecom. From the perspective of services, resources, and infrastructure waste water facilities, electricity, natural gas facilities, and telecom infrastructure incur the most damage. EOC, police, fire, hospital, potable water facilities and schools also incur comparable damage, but in fewer counties.

| Impacted Counties (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossing | Hwy Bridges | Schools | Telecom |
| Ballard | R | R | R | G | R | R | R | R | R | R | R | R |
| Caldwell | G | G | G | G | G | R | R | R | G | G | G | R |
| Calloway | R | R | R | R | Y | R | R | R | G | G | R | R |
| Carlisle | R | R | R | G | R | R | R | R | G | G | R | R |
| Crittenden | G | G | G | G | G | R | R | R | G | G | G | R |
| Daviess | G | G | G | R | G | G | Y | G | G | G | G | G |
| Fulton | R | R | R | R | R | R | R | R | G | G | R | R |
| Graves | R | R | R | R | R | R | R | R | G | G | R | R |
| Henderson | G | G | G | G | G | G | Y | G | G | G | G | G |
| Hickman | R | R | R | G | R | R | R | R | G | G | R | R |
| Hopkins | G | G | G | G | G | G | R | G | G | G | G | G |
| Livingston | R | R | Y | G | G | R | R | R | G | G | R | R |
| Lyon | G | G | G | G | G | R | R | R | G | G | G | R |
| Marshall | R | R | Y | R | R | R | R | R | G | G | R | R |
| McCracken | R | R | R | R | R | R | R | G | R | Y | R | R |
| Muhlenberg | G | G | G | G | G | G | Y | G | G | G | G | G |
| Trigg | G | G | G | G | G | R | R | R | G | G | G | R |
| Union | G | G | G | G | G | Y | Y | R | G | G | G | Y |
| Webster | G | G | G | G | G | Y | R | G | G | G | G | G |

**Figure 41: SWEAT Analysis for the Impacted Counties of Kentucky**

The Mississippi SWEAT analysis is shown in Figure 42. Desoto and Tate Counties experience the most significant impact. These two counties lose all SWEAT capacity except for major river crossings and highway bridges. Benton, Coahoma, Lafayette, Marshall, Panola, and Tunica Counties also lose significant capacity, but in most instances, those capacity losses are limited to EOC, police, fire and hospital facilities, and to a lesser extent potable water, waste water, electricity infrastructure, and schools. While service, resource, and infrastructure capacity losses are not as widespread in Mississippi as in other states, the single most impacted resource is hospitals. EOC, police, fire, and school infrastructure damage also lead to reduced capacities. Waste water facilities, natural gas facilities, major river crossings, highway bridges and telecom experience minimal impact in many instances.

| Impacted Counties (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossing | Hwy Bridges | Schools | Telecom |
| Alcorn | R | R | Y | Y | G | G | Y | G | G | G | Y | G |
| Benton | R | R | R | R | G | G | R | G | G | G | R | G |
| Bolivar | G | G | G | R | Y | G | G | G | R | G | G | G |
| Coahoma | R | R | Y | R | R | G | Y | G | G | G | G | G |
| Desoto | R | R | R | R | R | R | R | R | G | G | R | R |
| Lafayette | R | R | R | R | G | G | Y | G | G | G | R | G |
| Marshall | R | R | R | R | G | Y | R | G | G | G | R | Y |
| Panola | R | R | R | R | Y | G | Y | G | G | G | R | G |
| Pontotoc | G | G | G | R | G | G | Y | G | G | G | G | G |
| Prentiss | G | Y | Y | R | G | G | Y | G | G | G | G | G |
| Quitman | R | Y | Y | R | R | G | Y | G | G | G | Y | G |
| Sunflower | G | G | G | Y | G | G | G | G | G | G | G | G |
| Tallahatchie | G | G | G | R | R | G | Y | G | G | G | G | G |
| Tate | R | R | R | R | R | R | R | R | G | G | R | R |
| Tippah | G | R | Y | R | G | G | R | G | G | G | R | G |
| Tishomingo | G | G | Y | G | G | G | Y | G | G | G | Y | G |
| Tunica | R | R | R | G | R | Y | Y | R | G | G | R | R |
| Union | G | G | G | R | G | G | Y | G | G | G | Y | G |
| Yalobusha | G | G | G | R | G | G | Y | G | G | G | G | G |

**Figure 42: SWEAT Analysis for the Impacted Counties of Mississippi**

The Missouri SWEAT analysis is illustrated in Figure 43. The matrix shows that Cape Girardeau, Dunklin, Mississippi, New Madrid, Pemiscot, Scott, and Stoddard Counties sustain the most significant impact. These counties experience total SWEAT capacity losses in almost all services, resources and infrastructure. Bollinger, Butler, Perry and Wayne Counties also incur some SWEAT impact, but in most cases those impacts are partial capacity losses in waste water, electricity, natural gas and telecom facilities. For Missouri, it is difficult to generalize a cluster of services, resources, and infrastructure that sustain specific impacts. While it is observed that electricity infrastructure is the most frequently damaged infrastructure in Missouri, damage is more scattered and dependent on the overall physical damage the county incurs for other SWEAT components.

The Tennessee SWEAT analysis appears in Figure 44. Tennessee has the most widespread and significant SWEAT impacts within the entire NMSZ region. With the exception of Benton and Hardin Counties, the impacted counties in Tennessee experience full SWEAT capacity losses. The only service, resource and infrastructure that does not incur significant capacity losses are major river crossings and highway bridges.

| Impacted Counties (incl. St. Louis City) (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossing | Hwy Bridges | Schools | Telecom |
| Bollinger | G | G | G | G | G | R | R | R | G | G | G | R |
| Butler | G | G | Y | G | R | R | R | R | G | G | Y | R |
| Cape Girardeau | G | Y | Y | R | Y | R | R | R | R | G | Y | R |
| Carter | G | G | G | G | R | G | Y | G | G | G | G | G |
| Dunklin | R | R | R | R | R | R | R | R | G | R | R | R |
| Iron | G | G | G | G | G | G | Y | G | G | G | G | G |
| Jefferson | G | G | G | G | G | G | G | G | G | G | G | G |
| Madison | G | G | G | G | G | G | Y | G | G | G | G | G |
| Mississippi | R | R | R | G | R | R | R | R | R | R | R | R |
| New Madrid | R | R | R | G | R | R | R | R | G | R | R | R |
| Oregon | G | G | G | G | R | G | Y | G | G | G | G | G |
| Pemiscot | R | R | R | R | R | R | R | R | R | R | R | R |
| Perry | G | G | G | G | R | Y | Y | R | Y | G | G | Y |
| Reynolds | G | G | G | G | R | G | Y | G | G | G | G | G |
| Ripley | G | G | G | G | G | Y | Y | G | G | G | G | G |
| Saint Charles | G | G | G | G | G | G | G | G | G | G | G | G |
| Saint Francois | G | G | G | G | G | G | Y | G | G | G | G | G |
| Saint Louis | G | G | G | G | G | G | G | G | G | G | G | G |
| Saint Louis City | G | G | G | G | G | G | Y | G | G | G | G | G |
| Sainte Genevieve | G | R | G | G | G | G | Y | G | G | G | Y | G |
| Scott | R | R | R | R | R | R | R | R | G | Y | R | R |
| Stoddard | R | R | R | R | R | R | R | R | G | Y | R | R |
| Wayne | G | G | G | G | R | Y | Y | Y | G | R | G | Y |

**Figure 43: SWEAT Analysis for the Impacted Counties of Missouri**

| Impacted Counties (IC) Day 1 | S | | | | W | | E | | A | | | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOC | Police | Fire | Hosp | Potable Water | Waste Facilities | Elect | NG Facilities | Major River Crossing | Hwy Bridges | Schools | Telecom |
| Benton | G | G | G | G | G | R | Y | G | G | G | G | R |
| Carroll | R | R | R | R | G | R | R | G | G | G | R | R |
| Chester | R | R | R | G | Y | R | R | G | G | G | R | R |
| Crockett | R | R | R | G | R | R | R | R | G | G | R | R |
| Dyer | R | R | R | R | R | R | R | R | R | R | R | R |
| Fayette | R | R | R | R | R | R | R | G | G | G | R | R |
| Gibson | R | R | R | R | R | R | R | R | G | Y | R | R |
| Hardeman | R | R | R | R | R | R | R | G | G | G | R | R |
| Hardin | G | G | G | G | Y | G | Y | G | G | G | G | G |
| Haywood | R | R | R | R | R | R | R | R | G | G | R | R |
| Henderson | R | R | R | R | G | R | R | G | G | G | R | R |
| Henry | R | R | Y | R | R | R | R | R | G | G | R | R |
| Lake | R | R | R | G | R | R | R | G | G | R | R | R |
| Lauderdale | R | R | R | R | R | R | R | R | G | Y | R | R |
| Madison | R | R | R | R | R | R | R | R | G | G | R | R |
| McNairy | R | Y | Y | R | Y | Y | Y | R | G | G | R | R |
| Obion | R | R | R | R | R | R | R | R | G | Y | R | R |
| Shelby | R | R | R | R | R | R | R | R | R | G | R | R |
| Tipton | R | R | R | R | R | R | R | R | G | G | R | R |
| Weakley | R | R | R | R | R | R | R | R | G | G | R | R |

**Figure 44: SWEAT Analysis for the Impacted Counties of Tennessee**

**Mass Care Needs Models**

Mass care and emergency requirements comprise the commodities (water, ice, food) and shelter requirements of the "At Risk" Population. "At Risk" Population is defined as displaced households (due to structural damage) and those without water and/or power for 72 hours. Shelter-seeking population is a subset of the 'At Risk' population based on demographic and socio-economic characteristics such as ethnicity and income level. The details of the methodology and models used to estimate mass care quantities have been detailed in previous sections.

*Location and Size of "At Risk" and Displaced Population*

The "At Risk" population is defined as the combined number of households who were displaced due to structural damage to their residence and those without water and/or power for at least 72 hours. The estimates reflect that by day 3 the size of the "At Risk" population is expected to exceed seven million people. Table 104 shows the distribution of "At Risk" population by state. With over two million "At Risk" people, Tennessee has the greatest mass care needs. Arkansas, with slightly less than one million "At Risk" people, is a distant second. Table 105 displays the distribution of "At Risk" and shelter-seeking population for the impacted counties in each state. As expected, Table 105 reveals that more than 50% of "At Risk" population resides in an impacted county. More than half (3.8 million) of the residents in the impacted counties are "At Risk" by day 3.

**Table 104: Distribution of "At Risk" and Shelter-Seeking Population by State**

| FEMA Region | State Total | Total Population | Day 1 | | Day 3 | |
|---|---|---|---|---|---|---|
| | | | # at risk | # shelter seeking | # at risk | # shelter seeking |
| Region IV | Alabama | 4,447,100 | 9,645 | 3,081 | 601,561 | 173,412 |
| | Kentucky | 4,041,769 | 53,860 | 14,952 | 850,615 | 233,909 |
| | Mississippi | 2,844,658 | 61,997 | 18,345 | 705,032 | 205,507 |
| | Tennessee | 5,689,283 | 316,681 | 91,103 | 2,072,942 | 562,468 |
| | Total RIV | 17,022,810 | 442,183 | 127,481 | 4,230,150 | 1,175,296 |
| Region V | Illinois | 12,419,293 | 50,285 | 15,588 | 650,247 | 185,139 |
| | Indiana | 6,080,485 | 9,932 | 2,701 | 579,627 | 153,570 |
| | Total RV | 18,499,778 | 60,217 | 18,289 | 1,229,874 | 338,709 |
| Region VI | Arkansas | 2,673,400 | 124,730 | 38,827 | 937,518 | 285,865 |
| | Total RVI | 2,673,400 | 124,730 | 38,827 | 937,518 | 285,865 |
| Region VII | Missouri | 5,595,211 | 103,665 | 30,074 | 842,002 | 237,991 |
| | Total RVIi | 5,595,211 | 103,665 | 30,074 | 842,002 | 237,991 |
| Total | | 43,791,199 | 730,795 | 214,671 | 7,239,544 | 2,037,861 |

**Table 105: Distribution of "At Risk" and Shelter-Seeking Population in Impacted Counties**

| Impacted Counties (IC) | Population in IC | Day 1 | | Day 3 | |
|---|---|---|---|---|---|
| | | # at risk | # shelter seeking | # at risk | # shelter seeking |
| Alabama | - | - | - | - | - |
| Arkansas | 558,495 | 113,222 | 35,070 | 478,639 | 147,618 |
| Illinois | 1,093,665 | 48,104 | 14,939 | 404,993 | 118,916 |
| Indiana | 535,588 | 4,129 | 1,171 | 176,235 | 49,396 |
| Kentucky | 490,909 | 53,603 | 14,879 | 328,130 | 90,386 |
| Mississippi | 553,719 | 47,841 | 14,066 | 359,367 | 107,176 |
| Missouri* | 2,288,445 | 95,145 | 28,851 | 684,838 | 198,038 |
| Tennessee | 1,488,071 | 316,555 | 91,088 | 1,388,861 | 399,621 |
| **Total IC** | **7,008,892** | **678,599** | **200,064** | **3,821,063** | **1,111,151** |

*Location and Size of Shelter-Seeking Population*

Table 104 and Table 105 include the information on the shelter-seeking population in each state as well as a regional total of all impacted counties. According to Table 104, more than two million people are expected to seek shelter by day 3. With more than 560,000 seeking shelter, Tennessee is the most heavily impacted among all states. Out of the two million shelter-seeking people within the NMSZ, more than 1.8 million reside in impacted counties. Along with the aforementioned shelter-seeking population, approximately 815,000 dogs and 738,000 cats are displaced and will need shelter. This is an important consideration since many people will refuse to leave their homes without taking their pets.

*Location and Size of Population Without Power and/or Water*

Figure 45 shows the severity of water outages within the NMSZ. According to Table 106, more than one million households are expected to be without water service following the earthquake.

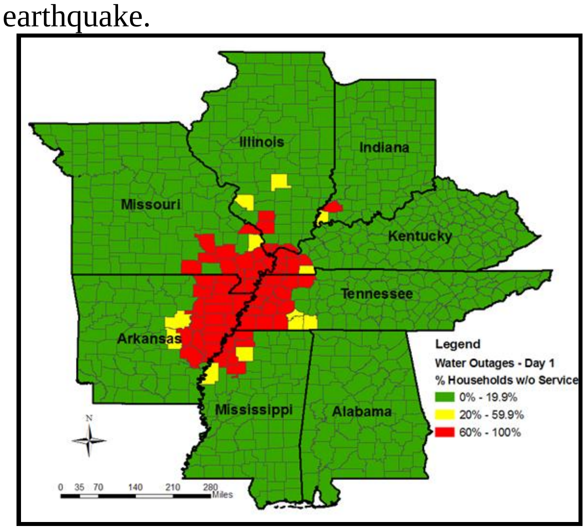


**Figure 45: Distribution of Water Outages on Day 1 in NMSZ**

| FEMA Region | State | Households w/o Water (Day 1) | Total Households |
|---|---|---|---|
| Region IV | Alabama | - | 1,737,080 |
| | Kentucky | 76,170 | 1,590,647 |
| | Mississippi | 80,128 | 1,046,434 |
| | Tennessee | 507,346 | 2,232,905 |
| | Total RIV | 663,644 | 6,607,066 |
| Region V | Illinois | 94,626 | 4,591,779 |
| | Indiana | 14,577 | 2,336,306 |
| | Total RV | 109,203 | 6,928,085 |
| Region VI | Arkansas | 193,248 | 1,042,696 |
| | Total RVI | 193,248 | 1,042,696 |
| Region VII | Missouri | 123,719 | 2,194,594 |
| | Total RVIi | 123,719 | 2,194,594 |
| Total | | 1,089,814 | 16,772,441 |

**Table 106: Distribution of Water Outages on Day 1 in NMSZ**

Figure 46 shows the severity of water outages within the impacted counties of NMSZ. According to Table 107, more than one million households within the impacted counties are expected to be without water service one day after the earthquake. Outages in the impacted counties represent the majority of all outages in the region.

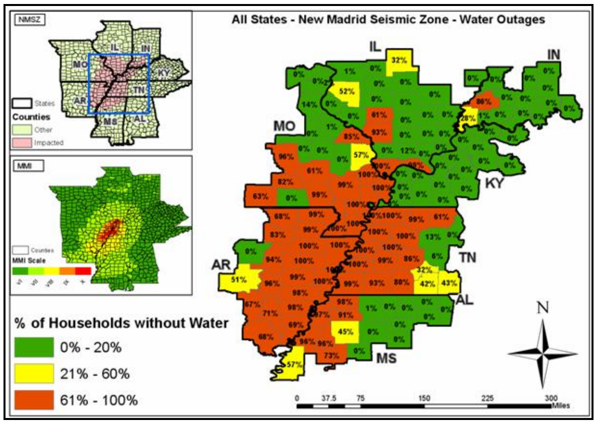


Figure 46: Distribution of Water Outages on Day 1 in NMSZ Impacted Counties

| Impacted Counties (IC) | Households w/o Water | Total Households (IC) |
|---|---|---|
| Alabama | - | - |
| Arkansas | 174,743 | 213,587 |
| Illinois | 94,626 | 425,860 |
| Indiana | 14,577 | 210,873 |
| Kentucky | 76,169 | 197,823 |
| Mississippi | 80,068 | 200,674 |
| Missouri | 123,719 | 898,507 |
| Tennessee | 507,346 | 566,153 |
| Total IC | 1,071,248 | 2,713,477 |

Table 107: Distribution of Water Outages on Day 1 in NMSZ Impacted Counties

Figure 47 illustrates the severity of power outages within the NMSZ. While there is still a strong correlation between the areas that suffer power losses and the local intensity of the earthquake, power outages cover a much larger geographical area than water outages. Also, while water outages as observed in Figure 45 alternate between severe or none, a large area of moderate power outages is observed at moderate distances from the rupture zone. It is shown in Table 108 that nearly 2.5 million households are expected to lose power service following the earthquake.

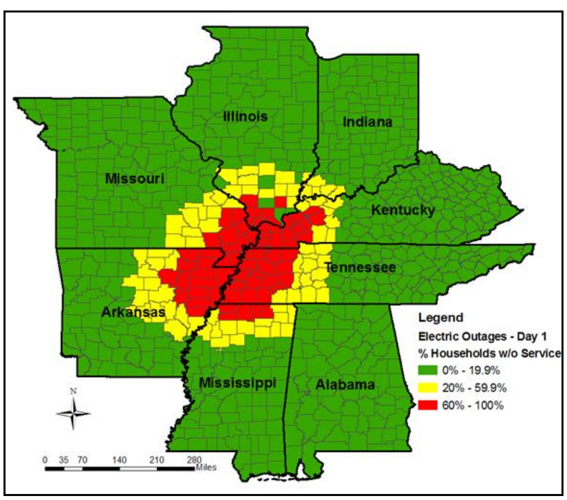


Figure 47: Distribution of Power Outages on Day 1 in NMSZ

| FEMA Region | State | Households w/o Power (Day 1) | Total Households |
|---|---|---|---|
| Region IV | Alabama | 234,842 | 1,737,080 |
| | Kentucky | 328,756 | 1,590,647 |
| | Mississippi | 232,990 | 1,046,434 |
| | Tennessee | 709,325 | 2,232,905 |
| | Total RIV | 1,505,913 | 6,607,066 |
| Region V | Illinois | 236,677 | 4,591,779 |
| | Indiana | 106,853 | 2,336,306 |
| | Total RV | 343,530 | 6,928,085 |
| Region VI | Arkansas | 329,655 | 1,042,696 |
| | Total RVI | 329,655 | 1,042,696 |
| Region VII | Missouri | 302,173 | 2,194,594 |
| | Total RVIi | 302,173 | 2,194,594 |
| Total | | 2,481,271 | 16,772,441 |

Table 108: Distribution of Power Outages on Day 1 in NMSZ

Figure 48 illustrates the severity of power outages within the impacted counties of NMSZ. Similar to the distribution of power service impacts within the entire NMSZ, the location of impacted counties with 60%-100% power service interruption on day 1 is illustrated by the red areas in the map. According to Table 109, more than 1.25 million households within the impacted counties are expected to be without power service. Only half of the households that suffer power outages are located within an impacted county. HAZUS calculates electric outages are solely on the likelihood of any structural damage to electric substations and does not account for damage to electric power plants or the electric grid (power lines). Therefore, network outages would most likely be much greater than estimated.

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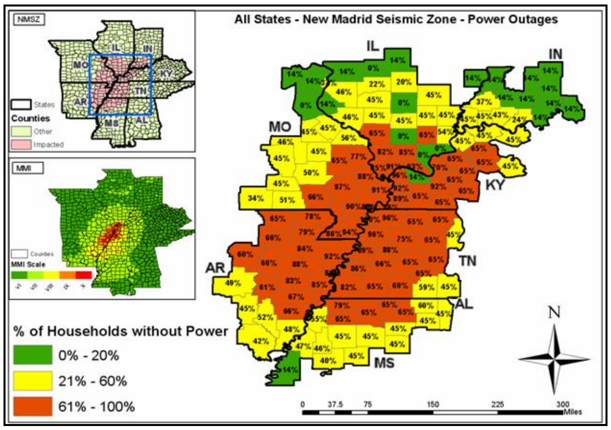


Figure 48: Distribution of Power Outages on Day 1 in NMSZ Impacted Counties

| Impacted Counties (IC) | Households w/o Power | Total Households (IC) |
|---|---|---|
| Alabama | - | - |
| Arkansas | 151,259 | 213,587 |
| Illinois | 140,402 | 425,860 |
| Indiana | 63,028 | 210,873 |
| Kentucky | 124,895 | 197,823 |
| Mississippi | 104,936 | 200,674 |
| Missouri | 243,763 | 898,507 |
| Tennessee | 440,194 | 566,153 |
| **Total IC** | **1,268,477** | **2,713,477** |

Table 109: Distribution of Power Outages on Day 1 in NMSZ Impacted Counties

*Location and Size of Other Relevant Populations*

In estimating the numbers for “At Risk” and shelter-seeking population, the base data used is primarily permanent residences. Therefore, the numbers estimated do not take into account other relevant populations that use facilities and services of a more temporary nature, such as visitors and individuals who reside in dormitories, nursing homes, and institutions.

Visitors include business and leisure travelers as well as others that are temporarily within the earthquake zone. Dormitories include, but are not limited to, school dormitories, military quarters, and homeless shelters. Nursing homes provide temporary or permanent housing to the elderly. Institutions include correctional facilities, juvenile facilities, and others. Since these entities are not included in previous estimations, it is important to have at least a high-level understanding of their presence in order to make necessary adjustments when planning for an extreme event. Table 110 provides an overview of the additional population for each of the facility categories.

As delineated in Table 110, the other relevant population includes nearly 325,000 people. While is unlikely that this entire group of people will be “At Risk” or seek shelter after the earthquake, requirements planning should make plausible assumptions regarding how these populations are provided with the basic care they may need in the aftermath of the earthquake.

**Table 110: Distribution of Other Relevant Populations**

| Impacted Counties (IC) | Dorms | Nursing Homes | Institutions | Visitors | Total |
|---|---|---|---|---|---|
| Alabama | - | - | - | - | - |
| Arkansas | 6,056 | 4,863 | 7,298 | 7,744 | 25,961 |
| Illinois | 12,236 | 11,569 | 19,696 | 9,373 | 53,681 |
| Indiana | 7,010 | 5,379 | 2,550 | 3,790 | 18,729 |
| Kentucky | 5,792 | 5,304 | 4,642 | 536 | 16,274 |
| Mississippi | 9,534 | 2,994 | 7,578 | 17,138 | 37,244 |
| Missouri | 20,159 | 19,659 | 8,782 | 47,231 | 96,427 |
| Tennessee | 13,158 | 10,322 | 17,873 | 35,288 | 76,641 |
| **Total (IC)** | **73,945** | **60,090** | **68,419** | **121,100** | **324,957** |

**Response Requirements Models**

Response requirement models estimate resources necessary to respond to a given a disaster scenario. Typical inputs to these models are outputs from damage estimation models and other quantitative information relevant to the physical, social, economic and medical impacts of the disaster along with the scope of the response triggered. Details of these models are covered in previous sections. This section summarizes the outputs of such models as they relate to the NMSZ earthquake scenario.

*Commodities Required*

The estimates calculated for commodities required include the immediate needs of the "At Risk" population within the first 72 hours of the earthquake. The reported quantities for water, MRE's (meals ready-to-eat) and ice were calculated based on methodologies adapted by the American Red Cross, USACE, Sphere Standards, and FEMA.

**Table 111: Commodities Required to Support the "At Risk" Population in the Eight-State Region**

| FEMA Region | State | Commodities (First 72 hours) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Water | | MREs | | Ice | |
| | | Liters | Truckloads | Number | Truckloads | Pounds | Truckloads |
| Region IV | Alabama | 1,823,169 | 102 | 1,215,446 | 56 | 4,861,784 | 122 |
| | Kentucky | 2,641,557 | 147 | 1,761,038 | 81 | 7,044,152 | 176 |
| | Mississippi | 2,225,166 | 124 | 1,483,444 | 68 | 5,933,776 | 148 |
| | Tennessee | 6,765,444 | 376 | 4,510,296 | 207 | 18,041,184 | 451 |
| | Total RIV | 13,455,336 | 749 | 8,970,224 | 412 | 35,880,896 | 897 |
| Region V | Illinois | 2,044,269 | 114 | 1,362,846 | 63 | 5,451,384 | 136 |
| | Indiana | 1,755,087 | 98 | 1,170,058 | 54 | 4,680,232 | 117 |
| | Total RV | 3,799,356 | 212 | 2,532,904 | 117 | 10,131,616 | 253 |
| Region VI | Arkansas | 3,045,516 | 169 | 2,030,344 | 93 | 8,121,376 | 203 |
| | Total RVI | 3,045,516 | 169 | 2,030,344 | 93 | 8,121,376 | 203 |
| Region VII | Missouri | 2,706,450 | 150 | 1,804,300 | 83 | 7,217,200 | 180 |
| | Total RVIi | 2,706,450 | 150 | 1,804,300 | 83 | 7,217,200 | 180 |
| Total | | 23,006,658 | 1,280 | 15,337,772 | 705 | 61,351,088 | 1,533 |

As shown in Table 111, the logistics of providing the commodities for the entire NMSZ requires 3,500 truckloads. It is estimated that 23 million liters (1,280 truckloads) of water, 15.3 million (705 truckloads) MRE's and 61.3 million pounds (1,533 truckloads) of ice are necessary to support the "At Risk" population for the first 72 hours. It is assumed that each truck has a 25-ton capacity. The water estimate only includes the required amount for drinking water, though up to four times the amount of drinking water may be required for washing and other uses.

Table 112 summarizes the commodities required within the impacted counties. For each of the commodities, more than 50% of the regional total is required to support the "At Risk" population within the impacted counties.

**Table 112: Commodities Required to Support the "At Risk" Population in Impacted Counties**

| Impacted Counties (IC) | Water | | MREs | | Ice | |
|---|---|---|---|---|---|---|
| | Liters | Truckloads | Number | Truckloads | Pounds | Truckloads |
| **Alabama** | - | - | - | - | - | - |
| **Arkansas** | 1,646,337 | 92 | 1,097,558 | 68 | 4,390,232 | 148 |
| **Illinois** | 1,304,613 | 68 | 869,742 | 34 | 3,478,968 | 81 |
| **Indiana** | 521,913 | 27 | 347,942 | 12 | 1,391,768 | 30 |
| **Kentucky** | 1,073,664 | 92 | 715,776 | 33 | 2,863,104 | 72 |
| **Mississippi** | 1,162,497 | 65 | 774,998 | 36 | 3,099,992 | 77 |
| **Missouri*** | 2,227,620 | 119 | 1,485,080 | 68 | 5,940,320 | 148 |
| **Tennessee** | 4,713,111 | 262 | 3,142,074 | 145 | 12,568,296 | 314 |
| **Total IC** | **12,649,755** | **723** | **8,433,170** | **396** | **33,732,680** | **872** |

*Search and Rescue Teams and Personnel Required*

Search and Rescue (S&R) requirements are calculated based on a methodology developed by D. Bausch. The methodology considers four categories of S&R teams and it estimates the number of different teams required as well as the required number of personnel. The details of the methodology are details in previous sections.

Table 113 summarizes the number of collapsed buildings for the four different categories which are based on construction material. With more than 10,000 collapsed buildings, Tennessee is the most heavily impacted state within the NMSZ region. Arkansas and Missouri follow with more than 8,000 and 5,000 total collapses, respectively.

S&R teams are organized into four groups based on their capabilities. Type I Teams are the most sophisticated teams with advanced S&R training, possession of advanced search equipment and heavy rescue equipment. Type IV teams are the least sophisticated and are equipped to provide search and rescue efforts in light frame construction buildings. The typical size of a Type I team is 70 people. Sizes of Type II, III, and IV teams are 32, 22, and 6, respectively. While a Type I team can perform S&R operations on 2 buildings per day, on average, a typical Type IV team can respond to as many as 16 buildings per day. The estimated need for each type of team is summarized by state in Table 114.

Based on these estimates, approximately 1,500 S&R teams, comprised of 42,000 personnel, are necessary to perform search and rescue activities at the more than 32,000 collapsed buildings in the NMSZ. With 28 federally-funded national search and rescue teams (FEMA, 2009), and around 1,150 local search and rescue teams throughout the nation (Denver et al., 2007) the large number of S&R teams needed to respond to a NMSZ earthquake incident of this magnitude will inevitably mandate deployment of international S&R teams, as well as the spontaneous formation of teams comprised of people located within the impacted area.

**Table 113: Distribution of Building Collapse Types by State**

| FEMA Region | State | Type I Collapsed Buildings | Type II Collapsed Buildings | Type III Collapsed Buildings | Type IV Collapsed Buildings | Total |
|---|---|---|---|---|---|---|
| Region IV | Alabama | 7 | 3 | 62 | 212 | 284 |
| | Kentucky | 84 | 47 | 1,491 | 1,120 | 2,742 |
| | Mississippi | 39 | 18 | 452 | 1,227 | 1,736 |
| | Tennessee | 355 | 201 | 4,964 | 5,215 | 10,735 |
| | Total RIV | 485 | 269 | 6,969 | 7,774 | 15,497 |
| Region V | Illinois | 74 | 19 | 1,486 | 950 | 2,529 |
| | Indiana | 3 | 2 | 151 | 138 | 294 |
| | Total RV | 77 | 21 | 1,637 | 1,088 | 2,823 |
| Region VI | Arkansas | 454 | 289 | 4,643 | 3,040 | 8,426 |
| | Total RVI | 454 | 289 | 4,643 | 3,040 | 8,426 |
| Region VII | Missouri | 78 | 47 | 4,079 | 1,562 | 5,766 |
| | Total RVIi | 78 | 47 | 4,079 | 1,562 | 5,766 |
| Total | | 1,094 | 626 | 17,328 | 13,464 | 32,512 |

**Table 114: Number and Type of S&R Teams by State**

| FEMA Region | State | Type I | | Type II | | Type III | | Type IV | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Teams | Personnel | Teams | Personnel | Teams | Personnel | Teams | Personnel | Teams | Personnel |
| Region IV | Alabama | 2 | 140 | 1 | 32 | 3 | 66 | 5 | 30 | 11 | 268 |
| | Kentucky | 21 | 1,470 | 6 | 192 | 68 | 1,496 | 26 | 156 | 121 | 3,314 |
| | Mississippi | 10 | 700 | 2 | 64 | 21 | 462 | 28 | 168 | 61 | 1,394 |
| | Tennessee | 89 | 6,213 | 25 | 804 | 226 | 4,972 | 119 | 714 | 459 | 12,703 |
| | Total RIV | 122 | 8,523 | 34 | 1,092 | 318 | 6,996 | 178 | 1,068 | 652 | 17,679 |
| Region V | Illinois | 19 | 1,330 | 3 | 96 | 68 | 1,496 | 22 | 132 | 112 | 3,054 |
| | Indiana | 4 | 280 | 1 | 32 | 18 | 396 | 8 | 48 | 31 | 756 |
| | Total RV | 23 | 1,610 | 4 | 128 | 86 | 1,892 | 30 | 180 | 143 | 3,810 |
| Region VI | Arkansas | 114 | 7,980 | 36 | 1,152 | 211 | 4,642 | 69 | 414 | 430 | 14,188 |
| | Total RVI | 114 | 7,980 | 36 | 1,152 | 211 | 4,642 | 69 | 414 | 430 | 14,188 |
| Region VII | Missouri | 20 | 1,400 | 6 | 192 | 195 | 4,290 | 39 | 234 | 260 | 6,116 |
| | Total RVIi | 20 | 1,400 | 6 | 192 | 195 | 4,290 | 39 | 234 | 260 | 6,116 |
| Total | | 279 | 19,513 | 80 | 2,564 | 810 | 17,820 | 316 | 1,896 | 1,485 | 41,793 |

*Shelter Capacity, Shelter Space Requirements and Staffing Requirements*

Shelter capacity, space, resources and staffing requirements provide a high-level needs assessment of the essential components of temporary accommodation for the shelter-seeking population in the NMSZ. More than 10,000 shelters, each with a capacity of 200 people, are necessary to accommodate the estimated number of people seeking temporary shelter. This is equivalent to almost one billion square feet of shelter space. To operate these shelters, a staff of approximately 220,000 is necessary. Tasks performed by shelter staff include operations, feeding, and bulk distribution. Table 115 provides an overview of the shelter capacity and staffing requirements for all states. All shelter calculations are based on shelters with a 200-person capacity.

As described in Table 115, approximately 1100 shelters or less will be sufficient for most states, with the exceptions of Tennessee and Arkansas. For these two states, approximately 2,800 and 1,400 shelters are necessary to accommodate the shelter-seeking population, respectively.

**Table 115: Shelter Capacity and Staffing Requirements by State**

| Region | State | Number of Shelters (capacity of 200) | Space | | Staffing | | |
|---|---|---|---|---|---|---|---|
| | | | Sleeping (sq ft) | Total (sq ft) | Operations | Feeding | Bulk Distribution |
| Region IV | Alabama | 867 | 10,404,720 | 83,237,760 | 8,671 | 3,468 | 6,936 |
| | Kentucky | 1,170 | 14,034,540 | 112,276,320 | 11,695 | 4,678 | 9,356 |
| | Mississippi | 1,028 | 12,330,420 | 98,643,360 | 10,275 | 4,110 | 8,220 |
| | Tennessee | 2,812 | 33,748,080 | 269,984,640 | 28,123 | 11,249 | 22,499 |
| | Total RIV | 5,876 | 70,517,760 | 564,142,080 | 58,765 | 23,506 | 47,012 |
| Region V | Illinois | 926 | 11,108,340 | 88,866,720 | 9,257 | 3,703 | 7,406 |
| | Indiana | 768 | 9,214,200 | 73,713,600 | 7,679 | 3,071 | 6,143 |
| | Total RV | 1,694 | 20,322,540 | 162,580,320 | 16,935 | 6,774 | 13,548 |
| Region VI | Arkansas | 1,429 | 17,151,900 | 137,215,200 | 14,293 | 5,717 | 11,435 |
| | Total RVI | 1,429 | 17,151,900 | 137,215,200 | 14,293 | 5,717 | 11,435 |
| Region VII | Missouri | 1,190 | 14,279,460 | 114,235,680 | 11,900 | 4,760 | 9,520 |
| | Total RVIi | 1,190 | 14,279,460 | 114,235,680 | 11,900 | 4,760 | 9,520 |
| Total | | 10,189 | 122,271,660 | 978,173,280 | 101,893 | 40,757 | 81,514 |

Table 116 provides shelter requirements for the impacted counties only. Once again, it is observed that for almost every shelter requirement, more than 50% of the need is generated within impacted counties.

**Table 116: Shelter Capacity and Staffing Requirements for Impacted Counties**

| Impacted Counties (IC) | Number of Shelters (capacity of 200) | Space | | Staffing | | |
|---|---|---|---|---|---|---|
| | | Sleeping (sq ft) | Total (sq ft) | Operations | Feeding | Bulk Distribution |
| Alabama | - | - | - | - | - | - |
| Arkansas | 738 | 8,857,080 | 70,856,640 | 7,381 | 2,952 | 5,905 |
| Illinois | 595 | 7,134,960 | 57,079,680 | 5,946 | 2,378 | 4,757 |
| Indiana | 247 | 2,963,760 | 23,710,080 | 2,470 | 988 | 1,976 |
| Kentucky | 452 | 5,423,160 | 43,385,280 | 4,519 | 1,808 | 3,615 |
| Mississippi | 536 | 6,430,560 | 51,444,480 | 5,359 | 2,144 | 4,287 |
| Missouri* | 990 | 11,882,280 | 95,058,240 | 9,902 | 3,961 | 7,922 |
| Tennessee | 1,998 | 23,977,260 | 191,818,080 | 19,981 | 7,992 | 15,985 |
| Total | 5,556 | 66,669,060 | 533,352,480 | 55,558 | 22,223 | 44,446 |

Figure 49 provides a spatial gap analysis of shelter availability and expected shelter needs within the NMSZ. The data concerning available shelters comes from the NSS database. Unfortunately, the NSS database is somewhat incomplete and many data entries are incomplete and/or incorrect as was presented in previous sections. The green color in Figure 49 represents planning areas where there is no shelter gap, meaning there is sufficient shelter capacity in these locations. The yellow color represents areas where there is a shelter gap, however with a shelter demand is less than double the available shelter capacity. The red color represents areas with significant shelter gaps where shelter demand is more than double the available shelter capacity.

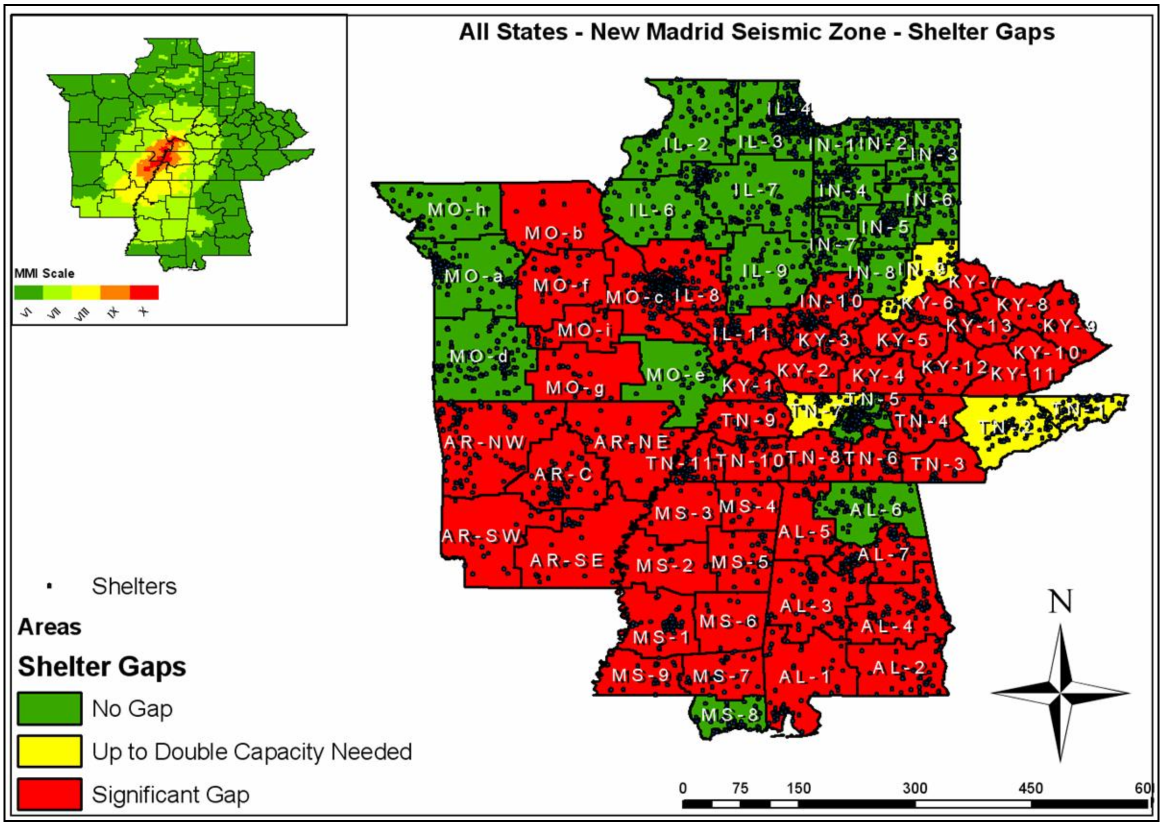


**Figure 49: Shelter Gaps in NMSZ Planning Areas**

There are significant shelter gaps throughout the entire NMSZ except for the northern parts of Illinois and Indiana, as well as Missouri. While some areas such as Alabama and southern Mississippi experience very little physical impact, shelter gaps still exist due to the number of people who are without power and/or water 72 hours post event. The shelter gaps identified in Figure 49 should be validated by prior to developing appropriate strategies to reduce those gaps shown. Once the NSS database has been validated, the shelter gap analysis can be used to determine strategies such as the creation of a transportation plan to relocate people seeking temporary shelter in areas with large shelter gaps to areas with greater shelter capabilities.

Table 117 provides the quantities of shelter resources other than physical space and staffing. These resources include blankets, cots, sinks, portable toilets, and trash cans.

More than four million blankets, two million cots, 25,000 sinks, 50,000 portable toilets, and 40,000 trash cans are necessary to achieve an acceptable level of service based on general shelter standards. Table 117 reveals that compared to other states, resource requirements for shelter resources are significantly greater in Tennessee than the other seven states included in this study. Table 118 provides the same shelter resource needs for the impacted counties.

Table 117: Shelter Resource Needs (Except for Physical Space and Staffing) by State

| Region | State | Blankets | Cots | Sinks | Port-a-Pottys Toilets | Trash Cans |
|---|---|---|---|---|---|---|
| Region IV | Alabama | 346,824 | 173,412 | 2,170 | 4,333 | 3,467 |
| | Kentucky | 467,818 | 233,909 | 2,926 | 5,851 | 4,682 |
| | Mississippi | 411,014 | 205,507 | 2,567 | 5,144 | 4,109 |
| | Tennessee | 1,124,936 | 562,468 | 7,030 | 14,064 | 11,244 |
| | Total RIV | 2,350,592 | 1,175,296 | 14,693 | 29,392 | 23,502 |
| Region V | Illinois | 370,278 | 185,139 | 2,313 | 4,630 | 3,704 |
| | Indiana | 307,140 | 153,570 | 1,920 | 3,840 | 3,073 |
| | Total RV | 677,418 | 338,709 | 4,233 | 8,470 | 6,777 |
| Region VI | Arkansas | 571,730 | 285,865 | 3,574 | 7,151 | 5,713 |
| | Total RVI | 571,730 | 285,865 | 3,574 | 7,151 | 5,713 |
| Region VII | Missouri | 475,982 | 237,991 | 2,972 | 5,946 | 4,755 |
| | Total RVIi | 475,982 | 237,991 | 2,972 | 5,946 | 4,755 |
| Total | | 4,075,722 | 2,037,861 | 25,472 | 50,959 | 40,747 |

Table 118: Shelter Resource Needs (Except for Physical Space and Staffing) for Impacted Counties

| Impacted Counties (IC) | Blankets | Cots | Sinks | Port-a-Pottys Toilets | Trash Cans |
|---|---|---|---|---|---|
| Alabama | - | - | - | - | - |
| Arkansas | 295,236 | 147,618 | 1,845 | 3,692 | 2,950 |
| Illinois | 237,832 | 118,916 | 1,486 | 2,973 | 2,380 |
| Indiana | 96,640 | 48,320 | 605 | 1,209 | 968 |
| Kentucky | 180,772 | 90,386 | 1,131 | 2,259 | 1,808 |
| Mississippi | 214,352 | 107,176 | 1,340 | 2,680 | 2,144 |
| Missouri* | 396,076 | 198,038 | 2,476 | 4,950 | 3,959 |
| Tennessee | 799,242 | 399,621 | 4,994 | 9,991 | 7,991 |
| Total (IC) | 2,220,150 | 1,110,075 | 13,877 | 27,754 | 22,200 |

*Medical Response Requirements*

Overall, the scenario generates approximately 82,000 injuries and 3,500 deaths. Those estimates include casualties resulting from structural building and bridge damage only. Therefore, the estimates do not included injuries and fatalities related to transportation accidents, fires, or hazmat exposure. This section deals only with injuries. Fatalities are addressed under mortuary services. The injuries and casualties estimated by the model are only for those that occur at the time of the event. The model does not provide for increases in these numbers that occur post event. For example, those that sustain injuries may die later, or injuries incurred as a result of response activities may result in fatalities.

Table 119 shows that Tennessee and Arkansas have the largest number of injuries. Many of these require hospital care and are life-threatening. Both of these states also incur a large number of damaged health care facilities that correspond to a large number of hospital beds being unavailable. It is clear that these states will need to not only evacuate hospitals to other areas but will also need to evacuate a number of the people sustaining injuries. While Missouri also has a high number of people injured, a larger percentage of their health care facilities remain functional.

Table 119: Injuries and Hospital Status

| State | Injuries (2 AM) | | | | Hospitals | | | |
|---|---|---|---|---|---|---|---|---|
| | Medical Aid Needed | Hospital Care | Life Threatening | Total | Total | | Loss | |
| | | | | | Facilities | Beds | Facilities | Beds |
| Alabama | 726 | 179 | 16 | 921 | 210 | 23,107 | - | - |
| Arkansas | 11,245 | 3,075 | 344 | 14,664 | 125 | 11,592 | 24 | 2,094 |
| Illinois | 4,597 | 1,270 | 145 | 6,011 | 413 | 52,153 | 7 | 951 |
| Indiana | 1,457 | 395 | 43 | 1,896 | 1,285 | 92,092 | 5 | 190 |
| Kentucky | 5,042 | 1,358 | 153 | 6,553 | 189 | 20,755 | 9 | 1,593 |
| Mississippi | 4,588 | 1,181 | 104 | 5,872 | 163 | 18,288 | 23 | 1,913 |
| Missouri | 10,177 | 2,897 | 360 | 13,434 | 208 | 27,343 | 7 | 846 |
| Tennessee | 25,431 | 6,765 | 715 | 32,911 | 232 | 29,985 | 54 | 8,003 |
| Total | 63,265 | 17,119 | 1,880 | 82,264 | 2,825 | 275,315 | 129 | 15,590 |

Table 120: Cases of Illnesses

| State | "At Risk" Population | Cancers | Diabetes | Heart Disease | Hyper-tension | Stroke | Mental Disorders | Pulmonary Conditions |
|---|---|---|---|---|---|---|---|---|
| Alabama | 601,561 | 26,469 | 41,508 | 52,336 | 99,258 | 5,414 | 49,930 | 104,672 |
| Arkansas | 937,518 | 43,126 | 43,126 | 76,876 | 141,565 | 11,250 | 95,627 | 173,441 |
| Illinois | 650,247 | 22,759 | 27,961 | 43,567 | 80,631 | 5,852 | 58,522 | 108,591 |
| Indiana | 579,627 | 19,707 | 26,663 | 41,154 | 80,568 | 5,796 | 58,542 | 106,072 |
| Kentucky | 850,615 | 35,726 | 45,083 | 67,199 | 125,040 | 7,656 | 78,257 | 210,953 |
| Mississippi | 705,032 | 31,021 | 48,647 | 61,338 | 116,330 | 6,345 | 58,518 | 122,676 |
| Missouri | 842,002 | 27,786 | 33,680 | 69,044 | 119,564 | 8,420 | 87,568 | 152,402 |
| Tennessee | 2,072,942 | 91,209 | 122,304 | 161,689 | 310,941 | 20,729 | 221,805 | 414,588 |
| Total | 7,239,544 | 297,803 | 388,970 | 573,202 | 1,073,898 | 71,463 | 708,768 | 1,393,394 |

Table 120 shows the number of cases of chronic illnesses in the "At Risk" population. While the majority of these illnesses are often able to be treated on a day-to-day basis by the patient themselves, this will most likely not be the case in the days following the earthquake. The "At Risk" population will either be displaced from their home due to structural damage or will find themselves without power and/or water in the days following the event. This will severely limit their ability to care for their illnesses themselves. Another complicating factor will be the availability of prescription medicine to treat these illnesses. Due to the policies of healthcare insurance companies regarding the number of days of medications that a patient may have on hand, combined with the cost of prescription medications, approximately 50% of this population will have less than a 14-day supply of medication on the day following the event.

*Mortuary Services*

Approximately 3,500 people die as a result of the initial event. It is to be expected that this number will increase as a result of injuries to first responders as well as the inability to treat life-threatening injuries post event. Table 121 shows the number of initial fatalities by state. The mortuary services required, such as victim identification and the establishment of temporary morgue facilities, will quickly overwhelm local resources even enhanced by Mortuary Operational Response Teams (DMORTs).

**Table 121: Fatalities**

| Fatalities (2 AM) | |
|---|---|
| Alabama | 28 |
| Arkansas | 641 |
| Illinois | 271 |
| Indiana | 80 |
| Kentucky | 287 |
| Mississippi | 183 |
| Missouri | 686 |
| Tennessee | 1,319 |
| **Total** | 3,494 |

*Security Needs*

In this section, statistics of prison population within the NMSZ are discussed as a potential indicator of security needs. Based on data from the Federal Bureau of Prisons (2009), Department of Corrections for different states (2009) and the Census of Jail Inmates, 2005 (U.S. Department of Justice 2007), there are approximately 350,000 prisoners in the NMSZ. Figure 50 provides the distribution of prisoners throughout the eight states.

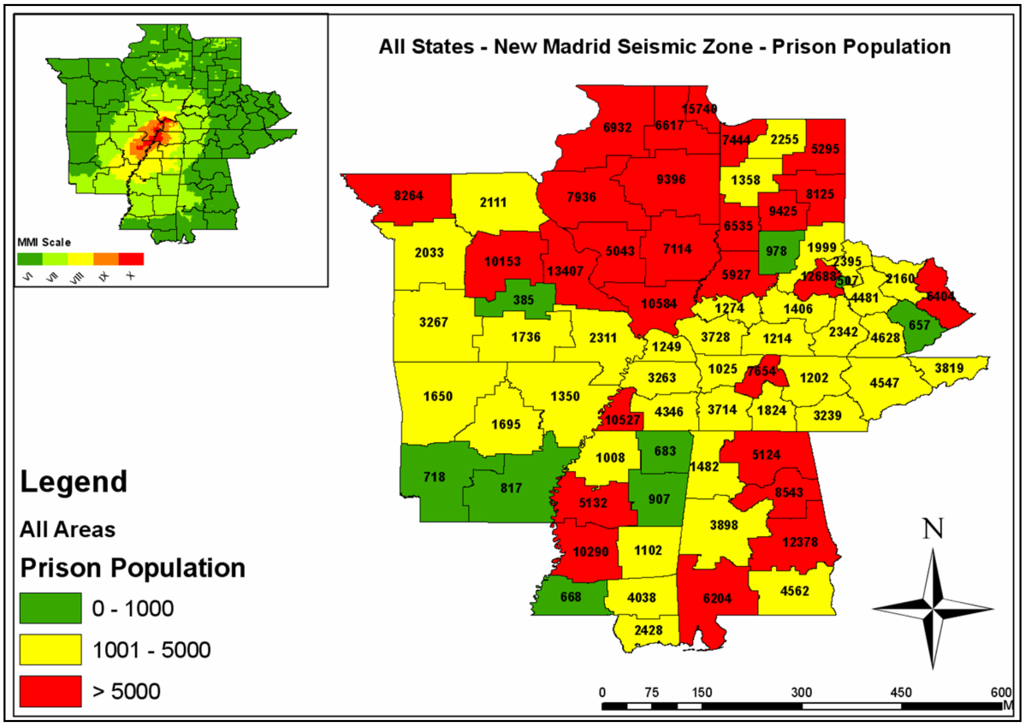


**Figure 50: Distribution of Prison Population in Planning Areas**

Table 122 provides the distribution of prisoner population in each state for the following facilities: local jails, state prisons, and federal prisons.

**Table 122: Distribution of Prison Population by State**

| FEMA Region | State | Local Jails | State Prisons | Federal Prisons | Total |
|---|---|---|---|---|---|
| Region IV | Alabama | 15,047 | 25,090 | 2,054 | 42,191 |
| | Kentucky | 22,563 | 14,352 | 8,218 | 45,133 |
| | Mississippi | 11,280 | 11,396 | 3,580 | 26,256 |
| | Tennessee | 24,415 | 19,182 | 1,563 | 45,160 |
| | Total RIV | 73,305 | 70,020 | 15,415 | 158,740 |
| Region V | Illinois | 23,027 | 45,536 | 799 | 69,362 |
| | Indiana | 19,141 | 26,850 | 3,350 | 49,341 |
| | Total RV | 42,168 | 72,386 | 4,149 | 118,703 |
| Region VI | Arkansas | 6,230 | 12,723 | 4,009 | 22,962 |
| | Total RVI | 6,230 | 12,723 | 4,009 | 22,962 |
| Region VII | Missouri | 10,799 | 31,750 | 1,118 | 43,667 |
| | Total RVIi | 10,799 | 31,750 | 1,118 | 43,667 |
| Total | | 132,502 | 186,879 | 24,691 | 344,072 |

Figure 51 shows the distribution of prison population in impacted counties.

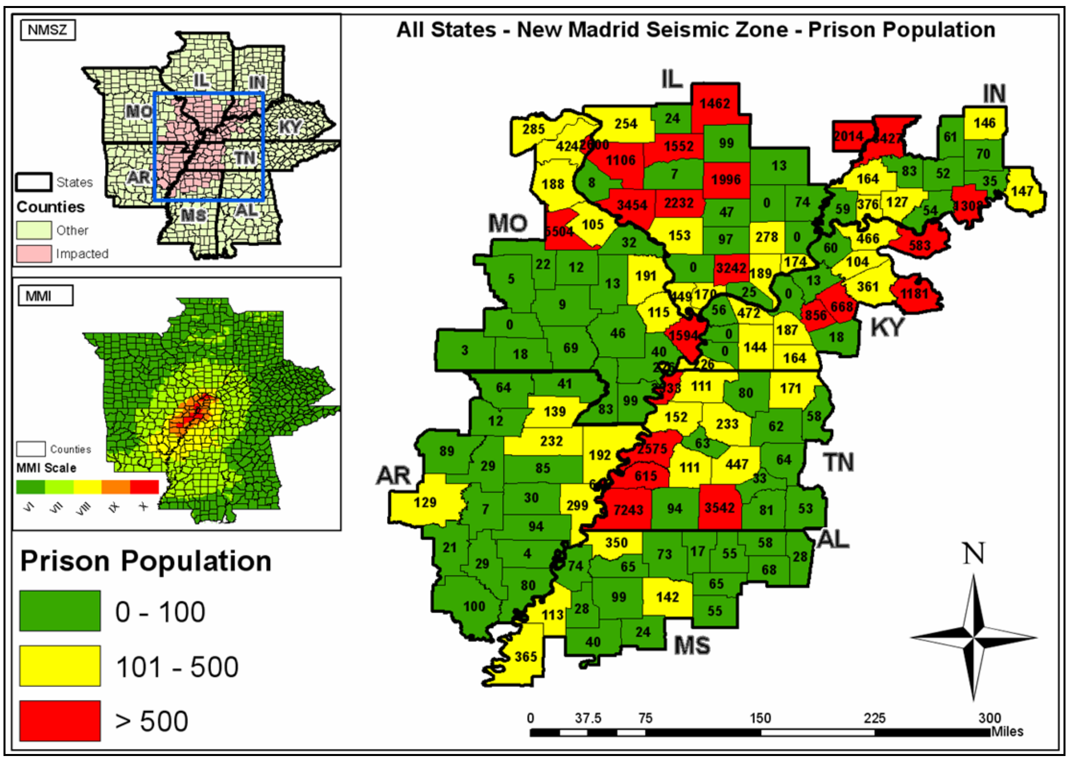


**Figure 51: Distribution of Prison Population in Impacted Counties**

While most impacted counties have a relatively low prison population, a few counties such as Shelby, Lauderdale, and Hardeman Counties in Tennessee: Muhlenberg County in Kentucky; Knox and Perry Counties in Indiana; Mississippi and St. Francois Counties in Missouri; Fayette, Clinton, St. Clair, Randolph, Perry, Jefferson, Lawrence and Johnson Counties in Illinois show comparatively larger prison population. Table 123 provides the distribution of prisoner population in the impacted counties.

**Table 123: Distribution of Prison Population in Impacted Counties**

| Impacted Counties (IC) | Local Jails | State Prisons | Federal Prisons | Total IC |
|---|---|---|---|---|
| Alabama | - | - | - | - |
| Arkansas | 1,676 | 3,253 | 4,009 | 8,938 |
| Illinois | 1,738 | 17,381 | - | 19,119 |
| Indiana | 1,494 | 1,265 | 3,350 | 6,109 |
| Kentucky | 3,911 | 2,485 | - | 6,396 |
| Mississippi | 1,719 | - | - | 1,719 |
| Missouri | 7,596 | 6,870 | - | 14,466 |
| Tennessee | 7,960 | 8,598 | 1,563 | 18,121 |
| Total IC | 26,094 | 39,852 | 8,922 | 74,868 |

# Required Extensions of Earthquake Impact Modeling

## Improvements to Current Models

Whereas the detailed and refined analytical earthquake impact assessment presented above is by far the most realistic and reliable study of its kind ever undertaken in the USA, many extensions are acutely required. In spite of the immense efforts of the large team from 3 universities and their partners in many state and federal agencies, supported and advised by FEMA, there are many missing model components the inclusion of which will improve the comprehensiveness and reliability of the results. Below are modeling and analysis features that are deemed by the project team and their partners in state and regional emergency management agencies to be of the utmost importance. The project team hopes that they or others will be supported to undertake the scope of work below, and to consequently contribute to the disaster preparedness of the Central US, and therefore the entire nation.

### Roadway Fragilities

Determining damage to roadways is a mode component vital to numerous aspects of earthquake impact assessment. In order to evaluate damage properly a new set of fragility relationships must be developed, either analytically, through experimentation, or a combination of both. The method chosen is likely dependent upon the time allotted to complete this task. Estimating probabilities for each damage state helps define the status of the road network post-event. Once damage is known, ingress routes for emergency personnel and egress routes for evacuees can be laid out. Furthermore, injury and/or fatality collection points can be assigned based on the viability of the road network. Conversely, roads identified as critical by local, state, regional, or national jurisdictions could be mitigated prior to the event if they are estimated to incur substantial damage thus rendering them impassible.

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 1: Transportation
- ESF 3: Public Works and Engineering
- ESF 5: Emergency Management
- ESF 7: Logistics Management and Resource Support
- ESF 8: Public Health and Medical Services
- ESF 9: Search and Rescue
- ESF 11: Agriculture and Natural Resources
- ESF 13: Public Safety and Security
- ESF 14: Long-Term Community Recovery

**Fragility Relationships for Dams and Levees**

The earthquake impact assessment detailed in this study utilizes threshold values to determine the likelihood of damage for dams and levees. As discussed previously, threshold values are a very basic and approximate method by which to determine damage. It is desirable to use fragility relationships for damage determinations of dams and levees as the fragilities are developed with far more scientific rigor than threshold values. Improving the damage estimations of these two types of critical infrastructure improves several other facets of current impact assessments. First, direct damage characterizations of dams and levees should be improved. With more refined damage estimations, flood risk analyses can be updated and potentially new structures at risk from secondary flooding identified. Dams and levees that are particularly vulnerable to damage and secondary flooding may also be mitigated prior to an event in an effort to minimize damage.

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 3: Public Works and Engineering
- ESF 5: Emergency Management
- ESF 7: Logistics Management and Resource Support
- ESF 11: Agriculture and Natural Resources
- ESF 13: Public Safety and Security
- ESF 14: Long-Term Community Recovery

**Transportation Network Model in MAEViz**

Transportation systems constitute one class of major civil infrastructure systems that form a critical backbone of modern society. Transportation systems also serve as the evacuation routes for disaster survivors and provide an emergency transport network for rescue workers, construction repair teams and disaster relief. Under emergency conditions such as an earthquake, it is critical to secure the ingress and egress transport of emergency response vehicles as well as avoid excessive queues and delays. When considering measures to secure traffic function immediately after the earthquake and restore the performance of the highway systems (Masuya, 1998), it is essential to understand and model the travel pattern under the emergency operation of highway systems.

Future research will evaluate the seismic performance of complex transportation infrastructure under extreme events such as earthquake impact. Both static and dynamic traffic simulation models should be employed for simulating the post-disaster emergency traffic. Dynamic traffic assignment (DTA) models provide an alternative way to address the unrealistic issues with the static assignment models that have been utilized in current study. Instead of assuming static traffic demand, the DTA models take into account the fluctuation of road traffic by introducing time-dependent traffic flow and route choices. The state-of-the-art dynamic models (i.e., Visual Interactive System for Transport Algorithms, VISTA), which incorporate the enhanced cell transmission model (CTM), and supports for variable-sized cells and signalized intersections, will be employed to simulate the dynamic traffic flow over the network.

Additionally, various emergency scenarios representing different post-event traffic patterns should be designed to evaluate emergency response plans. Emergency routes' seismic performance and corresponding congestion should also be evaluated to facilitate the post-earthquake ingress and egress to the impacted area (e.g., disaster relief dispatch and evacuation) (Shen, et al., 2009).

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 1: Transportation
- ESF 3: Public Works and Engineering
- ESF 5: Emergency Management
- ESF 6: Mass Care, Emergency Assistance, Housing, and Human Services
- ESF 7: Logistics Management and Resource Support
- ESF 9: Search and Rescue
- ESF 13: Public Safety and Security
- ESF 14: Long-Term Community Recovery

**Utility Network Model in MAEViz**

Current damage algorithms in the MAEViz utility network model can be improved with the addition of more recent fragilities and damage functions to the fragility sets from the literature. The utility network model would benefit from the future development of a retrofit prioritization model that will compare possible pipeline and facility retrofitting strategies based on their affects on the network performance. The identification of critical components of networks can be achieved by this improvement. One further improvement to the utility network model would be hydraulic modeling of the networks, with improvements over the topological model. Hydraulic modeling will also enable the modeling of leaks and breaks on pipelines, thus resulting in an improved failure assessment methodology.

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 3: Public Works and Engineering
- ESF 4: Firefighting
- ESF 5: Emergency Management
- ESF 7: Logistics Management and Resource Support
- ESF 10: Oil and Hazardous Materials Response
- ESF 11: Agriculture and Natural Resources
- ESF 13: Public Safety and Security

### Uncertainty Modeling

*Based on Approach 1:*

In order to quantify the actual level of the uncertainties in seismic loss estimates using the developed framework, further research efforts should be focused on the following topics:

- **Effect of spatial correlation:** Despite the significant impact of the spatial correlation on the loss estimates of spatially distributed system or structures, this study did not consider the spatial correlation.
- **Generalization:** The developed framework for uncertainty quantification can be generalized to other types of infrastructure systems (e.g., lifeline networks) and hazard (e.g., flood, wind).
- **Implementation into HAZUS:** In this study, a semi-automated tool was developed for uncertainty quantification by HAZUS, but eventually, such a process needs to be implemented into HAZUS. This may give rise to some challenges in computations, GIS or database, which would require further research efforts.
- **Other types of uncertainties:** This study does not cover other types of uncertainties such as statistical uncertainties of the parameters in loss-estimation models, erroneous or outdated data in inventory databases, and model errors. A sensitivity analysis is desired to identify relatively important uncertainties that need to be considered during regional seismic loss assessment.

*Based on Approach 2:*

A simplified framework for uncertainty propagation analysis has a simple procedure and requires little information input. Also, it is quite convenient to use in practice because it directly utilizes standard outputs from loss assessment tools such as HAZUS. In addition, it requires much less computational effort than Monte Carlo simulation by adopting approximation of uncertainty propagation. It can give consistent and reasonable estimates in earthquake impact assessment. Thus, the proposed procedure will be powerful to obtain considerably reliable estimates for a complex system.

A reliable estimation should be accomplished by using objectively acceptable uncertainty included in the earthquake loss estimation procedures. Since reliability of the information and data used in the assessment depends on the uncertainty from the definition of seismic sources to the estimation of economic loss, more efforts to understand the physical phenomena of the seismic hazard and fragility and to collect the reliable and sufficient inventory data should be required for better decision-making.

These particular investigations and research tasks will assist most emergency support functions (ESFs) with their planning and operations as outcomes include ranges of many impact parameters that are vital to the development of response approaches and plans.

**Mass Care and Social Impact Analysis**

Future work will improve social impact and response requirements models including displaced population, shelter requirements, health and medical requirements, resource requirements and temporary housing needs that are dependent on social vulnerability, infrastructure resilience, and time since the earthquake. This should be done by including consideration of secondary disasters (fire following, inundation, aftershocks) and by estimating the impacts of cascading infrastructure failure from multiple sequential earthquakes.

This particular investigation and research task will assist emergency support functions (ESFs) with their planning and operations:

- ESF 8: Public Health and Medical Services

**Populations Affected by Utility Service Interruptions**

Current models do not estimate damage to the electrical grid and use very rough models for energy and water infrastructure impacts. These models should be improved with the cooperation of the Department of Energy and the populations potentially impacted will be identified. Requirements for provision of emergency water and energy should be identified and tools to support system restoration will be developed.

Social impact and requirements models will be extended to facilitate the transition to short term and long term recovery. Recovery, the last phase of emergency management, is the least understood and most poorly coordinated phase of disaster management. Coordinated by FEMA, the current goal of long-term recovery is minimal: to identify and facilitate availability and use of sources of recovery funding, and providing technical assistance (such as impact analyses) for community recovery and recovery planning support. Recovery planning and management will involve a broad range of government agencies. Models will be able to forecast temporary and long-term housing requirements, infrastructure restoration requirements, and individual and community assistance needs.

This particular investigation and research task will assist emergency support functions (ESFs) with their planning and operations:

- ESF 14: Long Term Community Recovery

## New Models and New Components

### River Navigation Methodology

The geography of the Central US is defined by numerous major rivers, many of which are used to transport large amounts of commodities to and from the region. The Mississippi River, for example, is a major shipping artery connecting northern states to the Gulf Coast. If this main shipping channel, or other regional shipping channels, is cutoff there are significant impacts on several major industries that use these rivers to transport commodities. The development of a methodology to determine obstructions in rivers and major navigation channels will help planners, response workers, and private industry address debris removal and potential rerouting of shipments due to river obstructions. Additionally, river obstructions may prevent or cause the rerouting of any evacuation that utilizes water transportation. Finally, river obstructions are often bridges that have collapsed in major rivers and these collapsed bridges may have trapped victims that need assistance from search and rescue teams.

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 1: Transportation
- ESF 3: Public Works and Engineering
- ESF 5: Emergency Management
- ESF 7: Logistics Management and Resource Support
- ESF 9: Search and Rescue
- ESF 11: Agriculture and Natural Resources

## Cumulative Damage Fragilities

This research activity will investigate the response behavior of typical structures and lifeline facilities in the NMSZ under multiple earthquakes. It is well known that the New Madrid Fault could be divided into three segments, namely: (i) the northeast segment; (ii) the reelfoot thrust; and (iii) the southwest segment (Figure 52).

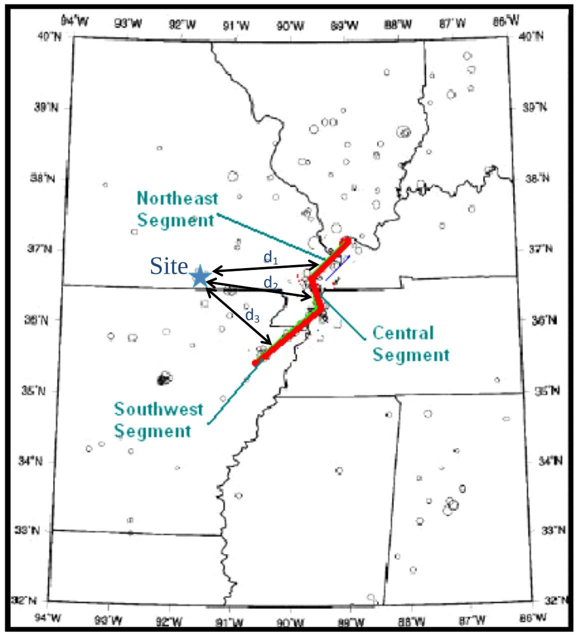


**Figure 52: Proposed New Madrid Fault Segments**

Each segment can generate an individual earthquake record of magnitude 7.7 or more. Therefore the vulnerability of structures and lifelines in the NMSZ should consider multiple earthquake effects. The 1811-1812 series of earthquake events is a good example of such a situation where three earthquakes having three different sources, each of high magnitude, were felt at far distances. This section will study all possible scenarios of successive earthquakes that can be generated from the New Madrid Fault along its three main segments. Artificial records at bedrock developed in previous studies should be used. The records consider source-to-site distance effects for ground motions of different sources using attenuation relationships developed particularly for the central and eastern United States rock type (Atkinson and Boore, 1995). Site response analyses should be conducted based on the dynamic soil properties of the soil underneath the structure or facility of interest. Numerical models should be established using Zeus-NL software, which is capable of analyzing different types of structures taking into consideration the material and geometrical non-linearities. New material models should be implemented in this software. The models account for accumulated any structural damage and energy dissipation that occurred in the preceding ground motions/earthquakes (Gomes and Appleton, 1997). The behavior of the structures subjected to two and three earthquakes should be compared with that subjected to one individual record. The results will reveal that considering only one earthquake record, even if the main shock is the one considered, in deriving fragilities of structural damage may underestimate their vulnerability if they are susceptible to more than one earthquake (Ascheim and Black, 1999). In addition to the numerical modeling, further experimental work should be conducted for typical structures in the NMSZ. Typical reinforced concrete frames with different design criteria should be tested for one, two and three earthquakes (Lee and Fenves, 1998). Structural regions of highly predicted non-linearities will be tested using the small scale Loading and Boundary Condition Boxes (LBCBs).

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 1: Transportation
- ESF 3: Public Works and Engineering
- ESF 5: Emergency Management
- ESF 6: Mass Care, Emergency Assistance, Housing, and Human Services
- ESF 7: Logistics Management and Resource Support
- ESF 8: Public Health and Medical Services
- ESF 9: Search and Rescue
- ESF 14: Long-Term Community Recovery

**Fire Following Earthquake (FFE)**

Earthquakes are often followed by subsequent fires that result directly from earthquake damages; however, losses due to fire are not considered in the current loss assessment model. Fires following earthquakes have the potential to cause major damage and can cause losses multiple times larger than the losses caused by the earthquake event itself. An excellent example of fire damage after an earthquake is the 1906 San Francisco earthquake where it is estimated that up to 90% of the total loss was caused by the fires that ignited subsequent to the earthquake (Tobriner, 2006). Regions with high percentage of wood structures are more prone to fire damage following earthquakes. Based on the inventory analysis for the 8 states, about 80% of inventory is comprised of wood buildings, causing the fire damage probability to be high. Therefore, it is essential that in future stages of impact assessment adequate FFE models be implemented. FFE models differ from spontaneous fire models because of significant differences in both situations. In FFE model applications there are several factors that significantly affect the fire initiation, spread, and duration. Unlike normal fires, during FFEs, initial structural damage is probable (due to earthquake damage). In addition, it should be taken into consideration that initial firefighting capabilities are compromised as well. For example, there could be damaged water pipelines, fire stations, fire engines, etc. Due to these major differences, normal fire models would not be applicable.

FFE models are relatively recent and they could be divided into three main groups: ignition, spread/suppression, and suppression models. Ignition models usually estimate the number, location, and times of fire ignition after an earthquake. Most ignition models relate an earthquake intensity measure to ignition frequency through regression models.

Spread/suppression models involve the estimation of fire spread, given the initial ignition locations. The estimate can involve several degree, including the geographic spread or status (e.g, burned or not, percentage burned) as a function or time, with or without suppression measures. Models are used to estimate the suppression time given the burn status. Integrated FFE models incorporate all three aforementioned models and are preferred because of integrated variables (Lee et al., 2008).

Some limitations that should be taken into consideration are the lack of validation (because models are without precedents) and the accurate physical inventory requirements. During the process of FFE model selection, several factors to be considered would involve input parameters (number of parameters and respective uncertainty), required level of analysis, degree of model verification, and time available to complete the FFE studies. The selected model should represent a scientifically sound FFE application.

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 1: Transportation
- ESF 3: Public Works and Engineering
- ESF 4: Firefighting
- ESF 5: Emergency Management
- ESF 7: Logistics Management and Resource Support
- ESF 9: Search and Rescue
- ESF 10: Oil and Hazardous Materials Response
- ESF 12: Energy
- ESF 13: Public Safety and Security

**Utility System Interdependencies**

Given that all lifeline networks interact with each other forming a complex system, those interactions have to be considered in the analysis in order to achieve more accurate assessments. One example of a network dependency is the relationship between electric power and potable water networks. A water network requires electric power for pumping water to higher elevations. Thus, an undamaged water pumping station may still be dysfunctional due to a power failure caused by damage to the power network. Kim (2007) quantified the effect of network interdependency to the proposed network performance measures (Figure 53).

The interdependency model can be enhanced by the addition of two-way modeling of network interactions instead of one directional dependency. The implementation of multi-modal networks would also enable modeling of more than two networks with more complex interactions in a single analysis.

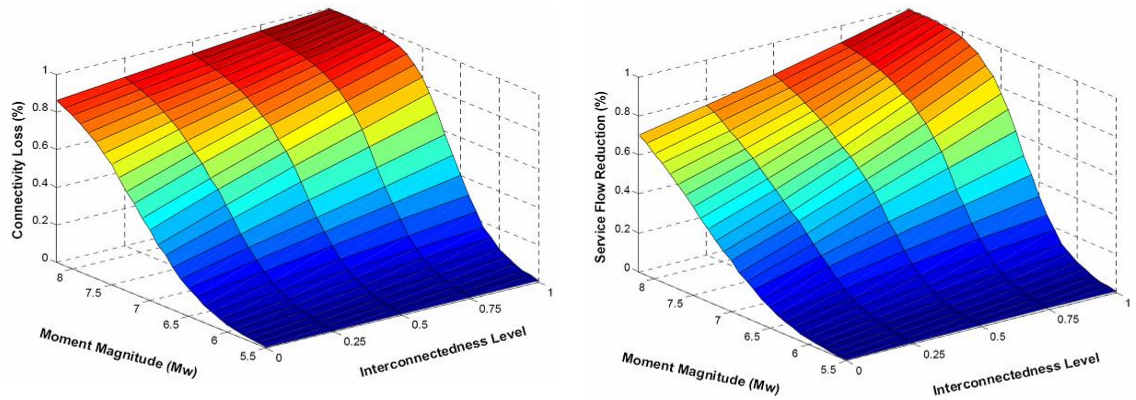


**Figure 53: Effect of Interdependencies on Network Performance (Kim, 2007)**

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 3: Public Works and Engineering
- ESF 4: Firefighting
- ESF 5: Emergency Management
- ESF 7: Logistics Management and Resource Support
- ESF 10: Oil and Hazardous Materials Response
- ESF 11: Agriculture and Natural Resources
- ESF 13: Public Safety and Security

**Situational Awareness**

Disaster operations personnel require situational awareness immediately after a disaster to begin their response efforts. Often, it takes several hours or a full day to obtain useful situational awareness which prevents commodities, aid workers and response management staff from deploying resources fully. Maps of seismic ground motions are developed very rapidly after an earthquake event and these ground motions can be added to earthquake impact assessment models. Within an hour or two after the event, a complete earthquake impact assessment model can be run and the results used for basic situational awareness. Based on the results of the initial modeling, deployments of key personnel and commodities can begin and help reach victims more quickly. This effort will likely be coordinated with the Mapping Analysis Center (MAC) within FEMA.

This particular investigation and research task will assist all emergency support functions since all require basic situational awareness prior to initiation of services and response activities.

**Tools for Logistics Planning Support**

Models developed in this study and those under development currently and intended for future use will support the logistics planning required for response activities. The response needs analysis will identify the commodities and supplies needed in each geographic area. The transportation network damage and availability analysis will support optimal logistics routing. Damage and liquefaction models will identify areas unsuitable for distribution center location. Additional analysis will identify efficient locations for logistics facilities and will provide support for routing/distribution decisions.

This particular investigation and research task will assist emergency support functions (ESFs) with their planning and operations:

- ESF 7: Logistics Management and Resource Support

**Tools for Health, Medical, and Mass Care Management**

The estimation of location and types of injuries, along with location of fatalities, the analysis of the medical needs of impacted and displaced persons, the identification of special needs population, the estimation of damage and loss of functionality to hospitals and other medical service delivery facilities, all provide a basis for the development of decision support tools for health, medical and mass fatality management. Models will be developed to support planners to calculate the medical, public health, mental health staff and resource requirements and to develop and test resource allocation strategies.

This particular investigation and research task will assist numerous emergency support functions (ESFs) with their planning and operations:

- ESF 6: Mass Care, Emergency Assistance, Housing, and Human Services
- ESF 8: Public Health and Medical Services

**Modeling Requirements for National Level Exercise (NLE) 2011**

This effort will assist federal response organizations by supporting the requirements for a common operating picture, organizational coordination and communication, and logistics management during actual incidents or for exercise preparation and execution. The modeling will support strategic planning and decision making. It will, for example, provide a comparison of strategic alternatives for supporting large populations in areas deprived of sustaining infrastructure. Should the government evacuate large numbers of people to areas where they can obtain necessary services or should the services be brought to the impacted area? Should special shelters be established for displaced people with medical needs or should shelters be staffed with medical personnel. What are the limits to services that can be provided with present capacity?

Models of cascading disaster impacts and failures designed to fit NLE 2011 design scenario will be developed, and the social impacts and potential response requirements will be calculated for time intervals determined by the NLE 2011 scenario. Modeling efforts will include analysis of response decision-making, coordination activities, development of time-phased force and deployment plans, determination of information and analysis requirements for situational awareness, support of incident action planning and an analysis of logistics system objectives and requirements

This particular research task will assist most emergency support functions (ESFs) with their planning and operations as models are designed to assist numerous ESFs in preparation efforts for the NLE 2011.

## Applications Requiring Earthquake Impact Results

### Regional Response Planning

It was essential that the results of this analysis be presented to state and regional planners in the most effective way possible. A large portion of the catastrophic planning effort took place at regional and state workshops. Many of the participants at these workshops were not familiar with the hazard in the NMSZ and were not prepared for the magnitude of physical and social impacts nor the response requirements. In an effort to rapidly familiarize the planning community with the impact assessment results and utilize them in planning workshops, an operational analysis was performed. The goal was to provide participants with a common operating picture.

An in-depth review of FEMA documents, used in past disasters, such as Hurricanes Katrina, Rita, Gustav and Ike, was conducted. Using these documents as guidelines, a template for presenting the analysis at the workshops was developed. This template was reviewed by FEMA regional and national headquarters personnel as well as other members of the emergency management community. Changes were made based upon comments from various reviewers.

While earthquake impact assessments are inherently useful to emergency managers and planners, it is necessary to present results of these analytical impact models in forms that are valuable to the specific audience. Under the guidance of project partners in the emergency management sector, products were created for a series of four FEMA regional workshops and designed to facilitate discussion among participants. These general sessions utilized the wide variety of materials presented by the project team to develop response timelines and goals in the hours and days after the event. In addition to providing materials for general sessions, the project team provided impact results for regional senior leaders meetings. This group of top decision-makers requires data in a more malleable form. The static images that are used for general sessions were insufficient for the types of activities completed by senior leaders.

Taking the above into account, the project team developed a series of interactive maps that permitted users to view numerous impact parameters simultaneously. The Geo-PDF software from Terra Go Technologies© was utilized to create simple Portable Document Format files that work in the free Acrobat Reader© software. The ability to view multiple impacts at one time allowed the senior emergency response leadership to better grasp overall post-event awareness. The ability to focus on various key response efforts by simply changing the display features of impact maps allows the top management personnel to rapidly move between discussion topics such as evacuation, health care, public sheltering and others. Additionally, numerous systems that factor into a response effort can be incorporated into the visual display. As an example, post-event medical services are needed to treat the injured, as well as care for current hospital patients. While it is vital to know the status of hospitals, the transportation network must be intact in order to transport victims to medical care centers. Furthermore, transportation routes must stay clear of potentially flooded areas and avoid congestion on roadways. The ability of senior leaders to consider a wide variety of factors in an interactive map form was an extremely beneficial addition to the other products developed by the project team for emergency management workshops at the FEMA regional level.

# Conclusions

The earthquake impact assessment completed in this study employs the most current and reliable data available for the Central US, as well as the most advanced and verified models of earthquake impact. The resulting quantitative assessment results provide critically-important information for the response planning process. HAZUS modeling software is used to determine damage to infrastructure, economic losses, and casualties. MAEViz, the Mid-America Earthquake Center's impact assessment software, is used to analyze detailed transportation and utility networks in two major metropolitan areas in the Central US, namely St. Louis, Missouri, and Memphis, Tennessee. Moreover, major river crossings, dams, leaves, hazardous materials and secondary flood risk are all assessed with regard to earthquake damage. Uncertainty is also quantified and ranges of results are provided for several impact parameters. The uncertainty results are the first obtained in large-scale earthquake impact modeling. Numerous additional models are utilized to determine various social vulnerabilities, social impacts, commodities requirements, and search and rescue requirements.

Model results indicate extensive infrastructure damage, casualties, economic loss, and local flood risk. Direct infrastructure damage includes:

- Nearly 715,000 damaged buildings
- Limited medical, firefighting, and law enforcement services in the impacted counties of the eight-state study region
- Extensive damage to transportation infrastructure, including over 3,500 damaged bridges
- Severely inhibited road, rail, air, and river travel in the Central USA
- Substantial damage to utility infrastructure, particularly in the impacted counties, leaving 2.6 million households without electricity and 1.1 million households without water after the event
- Nearly 86,000 casualties, including 3,500 fatalities
- Severe congestion on major interstates in and around St. Louis, Missouri, and Memphis, Tennessee, after the event which substantially increases the time required to complete road travel
- Damage to utility networks in St. Louis and Memphis
- 42,000 personnel required for nearly 1,500 search and rescue teams (Types I–IV)
- Over 730,000 people displaced and 215,000 people seeking shelter immediately after the event, though over 7.2 million are displaced and over two million require temporary shelter three days after the event due to extended lack of utility services
- Approximately $300 billion in direct economic loss

The extent of impact measured in this study is confined to the eight states near the New Madrid Fault; namely Alabama, Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee. Both direct and indirect impacts are likely to extend far beyond the eight states modeled in this study, however. Many major pipelines for oil and natural gas that pass through the eight states experience damage and require thousands of repairs. The flow of these commodities is interrupted by the event and must be diverted to intact pipelines, if available. It is likely that the upper Midwest, east coast, and potentially several states just west of the study region are without adequate amounts of commodities for an extended period based upon the restoration and repair process. Power outages are likely to extend beyond the eight-state study region, particularly if damage near the rupture zone causes a substantial failure of the electric grid. If this occurs, lengthy power outages may persist over numerous states east of the Rocky Mountains.

Major transportation corridors are interrupted by damage to key infrastructure. Extensive bridge and road damage limits the viable routes for transporting commodities across the country. Damage to airports limits business, freight, and recreational air travel as many major airports and local fields are inoperable, some for extended periods. Waterways are blocked with debris reducing the viability of major shipping channels in the US, namely along the Mississippi, Ohio, Missouri, and Arkansas Rivers. Rail lines and bridges are also damaged and transportation of goods via the rail system will be limited across the impacted regions. Critical routes will require substantial restoration, while those experiencing only minor damage may be restored within several days. Many other routes (road, rail, air, and water) may not be fully restored for several months. In some cases it may take years if the infrastructure is completely damaged and must be fully rebuilt.

Modeling results indicate the truly catastrophic nature of the scenario earthquake considered in this study. Impact quantities will likely exceed those presented here due to uncertainties in the modeling and may overwhelm the response capabilities of local, state and federal agencies. Extensive federal and international resources and assistance will be required to respond and rebuild after a natural disaster of this magnitude. Some impacts may be mitigated by retrofitting infrastructure in the most vulnerable areas. By addressing infrastructure vulnerability prior to such a catastrophic event, the consequences described in this report may be reduced substantially.

The resource gaps and infrastructure damage described in this analysis present significant unresolved strategic and tactical challenges to response and recovery planners. It is highly unlikely that the resource gaps identified can be closed without developing new strategies and tactics and expanded collaborative relationships.

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