December 2011

Risk Implications of Alternative Views of New Madrid Seismic Hazard

RMS Special Report

RMS

EXECUTIVE SUMMARY

Numerous scientific issues have been raised regarding the level and uncertainty of seismic hazard in the New Madrid Seismic Zone (NMSZ) and the surrounding region of the Central United States. However, the scientific community is in broad agreement with the geologic evidence of repeated large earthquakes in the last several thousand years. Moreover, ongoing seismicity rates suggest a 28–46% likelihood of a M6.0 or greater earthquake in the broad region around New Madrid in the next 50 years. In this paper, a sensitivity analysis is presented that demonstrates that ground motion attenuation relationships dominate the uncertainty in modeled loss, providing upper and lower bounds on losses for nearly all alternative hazard representations considered.

Specifically, expected regional total economic losses for the hazard level captured in the 2008 USGS National Seismic Hazard Maps are $50 billion for a 1-in-250-year return period loss and $150 billion for the 500-year return period loss. Memphis and surrounding Shelby County, directly adjacent to the southern end of the NMSZ, have the highest urban economic loss cost (defined as the average annual loss normalized per thousand dollars of total exposure value) in the region at 0.52. This value, however, is only 20–25% of the economic loss cost for Los Angeles and San Francisco counties, highlighting the contrast in hazard between the New Madrid region and California in shorter return periods (e.g., less than 100 to 200 years). Analysis of a range of scenarios in the New Madrid region indicate that even moderate earthquakes (M6.1–6.5) adjacent to major urban areas will generate total losses in the range of $10 to $100 billion and insured losses of $5 to $50 billion. Insurance payments are forecast to cover 60–80% of total economic losses, thus contributing significantly to recovery in the region. This ratio of insured to total loss is higher than the 45–55% ratio observed in hurricanes Ike (2008), Katrina (2005) and Andrew (1992), and significantly larger than the anticipated ratio of 10–15% for major California earthquakes.

INTRODUCTION

The year 2011 marks the 200th anniversary of the first in a sequence of three M7 or greater earthquakes that occurred over a 54-day period spanning 1811 to 1812 along the Mississippi River near the town of New Madrid, located 240 km south of St. Louis (Figure 1). Ground shaking from the three mainshocks, which struck on December 16, 1811, January 23, 1812, and February 7, 1812, was felt over the entire Eastern U.S. by people up to 1400 km from the epicenters (http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php). The aftershock sequence was also impressive, with hundreds of felt earthquakes lasting for months. A high level of seismicity persists in the New Madrid Seismic Zone (NMSZ) region to the present time and is considered by some to be part of the continuing aftershock series (e.g., Stein and Newman, 2004). Earthquakes in the region are well located by a dense seismic network operated by the Center for Earthquake Research and Information (CERI), at the University of Memphis since 1975 (http://www.ceri.memphis.edu/seismic/).

The strong shaking from the 1811–1812 earthquake cluster caused intense levels of ground failure in the form of liquefaction evidenced by sand blows in sandy soil in the river valley. The sand blows were noted at the time, and many are still visible in the fields today. Geologic studies over the past 30 years have revealed older, widespread severe ground failures similar to those caused by the earthquake sequence, indicating that the 1811–1812 earthquakes were not an isolated event. The New Madrid Seismic Zone is believed to have produced repeated sequences of major earthquakes, most recently around1450 A.D., 900 A.D., 300 A.D. and possibly 2350 B.C. (Tuttle et al., 2002; Tuttle et al., 2005). Additional geologic and seismic reflection studies have indicated that large earthquakes have occurred more broadly within the New Madrid region and in the Wabash Valley to the north throughout the Holocene epoch (i.e., over the last 10,000 years) (Munson et al., 1997; Pond and Martin, 1997; Obermeier, 1998; McNulty and Obermeier, 1999; McBride et al., 2002; Tuttle et al., 2006; and McBride et al., 1997).

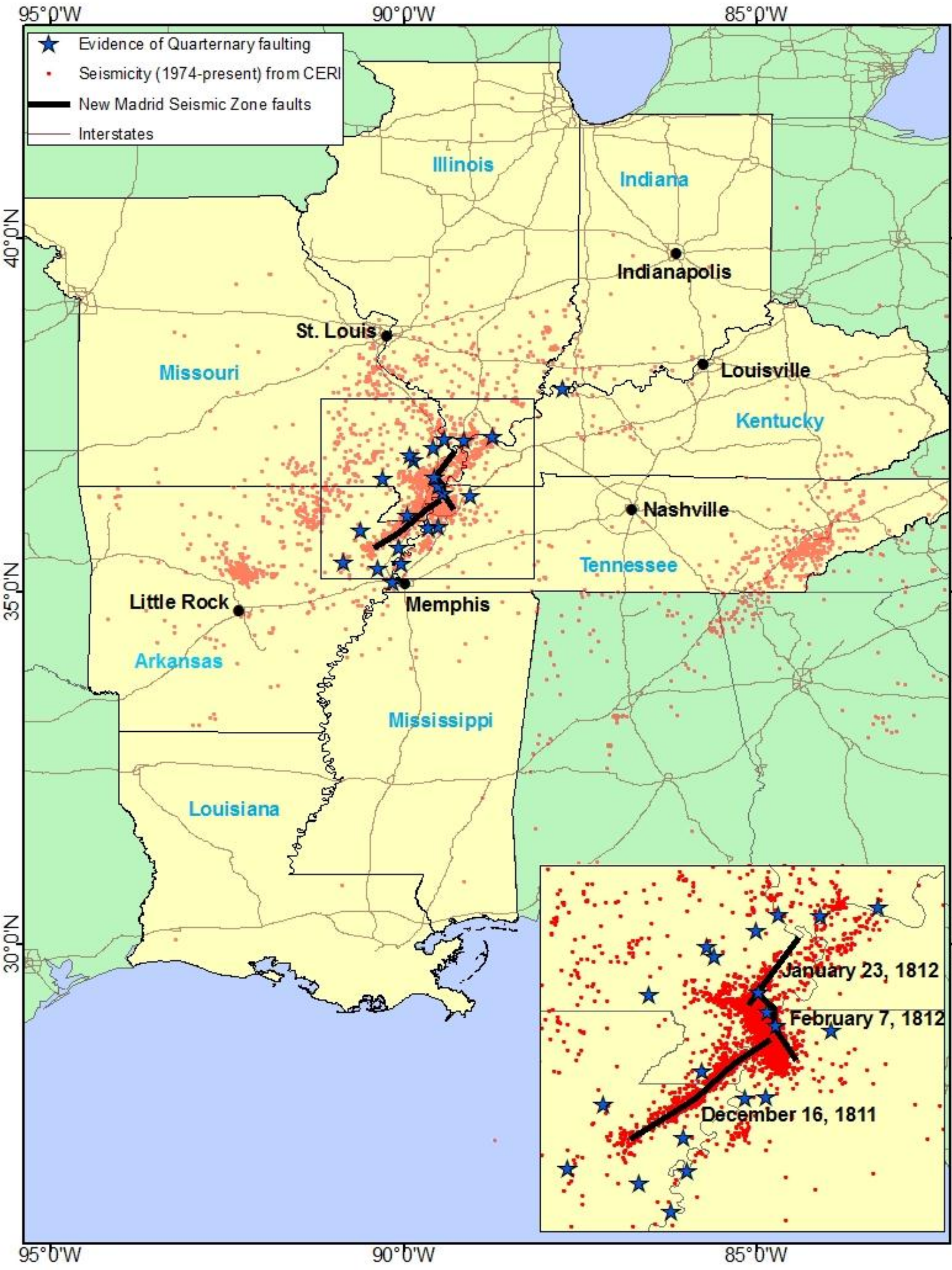
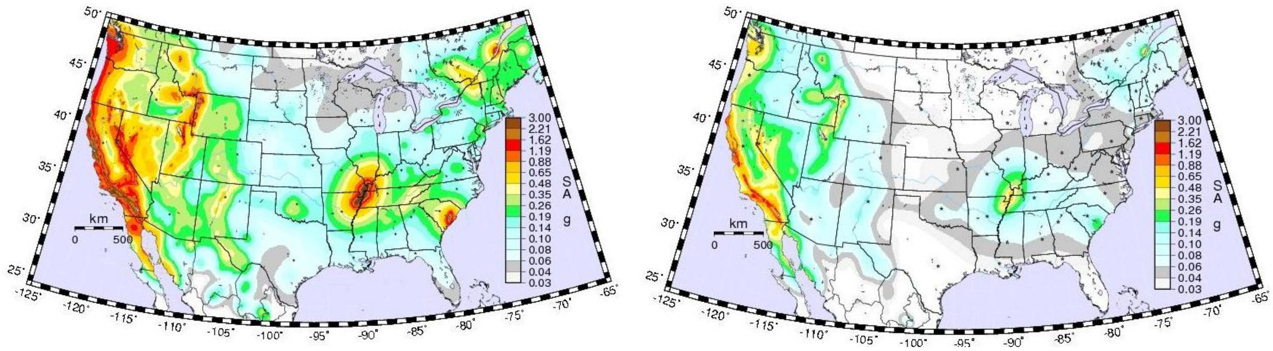


Figure 1: Map of New Madrid Seismic Zone, showing seismicity (1974–present from the Center for Earthquake Research and Information or CERI) and faults inferred responsible for the 1811–1812 sequence (after Cramer, 2001). Localities where Quaternary faulting has been documented shown by blue stars (http://earthquake.usgs.gov/regional/ceus/images/NMSZEricsMapFINAL.pdf), with the eight-state study region highlighted in yellow and interstate highways shown by brown lines.

In 2008, the USGS produced the most recent version of the U.S. National Seismic Hazard Maps. These maps were developed using a logic-tree approach, based on input from a series of regional and topical workshops with scientific experts in 2006 and 2007. The maps capture the present state of scientific knowledge on earthquake hazard throughout the U.S., including the New Madrid region. For long return period ground motion exceedance (i.e., 2% probability of exceedance in 50 years or approximately the 2,475 return period hazard), the USGS-computed hazard levels in the New

Madrid region are similar to hazard values along the Western U.S. plate boundary (Figure 2(a)). However, for shorter return periods (at the 10% in 50 years exceedance level or 474 return period hazard), the Western U.S. has significantly greater hazard, reflecting the plethora of short return period earthquake sources in California (e.g., well-constrained crustal faults) versus the Central U.S. (Figure 2(b)).



(a) (b)

Figure 2: 2008 USGS National Seismic Hazard Maps: (a) 0.2 second spectral acceleration at 2% probability of exceedance in 50 years (2,475-year return period) and (b) 0.3 second spectral acceleration at 10% probability of exceedance in 50 years (474-year return period).

While the occurrence and effects of the 1811–1812 earthquake sequence are now well-documented, there has been ongoing scientific debate around the level and uncertainty of seismic hazard in New Madrid and the surrounding region of the Central United States. For example, Hough and Page (2011) reanalyzed damage and intensity data and concluded that the magnitudes of the three main 1811–1812 New Madrid earthquakes are in the high 6 to low 7 range, rather than the M7.8–8.1 range originally suggested by Johnston et al. (1996). Furthermore, Newman et al. (1999) and Calais and Stein (2009) interpret the absence of measurable contemporary strain accumulation in the New Madrid region to indicate that the repeat times for New Madrid earthquakes may be much longer than assumed based on the paleoliquefaction data. Thus, the seismic hazard in the region must be substantially lower than represented on the USGS National Seismic Hazard Maps.

This report analyzes the impact of alternative hazard representations on the quantification of seismic risk across the New Madrid region. The primary focus is to evaluate how uncertainties in seismic hazard parameters impact estimated losses, both probabilistically and through a series of credible scenarios. This paper also explores the ability of the region to recover from a significant earthquake, with particular attention given to the role of earthquake insurance in funding reconstruction.

ALTERNATIVE HAZARD REPRESENTATIONS FOR THE NEW MADRID SEISMIC ZONE

In this analysis, alternative hazard representations of the New Madrid Seismic Zone are explored. Four key parameters influence the quantification of seismic hazard in the New Madrid region: empirically-based ground motion attenuation relationships, the location and geometry of seismic sources, the magnitude of potential earthquakes and their recurrence.

1. *Ground motion attenuation*: These mathematical relationships describe how the intensity of shaking decays with distance from the earthquake source. As these relationships are empirically-based, the uncertainty arises from the lack of validating strong ground motion recordings in stable continental regions like the Central and Eastern United States. In the development of the 2008 USGS National Seismic Hazard Maps, seven distinct attenuation relationships were considered potentially applicable to this region[1].
2. *Earthquake magnitude*: Estimates of magnitudes inferred for the three main faults within the New Madrid Seismic Zone (NMSZ) (responsible for the 1811–1812 sequence) range from M6.6 to M8 (Table 1). Because there are no seismograph records of these earthquakes, magnitudes are primarily inferred from damage reports, but are also tested against data from other large intra-continental events around the world.
3. *Earthquake recurrence rate*: Paleoliquefaction evidence, as noted above, has been interpreted as indicating an average repeat time for major New Madrid earthquakes of about 500 years (Tuttle et al., 2002). However, analysis of crustal strain using high precision GPS receivers in the region yields no detectable geodetic strain accumulation signal. There have been a range of explanations given to this result, including: a much longer repeat time than implied by the paleoliquefaction evidence, major earthquake sources that migrate over time broadly throughout the region, and/or possibly a fortuitous, present-day end to the New Madrid earthquake activity (Newman et al., 1999; Tuttle et al., 2009; Calais and Stein, 2009; and Calais et al., 2010).
4. *Location and geometry of sources*: The meandering of the Mississippi River has obscured surface evidence of faulting in the New Madrid Seismic Zone. Geologic evidence for a subsurface fault has only been found beneath the central segment of the 1811–1812 fault ruptures. Therefore, there is a significant potential for alternative faulting geometries. The paleoliquefaction data only attest to strong shaking in the region–not the location of specific fault sources. In addition, recent studies have revealed evidence of young faulting in a number of localities distributed throughout the Mississippi and Wabash river valleys (see Figure 1, Magnani and McIntosh, 2009; and list of references at: http://earthquake.usgs.gov/regional/ceus/images/NMSZEricsMapFINAL.pdf).

[1] The recent earthquakes in Virginia (M5.8 on August 23, 2011) and Oklahoma (M5.6 on November 5, 2011) will provide much needed data for validating current ground motion attenuation relationships.

Table 1: Magnitude estimates for three mainshocks in the 1811–1812 New Madrid earthquake sequence

Event	**Rupture Segment**	**Johnston (1996)**	**Hough et al (2002) Hough and Martin (2002)**	**Bakun and Hooper (2004)**	**Hough and Page (2011)**	**Cramer and Boyd (2011)**	**Magnitude assumed for Hazard Option 3**
December 16, 1811	Southern segment	8.1	7.2 – 7.3	7.2 – 7.6	6.8	~ 7.6	7.3
January 23, 1812	Northern segment	7.8	7.0	7.2 – 7.5	6.6	7.2 – 7.6	7.1
February 7, 1812	Central segment	8.0	7.4 – 7.5	7.4 – 7.8	7.0	> 7.6	7.3

In constructing the National Seismic Hazard Maps, the USGS takes scientific uncertainty into account using a logic-tree approach, in which all scientifically valid estimates for various hazard parameters are included and weighted by experts. In the 2008 version of the maps for the Central and Eastern U.S., the USGS considered and weighted seven distinct ground motion attenuation curves, as shown in Figure 3. The logic tree used for the seven attenuation curves, indicating the relative weights of the branches, is illustrated on the right. Additional logic tree branches were used to capture the full range of scientific opinion, including four different magnitude values for each of the NMSZ faults and two different recurrence intervals.

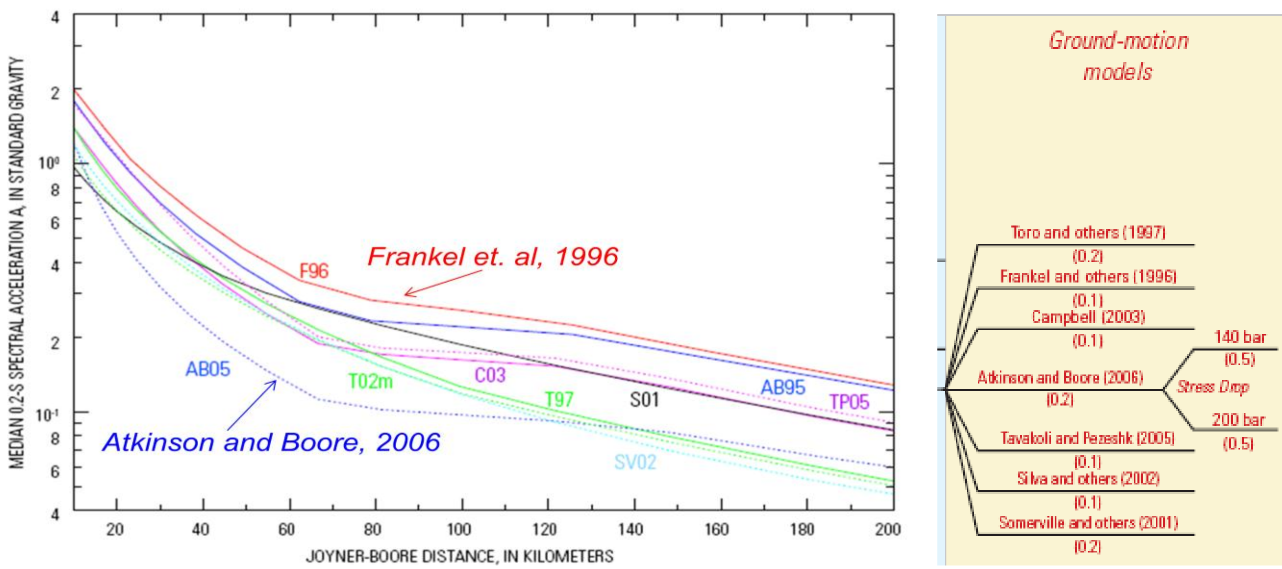


Figure 3: Central and Eastern U.S. 0.2 second spectral acceleration attenuation relationships for a M7 earthquake on a vertical strike-slip fault and Vs30 760-m/s site conditions (left). Attenuations are labeled as: AB95 (Atkinson and Boore, 1995), AB05 (Atkinson and Boore, 2006), F96 (Frankel et al., 1996), T97 (Toro et al., 1997), T02m (Toro, 2002), C03 (Campbell, 2003), S01 (Somerville et al., 2001), SV02 (Silva et al., 2002), and TP05 (Tavakoli and Pezeshk, 2005). Portion of USGS logic tree for New Madrid Seismic Zone ground motion relationships (right). (Source: Petersen et al., 2008).

Sensitivity Analysis

RMS has performed a series of sensitivity tests to explore the significance of the uncertainty associated with each of the four key hazard parameters listed above and their impacts on loss estimates. In this analysis, the baseline for comparison is the 2008 USGS National Seismic Hazard Maps (i.e., the test case loss is compared to the loss generated using the assumptions in the consensus-based 2008 USGS hazard maps).

In order to separate the effects of different parameters on risk, only one parameter is varied at a time. In all but the final option, the parameter variations follow branches of the USGS logic tree, simply changing the weight to test the assumptions. Table 2 summarizes the six alternative hazard representations analyzed. A modified version of the RMS® U.S. Earthquake Model was created to evaluate each option[2].

Note that the final option (denoted #6 – Distributed Source Region in Table 2) is not a branch of the logic tree used in the development of USGS National Seismic Hazard Map, but rather represents an effort to reconcile the elevated regional seismicity around the New Madrid Seismic Zone (NMSZ), the lack of a geodetically measured strain accumulation within the NMSZ proper, and the regional distribution of Quaternary faulting shown in Figure 1. This option can be considered a proxy representation of two of the proposed explanations for the lack of a geodetic strain signal: either major earthquake sources migrate over time (Tuttle et al., 2009; Calais et al., 2010) or the phase of activity in and around New Madrid has now ended (Calais and Stein, 2009). Both explanations acknowledge the paleoliquefaction and other geologic evidence of repeated major earthquake faulting broadly throughout the region and the high seismicity within the NMSZ and surrounding region.

Table 2: Alternative New Madrid Seismic Zone hazard representations

Alternative Hazard Option	**Description**	**Comparison to 2008 USGS Hazard Maps**
#1 – Upper bound attenuation (High ground motion/slow attenuation)	Highest predicted ground motions; 100% weight on relationship of Frankel et al. (1996)	10% weight on Frankel et al., 1996 relationship; upper bound of 7 attenuation relationships used in the NMSZ
#2 – Lower bound attenuation (Low ground motion/fast attenuation	Lowest predicted ground motions; 100% weight on relationship of Atkinson and Boore (2006)	10% weight on Atkinson and Boore (2006); lower bound of 7 attenuation relationships used in the NMSZ
#3 – Reduced magnitudes	100% weight on lowest magnitude considered by the USGS for each of the 3 NMSZ sources (see Table 1)	15% weight on lowest magnitude; one of four magnitudes considered for each of the NMSZ fault segments
#4 – Single source for NMSZ	100% weight on “central” pseudo-fault	70% weight on central pseudo-fault, 10% on parallel faults offset 15 km, 5% on pseudo-faults offset 30 km
#5 – Reduced recurrence rates	90% weight on 1,000 years, 10% weight on 500 years (i.e., flipped USGS weighting)	90% weight on 500 years and 10% on 1,000 years
#6 – Distributed source region	Eliminate specific New Madrid faults and redistribute seismic moment uniformly over high seismicity zone	No equivalent

Boyd (2010) analyzed instrumental and historic seismicity rates in a broad zone of elevated seismicity including and surrounding the New Madrid region and concluded that there is a 95–99% likelihood of a M5 or greater earthquake in the next 50 years and a 28–46% likelihood of a M6 or greater event in next 50 years throughout the region highlighted in Figure 4. The paleoliquefaction data of past major events (e.g., on the scale of the 1811–1812 cluster, M7 and greater) suggests a rate of about 10% in 50 years.

In hazard option #6, the geologic seismic moment (energy release) rates attributed to earthquakes on the NMSZ are uniformly redistributed onto a series of approximately 300 evenly spaced seismic sources throughout a roughly

[2] For example, an alternative stochastic event set was developed to explore varying recurrence rates and weights on the attenuation relationships were varied to explore ground motion predictions.

elliptically-shaped zone of elevated seismicity around the NMSZ (Figure 4). These redistributed rates are added to the existing background seismicity rates in the USGS model. This alternate representation has the effect of greatly "smearing" out the NMSZ hazard and creates very low rates of return for large magnitude earthquakes (M7.1+) throughout the entire region. This redistribution of the NMSZ seismic moment preserved the total moment release throughout the region. This final hazard option could be thought of as representing a case in which the NMSZ earthquakes 200 years ago are simply part of a regionally elevated zone of high seismicity and that the paleoliquefaction evidence could be related to multiple sources throughout the region, consistent with the more broadly distributed incidences of Quaternary faulting shown in Figures 1 and 4. The boundaries of the zone selected for this final hazard alternative were drawn in consultation with Rob L. Williams of the USGS (Williams, 2011, written communication) and generally follow the distribution of elevated seismicity, as well as gravity and magnetic anomalies indicating major crustal boundaries.

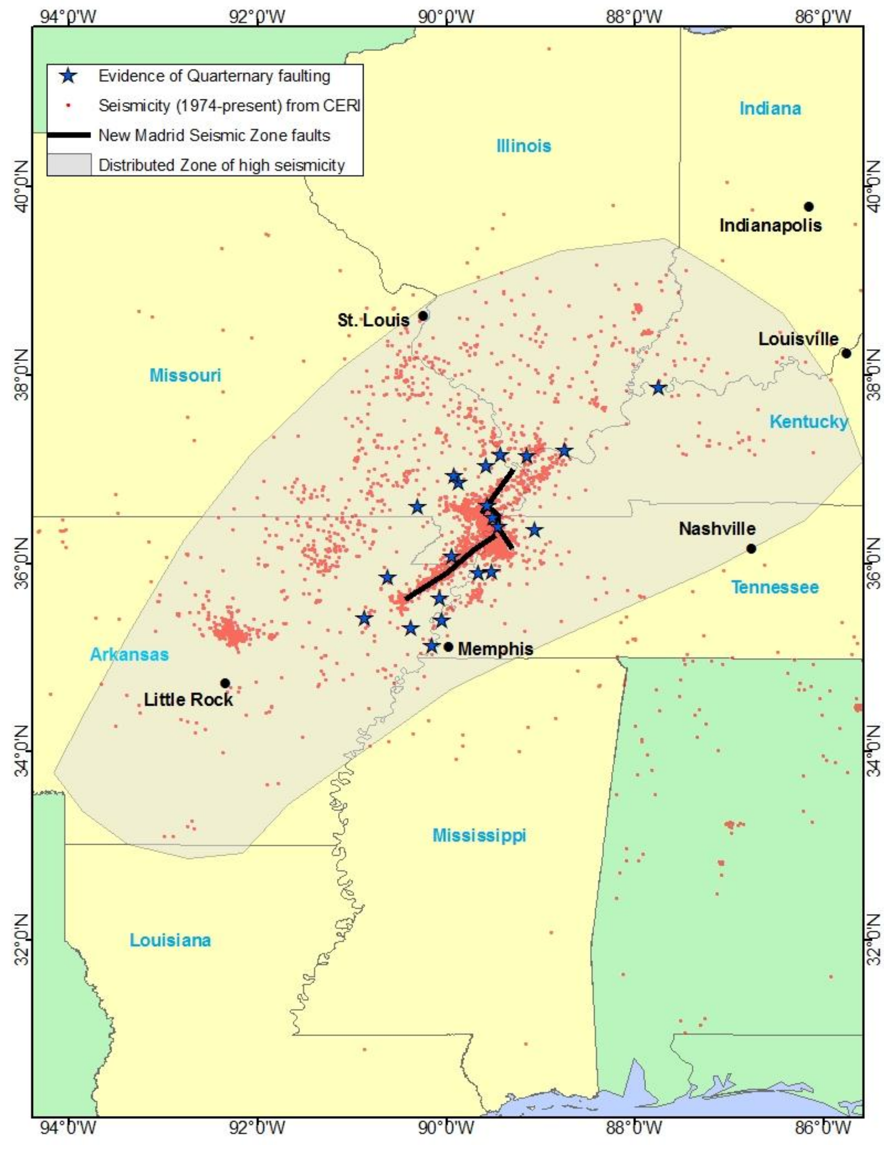


Figure 4: Distributed zone of high seismicity: Brown ellipse outlines the distributed source region surrounding the New Madrid Seismic Zone; red dots indicate earthquakes occurring since 1974 (from the CERI catalog). Blue stars show the location of sites where Quaternary faulting has been identified (http://earthquake.usgs.gov/regional/ceus/images/NMSZEricsMapFINAL.pdf) and heavy black lines indicate inferred faults activated in the 1811–1812 earthquake sequence after Cramer (2001).

RESULTS

The expected losses for the alternative hazard representations are modeled both probabilistically and for specific earthquake scenarios. The probabilistic analysis combines the impact of all likely earthquake scenarios weighted by their annual likelihood of occurrence and explores the sensitivity of loss to the various hazard parameters. The earthquake scenarios help explore the effects of earthquake location, magnitude, and ground motion attenuation relationships on loss estimates.

Losses are analyzed both for the entire eight-state study region (as shown in Figure 1) and also for six major urban centers within it. As indicated in Table 3, more than 46 million people live in the eight-state study region, which has nearly $9 trillion total economic exposure value. Property exposures are based on U.S. Census data, as well as the 2011 RMS® U.S. Industry Exposure Database (IED), which estimates total insured values for building and contents coverages. The exposure in the six urban centers, aggregated at the county level, totals more than $1.1 trillion and has slightly more commercial exposure value than residential exposure value. Together, these six urban centers represent roughly 11% of the population and more than 12% of the total exposure value of the eight-state study region. Concentrations of property exposure are illustrated in Figure 5.

Table 3: People and property at risk in the greater New Madrid region

Urban Center (County)	2010 County level population*	Total Exposure Value	Residential Exposure Value	Commercial Exposure Value
Indianapolis, IN (Marion County)	903,390	$200 billion	$95 billion	$105 billion
St. Louis, MO[1] (St. Louis County & City County)	1,349,000	$365 billion	$205 billion	$160 billion
Louisville, KY (Jefferson County)	741,100	$165 billion	$85 billion	$80 billion
Nashville, TN (Davidson County)	626,680	$140 billion	$75 billion	$65 billion
Memphis, TN (Shelby County)	927,640	$195 billion	$110 billion	$85 billion
Little Rock, AK (Pulaski County)	382,750	$75 billion	$40 billion	$35 billion
Totals for six urban centers	**4,930,560**	**$1,140 billion**	**$610 billion**	**$530 billion**
Total for eight-state region	**46,405,430**	**$8,950 billion**	**$5,430 billion**	**$3,520 billion**

* http://quickfacts.census.gov/qfd/states

1 St. Louis City County and St. Louis County are combined for this analysis in order to encompass the entire metropolitan area.

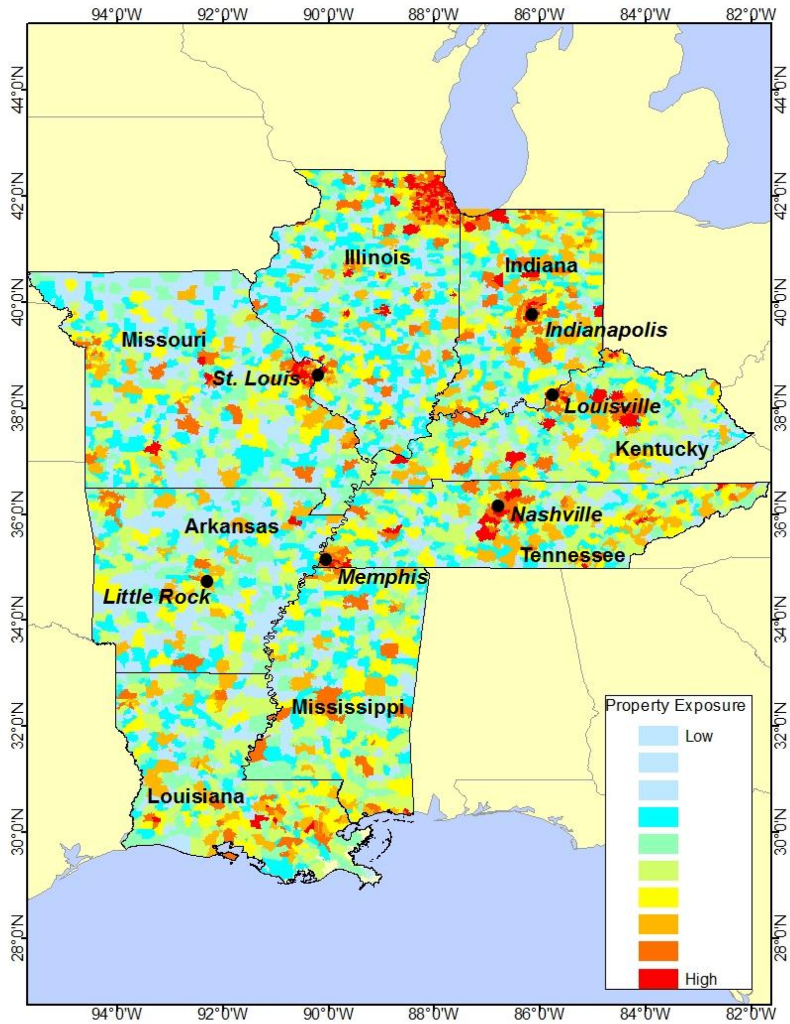
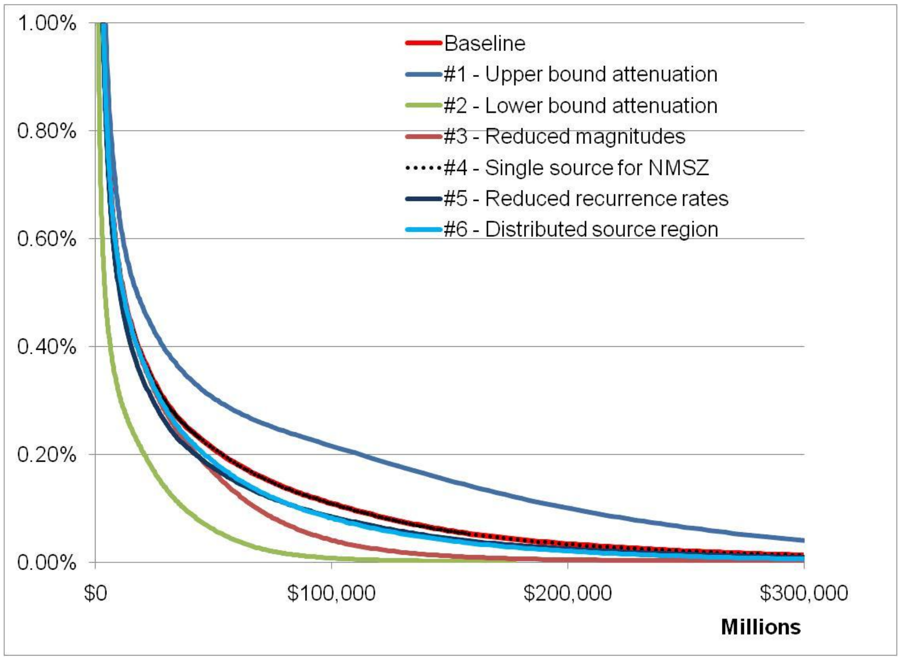


Figure 5: Value of exposure at risk in the eight-state study region, illustrating concentrations of value by ZIP Code. The six urban study areas are indicated in italics.

Probabilistic Risk Results

The impact of alternative hazard representations on loss for the entire eight-state study region, as well as for the six major urban centers within it, is summarized as "shifts" in the loss exceedance probability (EP) curve and increases (or decreases) in return period losses, respectively. In Figure 6, the regional EP curves for "total economic loss" for each of the alternative hazard options are compared with the modeled loss corresponding to the baseline hazard from the USGS 2008 National Seismic Hazard Maps. In this study, total economic losses represent losses to private property and do not include losses to public buildings and utility and transportation networks. These "ground up" losses were calculated by running the RMS® U.S. Earthquake Model against the 2011 RMS® U.S. Industry Exposure Database (IED), which is used as a proxy for all private building and contents exposure (as summarized in Table 3). Both ground shaking and fire following earthquake perils were considered in the analysis, as well as the impacts of post-event loss amplification (PLA).

Residential



Commercial

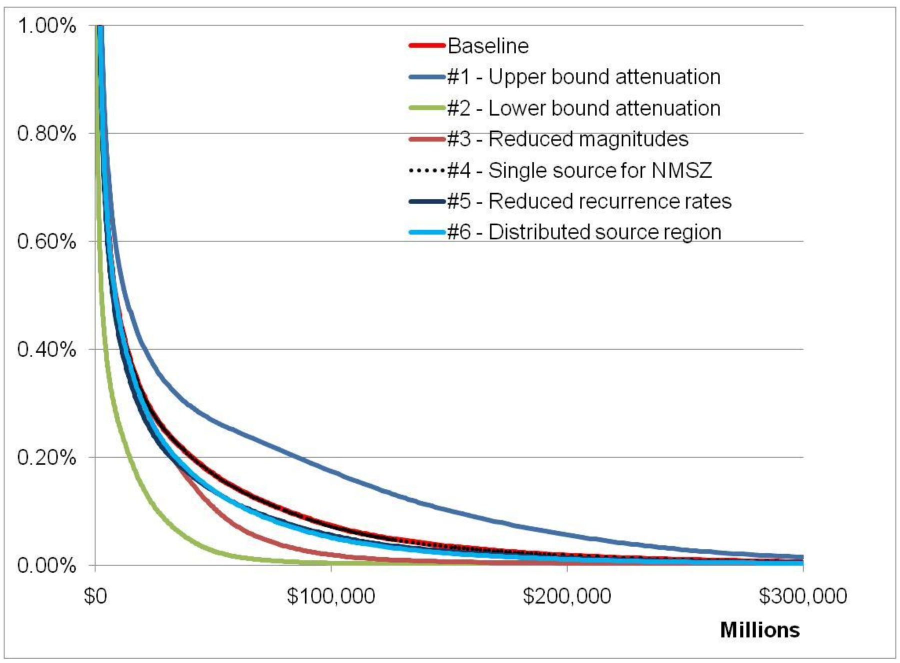


Figure 6: Loss exceedance probability (EP) curves, comparing regional total economic losses for the residential line of business (top) and the commercial line of business (bottom) for the alternative hazard options; baseline losses are those based on the USGS 2008 National Seismic Hazard Map (highlighted in red)

Figure 7 compares the regional insured (or gross) losses for the six alternative hazard options at key return periods for the residential and commercial lines of business. Figure 8 provides the same insured loss comparisons at key return periods for the six urban centers. In both cases, the insured losses are estimated by running the RMS® U.S. Earthquake Model against the 2011 RMS® U.S. Industry Exposure Database (IED). As with the case of the economic losses, both ground shaking and fire following earthquake perils were considered in the insured loss analysis, which also included the modeled impacts of post-event loss amplification.

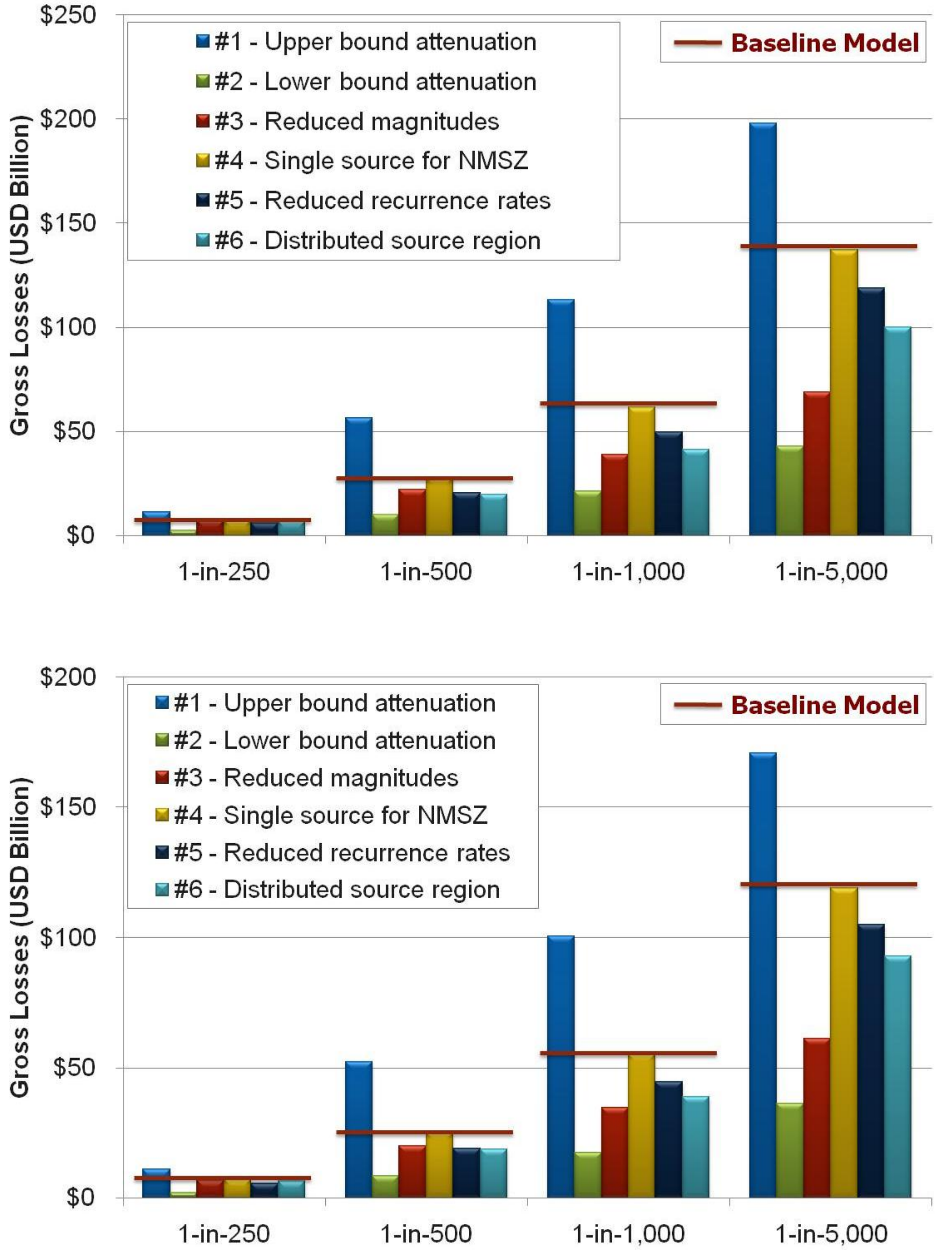


Figure 7: Comparison of regional insured losses for the residential line of business (top) and the commercial line of business (bottom) at key return periods for the alternative hazard options and baseline model.

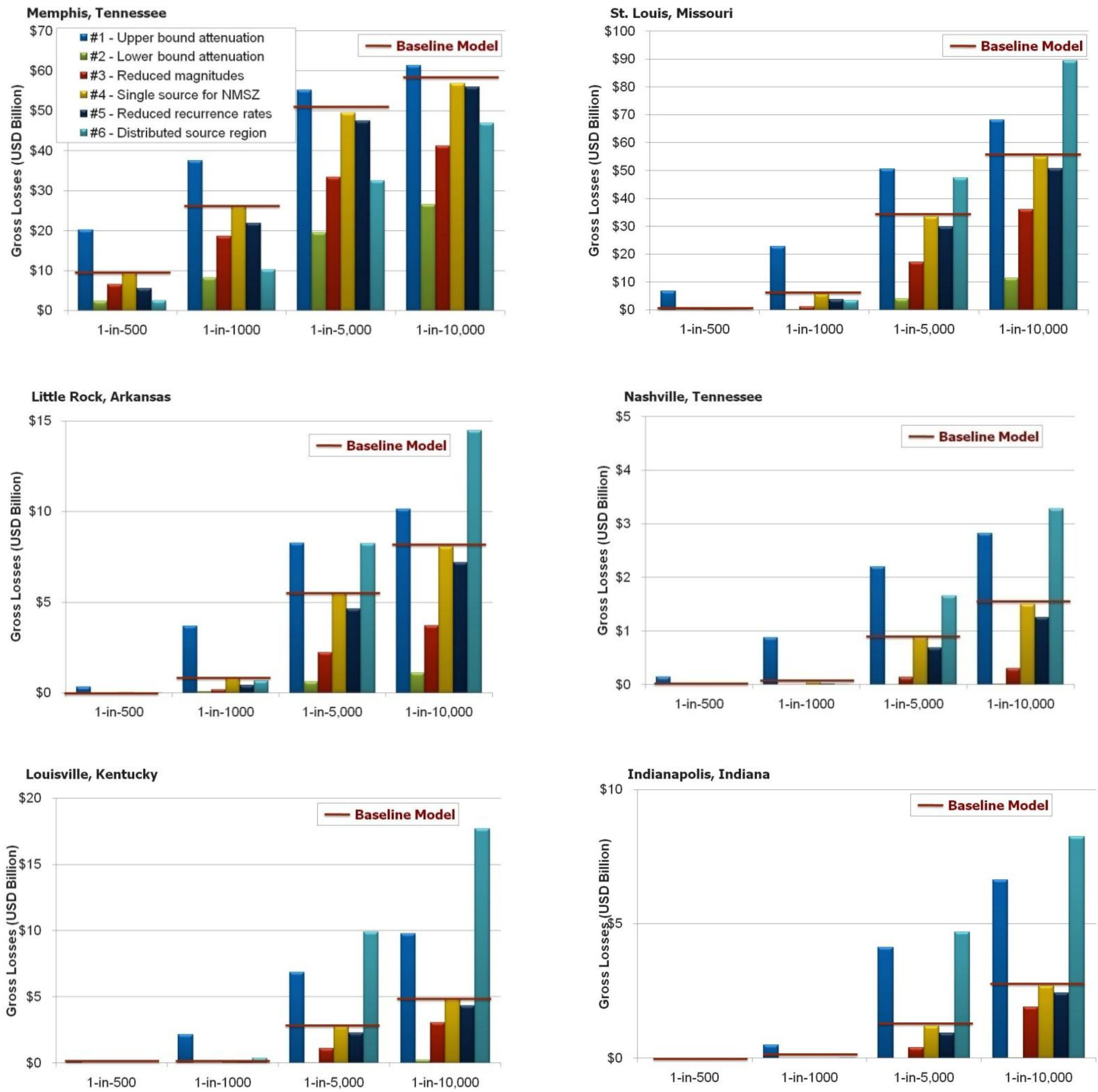


Figure 8: Insured loss by alternative hazard option for six urban centers, arranged by distance from center of the New Madrid Seismic Zone (from top left to bottom right): Memphis, St. Louis, Little Rock, Nashville, Louisville, and Indianapolis

As shown in Figures 6 through 8, the sensitivity analyses demonstrate that the largest source of uncertainty in losses both at the regional and city level is related to the assumed ground motion attenuation model (Options #1 and #2).

Regional Level Results

At the regional level (Figures 6 and 7), both total economic and insured losses vary by a factor of 4 to 5 between the two assumptions for ground motion attenuation models, depending on the return period. At the 1-in-250 year return period (or annual frequency 0.4%), the estimated regional insured losses range from a high of $22 billion for the upper bound attenuation model (Option #1) to only $5 billion for the lower bound attenuation model (Option #2), whereas at the 1-in-500 year return period (annual frequency 0.2%), the regional insured losses vary from $18 billion to $108 billion (Figure 7).

Using a single source location for the NMSZ (i.e., Option #4, which removes any uncertainty in the location of the NMSZ pseudofault source), there is virtually no impact on regional insured or total economic losses at any return period, relative to the baseline model. In contrast, reducing the NMSZ earthquake magnitudes (Option #3) greatly curtails “tail” loss (i.e., at long return periods) relative to the baseline hazard model, producing ~35% decrease in loss at the 1-in-1,000 return period and ~55% reduction in the 1-in-5,000 return period loss (Figure 7). Not surprisingly, reducing the recurrence rates (Option #5, with a recurrence interval of 500 years down to 1,000 years) has the greatest impact at the 1- in-500 year return period loss, resulting in a 25% reduction in loss; only modest reductions (12–14%) in both total economic and insured loss are observed at all other return periods. The distributed source region (Option #6) reduces losses relative to the baseline model, and for long return periods (1,000 years and longer), results in losses between the reduced magnitudes (Option #3) and reduced recurrence rates (Option #5) options. It is noteworthy that none of the return period losses for the alternative changes in the NMSZ sources (Options #3 through #6) are as low as the losses for Option #2 (lower bound attenuation).

The baseline hazard representation used in the 2008 USGS Seismic Hazard Maps proves to be quite conservative, providing an upper bound on losses for all hazard options except the “upper bound attenuation” case (Option #1) across all return periods. As a result, the current scientific controversy over the exact magnitudes and rate of occurrence of NMSZ earthquakes has very little impact on modeled losses, relative to the broad uncertainty related to ground motion attenuation relationships. The only possible exception would be if both lower magnitudes and longer recurrence intervals were to act together (i.e., combine Options #3 and #5, wherein the earthquake magnitudes are in fact at the very low end of the suggested range and the geologically inferred recurrence rate has increased from 500 years to a value closer to 1,000 years). Both suggestions have serious scientific proponents, as well as detractors. If one considers this scenario (combining Options #3 and #5), then the modeled losses will be close to those from the “lower bound attenuation” case (Option #2).

Urban Center (City) Level Results

At the urban center level, the two extreme ground motion attenuation relationships (Options #1 and #2) once again provide clear upper and lower bounds on losses at all return periods (Figure 8), with the exception of the distributed source region option (Option #6). As expected, this final hazard alternative, in which the specific NMSZ source is eliminated and the equivalent hazard is redistributed uniformly, increases tail losses (particularly for the 1-in-5,000 and 1-in-10,000 year losses) for all urban centers except Memphis, which is located only 20 km from the center of the NMSZ. Significantly, Option #6 is the only option in which losses exceed the upper bound provided by Option #1 (upper bound attenuation relationship) across all urban centers except Memphis.

Removing uncertainty in the location of the NMSZ (Option #4) is seen to have virtually no impact on losses, except in Memphis, the closest urban center to the NMSZ, and then only for longer return periods (at the 5,000-year return period or longer). Reducing hazard parameters within the New Madrid Seismic Zone (reduced magnitudes and reduced recurrence rates, Options #3 and #5 respectively) has the greatest impact on losses on the three urban centers at moderate distances from the NMSZ: St. Louis, Little Rock, and Nashville. For example, losses for Option #3 drop by as much as 80% relative to the baseline hazard at the 1,000 and 5,000 year return period for St. Louis, Little Rock, and

Nashville. As expected, the impact of reducing the recurrence rate from 500 years to 1,000 years (Option #5) is most pronounced in Memphis and at the 500-year return period, where the baseline loss is reduced by about 25%.

The total economic loss cost (defined as the average annual loss [AAL] per $1000 of exposure value) provides a comparison of relative risk level across the six urban centers for the baseline hazard (Figure 9). Memphis and Shelby County, with the closest proximity to NMSZ, dominate the New Madrid region loss cost at $0.52, nearly four times that for St. Louis and Little Rock, the next closest and most impacted urban centers. Figure 9 indicates that loss cost decays with distance from NMSZ; the similarity of loss cost for the three most distant urban centers, however, highlights the fact that, locally, other earthquake sources are important. It should be noted that while the Memphis loss cost dominates as compared to other Central U.S. urban centers, the value pales in comparison with total economic loss costs for Los Angeles and San Francisco counties (at $2.27 and $2.85, per $1000 of exposure value, respectively). That loss costs in California are factor of four to five higher than the NMSZ is a function of the much higher rate of earthquake occurrence at shorter return periods in California relative to the Central United States.

Figure 9: Total economic loss costs for the six New Madrid Region urban centers analyzed in this study; distance of urban center from New Madrid Seismic Zone is indicated.

Scenario Results

The potential losses from a series of scenarios for both moderate and large earthquakes were investigated throughout the New Madrid region, using events generated from seismic sources in the RMS® U.S. Earthquake Model (Figure 10). In addition to exploring a range of magnitudes on the NMSZ proper (M7.1, M7.3, M7.5, and M7.7), RMS also investigated the impacts of a moderate earthquake (M6.5) on a variety of sources distributed throughout the Wabash Valley, and various magnitude events on sources directly adjacent to two major urban centers (Memphis and St. Louis). Recent marine seismic reflection profiling along the Mississippi River has revealed an active fault in river sediments just offshore from Memphis (Magnani and McIntosh, 2009). The scenario segment adjacent to Memphis shown in Figure 10 trends about 30 degrees more easterly than the fault inferred from the seismic profiling, but provides representative results. The scenario segments adjacent to St. Louis were selected to represent regional elevated "background" seismicity; there is no direct evidence that such specific sources exist.

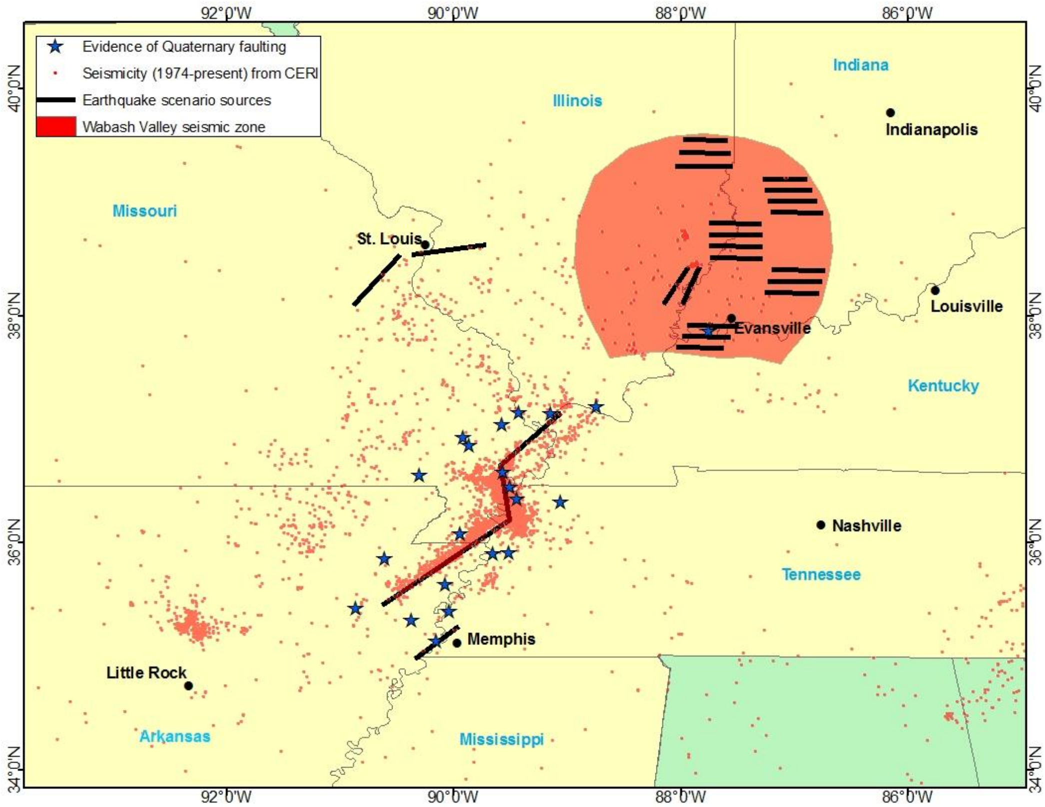


Figure 10: Location of earthquake sources used in scenario analysis; seismic sources highlighted in black with Wabash Valley seismic zone denoted in red (after 2008 USGS National Seismic Hazard Maps); red dots indicate earthquakes occurring since 1974 (from the CERI catalog) and blue stars show the location of sites where Quaternary faulting has been identified.

Total economic and insured losses for the different scenarios are summarized in Table 4. A range of hazard factors was explored for each scenario to provide a range of loss estimates, reflecting the uncertainty in the results. In the case of the Wabash Valley M6.5 scenarios, the loss range represents different earthquake source locations (i.e., the red area in Figure 10) and hence different proximities to urban centers. Two distinct scenario sources were explored for St. Louis, one directly beneath the city (St. Louis-A), and a second adjacent to the city to the Southwest (St. Louis-B). For these scenarios, earthquake magnitudes range from M6.1 to M7.2. As noted above, the Memphis scenario source was selected to approximately coincide with young Quaternary faulting with an inferred fault length of 60 km (Magnani and McIntosh, 2009). The range of earthquake magnitudes considered in the analysis span from M5.9 to M7.4. For both the St. Louis and Memphis scenarios, losses are given (in Table 4) for a mid-range magnitude earthquake; the coinciding ranges reflect losses for the extremes of the magnitude ranges indicated.

Three separate scenarios were chosen for the NMSZ: a M7.7 "full" rupture of the three NMSZ pseudofault segments (shown in the middle of Figure 10, surrounded by evidence of Quaternary faulting), together with a M7.3 and M7.5 on the southwest (SW) pseudofault segment. The range of losses represents the variability related to the different ground motion attenuation relationship choices within the RMS model. It should be noted that the losses are weighted by the choice of attenuation and are consistent with the weighting scheme used in the 2008 USGS National Seismic Hazard Maps.

The scenario loss results summarized in Table 4 demonstrate that even moderate-sized earthquakes adjacent to major urban areas in the Central U.S. are projected to cause losses in the range of tens to hundreds of billions of dollars. The mean loss for twenty different M6.5 scenarios within the Wabash Valley is $25 billion economic, $15 billion insured, but could range as high as $55 billion and $33 billion, respectively, depending on the event's proximity to urban centers. A moderate M6.6 earthquake near St. Louis could result in total economic losses between $215–310 billion, with insured losses between about $165–$205 billion, while a M6.4 adjacent to Memphis could cause $90 billion in total economic loss and about $55 billion in insured loss. Even the lowest magnitude events analyzed for these two urban centers (M6.1 event near St. Louis or a M5.9 near Memphis) are forecast to cause tens of billions of dollars in insured loss, and potentially close to $170 billion in total economic loss.

Table 4: Estimated scenario losses (average rounded to nearest $5 billion, with ranges rounded to the nearest $1 billion); ranges represent the upper and lower bounds on loss, considering hazard parameter variation (e.g., scenario magnitude, scenario location, or choice of attenuation relationship)

Scenario	**Total Economic Loss**	**Total Insured Loss**	**Ratio (Insured/Economic)**
Wabash Valley M6.5 (*20 different locations*)	$25 billion *$13–55 billion*	$15 billion *$7–$33 billion*	60% *43–68%*
St. Louis-A M6.6 (*M6.1–7.2*)	$310 billion *$169–488 billion*	$205 billion *$123–$306 billion*	66% *63–73%*
St. Louis-B M6.6 (M6.1–7.2)	$215 billion *$54–379 billion*	$165 billion *$40–$266 billion*	77% *70–77%*
Memphis M6.4 (*M5.9–7.4*)	$90 billion *$34–226 billion*	$55 billion *$21–$120 billion*	61% *53–61%*
NMSZ M7.7 full rupture *(7 attenuations)*	$290 billion *$90–526 billion*	$175 billion *$55–$309 billion*	61% *58–66%*
NMSZ SW fault M7.5 *(7 attenuations)*	$150 billion *$46–276 billion*	$90 billion *$27–$160 billion*	60% *56–64%*
NMSZ SW fault M7.3 *(7 attenuations)*	$115 billion *$35–$198 billion*	$70 billion *$20–$117 billion*	61% *58–64%*

For the NMSZ scenarios presented in Table 4, seven ground motion attenuation relations that have been suggested applicable to the NMSZ were utilized. Just as described in the probabilistic results section, the two extreme ground motion relations (Frankel et al., 2006 and Atkinson and Boore, 2006) produce a large uncertainty in loss. These attenuation assumptions result in up to an 80% increase or decrease in loss, relative to the baseline 2008 USGS hazard representation.

Interestingly, the losses for a M7.5 on the southwest arm of the NMSZ are $150 billion and $90 billion (for total economic and insured loss, respectively) and are roughly 25% higher than losses than for a slightly smaller M7.3 event on the same fault. While a 0.2 difference in magnitude seems quite small, it corresponds to a factor of two difference in seismic energy release, which helps explain the 25% disparity in modeled loss.

The M7.7 NMSZ scenario involves simultaneous rupture on the three pseudofault segments within the seismic zone and was chosen to be similar to the scenario that the Mid-America Earthquake (MAE) Center analyzed using the HAZUS model (Elnashai et al., 2009) and which formed the basis for the FEMA-led National Leadership Exercise emergency response drill held May 16–20, 2011 (http://www.ready.gov/nle2011). The MAE Center selected this particular scenario in consultation with the USGS. It was intended to provide credible impacts for the NMSZ that are suitable for planning at the national level.

As illustrated in the map of RMS loss cost estimates shown in Figure 11, the M7.7 NMSZ scenario has significant impacts across six states, including Arkansas, Illinois, Indiana, Kentucky, Missouri, and Tennessee. Memphis, Tennessee and Little Rock, Arkansas are the urban centers most directly affected. Total economic losses estimated by RMS for this M7.7 scenario range from $90 to $526 billion, depending on the ground motion attenuation relation used.

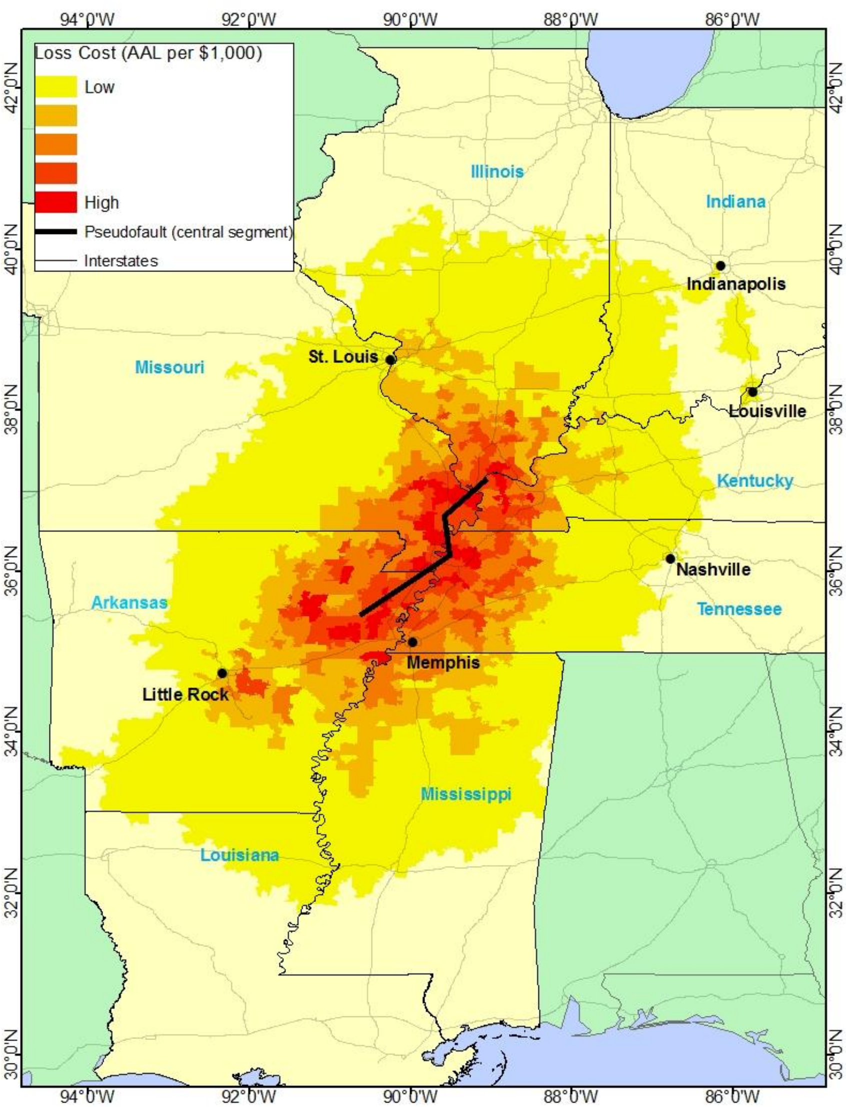


Figure 11: Total economic loss cost by ZIP Code for M7.7 NMSZ scenario, based on the RMS® U.S. Earthquake Model and utilizing the Silva et al. (2002) attenuation relationship.

Comparison to HAZUS Analysis

While the RMS estimate of $290 billion economic loss for the baseline 2008 USGS hazard map representation seems to compare well with an approximately $300 billion in direct economic losses as estimated by the HAZUS model, these loss estimates correspond to very different exposures. The HAZUS study, summarized in Elnashai and others (2009), invested considerable effort in populating the public infrastructure database in HAZUS and determining appropriate infrastructure fragility relationships. The HAZUS ~$300 billion total economic loss figure includes the cost of substantial damage to transportation networks, utility facilities, and pipelines. The RMS study and loss estimates apply to property exposures, including buildings, contents and business interruption coverage for commercial property, as well as additional living expenses for occupants of severely damaged residential structures. Furthermore, there are differences in the area included in these studies. While both studies included Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee, the MAE FEMA study also covered Alabama, whereas the RMS study included Louisiana. (This difference had only a small impact on the regional results, because the losses were extremely small in the additional states). The total population at risk in the two studies was quite similar, with 43.8 million people at risk in the FEMA study and 46.4 million people in the RMS study.

Total HAZUS direct economic loss to buildings in the eight-state study region was $113 billion, considering a total building exposure of $3.22 trillion, equivalent to a 3.51% overall building loss ratio. However, infrastructure damage accounted for more than 60% of the total HAZUS loss estimate. The estimated direct economic loss to infrastructure over the eight-state region was $183 billion on an estimated infrastructure exposure value of $8.565 trillion (2.14% overall loss ratio). RMS' estimated loss of $290 billion was for a combined private residential and commercial inventory of $8.950 trillion, amounting to 3.24% overall loss ratio, similar to the HAZUS building loss ratio. The similarity in the HAZUS and RMS overall building loss ratios suggests the two methodologies are assessing damage consistently. However, because the value of the HAZUS building exposure is only one-third of the exposure carefully estimated and updated annually by RMS ($3.22 trillion versus $8.95 trillion, respectively), it can be expected that HAZUS-based building loss estimates may represent a significant under-representation of the true expected loss. A recent comparison of RMS and HAZUS-based losses for earthquake scenarios occurring on the Hayward Fault in California yielded a similar result: nearly identical overall building loss ratios, but a factor of three difference in the exposure values and (hence also) in the total estimated losses (Zoback and Grossi, 2011).

Road to Recovery and the Role of Insurance

A significant earthquake in the New Madrid Seismic Zone or the surrounding region (such as the M7.7 scenario used in the MAE HAZUS study) would have devastating consequences for the entire region and the nation. The MAE study delineates substantial damage to the highway infrastructure as a result of the earthquake shaking. Elnashai et al (2009) estimated that roughly 15 major bridges crossing rivers in the region would be damaged and impassable. In addition to carrying high volumes of traffic, many of the bridges also support major pipelines and communication lines. This region of the U.S. is a central corridor for ground shipping (e.g. FEDEX is based in Memphis). A significant fraction of all U.S. goods and products (i.e., commodity flows) pass through the Midwest region, which includes the New Madrid Seismic Zone (See http://www.bts.gov/publications/commodity_flow_survey/).

Although the RMS estimates do not cover the cost of damage to publicly-owned infrastructure, the extensive damage and disruption of the transportation, utilities, and other networks is considered in RMS' projected business interruption costs and will substantially contribute to post-event loss amplification.

Fortunately, insurance payments are expected to play a significant role in recovery from central U.S. earthquakes. The ratio of insured to total economic loss (as shown in Table 4) range from 43% to 77% across all scenarios considered. Figure 12 compares the percentage of the total economic losses that is expected to be covered by insurance payments (for earthquake shaking and fire following earthquake damage) for the central U.S. scenarios analyzed in this report, along with the percentage expected to be covered by scenarios on the Hayward Fault in California (shown in blue). These ratios are compared alongside actual insured to economic loss ratio for several recent U.S. earthquakes and hurricanes (in red). These events include the 1989 M6.9 Loma Prieta and 1994 M6.7 Northridge earthquakes, as well as Hurricane Andrew (2002), Hurricane Katrina (2005), and Hurricane Ike (2008).

A high uptake of earthquake insurance in the greater New Madrid region indicates that in general between 60–80% of the total estimated economic losses will be covered by insurance payments. In contrast, for the California earthquake scenarios (which represent 66% of the nation's annualized earthquake loss, according to FEMA, 2008), only 10–15% of total economic losses are expected to be covered by insurance. This conclusion is the result of low statewide insurance take-up rates—particularly in the residential market.

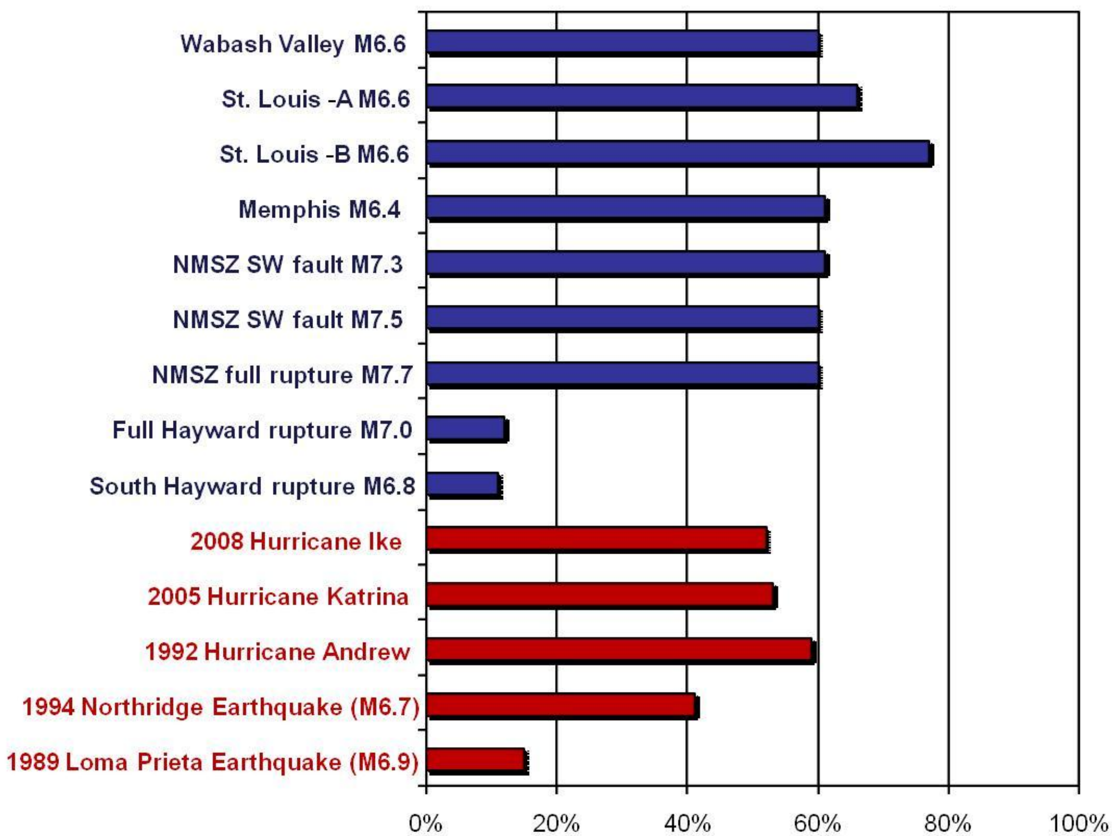


Figure 12: Percentage of total economic loss covered by insurance payments for New Madrid earthquake scenarios as described in Table 4 and Hayward Fault scenarios from RMS (2010) (above in blue), and actual data from recent hurricanes and earthquakes (below in red).

CONCLUSIONS

The 200th anniversary of the 1811–1812 New Madrid earthquake sequence is a reminder of the susceptibility of the region to earthquake hazards and the need for preparation for a possible future event. Numerous scientific issues have been raised regarding the level and uncertainty of seismic hazard in the New Madrid Seismic Zone (NMSZ) and the surrounding region of the Central United States. However, the scientific community is in broad agreement with the geologic evidence of repeated large earthquakes in the last several thousand years. Moreover, a recent USGS analysis of regional seismicity rates suggests a 95–99% likelihood of a M5.0 or greater earthquake and a 28–46% likelihood of a M6.0 or greater earthquake in the broad region around New Madrid in the next 50 years.

The sensitivity analyses presented in this paper demonstrate that ground motion attenuation relationships dominate the uncertainty in modeled loss, providing upper and lower bounds on losses for nearly all alternative hazard representations considered. At the regional level, both total economic and insured probabilistic losses vary by a factor of four to five between the two extreme ground motion attenuation models considered in the 2008 USGS National Seismic Hazard Maps. Reducing earthquake magnitudes or increasing the recurrence interval in the New Madrid Seismic Zone (as has been proposed) does lower losses relative to the baseline hazard representation in the 2008 USGS National Seismic Hazard Maps; however, the differences in implied risk costs are well within the broad bounds imposed by the alternative ground motion attenuation relationships. Expected regional economic losses for the “baseline” USGS hazard (i.e., as based on the 2008 USGS National Seismic Hazard Maps) total $50 billion at the 250-year return period and $150 billion for the 500-year return period. Memphis and surrounding Shelby County, directly adjacent to the southern end of the NMSZ, have the highest urban economic loss cost (defined as the average annual loss normalized per thousand dollars of total exposure value) in the region at $0.52. This value, however, is only 20–25% of the loss cost for Los Angeles and San Francisco counties, highlighting the contrast in hazard between the New Madrid region and California in shorter return periods (e.g., less than 100 to 200 years).

Analysis of a range of scenarios indicated that even moderate earthquakes (M6.1–6.5) adjacent to major urban areas will generate total losses in the range of $10 to $100 billion, and insured losses of $5 to $50 billion. Insurance payments are forecast to be 60–80% of total economic losses, thus contributing significantly to recovery in the region. This percentage is higher than the 45–55% insured to total loss costs observed in hurricanes Ike (2008), Katrina (2005), and Andrew (2002), as well as significantly larger than the anticipated 10–15% of economic loss that is insured for major California earthquakes.

REFERENCES

Atkinson, G.M. and Boore, D.M. (1995). New ground motion relations for earthquakes in eastern North America. *Bulletin of the Seismological Society of America*, 85, 17–30.

Atkinson, G.M. and Boore, D.M. (2006). Ground motion prediction equations for earthquakes in eastern North America. *Bulletin of the Seismological Society of America*, 96, 2181–2205.

Bakun, W.H., and Hopper, M.G. (2004). Magnitudes and Locations of the 1811–1812 New Madrid, Missouri, and the 1886 Charleston, South Carolina, Earthquakes. *Bulletin of the Seismological Society of America*, 94, 1, 64–75.

Boyd, O. (2010). Earthquake hazards (Timing/reoccurrence/probability of an event). in *Proceedings of Preparing for a Significant Central U. S. Earthquake—Science Needs of the Response and Recovery Community*, E. C. Witt, ed., USGS Science Investigation Report 2010–5173, 14–20.

Calais, E., and Stein, S. (2009). Time variable deformation in the New Madrid Seismic Zone. *Science,* 323, 1424.

Calais, E., Freed, A.M., Van Arsdale, R., and Stein, S. (2010). Triggering of New Madrid seismicity by Late-Pleistocene erosion. *Nature*, 466, 608–611.

Campbell, K.W. (2003). Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America. *Bulletin of the Seismological Society of America,* 93, 1012–1033.

Cramer, C.H. (2001). The New Madrid seismic zone: capturing variability in seismic hazard analyses. *Seismological Research Letters,* 72, 664–672.

Elnashai, A.S., Cleveland, L.J., Jefferson, T. and Harrald, J. (2009). *Impact of New Madrid Seismic Zone Earthquakes on the Central USA*. MAE Center Report No. 09-03, available at http://mae.cee.uiuc.edu/publications/2009/Impact of NMSZ Earthquakes on the Central USA.pdf

FEMA (2008). *HAZUS-MH Estimated Annualized Earthquake Losses for the United States*. FEMA Publication Number 366, 66 p. Summary of findings available at: http://www.fema.gov/plan/prevent/hazus/hz_aelstudy.shtm#1

Hough, S.E., Martin, S., Bilham, R., and Atkinson, G.M. (2002). The 26 January 2001 M7.6 Bhuj, India, earthquake: observed and predicted ground motions. *Bulletin of the Seismological Society of America*, 92, 2061–2079.

Hough, S.E. and Martin, S. (2002). Magnitude estimates of two large aftershocks of the 16 December 1811 New Madrid earthquake. *Bulletin of the Seismological Society of America*, 92, 3259–3268.

Hough, S.E. and Page, M. (2011). Towards a consistent model for strain accrual and release for the New Madrid, central U.S., seismic zone. *Journal of Geophysical Research*, 116, B03311.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hopper, M., (1996). *National Seismic Hazard Maps Documentation, June 1996*. U.S. Geological Survey Open-File Report 96–532, 110 p.

Johnston, A.C. (1996). Seismic moment assessment of earthquakes in stable continental regions—III. New Madrid 1811–1812, Charleston 1886 and Lisbon 1755. *Geophysical Journal International*, 126, 314–344.

Magnani, M.B. and McIntosh, K. (2009). *Toward an understanding of the long-term deformation in the Mississippi Embayment: Collaborative research with the University of Memphis and the University of Texas*. USGS NEHRP Final Technical Report, Award Numbers 08HQGR0089 and 08HQGR0090, available at http://www.ceri.memphis.edu/people/mmagnani/webpage/missriver/08HQGR0089_08HQGR0090.pdf

McBride, J.H., Sargent, M.L., and Potter, C.J. (1997). Investigating possible earthquake related structure beneath the southern Illinois basin from seismic reflection. *Seismological Research Letters*, 68, 641–649.
McBride, J. H. Hildenbrand, T.G., Stephenson, W.J., and Potter, C.J. (2002). Interpreting the earthquake source of the Wabash Valley seismic zone (Illinois, Indiana, and Kentucky) from seismic-reflection, gravity, and magnetic-intensity data. *Seismological Research Letters*, 73, 660–697.

McNulty, W.E., and Obermeier, S.F. (1999). Liquefaction evidence for at least two strong Holocene paleoearthquakes in central and southwestern Illinois, USA. *Environmental and Engineering Geoscience*, 2, 133–146.

Munson, P.J., Obermeier, S.F., Munson, C.A., and Hajic, E.R. (1997). Liquefaction evidence for Holocene and latest Pleistocene seismicity in the southern halves of Indiana and Illinois: a preliminary overview. *Seismological Research Letters*, 68, 521–536.

Newman, A., Stein, S., Weber, J., Engeln, J., Mao, A., and Dixon, T. (1999). Slow deformation and lower seismic hazard at the New Madrid seismic zone. *Science*, 284, 619–621.

Obermeier, S.F. (1998). Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, USA. *Engineering Geology*, 50, 227–254.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson,R.L., Zeng,Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S. (2008). *Documentation for the 2008 Update of the United States National Seismic Hazard Maps*, USGS Open-File Report 2008–1128, 128 p., available at: http://pubs.usgs.gov/of/2008/1128/pdf/OF08-1128_v1.1.pdf

Pond, E.C., and Martin, J.R. (1997). Estimated magnitudes and accelerations associated with prehistoric earthquakes in the Wabash Valley region of the central United States. *Seismological Research Letters*, 68, 611–623.

RMS (2010). *1868 Hayward Earthquake: 140-Year Retrospective*, Risk Management Solutions. http://www.rms.com/publications

Silva, W., Gregor, N., and Darragh, R. (2002). *Development of hard rock attenuation relations for central and eastern North America,* Report from Pacific Engineering, November 1, 2002, http://www.pacificengineering.org/gulf/Development%20ENA%20Midcontinent%20Gulf.pdf

Somerville, P., Collins, N., Abrahamson, N., Graves, R., and Saikia, C. (2001). *Ground motion attenuation relations for the central and eastern United States*. Final Report to the USGS, June 30, 2001, Contract No. 99HQGR0098, URS Group, Inc., Pasadena, CA, 36 p.

Stein, S., and Newman, A. (2004). Characteristic and uncharacteristic earthquakes as possible artifacts: applications to the New Madrid and Wabash seismic zones. *Seismological Research Letters*, 75, 173–187.

Tavakoli, B., and Pezeshk, S. (2005), Empirical-stochastic ground-motion prediction for eastern North America. *Bulletin of the Seismological Society of America*, 95, 2283–2296.

Toro, G., Abrahamson, N., and Schneider, J. (1997). Model of strong ground motions from earthquakes in central and eastern North America: best estimates and uncertainties. *Seismological Research Letters*, 68, 41–57.

Toro, G.R. (2002). *Modification of the Toro et al. (1997) attenuation relations for large magnitudes and short distances*. Risk Engineering, Inc. Report, available at http://www.riskeng.com/PDF/atten_toro_extended.pdf

Tuttle, M. P., Al-Shukri, H., and Mahdi, H. (2006). Very large earthquakes centered southwest of the New Madrid seismic zone 5,000–7,000 years ago. *Seismological Research Letters*, 77, 755–770.

Tuttle, M.P., Schweig, E.S., Sims, J.D., Lafferty, R.H., Wolf, L.W., and Haynes, M.L. (2002). The earthquake potential of the New Madrid Seismic Zone. *Bulletin of the Seismological Society of America*, 92, 2,080–2,089.

Tuttle, M.P., Schweig, E.S., Campbell, J., Thomas, P. M., Sims, J.D., and Lafferty, R.H. (2005). Evidence for New Madrid earthquakes in A.D. 300 and 2350 B.C. at the Burkett archeological site. *Seismological Research Letters*, 76, 489–501.

Tuttle, M.P., Schweig, E., Al-Shukri, H., and Cox, R. (2009). *Geological record of ancient earthquakes in the central United States*. Association of Engineering Geologists, Shlemon Specialty Conference on advancing New Madrid Region Time-History Determination, Memphis, Tennessee.

Zoback, M.L. and Grossi, P. (2011). *The next Hayward earthquake—who will pay?* K. Knudsen (ed.), Proceedings of the Third Conference on Earthquake Hazards in the eastern San Francisco Bay Area, California Geological Survey, Special Publication/Report 219.

ACKNOWLEDGEMENTS

Authors: Mary Lou Zoback, Patricia Grossi, and Chesley Williams

RMS Contributor: Robert Muir-Wood

Editor: Shelly Ericksen

About RMS

Risk Management Solutions is the world's leading provider of products and services for catastrophe risk management. More than 400 leading insurers, reinsurers, trading companies, and other financial institutions rely on RMS models to quantify, manage, and transfer risk. Founded at Stanford University in 1988, RMS serves clients today from offices in the U.S., Bermuda, the U.K., France, Switzerland, India, China, and Japan. For more information, visit our website at www.rms.com.

