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Earthquake Hazard Mitigation in the New Madrid Seismic Zone: Science and Public Policy

Alice M. Orton, Zhenming Wang, Lanmin Wang, and Edward W. Woolery

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Earthquake Hazard Mitigation in the New Madrid Seismic Zone: Science and Public Policy

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Abstract

In the central United States, earthquake sources that are not well defined, long earthquake recurrence intervals, and uncertain ground-motion attenuation models have contributed to an overstatement of seismic hazard for the New Madrid Seismic Zone on the national seismic hazard maps published by the U.S. Geological Survey. A series of informal interviews in western Kentucky with local businesspersons, public officials, and other professionals in occupations associated with seismic-hazard mitigation discussed seismic-mitigation policies in relation to depressed local economy. Scientific and relative economic analysis was then performed using scenario earthquake models developed with the Federal Emergency Management Agency's Hazus-MH software. The ground-motion hazard generated by the 2008 Wenchuan, China, earthquake and seismic mitigation policies in that area were compared with those of the New Madrid Seismic Zone. Continued scientific research, additional educational opportunities for laymen and engineering professionals, and changes in the application of current earthquake science to public policy in the central United States should help improve public safety and economic development.

Introduction

The New Madrid Seismic Zone is a well-documented region of historic and prehistoric seismicity underlying the upper Mississippi Embayment in the central United States (Fig. 1). Sensational eyewitness accounts of the Mississippi River flowing backward (Johnston and Schweig, 1996), coal and sand being thrown out of the earth, house chimneys being toppled, and hills and islands sinking into rivers or swamps (Nuttli, 1973) attest to the violence of the last great earthquake sequence along this fault zone in the winter of 1811-12. The New Madrid Seismic Zone has also undergone long quiet periods characterized by minor seismic activity, as illustrated by the small number of earthquakes greater than magnitude 5.0 occurring since the aftershocks of the 1811-12 earthquake sequence died down 200 yr ago. In fact, a query of the U.S. Geological Survey earthquake catalog (earthquake.usgs.gov/earthquakes/search) for events greater than magnitude 5.0 anywhere in the United States east of the Rocky Mountains returns only 10 events since 1973, only two of which are even remotely close to the New Madrid Seismic Zone.

Because earthquakes with magnitudes greater than 5.0 are much less common in this intraplate region than they are along tectonic plate bound-

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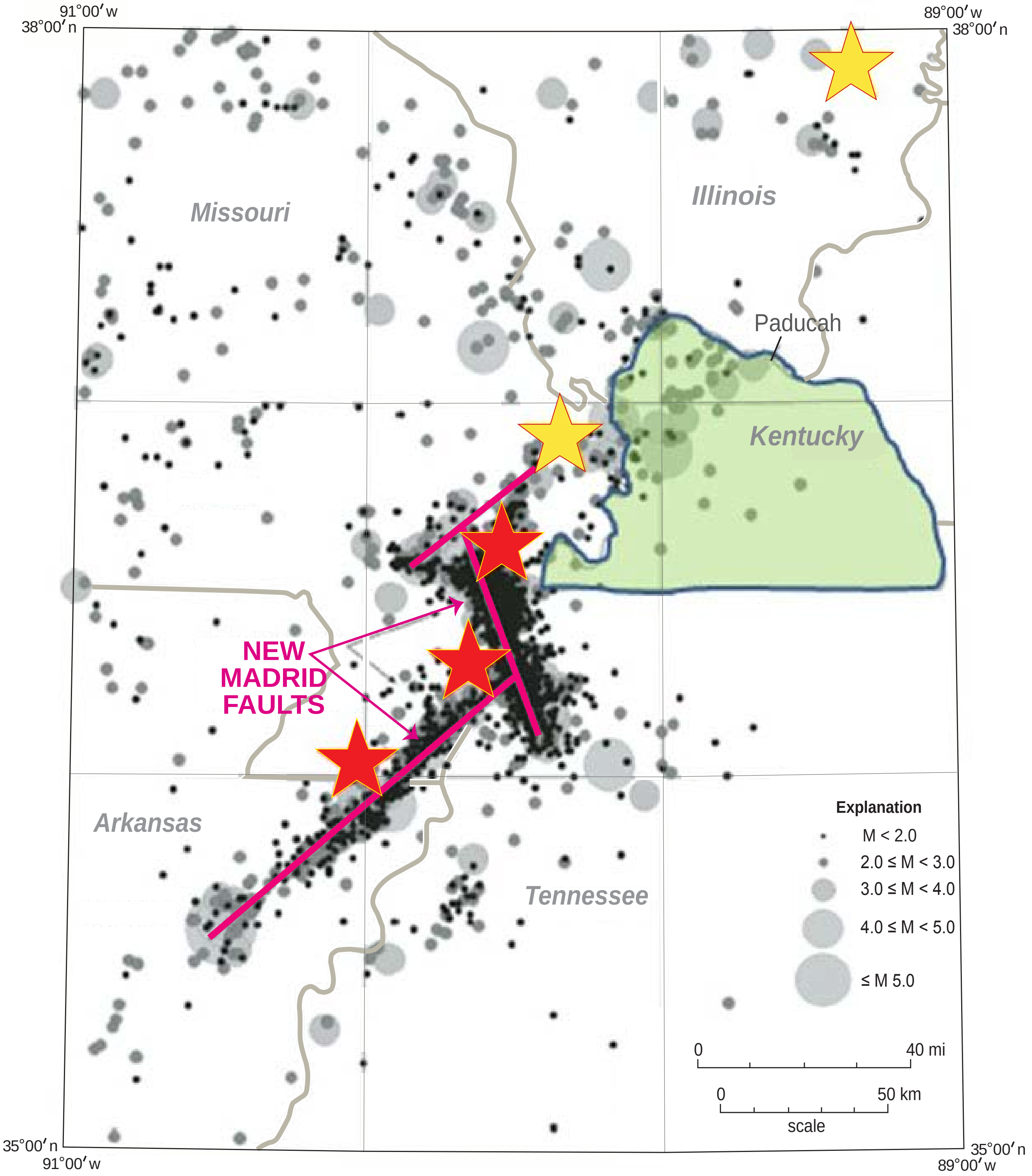


Figure 1. Seismic activity between 1974 and 2004 in the New Madrid Seismic Zone of the central United States. Red stars are approximate locations of the three main 1811-12 earthquakes on (from southwest to northeast) Dec. 16, 1811 (approximately M 7.7), Jan. 23, 1812 (approximately M 7.5), and Feb. 7, 1812 (approximately M 7.7). Yellow stars are locations of large earthquakes since then: near Charleston, Mo. (1895, M 6.6), and in southern Illinois (1968, M 5.4). The green highlighted area is the Jackson Purchase Region in western Kentucky. Modified from Wang (2007). Used with the permission of the Geological Society of America.

aries, more behavioral patterns must be inferred from less data than in regions where data are ample (Stein and Wysession, 2003). Rather than relying on documented ground motions and objectively recorded data as we would like to do, scientists and local residents alike are left to interpret a very few subjective accounts of historical events, and when possible piece together prehistoric events from paleoseismic studies of sand blows and other structural and stratigraphic evidence (Johnston and Schweig, 1996; Van Arsdale and others, 1998; Tuttle and others, 2002, 2005). Furthermore, despite widespread research into area seismicity, the causal mechanism of the New Madrid Seismic Zone has yet to be identified (Grollimund and Zoback, 2001; Pollitz and others, 2001; Calais and others, 2010). These circumstances make it difficult to assess the regional seismic hazard with a high degree of confidence.

As is often the case with necessarily incomplete science, mathematical models have been created to attempt to explain and recreate seismicity patterns for many earthquake-prone areas around the world, including the New Madrid region. But models are by definition an uncertain substitute for adequate real data. They are representative only in the limited circumstances in which the variables they consider are adequately represented and no other factors are present. The number of seismic-attenuation models alone (Frankel and others, 1996; Toro and others, 1997; Somerville and others, 2001; Silva and others, 2002; Campbell, 2003; Tavakoli and Pezeshk, 2005; Atkinson and Boore, 2006; and others) and publications detailing the differences between them should alert any thoughtful reader to the potential pitfalls of adopting any one model over another. Many earthquake hazard and risk models are based on data from the San Andreas Fault Complex and other western U.S. seismic zones, for which many data have been collected (Cornell, 1968; Bazzurro and Cornell, 1999; Campbell, 2003), but a combination of differences in ground-motion attenuation rates related to soil and bedrock conditions and differences in recurrence intervals of major seismic events makes West Coast data less applicable for central U.S. probability analysis.

In the United States, most decisions about earthquake hazard mitigation are based on the national seismic hazard maps produced by the U.S. Geological Survey as part of the National Earthquake Hazards Reduction Program. Documentation included with the maps states that they

> display earthquake ground motions for various probability levels across the United States and are applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy…. The resulting maps … describe the frequency of exceeding a set of ground motions

(Petersen and others, 2008, p. 1). There are problems associated with the maps and the resulting engineering design criteria and regulations, however, which deserve further attention. In fact, the 2008 maps indicate that the New Madrid Seismic Zone has a higher ground-motion hazard than either San Francisco or Los Angeles (Figs. 2–3), both areas located along the San Andreas and associated fault systems (Petersen and others, 2008). The higher hazard assigned to the New Madrid Seismic Zone seems contradictory when earthquakes are much more frequent in the San Andreas region than in the New Madrid region.

The national seismic hazard maps are produced using probabilistic seismic hazard analysis, first published in the late 1960's as a mathematical model to determine a probability for a given ground-motion value at a site of interest (Cornell, 1968). In other words, PSHA was developed to assess seismic risk of individual sites for engineering purposes (Cornell, 1968). PSHA methodology uses statistical models of earthquake occurrence and ground-motion attenuation to calculate the annual probability of a specified ground-motion level being exceeded at a given site. PSHA methods are not viable without sufficient observations (data) for meaningful statistical and probability analysis, however. The acknowledged lack of data for the central United States (Petersen and others, 2008) requires more speculative calculations when applying PSHA for the central United States than for the western United States, where data are numerous. Flaws in the underlying PSHA assumptions include equal likelihood of earthquake occurrence in a source zone, constant average occurrence rate, Poisson (memory-less) earthquake occurrence, and equating the annual probability of exceedance (i.e., exceedance probability in 1 yr—a dimension-

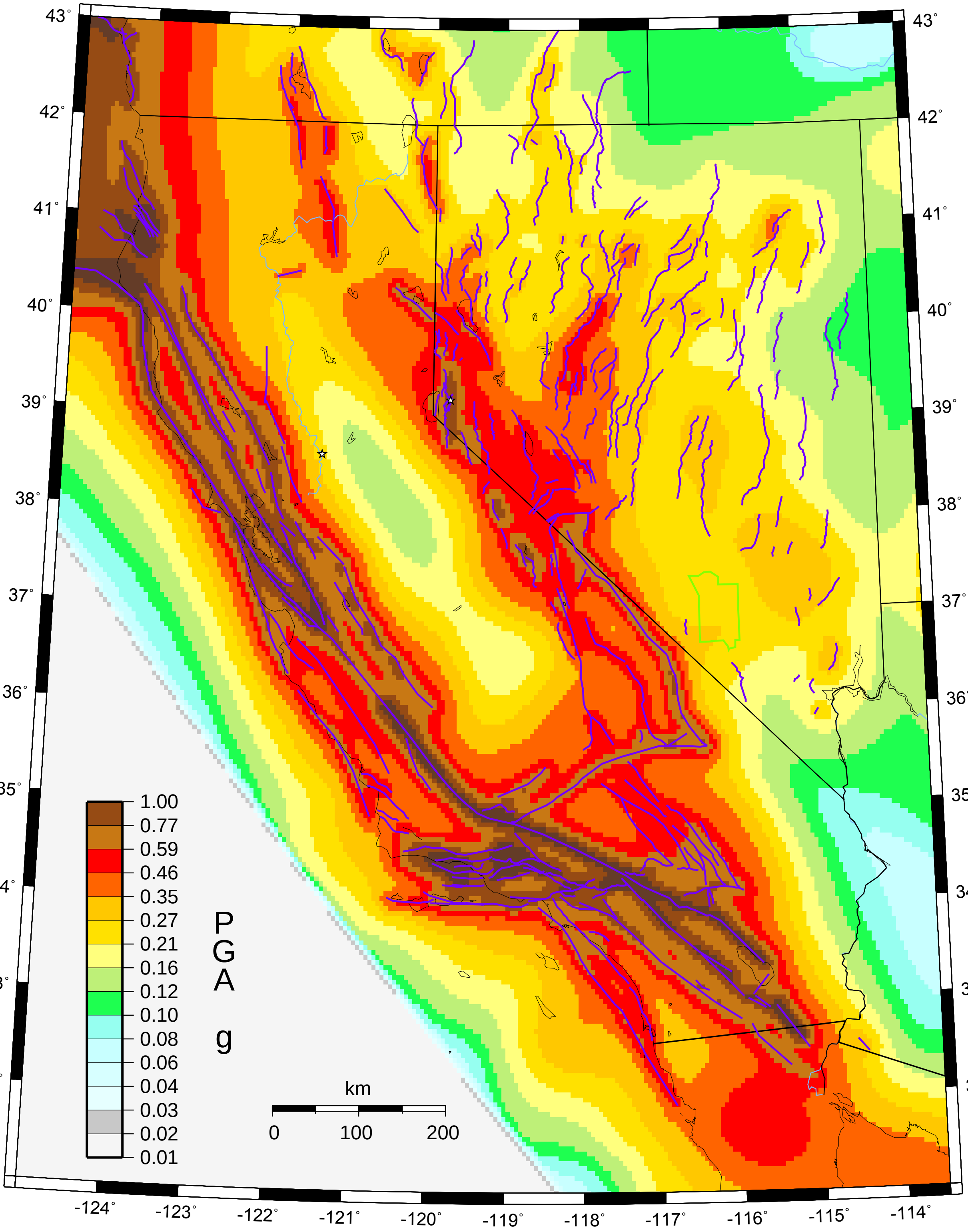


Figure 2. The 2008 national seismic hazard map showing peak ground acceleration *(g)* in California and Nevada with 2 percent probability of exceedance in 50 yr. The high value is 1.0*g.* From U.S. Geological Survey (2012).

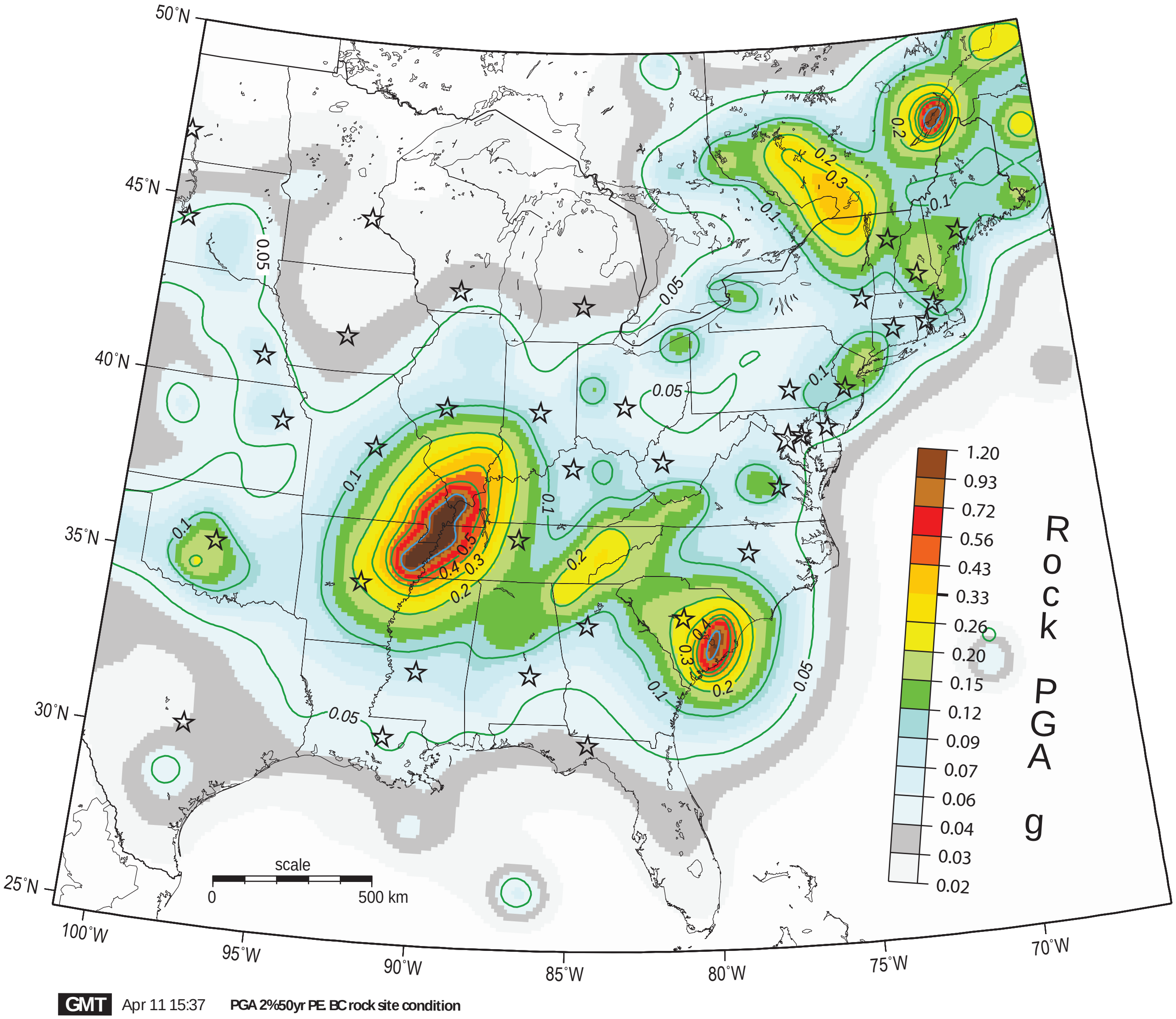


Figure 3. The 2008 national seismic hazard map showing peak ground acceleration in the central and eastern United States with 2 percent probability of exceedance in 50 yr. Data for the map indicate a high value of greater than 1.2*g* for the New Madrid Seismic Zone. From U.S. Geological Survey (2012).

less quantity) to a frequency (i.e., exceedance frequency—a dimensional quantity with the unit of per year). These flaws lead to PSHA results being misused and misinterpreted (Wang, 2011; Wang and Cobb, 2012). Compounded uncertainty—the overstatement of uncertainty created by calculating a response from multiple uncertain variables—is a common result of working with models and applies to the use of PSHA methods. In addition, the requirement for weighting the significance of variables in PSHA calculations allows for bias through personal opinion of the particular scientists or engineers conducting the probabilistic analysis (Klügel, 2011). All of these complications with either PSHA or modeling in general contribute to a lack of confidence in the resulting national seismic hazard maps for the central United States. Either overstatement or understatement of hazard is possible, depending on the particular site in relation to the maps, but sites in or near the New Madrid Seismic Zone are likely to have an overstated seismic hazard because of the significance attributed to historic area seismicity during the weighting of hazards in the map creation process.

The national seismic hazard maps, with their overstated hazard assessment for the New Madrid Seismic Zone, have been used to develop engineering standards (for example, the American Society of Civil Engineers' Minimum Design Loads for Buildings and Other Structures); building codes (including the International Code Council's International Building Code and the commonwealth of Kentucky's building code); insurance rates; risk assessments; emergency management plans; and other public policies. The USGS Earthquake Hazards Program's website, Seismic Design Maps & Tools (U.S. Geological Survey, 2014) can be used to generate design maps for a specific site using any of four different building code reference documents: the International Building Code, the American Society of Civil Engineers' standard, the NEHRP Recommended Seismic Provisions, or the American Association of State Highway and Transportation Officials' Guide Specifications for LRFD (Load and Resistance Factor Design) Seismic Bridge Design. Each independent engineering organization is responsible for determining how to apply the information contained in the national seismic hazard maps, but the maps are universally accepted as the best current science. The building and engineering codes were then adopted by individual states as they saw fit, but again were generally accepted as authoritative in regard to engineering and construction best practices. And so as each expert organization relied on the other, the original science was passed on to the public through codification in local public policies. In this manner, the commonwealth of Kentucky adopted the International Building Code with few reservations and exceptions as its accepted building code. At each step in this process, any uncertainties in the underlying calculations were accepted, compounded, and codified as mitigation requirements.

Government officials, economic development agencies, and businesspersons in the Jackson Purchase Region of western Kentucky have complained that overly stringent seismic mitigation policies adversely affect economic development in the region by discouraging new businesses from locating in the area (City of Paducah, 2012; L. Hayes, Secretary of Economic Development, personal communication, 2013; Paducah Area Chamber of Commerce, 2012; C. Chancellor, Paducah Economic Development, personal communication, 2013; S. Doolittle, Paducah Riverfront Development Authority, personal communication, 2013). Wang and Cobb (2012) found that application of NEHRP provisions to public policy in the New Madrid Seismic Zone has resulted in unrealistic building code expectations and, in some areas, a disincentive for construction. For example, based on NEHRP recommendations resulting from the 2008 national seismic hazard maps, at the Paducah Gaseous Diffusion Plant, a federal facility, a seismic design of 0.8 *g* would be required for a new landfill (Wang and Cobb, 2012). In addition, residential construction in western Kentucky would require the services of a design professional under the terms of the International Residential Code of 2000 (Structural Engineers Association of Kentucky, 2002), which, in many cases, would make construction too costly.

One of the most frequently asked questions is why building codes are calibrated for a 2,500-yr earthquake return event when current science tells us to prepare for a 500-yr event—and even the 500-yr event is 10 times longer than the expected useful lifetime for new building construction. For comparison, flood building zones are based on a 100-yr return event (1 percent probability of occurring in 1 yr) (International Code Council, 2000). There appears to be a chain reaction, from the beginning seismic assumptions and PSHA methodology for the New Madrid Seismic Zone, through the results being applied to design maps and building codes, to the end result of suppressed economic growth rather than a safer society.

In an effort to address the concerns of citizens, businesspersons, and government officials about current seismic-hazard mitigation policies in western Kentucky, this study assessed the policy impacts on Kentucky, western Kentucky in particular, through informal interviews with stakeholders ranging from public officials to businesspersons and other professionals and private citizens. A range of historical parameters and alternative modeling methods were used to create scenario seismic-hazard maps to compare with the national seismic hazard maps. Relative economic and engineering analyses were performed using the revised models and a federal hazard and economic analysis software package, Hazus-MH (Federal Emergency Management Agency, 2012a). Comparisons were also made to seismic-hazard mitigation policies in the area affected by the 2008 Wenchuan, China, earthquake (magnitude 7.9, May 12, 2008, eastern Sichuan Province); the ground-motion attenuation model for Wenchuan is similar to that for the central and eastern United States (Wang and Lu, 2011). Lessons learned from the 2008 Wenchuan earthquake were used to recommend more informed policy decisions for the New Madrid Seismic Zone. Finally, several recommendations were developed with the intention of reducing impacts to the western Kentucky economy while still maintaining reasonable safety standards.

Seismicity

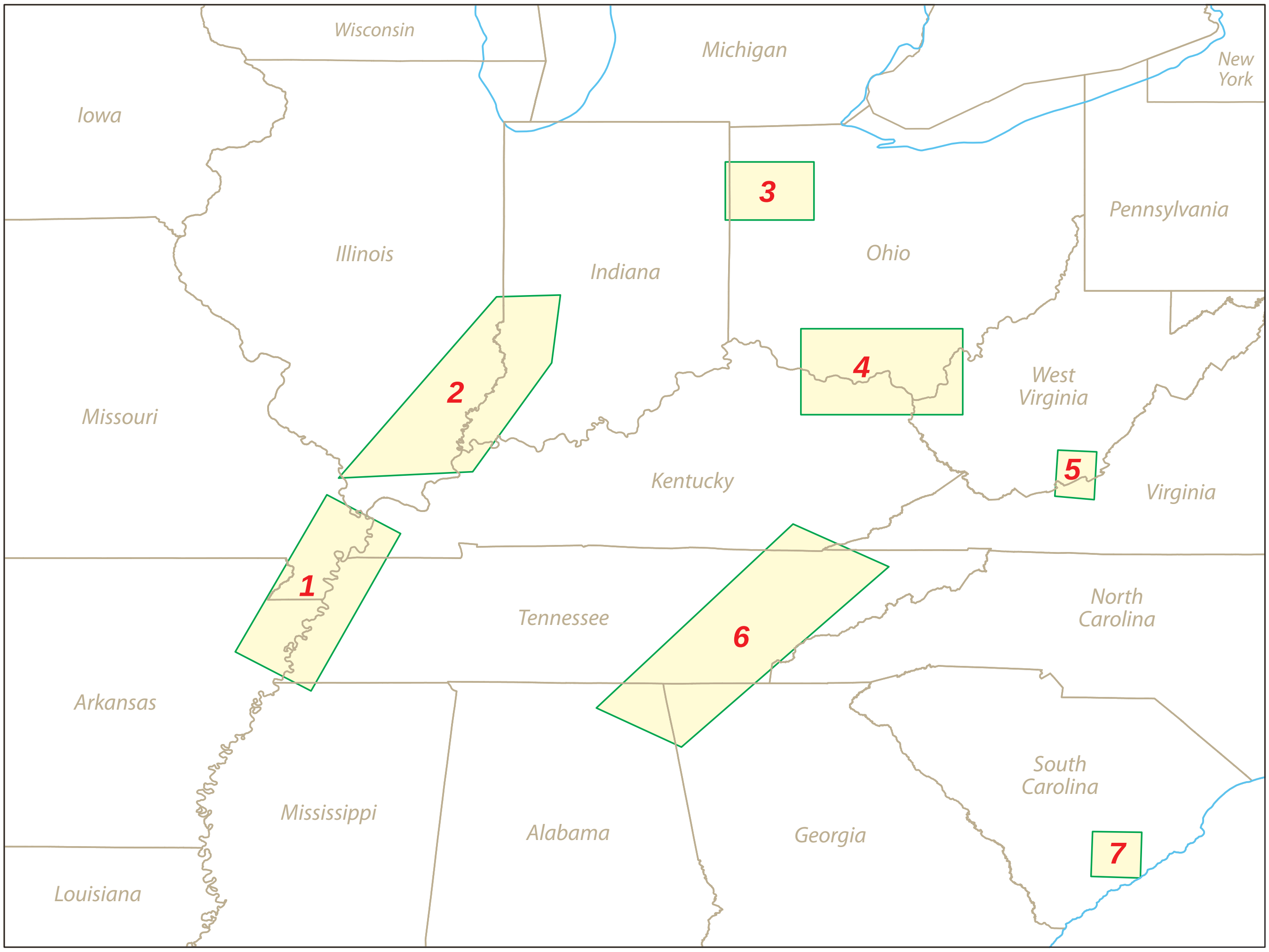
The New Madrid Seismic Zone

The New Madrid Seismic Zone is an intraplate fault zone in the North American tectonic plate. One of several seismic zones in the central and eastern United States that affect Kentucky (Fig. 4), the New Madrid was named for a series of earthquakes that occurred between December 1811 and February 1812; the last of these earthquakes destroyed the town of New Madrid, Mo. (Fig. 5). There were at least three large earthquakes in the 1811-12 cluster (Dec. 16, 1811, Jan. 23, 1812, and Feb. 7, 1812). Although no seismographic records were available at that time, estimates of the magnitudes and intensities of those earthquakes have been made using eyewitness accounts of the events and journals and logs of scientists who kept records of effects in their geographic areas. Each of the events has been estimated to be between magnitude 6.7 and 8.1, but no general consensus has been reached to narrow this range. Over the 2-mo period, the largest events occurred chronologically from south to north along the northeastern trend of the seismic zone (Fig. 1).

Shaking attributed to these earthquakes was reported from New Orleans to the south, the Atlantic Coast states to the east, New Hampshire to the northeast, and Toronto, Canada, to the north (Nuttli, 1973). Few reports came from farther west since at the time there were few settlements in that direction. Widespread effects of this series of earthquakes and their aftershocks included opening of ground chasms and rifts; changes of ground elevation, both as areas of uplifting and areas of subsidence across the region; sand blows and discharge of other earth materials; soil liquefaction; sulfurous smells; and unusual lights and sounds (Nuttli, 1973). Reelfoot Lake in northwestern Tennessee, for example, was formed when subsidence on the eastern side of the Reelfoot Fault dammed a small stream, causing a broad but shallow body of water to form. More than 200 yr later, trees that began life in a field continue to grow with their trunks submerged in the lake (Fig. 6). The only reason there was not more damage to the built environment is that the region was only sparsely populated at the time and structures in the area were low to the ground and of simple construction. The largest earthquakes since 1812 have been a magnitude 6.6 in 1895 and a magnitude 5.4 in 1968, both of which continued the northeastern trend (Fig. 1).

Lacking seismographic data from large earthquakes, researchers focused on the subsurface structure of the area (Zoback and others, 1980; Johnston and Schweig, 1996; Street and others, 1997a, b; Woolery and Street, 2002; McBride and others, 2003; Wang and Woolery, 2006; Csontos and Van Arsdale, 2008). Studies have shown that a large seismically active fault system underlies the Upper Mississippi Embayment; it is believed to be a reactivated failed rift zone. The zone extends 240 km in a southwest-northeast orientation from northeastern Arkansas into southeastern Missouri, touching the western boundaries of Tennessee and Kentucky, and exhibits shallow seismicity in the upper 25 km. It consists of three main fault sections: The southwestern and northeastern sections are right-lateral faults slightly offset from one another but generally striking northeast, following the southwest-northeast trend of the Mississippi Embayment, and the central stepover thrust-fault section extends southeast-northwest between them, connecting the offset. Sediments in this part of the Mississippi Embayment range from 0 to 1.1 km deep.

Part of the uncertainty for earthquake modeling in the region is that recurrence intervals for great earthquakes cannot be confirmed. We have only 200 yr of historical data, some of which is eyewitness accounts and possibly exaggerated. Paleoseismic data from investigation of sand blows and soil-horizon shifts (Tuttle and others, 2002; Hol-



Explanation

1 New Madrid Seismic Zone
2 Wabash Valley Seismic Zone
3 Anna, Ohio, Seismic Zone
4 Northeastern Kentucky Seismic Zone
5 Giles County Seismic Zone
6 Eastern Tennessee Seismic Zone
7 Charleston, S.C., Seismic Zone

Figure 4. Relative locations of several seismic zones in the central and eastern United States near Kentucky. Modified from Street and Woolery (1997).

brook and others, 2006) indicate prehistoric earthquake dates of 1400 and 900 A.D., and models from modern data (Hough and Page, 2011) indicate recurrence intervals in the range of 500 to 1,000 yr. The longer 1,000-yr estimate is supported by GIS data (Newman and others, 1999; Calais and Stein, 2009; Stein, 2010) showing little or no continuing deformation in the area.

Although much research has been conducted in the area, the seismic mechanism is still unclear. Theories include isostatic rebound from the last North American glaciation (Grollimund and Zoback, 2001), a sinking mafic body deforming the underlying crust (Pollitz and others, 2001), and extensive riverine erosion in the Mississippi River Valley allowing for crustal rebound (Calais and others, 2010).

The Wenchuan, China, Area

The People's Republic of China is located entirely upon the Eurasian tectonic plate and is greatly affected by interactions between the Indian Plate

Figure 5. Scarp of the New Madrid Fault line on the Mississippi River at New Madrid, Mo. (facing approximately west). Inset: Marker for the New Madrid Fault, immediately east of photo location. Photos ©Alice M. Orton, 2013. Used with permission.

to the west and the Pacific and Philippine Plates to the east (Fig. 7). As the Indian tectonic plate to the southwest pushes north against the Tibetan Plateau, the Tibetan Plateau spreads laterally, pushing east and north, and generates many large earthquakes (Fig. 7), including the 1556 Shansi earthquake, which resulted in about 830,000 fatalities (the most recorded fatalities for any earthquake in the world).

The Wenchuan earthquake (M7.9) of May 12, 2008, occurred along the Longmenshan Fault, which is the suture between the uplifted Tibetan Plateau and the Sichuan Basin (Fig. 8). Movement on the northeast-striking Longmenshan Fault or a related thrust fault along the northwestern edge of the Sichuan Basin caused the quake (Burchfiel and others, 2008). The event is often referred to as either the Eastern Sichuan earthquake, after the province, or the Wenchuan earthquake, after the county in which the epicenter occurred. The epicenter was only 80 km from Chengdu, the provincial capital of Sichuan. The focal point was estimated to be at a depth of 19 km (U.S. Geological Survey, 2008a) and the total length of the surface rupture was approximately 300 km (Xu and others, 2009).

Effects from the 2008 Wenchuan earthquake included widespread shaking with a maximum Mercalli intensity of IX near Wenchuan; landslides along the Tibetan Plateau front; ground-surface faulting and fracturing; ground subsidence; and seiches (standing waves) as far away as Bangladesh (U.S. Geological Survey, 2008b). Shaking was felt as far away as the Thailand coast to the south, the eastern continental coast and Taiwan to the east, and Beijing and beyond to the north (U.S. Geological Survey, 2008c). Damaged infrastructure included retaining walls, bridges, roads, dams, water pipelines, and tunnels (Free and others, 2008; U.S. Geological Survey, 2008b) (Fig. 9). More than 5 million buildings collapsed, and 21 million more

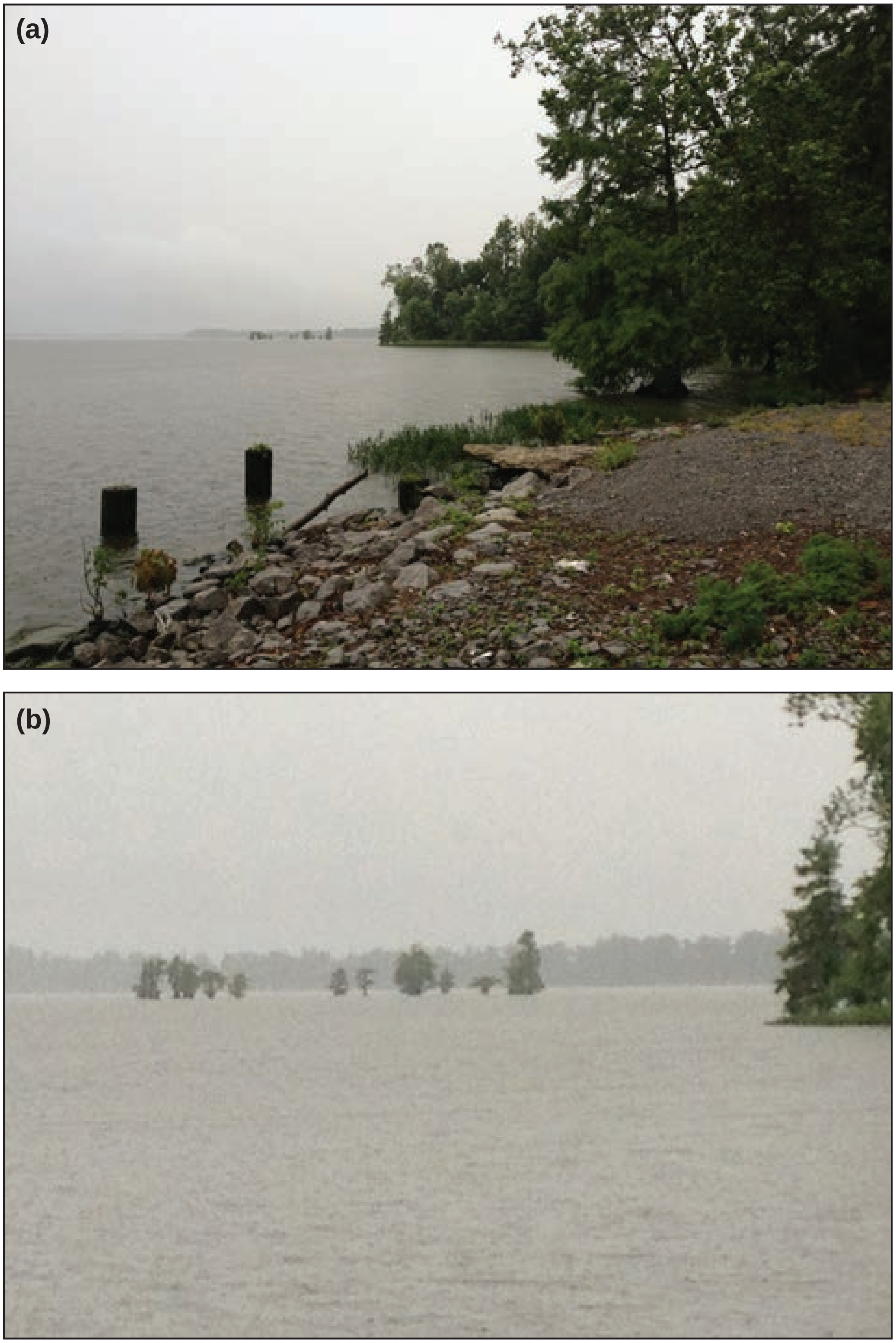


Figure 6. (a) The line of trees in the mid-left background originally marked the edge of a field. Subsidence following the Feb. 7, 1812, New Madrid earthquake caused the area to fill with water. (b) The trees have continued to grow submerged in the resulting lake for 200 yr. Photos ©Alice M. Orton, 2013. Used with permission.

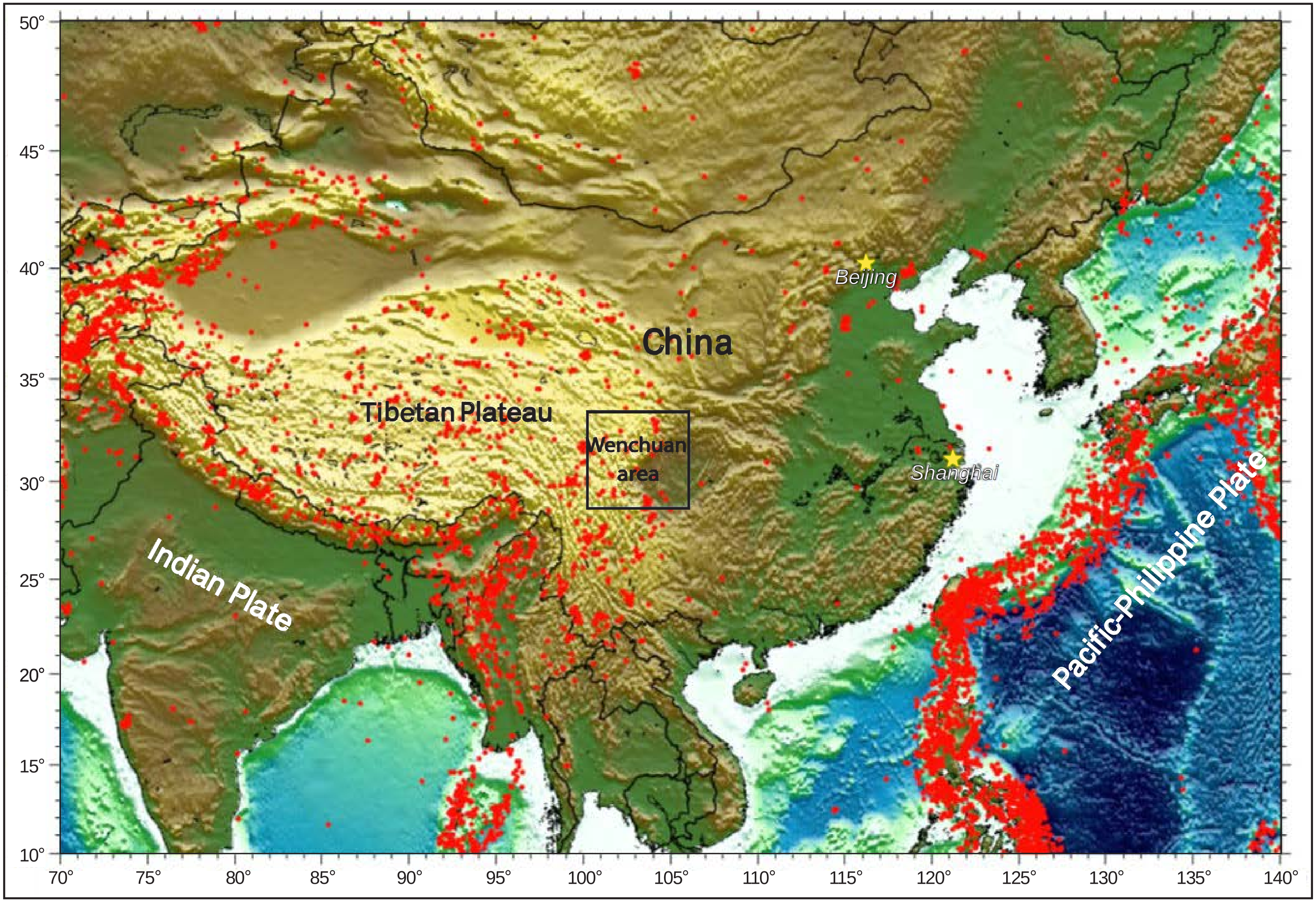


Figure 7. East Asian seismicity from 1898 to 2005, magnitude greater than 5, showing seismically active regions and plate boundaries affecting the 2008 Wenchuan, China, earthquake. From Geodynamics website, geophysics.eas.gatech.edu/anewman/classes/Geodynamics/misc. Used with permission of Andrew Newman.

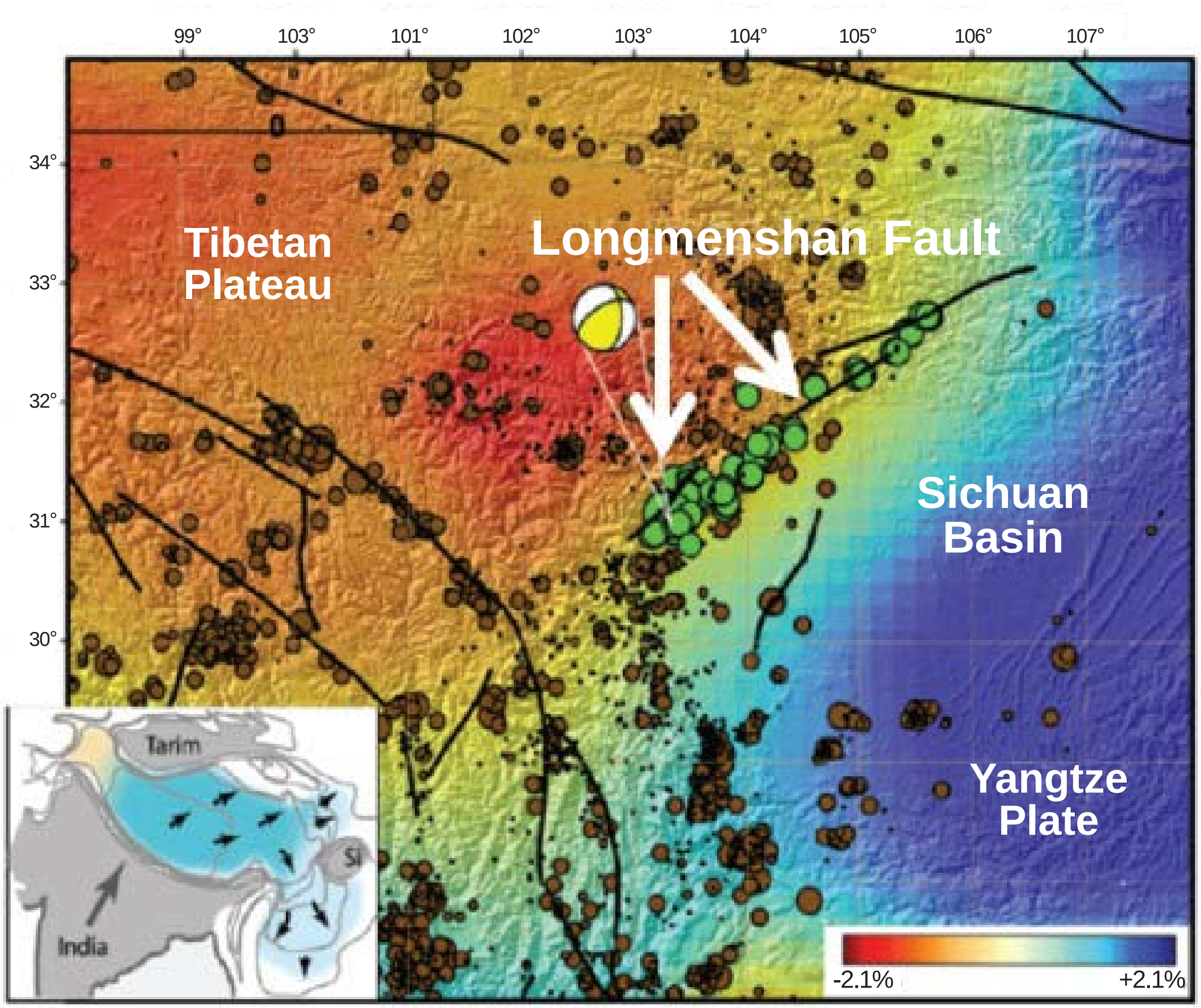


Figure 8. Epicenters of the May 12, 2008, Wenchuan earthquake. Longmenshan Fault and regional seismicity resulted from the M 7.9 Wenchuan earthquake. From Burchfiel and others (2008). Used with the permission of the Geological Society of America.

sustained damage, leaving more than 5 million people homeless and 15 million evacuated from damaged homes (U.S. Geological Survey, 2008b). The earthquake resulted in approximately 87,000 fatalities (U.S. Geological Survey, 2008b) and more than $110 billion in damage (Xie and others, 2009).

Although the mechanism for intraplate seismicity in the Wenchuan region is not the same as in the central United States, the regions share some similarities. As shown by Wheeler (2011) and Petersen and others (2008), the Longmenshan thrust belt is the western boundary of the Southeast Asian or Eastern China stable continental region. The Wenchuan area, most of which is in the Sichuan Basin, is geologically similar to the central and eastern United States stable continental region. A preliminary comparison shows that the ground-motion attenuation models for the central and eastern United States are similar to the ones for the Wenchuan area (Wang and Lu, 2011). Combined with China's longer historical record and much higher exposure of population and buildings, the Wenchuan earthquake can be compared to current conditions in the central United States, the New Madrid Seismic Zone in particular.

Figure 9. Examples of damage to bridges in the Wenchuan, China, area caused by the May 12, 2008, earthquake. Photo © Zhenming Wang. Used with permission.

Assessment of Seismic Policy Impact

In an effort to determine the science knowledge base and ascertain the effect of current seismic-hazard mitigation policies on the western Kentucky economy, informal interviews were arranged with a wide variety of professionals whose work could bring them in contact with seismic-hazard mitigation policies and their effects. Twenty-nine interviews were conducted in Lexington, Frankfort, Paducah, Calvert City, and Murray, Ky., or by phone with those unable to meet in person. With the permission of each participant, the interviews were recorded for later review. Table 1 gives interview participants' occupations and jurisdiction. Several participants hold overlapping positions, such as in emergency management and education, or transportation and engineering, and have therefore been counted twice.

A standard list of questions was provided in advance to each participant when possible, although questions asked in each interview reflected the jurisdiction, position, responsibilities, experience, and knowledge of earthquake mitigation policies. Follow-up questions were often asked based on information received during the course of the interview (Orton, 2014).

General Knowledge of Seismic Hazard

The general knowledge about underlying seismic science and how it relates to economic concerns for western Kentucky were assessed. Fifteen participants did not have scientific or engineering backgrounds, and 10 of them had little or no information about the actual seismic hazard for the New Madrid Seismic Zone, western Kentucky, McCracken County, or Paducah. Their knowledge was a broad collection of what they had read in newspaper accounts, heard from others, or experienced themselves while living in the region. Several had expectations of catastrophic events, although they were not specific about details. Four participants without scientific backgrounds had some sense of the actual hazard estimates, having explored the subject through personal or job-related interest; one participant with no scientific background had solid technical knowledge through job-related training. Among the 14 participants with scientific backgrounds, seven had solid technical knowledge, four had some knowledge of local earthquake hazard, and three had only little or anecdotal information.

The nonscience group expected the maximum-magnitude earthquake to range from 6.0 to 8.1; nine of the 15 participants did not answer or claimed no knowledge of this information. Several

Table 1. Occupations of participants.

Industry	*Jurisdiction*				
	Private/ Contractor	*City Government*	*County Government*	*State Government*	*Federal Government*
building/real estate development	3	1	1		
economic development	1	2		1	
education				2	
energy	1			2	2
engineering	3	1		3	2
finance/insurance	2				
healthcare	3				
safety/emergency management	4			2	1
seismology/science				1	1
transportation				2	
waste management				1	

participants indicated a general sense that disaster could be expected, but they did not know any details. The expected source of earthquake hazard was the New Madrid Seismic Zone, according to 12 of these participants. Four participants also had knowledge of the Wabash Valley Seismic Zone, and one could name several surrounding seismic zones that might contribute to local or regional earthquake hazard. One respondent knew generally that the earthquake hazard source was "near the river." Two respondents claimed no knowledge of the source for earthquake hazard.

The range for maximum-magnitude earthquakes given by the group with scientific backgrounds was broader than that given by the nonscience group, extending from greater than 6.0 to 8.5; this group was much more likely to qualify their responses with information about the earthquake source or the recurrence interval, however. Several of these respondents cited what they knew of historic events rather than giving a firm expectation for future events; and five of them did not answer this question. This group cited the New Madrid Seismic Zone as the most likely earthquake hazard source (10 times out of 14), but seven participants also named other regional seismic zones as potential sources, including the Wabash Valley Seismic Zone, the Rough Creek Graben, the Charleston, Mo., region, the Eastern Tennessee Seismic Zone, the Maysville-Sharpsburg region, the northeastern Kentucky region, the southeastern Kentucky region, the Charleston, S.C., region, and the Reelfoot Fault. A few answers were slightly more vague, including "40 to 50 miles away" and "to the west."

The nonscience group had little understanding of expected earthquake recurrence intervals; only one participant gave actual statistical expectations of a given magnitude in a given period. A few participants with scientific backgrounds had more knowledge (sometimes very specific because of the nature of their occupations) about seismic hazard for the region, but their return-period estimates ranged widely, from magnitude 8 in 200 to 500 yr to magnitudes 8 to 8.5 in 2,500 yr; some gave nonspecific magnitude estimates of "great earthquake" with recurrence-interval estimates of 500 yr and "moderate earthquakes" with recurrence interval of 100 yr.

The nonscience participants defined "experts" broadly and included scientists (nonspecific), engineers (nonspecific), federal government agencies (USGS and U.S. Department of Energy), Kentucky Geological Survey geologists, and research universities (specifically, Murray State University). Two of these participants gave the name of a person they considered to be an expert, and five did not respond to this question. Whether the response was general or specific, the underlying feeling was one of great trust in these experts. Among those with scientific backgrounds, the response was approximately the same: four participants did not respond, but the remaining 10 were much more likely than the nonscience participants to indicate at least one source of expert information (some general and some more specific), including seismologists or seismic consultants (nonspecific), geologists (nonspecific), engineers (nonspecific), architects (nonspecific), engineers with the American Association of State Highway and Transportation Officials, federal government agencies (USGS and U.S. Department of Energy), the Kentucky Geological Survey, and research universities (specifically, the University of Tennessee and St. Louis University). Five persons were specifically named as experts by their science-background peers.

Only one of the nonscience group claimed never to have seen a copy or a version of the national seismic hazard maps, but most had seen them at least once. Four had used the maps, or some derivative product of them, in their work. No one in this group claimed to understand the maps, however, just that the concentric rings indicated higher earthquake danger at the centers and lower danger as the rings expanded. Only a few indicated they were aware there was more than one map, although five indicated they questioned the validity of seismic-hazard maps for the New Madrid Seismic Zone. None claimed any knowledge of the vetting process for the maps or that the maps are reviewed and revised on a regular schedule.

All of the science-based participants had seen the maps, but only half (seven of 14) use them or a derivative product in their work. Only one participant claimed to trust the maps implicitly. Some of those who use the maps indicated they took other factors such as surface geology, underlying soils, other load sources (wind, thermal contraction), and other earthquake source areas into consideration when determining earthquake hazard rather than relying implicitly on the national seismic hazard maps. Several of these participants indicated they were more likely to consider scenarios from deterministic seismic hazard analysis for individual projects than relying on the general PSHA scenarios on which the maps are based. Most, however, accepted the science as fact, or as close to fact as we can get at the moment. They have been given a formula for implementing the current local, regional, or federal policies, such as building codes, and they do not spend time questioning either the formulas or the underlying science. As a group, they do not worry about the difference between models and actual data. Only a few engineers know or care to know anything about the development process for the national seismic hazard maps. They are caught in a no-man's land where their clients demand knowledge and expect absolute answers. Because engineers risk their livelihoods and reputations on their approval of construction plans, they calculate building and structural requirements based on engineering design codes (such as American Society of Civil Engineers' and American Association of State Highway and Transportation Officials' standards), then fall back on the expertise behind those codes and the authority of current design policies if anything goes wrong.

The response to questions about earthquake preparedness tended to depend less on a science versus nonscience background and more on whether individual participants deal with the public on a mass basis or on an individual basis. For example, those in charge of health-care facilities or public emergency response or education tended to have well-defined organizational emergency response plans in place that are reviewed and revised on a regular basis. Many of these participants rely on the advice of experts since the underlying science is unclear or unavailable to them in a simple form. Emergency response is usually applied to emergencies resulting from any natural hazard (flood, wind, fire, earthquake, ice, etc.); seismic hazard is not specifically addressed in most cases, but is just one of many hazard possibilities to be considered. One participant specifically asked why, if the seismic hazard is so extreme, do government agencies not focus more on preparing for a large earthquake other than requiring earthquake-resistant structures. Some organizations also have plans in place for response to terrorism or other manmade sources (fire, large-scale accident, etc.). Those who deal with the public on an individual basis and those who do not deal with the public at all tend to either not know about emergency response or not have plans in place.

Science-based participants as a rule had little to say about earthquake preparedness since as a group they deal less with the public, although a few with responsibility for large facilities had specific hazard response plans in place. Individual participants may or may not have had personal preparations in order, but those whose work emphasized emergency preparedness tended to also have developed personal emergency plans.

Several participants indicated they had seen a surge in emergency preparedness following a severe ice storm in western Kentucky in 2009, although the verdict was split about whether there can really be enough preparedness. Participants in both groups generally agreed that human beings cannot prepare for every natural hazard: No amount of preparation will stave off every possible danger. Most participants were in agreement that at some point, society and individuals choose which dangers are of most concern to them, determine how best to protect themselves, and then live with the consequences. Several participants expressed that these decisions are paramount to intelligent living and that people should be accountable for their personal choices of living environments.

Concerns About Public Policy

There was a range of responses to questions about public policy. At one end of the spectrum were those who trust the experts and believe that public policies are in place for the general good, so those with less knowledge should not question them. At the other end of the spectrum were those who question whether the science justifies current public policies. If the science is flawed (over- or understated hazard, or uncertainty in models), then current policies may not be appropriate. Several participants would like better scientific information to justify current public policy.

Public policy issues resulting from seismic-hazard analysis were mostly related to building codes and infrastructure engineering. Several participants from both science and nonscience backgrounds expressed concern that building codes are not regulated evenly, either within Kentucky or between Kentucky and surrounding states. In particular, the city of Paducah and McCracken County seem to have a better system for construction inspections than surrounding areas do. Many participants stated that companies or persons who do not want to incur the higher costs associated with seismic design and construction that will be enforced in Paducah and McCracken County simply go to a neighboring county or across the Ohio River into Illinois, where building codes are either less stringent or will not be enforced. One participant was careful to make clear that he was aware of this happening for residential buildings, but not for commercial buildings, which are more closely regulated.

A second policy concern was that federal agencies apply different standards, codes, or rules than local or State agencies do. Many federal agencies have jurisdiction for their own building codes and hazard mitigation requirements, but these requirements have to be met within the local areas where federal projects are built. One example was the Paducah Gaseous Diffusion Plant, operation of which is regulated by the federal Nuclear Regulatory Commission. Because of the current seismic-hazard rating assigned to western Kentucky by the national seismic hazard maps, upgrading the existing facilities to meet federal hazard mitigation requirements has been deemed too costly, and the operation is to be relocated out of the area. Local government officials, businesspersons, and even engineers question whether the science supports this decision. They do not see compelling evidence supporting high earthquake hazard for the region, regardless of what the national seismic hazard maps show. The perception is that federal agencies are not concerned about local issues or how federal decisions affect local regions. There is strong local feeling that doing the research is not enough, and when the results are inconclusive, the scientists should communicate that clearly.

In addition, there was some local concern that federal government officials often put local areas in political limbo by not making decisions. When an issue is inconclusive, the matter is put on hold, awaiting further investigation, further funding, or even a better political climate before resolution. But this delay often hampers local business decisions. If a decision were made at the federal level, then local matters could progress; but a lack of decision hangs up the process.

Another concern voiced during the interview process was that of appropriate representation. Because earthquakes happen less frequently in western Kentucky, there are fewer local experts who focus on them. This translates into less representation at the federal level when issues arise. For example, because the American Association of State Highway and Transportation Officials codes are created by a voting process, states with more earthquake experience have more to say about the associated hazard, and their opinions are more likely to influence the code-development process. States with less exposure to seismic hazard trust the opinions and advice of experts from states that have more exposure, but states in which the hazard is assumed to be high but the recurrence of seismic events is low are therefore underrepresented during building-code decisions.

A related issue is political or personal agendas, which many participants believe could lead to outcomes being manipulated in cases where the science was less than conclusive. Participants fell into two distinct categories: those who felt politics should have nothing to do with seismic-hazard mitigation decisions, and those who felt that the two issues were unequivocally connected. One federal science representative who was very knowledgeable about the process used to develop and revise the national seismic hazard maps stated that the process takes into account the best science available at the moment and gives fair representation to both supporting and opposing views prior to the release of map updates. A State-level science-based participant was concerned that policy gets muddied by people who want a particular outcome rather than “the truth,” and that some political decisions are driven by hidden agendas, not science. Another participant similarly commented that the issues are so complex that they are difficult for nonexperts to understand. For scientists and government officials, it is increasingly easy to ignore the issues they do not want to discuss and just pick the perspective they like. A State-level public official commented that how policy-makers feel about an issue sometimes has more to do with their decisions than actual facts about the issue. A private-sector engineer responsible for site-response investigation for a federal project commented that there was some political push to have their independent results match the federal expectations. A western Kentucky participant commented that it is not for policy-makers to influence the seismic-hazard determination since they are not experts on the science. On the other side of the argument, several local businesspersons felt that if the science was not definitive, then any policy decisions based on it were arbitrary and certainly should take into consideration other factors, such as how policy decisions based on that science would affect the local economy. Clearly, this interaction between science and policy is of key importance when the science is indecisive.

Taking responsibility for policy decisions was also mentioned as an area for concern. The general consensus was that although most professionals who are affected by seismic-hazard mitigation policy would prefer less micromanagement, no one wants to be the person responsible for downgrading the seismic-hazard rating. Because the science is uncertain—we do not know enough about historical seismicity in western Kentucky or the potential for future seismicity—it is possible that a large or great earthquake will occur in or near this area. Even those who do not want to believe this generally acknowledge the possibility, in which case, no one wants to be the one to take personal responsibility for downgrading the federally sanctioned seismic-hazard rating estimates. No one wants to be responsible if people die as a result of less stringent building requirements. The feeling was that taking precautions is correct, that if people are smart they learn from other people's mistakes, and that the current status quo is the best that can be done right now. Another participant quipped, however, that we know the earth has been hit by meteors in the past, but we do not build for those conditions and we should not be required to build for seismic conditions that have such great inherent uncertainty. These concerns for public policy, and ultimately public safety, must be considered against the very real economic cost of implementing earthquake mitigation policies.

Concerns About Economic Development

Not all participants had preconceived opinions about the relationship between seismic-hazard mitigation and economic development, but all were able to think of some ways that seismic hazard could or did have an impact on social costs. Opinions were split as to whether the costs were worthwhile. Some felt that any cost was justifiable if lives were saved. One participant commented that all the money we spend on education is of no worth if the buildings collapse on the students; he would rather throw the money away on the sensible investment of building reinforcement than live with the consequences if school buildings were built to a lower standard and lives were lost in a collapse. Others stated that the money being used to make buildings safer is not justified without some indication that there is a real risk of loss, of which they felt there was no evidence. There is no financial gain to the additional code requirements: A school built to the code costs more but is not safer if built to a higher seismic standard than needed; a house built according to the standards costs more but is not more valuable nor more desirable because it is built to too stringent seismic codes. These participants were not aware of each other's comments, but their concerns illustrate the scope of opinions.

Several participants with business interests in economic development for western Kentucky indicated that a current problem is the perception of putting a business in harm's way. Many participants, both engineers and public officials, related experiences where businesses were unwilling to risk loss of customers or facilities in the event of a major earthquake. Each project development team has to decide how much risk it is willing to assume, in terms of money, time, and inconvenience. For example, a large automobile manufacturing company briefly considered building a manufacturing plant in Paducah but ultimately did not because the local earthquake and wind hazards were too high. The participant who relayed this anecdote stated he had never experienced either an earthquake or a tornado in the area and felt the perceived threat was worse than the actual threat, but that made no difference to the automobile manufacturer. The bottom line is that many investors will simply not consider establishing a business in a high earthquake-hazard zone, similar to not wanting to build in a floodplain or in tornado alley. It is less risky simply to establish a business elsewhere. If the hazard rating is correctly evaluated, this is the best business decision. But if the high hazard rating currently assigned to western Kentucky is inappropriate, business opportunities are being lost as a result. Either way, the hazard evaluation published on the national seismic hazard maps, whether correctly evaluated or not, has a direct impact on the local economy.

If a business already has a base in the area, it is a simple thing to stay as long as no changes are necessary. If, however, a larger facility must be built, or if a business from outside the area is considering relocating to the area, then the costs associated with building to a high seismic-mitigation standard must be considered. These costs include additional environmental studies and site assessments, engineers and building consultants, building supplies, inspection/code enforcement, and infrastructure (roads, bridges, traffic improvements, etc.), plus the additional time to make all the necessary arrangements and complete the additional work. More stringent mitigation policies require more time to comply, and time is money. Estimates of these additional costs ranged from 1 percent to 20 percent by various participants. Some claimed that the costs were such a norm by now that no one paid them any attention; they were just part of the cost of doing business in western Kentucky. Others claimed that the costs were a major deterrent to new business, and especially big business concerns that would require large capital investments.

Beyond the immediate set-up costs, business maintenance costs were also of concern. Earthquake coverage may be as much as 25 percent of the cost of residential insurance and 30 to 50 percent of commercial insurance costs. All structures financed by local banks in western Kentucky are required to carry earthquake insurance to offset the high local investment ratios in case of loss. Other indirect costs include development of emergency management plans, support of emergency management personnel, and possibly insurance to cover interruption of business, although these costs would also be incurred for other natural hazards and cannot be attributed solely to seismic hazard.

One concern expressed by several participants was that the region suffers from a lack of jobs that will draw educated young people. Local youth who complete a college education are unable to stay in the area because there are few jobs requiring advanced education. As one participant put it, “And how many fast food places do you need?” (J. Cates, builder, personal communication, 2013). The lack of jobs for educated professionals also affects the loss of jobs down the line as communities need fewer grocery stores, restaurants, gas stations, garbage collectors, schoolteachers, healthcare providers, and other infrastructure service employers and employees. Increased seismic hazard ratings for the region are perceived as the cause of this inability to draw businesses, to maintain educated professionals, and therefore to support other community service employees.

Many participants were well aware that funds are limited. Whether in private or public coffers, there is only so much money, and each person and agency must use its resources to the best of its ability. Either overstated or understated seismic hazard for the New Madrid Seismic Zone would lead to a misuse of funds in western Kentucky as persons and public agencies conduct business daily. Several participants recalled implementation of the International Building Code in western Kentucky around 2002. The seismic policy had changed so severely that residential construction ground to a near halt while local agencies, engineers, and design consultants grappled with the best ways to implement the requirements in ways that were still affordable to family budgets. On a public level, projects must be juggled and adjusted to cover the higher seismic-mitigation requirements.

Although generally seen as having a negative economic impact, seismic-mitigation requirements also have positive economic aspects, according to a few participants. For example, one participant indicated that by having State-level seismic-hazard mitigation plans in place, the commonwealth of Kentucky has access to additional federal emergency funding if a state of emergency is declared. Another participant noted that cost savings to residential builders who went to adjoining states or counties might actually be negligible since property taxes were often higher in surrounding areas. Yet another participant commented that although mitigation requirements increased building costs, the money spent sometimes went back into the local economy in the form of construction materials purchased and jobs created in both building and regulation industries. On the other hand, several participants indicated that they felt certain types of organizations, including engineering and environmental consulting, often benefited economically from heightened earthquake hype and might in some cases promote or uphold high hazard ratings to suit their own interests.

In the end, the biggest economic concern had to do with the costs of implementing an inappropriate level of earthquake hazard mitigation. Some participants felt that in the current state of little to no seismic activity the cost was great to prepare for something that would not happen, but others felt that it was better to spend the required funds and have no regrets in case of a great earthquake. Proponents on both sides of this issue acknowledged, however, that we really have no way of knowing what will happen. Mankind cannot build or prepare for every possible hazard, so at some point we make decisions and live with the consequences.

Earthquake Scenario Analysis

Earthquake scenario analysis is used to determine the ground-motion hazards and resulting economic and life-safety impacts from specific earthquake scenarios. Earthquake scenarios (i.e., magnitudes, locations, and focal depths) were determined from the available scientific literature. In combination with ground-motion attenuation models, these earthquake scenarios were used to generate point-source ground-motion hazard scenarios. The hazard scenarios were used to determine resulting economic and life-safety impacts using FEMA's Hazus-MH software. Although fault-line scenarios would have been preferred, Hazus-MH does not include fault-line data for any area east of the Rocky Mountains. In other words, in order to analyze economic impact using Hazus-MH, we could only generate and analyze point-source hazard scenarios. We then compared these results from scenario analysis with observations from the Wenchuan earthquake.

Seismic Hazard Scenarios

A literature review was conducted to determine the estimated magnitudes, locations, and depths of the three main large earthquakes in the 1811-12 New Madrid sequence. Sources included the USGS earthquake catalog (Petersen and others, 2008) and several often-referenced older as well as newer publications (Nuttli, 1973; Johnston and Schweig, 1996; Hough and others, 2000; Bakun and Hopper, 2004; Cramer and Boyd, 2011; Hough and Page, 2011). Variables for the earthquake scenarios were limited to the following four categories:

1. Locations (latitude/longitude) of the 1811-12 main shocks
    - Dec. 16, 1811: 36.0, –90
    - Jan. 23, 1812: 36.3, –89.6
    - Feb. 7, 1812: 36.5, –89.6
2. Focal depths
    - 10 km
    - 20 km
3. Magnitudes (lower, middle, and upper best estimates for each historical event)
    - Dec. 16, 1811: M 7.2, M 7.7, M 8.2
    - Jan. 23, 1812: M 7.1, M 7.5, M 7.9
    - Feb. 7, 1812: M 7.4, M 7.8, M 8.1
4. Ground-motion attenuation functions
    - Atkinson and Boore's (2006) revised attenuation function for eastern North America (denoted A&B 2006)
    - The central and eastern United States combined ground-motion characterization model (denoted CEUS 2008), developed using weighted input from other attenuation functions (Federal Emergency Management Agency, 2012b).

Combinations of these four variables resulted in a total of 36 earthquake scenarios (Table 2). In addition, in order to facilitate comparison between the USGS historical fault-line scenario (New Madrid SW M 7.7 scenario) and the national seismic hazard maps, two additional hazard scenarios were created for the Dec. 16, 1811, location, M 7.7 at 0 km depth, also using the two ground-motion attenuation functions listed above. Although an event at 0 km is physically impossible, these scenarios were created for this particular location and magnitude to bracket the 10-km-depth fault-line scenario with point-source scenarios at 20 km and 0 km. Thus, we used 38 total point-hazard scenarios (Orton, 2014).

One additional scenario was created to use the USGS New Madrid SW M 7.7 scenario fault-line

Table 2. Seismic-hazard scenarios for the New Madrid Seismic Zone.

		Variables Modified for This Study					
Scenario ID	*Date of Historical Event (MM-DD-YYYY)*	*Attenuation Function*[1]	*Hazus-MH eqEpicenterID*[2]	*Magnitude (M)*	*Depth (km)*	*Latitude (degrees)*	*Longitude (degrees)*
A 4026 72 10	12-16-1811	A&B 2006	4026	7.2 (default)	10 (default)	36 (default)	–90 (default)
C 4026 72 10	12-16-1811	CEUS 2008 (default)	4026	7.2 (default)	10 (default)	36 (default)	–90 (default)
A 4026 72 20	12-16-1811	A&B 2006	4026	7.2 (default)	20	36 (default)	–90 (default)
C 4026 72 20	12-16-1811	CEUS 2008 (default)	4026	7.2 (default)	20	36 (default)	–90 (default)
A 4026 77 00	12-16-1811	A&B 2006	4026	7.7	0	36 (default)	–90 (default)
C 4026 77 00	12-16-1811	CEUS 2008 (default)	4026	7.7	0	36 (default)	–90 (default)
A 4026 77 10	12-16-1811	A&B 2006	4026	7.7	10 (default)	36 (default)	–90 (default)
C 4026 77 10	12-16-1811	CEUS 2008 (default)	4026	7.7	10 (default)	36 (default)	–90 (default)
A 4026 77 20	12-16-1811	A&B 2006	4026	7.7	20	36 (default)	–90 (default)
C 4026 77 20	12-16-1811	CEUS 2008 (default)	4026	7.7	20	36 (default)	–90 (default)
SW Fault 1	12-16-1811	B 1997	4026	7.7	10	(fault line)	(fault line)
A 4026 82 10	12-16-1811	A&B 2006	4026	8.2	10 (default)	36 (default)	–90 (default)
C 4026 82 10	12-16-1811	CEUS 2008 (default)	4026	8.2	10 (default)	36 (default)	–90 (default)
A 4026 82 20	12-16-1811	A&B 2006	4026	8.2	20	36 (default)	–90 (default)
C 4026 82 20	12-16-1811	CEUS 2008 (default)	4026	8.2	20	36 (default)	–90 (default)
A 4027 71 10	01-23-1812	A&B 2006	4027	7.1 (default)	10 (default)	36.3 (default)	–89.6 (default)
C 4027 71 10	01-23-1812	CEUS 2008 (default)	4027	7.1 (default)	10 (default)	36.3 (default)	–89.6 (default)
A 4027 71 20	01-23-1812	A&B 2006	4027	7.1 (default)	20	36.3 (default)	–89.6 (default)
C 4027 71 20	01-23-1812	CEUS 2008 (default)	4027	7.1 (default)	20	36.3 (default)	–89.6 (default)
A 4027 75 10	01-23-1812	A&B 2006	4027	7.5	10 (default)	36.3 (default)	–89.6 (default)
C 4027 75 10	01-23-1812	CEUS 2008 (default)	4027	7.5	10 (default)	36.3 (default)	–89.6 (default)
A 4027 75 20	01-23-1812	A&B 2006	4027	7.5	20	36.3 (default)	–89.6 (default)
C 4027 75 20	01-23-1812	CEUS 2008 (default)	4027	7.5	20	36.3 (default)	–89.6 (default)
A 4027 79 10	01-23-1812	A&B 2006	4027	7.9	10 (default)	36.3 (default)	–89.6 (default)
C 4027 79 10	01-23-1812	CEUS 2008 (default)	4027	7.9	10 (default)	36.3 (default)	–89.6 (default)
A 4027 79 20	01-23-1812	A&B 2006	4027	7.9	20	36.3 (default)	–89.6 (default)
C 4027 79 20	01-23-1812	CEUS 2008 (default)	4027	7.9	20	36.3 (default)	–89.6 (default)
A 4028 74 10	02-07-1812	A&B 2006	4028	7.4 (default)	10 (default)	36.5 (default)	–89.6 (default)
C 4028 74 10	02-07-1812	CEUS 2008 (default)	4028	7.4 (default)	10 (default)	36.5 (default)	–89.6 (default)
A 4028 74 20	02-07-1812	A&B 2006	4028	7.4 (default)	20	36.5 (default)	–89.6 (default)

Table 2. Seismic-hazard scenarios for the New Madrid Seismic Zone.

		Variables Modified for This Study					
Scenario ID	*Date of Historical Event (MM-DD-YYYY)*	*Attenuation Function*[1]	*Hazus-MH eqEpicenterID*[2]	*Magnitude (M)*	*Depth (km)*	*Latitude (degrees)*	*Longitude (degrees)*
C 4028 74 20	02-07-1812	CEUS 2008 (default)	4028	7.4 (default)	20	36.5 (default)	−89.6 (default)
A 4028 78 10	02-07-1812	A&B 2006	4028	7.8	10 (default)	36.5 (default)	−89.6 (default)
C 4028 78 10	02-07-1812	CEUS 2008 (default)	4028	7.8	10 (default)	36.5 (default)	−89.6 (default)
A 4028 78 20	02-07-1812	A&B 2006	4028	7.8	20	36.5 (default)	−89.6 (default)
C 4028 78 20	02-07-1812	CEUS 2008 (default)	4028	7.8	20	36.5 (default)	−89.6 (default)
A 4028 81 10	02-07-1812	A&B 2006	4028	8.1	10 (default)	36.5 (default)	−89.6 (default)
C 4028 81 10	02-07-1812	CEUS 2008 (default)	4028	8.1	10 (default)	36.5 (default)	−89.6 (default)
A 4028 81 20	02-07-1812	A&B 2006	4028	8.1	20	36.5 (default)	−89.6 (default)
C 4028 81 20	02-07-1812	CEUS 2008 (default)	4028	8.1	20	36.5 (default)	−89.6 (default)

[1] Three attenuation functions are used. For the point-hazard models, "CEUS 2008" refers to the composite attenuation function developed by the U.S. Geological Survey for use in the national seismic hazard maps and is designated "C" in the scenario ID; "A&B 2006" refers to Atkinson and Boore (2006) and is designated "A" in the scenario ID. For the single-fault hazard model, "B 1997" refers to Boore and others (1997), which is the attenuation function used by the USGS in their ShakeMap models (U.S. Geological Survey, 2008d).

[2] Hazus-MH eqEpicenterID: This is the historical event identification number assigned by the USGS and used in the Hazus-MH software to indicate a specific earthquake.

data. This scenario was developed to model ground motion from the southwest fault segment of the 1811-12 earthquakes (the Dec. 16, 1811, event) (D. Bausch, Federal Emergency Management Agency, personal communication, 2014) for emergency-management purposes. This hazard scenario differs in several ways from the other 38 scenarios. First, it is for a fault-line hazard rather than a point-source hazard, so resulting contour maps show the northeast-southwest trend expected along the major fault strike. Next, the contour maps were created by a modeling team and subsequently input into Hazus-MH as a user-defined scenario, rather than allowing Hazus-MH to create ground-motion contour maps. This required that the hazard parameters of location (fault line), attenuation function, magnitude, and depth be predetermined and specific to the supplied contour maps. The hazard scenario parameters cannot be modified in Hazus-MH without a new set of contour maps for the new scenario parameters. For the USGS data supplied, a magnitude-7.7 earthquake at 10 km depth was modeled. The fault location incorporated points between 35.537, –90.39 and 36.3, –89.5.

Scenario ground-motion maps were created using Hazus-MH to depict estimated peak ground acceleration (PGA), 0.3-s seismic acceleration (SA 0.3), and 1.0-s seismic acceleration (SA 1.0) on soft rock for each of the 38 point-source earthquake scenarios (Orton, 2014). Models were run for earthquake depths of 0, 10, and 20 km below ground surface. In all cases, changes in depth for earthquakes of the same magnitude and location had no effect on the minimum or maximum ground-motion values, and therefore no effect on the contour maps. Whether this was the result of calculation functions in Hazus-MH or whether the shallow depth (0–20 km) is still near enough to the surface to have no effect on the ground motion of a particular earthquake is unclear.

For the point-source-hazard contour maps, each of the motion variables (PGA, SA 0.3, and SA 1.0) affected larger geographic areas and range of acceleration values with increasing magnitude at each location, as expected (Figs. 10–11). Maximum PGA values ranged from 1.45 to 3.31 *g* for the various models. Table 3 shows the maximum values for all earthquake scenarios.

In addition, all ground-motion (PGA, SA 0.3, and SA 1.0) values and contours were consistently larger for models using the A&B 2006 attenuation function than for those using the CEUS 2008 composite attenuation function for events of the same magnitude at the same location (Figs. 12–13). The A&B 2006 attenuation function is based on a single-fault model, whereas the CEUS 2008 composite attenuation function gives weighted values to probabilities from various attenuation models. In the small number of models run for this study, the contours of SA 0.3 and SA 1.0 areas varied dramatically depending on the attenuation model applied. These differences in the contour maps based solely on which attenuation function was used is a clear illustration of the uncertainty in earthquake hazard models.

The single-fault or line-hazard model, model ID SW Fault 1 (Fig. 14), differed significantly from the point-hazard models in several ways. First, the contour maps for the fault-line model were created and input into Hazus-MH for economic evaluation only. The model variables, including attenuation function, event magnitude, location, and depth, were all pre-set, so no direct comparison could be made of models by modifying single variable parameters. Hazus-MH was able to generate contour maps only for the purpose of assigning ground-motion values to the various census tracts. These maps generally follow the contours of the input data sets, as expected, with slight variations to account for the differences between actual input contours versus size of individual census tracts. The census-tract–based contour maps incorporate blocks of area for a given ground-motion value, and therefore have blocky rather than smooth contour boundaries. Since each census tract must be assigned a single value for each ground-motion parameter, the contours on the maps generated by Hazus-MH were either larger or smaller than the original contour boundary, depending on the size of a given census tract. Because these census-tract contour maps are basically only a restatement of the input contour maps provided by the USGS, they were not analyzed further.

In addition to the expected result of oblong rather than circular ground-motion contours for the fault-line scenario, the differences in maximum ground-motion values resulted in extreme variations between contour diameters and patterns. Although some of this difference can be attributed to the differences in attenuation models used, it is also possible that the fault-line model reflected additional information about underlying geology and soils not included in the standardized Hazus-MH ground-motion contour maps. If so, the additional soils information should ultimately contribute to better-constrained model results.

Scenario Economic Analysis

Hazus-MH software was also used to generate a relative economic analysis for each of the seismic hazard scenarios. The software package includes default databases for each state containing estimates of building types within each census tract; locations of critical facilities such as police and fire stations, hospitals, schools, and utilities; and population data based on U.S. census figures (Federal Emergency Management Agency, 2012b). At the discretion of the user, these default databases can be used during the economic analysis step, or the databases can be modified or replaced with more specific local data if they are available. For the purposes of this study, the included databases were used without modification so that analysis results were, to the best of our ability, consistent with results that would be generated by a federal agency.

Within Hazus-MH, a standard geographic study region was created containing 178 counties in seven states along the central New Madrid Seismic Zone, set to calculate analyses at the census-tract level for the finest possible display allowed by the software. This region was then used for all scenarios so that each resulting economic analysis would be calculated for a standardized geographic area. Figure 15 illustrates the region selected for the Hazus-MH analyses. For a list of the states and counties included in the base region, see Orton (2014).

After the base region was created, the region was then duplicated and a hazard scenario specified for each model. A historical epicenter event scenario was created indicating the appropriate

Peak Ground Acceleration
Study Region: CC A 4028 74 10 H
Hazard Scenario: 7 February 1812 Point Location, M7.4

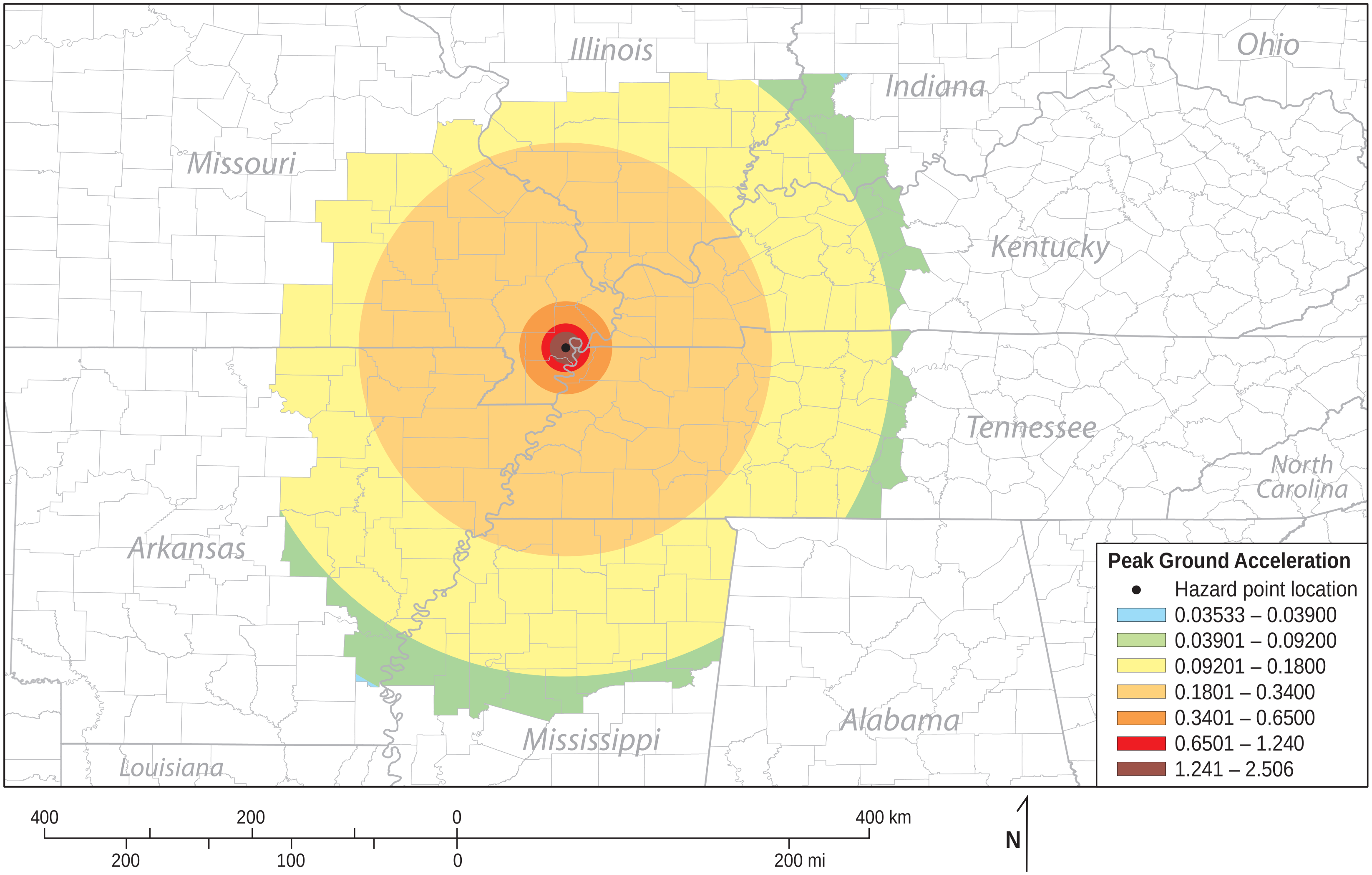


Figure 10. Peak ground acceleration for A 4028 74 10. A smaller earthquake magnitude for any location and attenuation function resulted in lower ground-motion values and contours than larger-magnitude events at the same location and attenuation function, as expected. For comparison, see Figure 11 for A 4028 81 10, a magnitude-8.1 event at the same location and using the same attenuation function.

Peak Ground Acceleration
Study Region: CC A 4028 81 10 H
Hazard Scenario: 7 February 1812 Point Location, M8.1

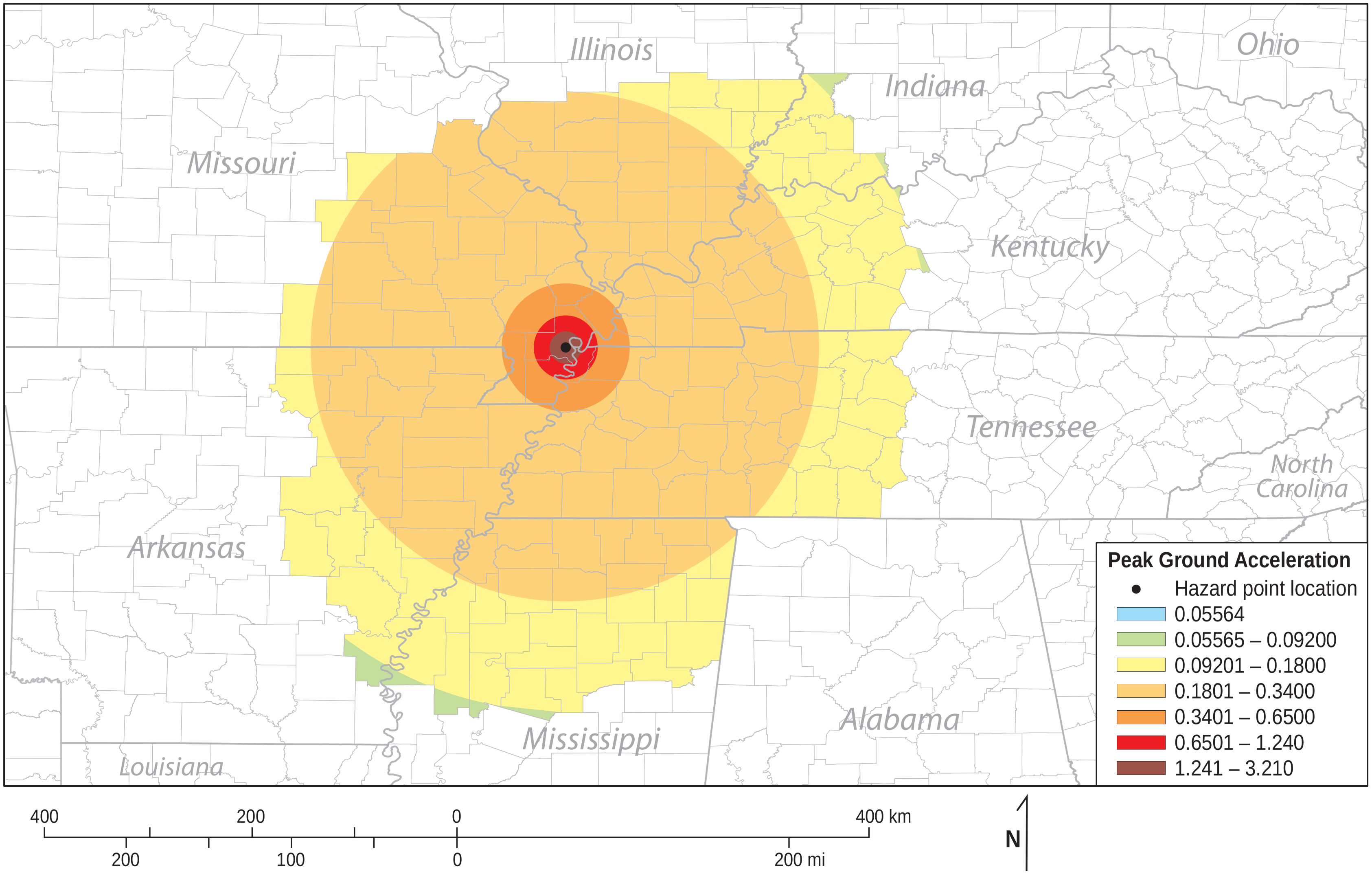


Figure 11. Peak ground acceleration for A 4028 81 10. A larger earthquake magnitude for any location and attenuation function resulted in higher ground-motion values and contours than smaller-magnitude events at the same location and attenuation function, as expected. For comparison, see Figure 10 for A 4028 74 10, a magnitude-7.4 event at the same location and using the same attenuation function.

Table 3. Maximum ground-motion values from the Hazus-MH model.

Model ID	*Maximum PGA Value* (g)	*Maximum SA 0.3 Value* (g)	*Maximum SA 1.0 Value* (g)
A 4026 72 10/20	2.308	3.914	4.222
C 4026 72 10/20	1.517	2.102	1.739
A 4026 77 00/10/20	2.809	4.649	5.150
C 4026 77 00/10/20	1.854	2.648	2.268
SW Fault 1	1.100	1.380	1.140
A 4026 82 10/20	3.308	5.263	5.839
C 4026 82 10/20	2.253	3.160	2.701
A 4027 71 10/20	2.210	3.760	4.022
C 4027 71 10/20	1.447	1.983	1.628
A 4027 75 10/20	2.607	4.365	4.799
C 4027 75 10/20	1.700	2.423	2.043
A 4027 79 10/20	3.011	4.914	5.463
C 4027 79 10/20	1.992	2.843	2.458
A 4028 74 10/20	2.506	4.217	4.612
C 4028 74 10/20	1.657	2.340	1.959
A 4028 78 10/20	2.910	4.785	5.312
C 4028 78 10/20	1.943	2.773	2.384
A 4028 81 10/20	3.210	5.154	5.728
C 4028 81 10/20	2.185	3.086	2.651

Models highlighted in light gray indicate the point-source hazard models and fault-line model that correlate for general location, depth, and earthquake magnitude. Differences include the attenuation function and fault-line rather than point-hazard source. Models highlighted in pink indicate the most important scenarios for western Kentucky.

historical event location, attenuation function, magnitude, and depth for each model. Historical epicenter events east of the Rocky Mountains in Hazus-MH are all specified as point-source locations rather than fault-line hazard sources, so contour maps expand circularly from the designated point source rather than in an oblong shape from a fault-line source.

Hazus-MH allows analysis of individual economic factors, such as damage to buildings, infrastructure, utilities, etc. For this study, an analysis of each hazard scenario was run for all possible analysis modules.

A Global Summary Report, a standardized report that Hazus-MH can generate from the results of any analysis, was generated for each hazard analysis. It contains information about the hazard scenario parameters as well as summary information, including direct and induced damage to buildings, critical facilities, transportation routes, and utility lifeline facilities; estimates of injuries and casualties based on building occupancy for various times of the day; and projected economic losses.

In addition to the 38 point-source hazard scenarios, one additional economic analysis was run using the ShakeMap data supplied by the USGS for the New Madrid SW M 7.7 Scenario. Economic analyses were run for all analysis modules for the fault-hazard event and a Global Summary Report was created as for the 38 point-source hazard scenarios.

The Global Summary Reports generated by Hazus-MH give a variety of estimated physical and economic results for each earthquake hazard scenario. These reports were generated using only the background databases included with the Hazus-MH software; no modifications were made to account for changes since the last database updates or specific information for any locale. Physical estimates of results included damage to buildings, infrastructure, and utility systems, and human casualty and injury scenarios for three different times of day to account for general population movements. Cost estimates included values of building, infrastructure, and utility system losses, and income and capital investment losses. The range of estimates of damages reflected the range of event magnitudes as well as the wide differences in attenuation-function results. The severity of A&B 2006 attenuation-function results shown on contour maps was similarly reflected in the physical and economic summary reports; A&B 2006 results consistently had much higher loss estimates than CEUS 2008 attenuation-function scenarios for events at the same locations and magnitudes. A selection of Global Summary Report results has been included in Table 4.

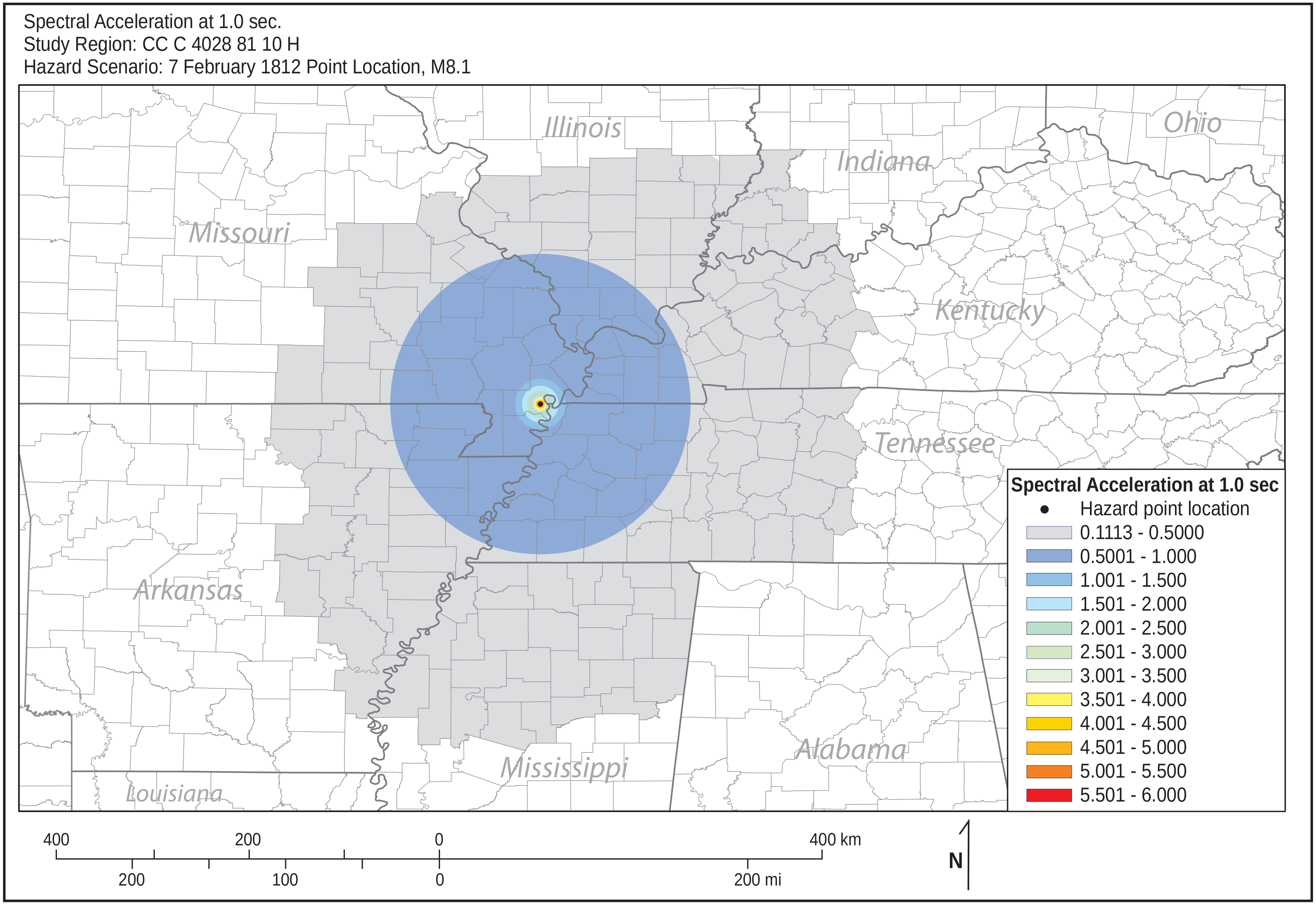


Figure 12. Spectral acceleration at 1.0 s for C 4028 81 10. Scenarios using the composite attenuation function, CEUS 2008, consistently resulted in lower ground-motion values and smaller contours than models at the same locations and magnitudes using the A&B 2006 attenuation function. For comparison, see Figure 13 for A 4028 81 10.

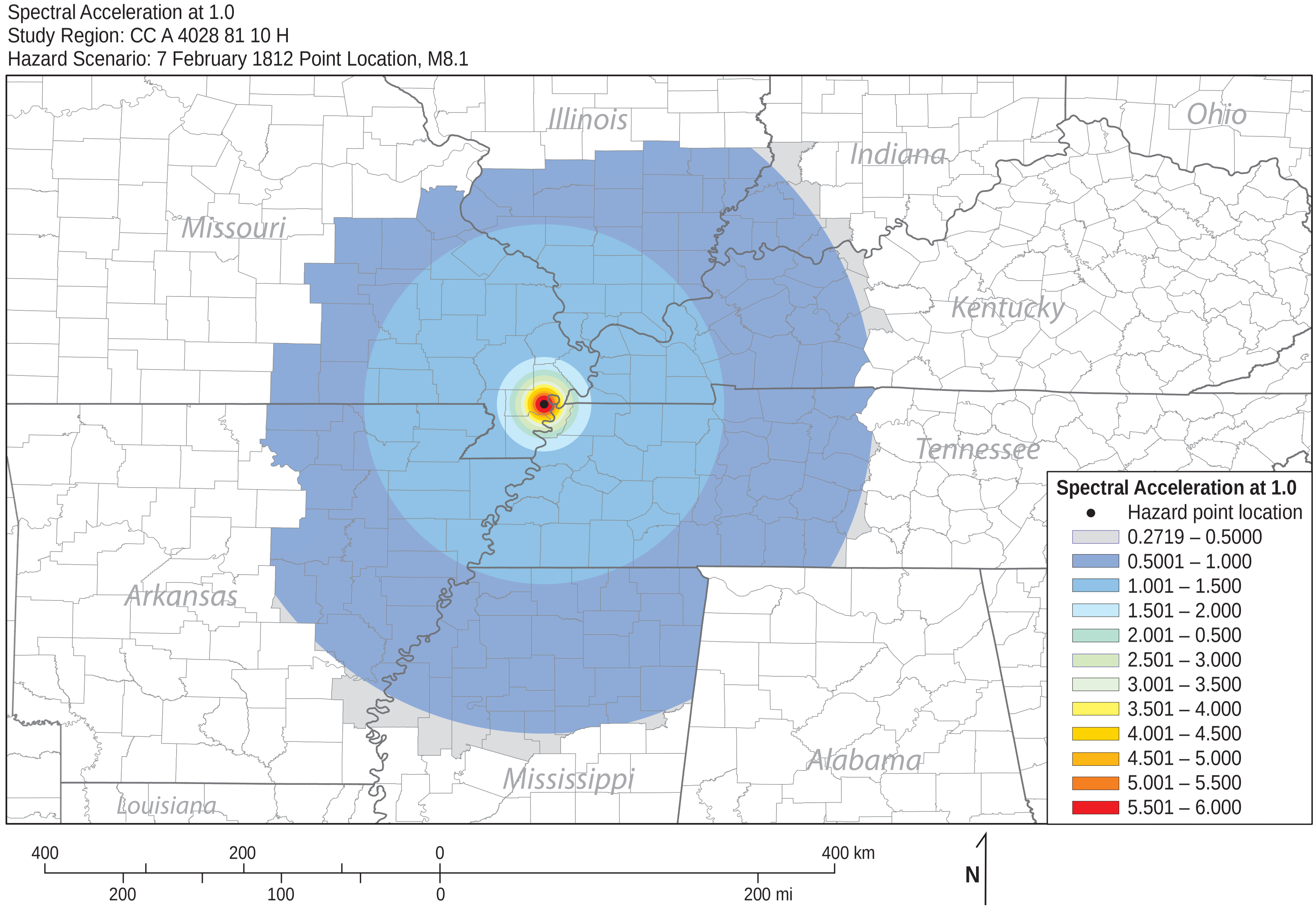
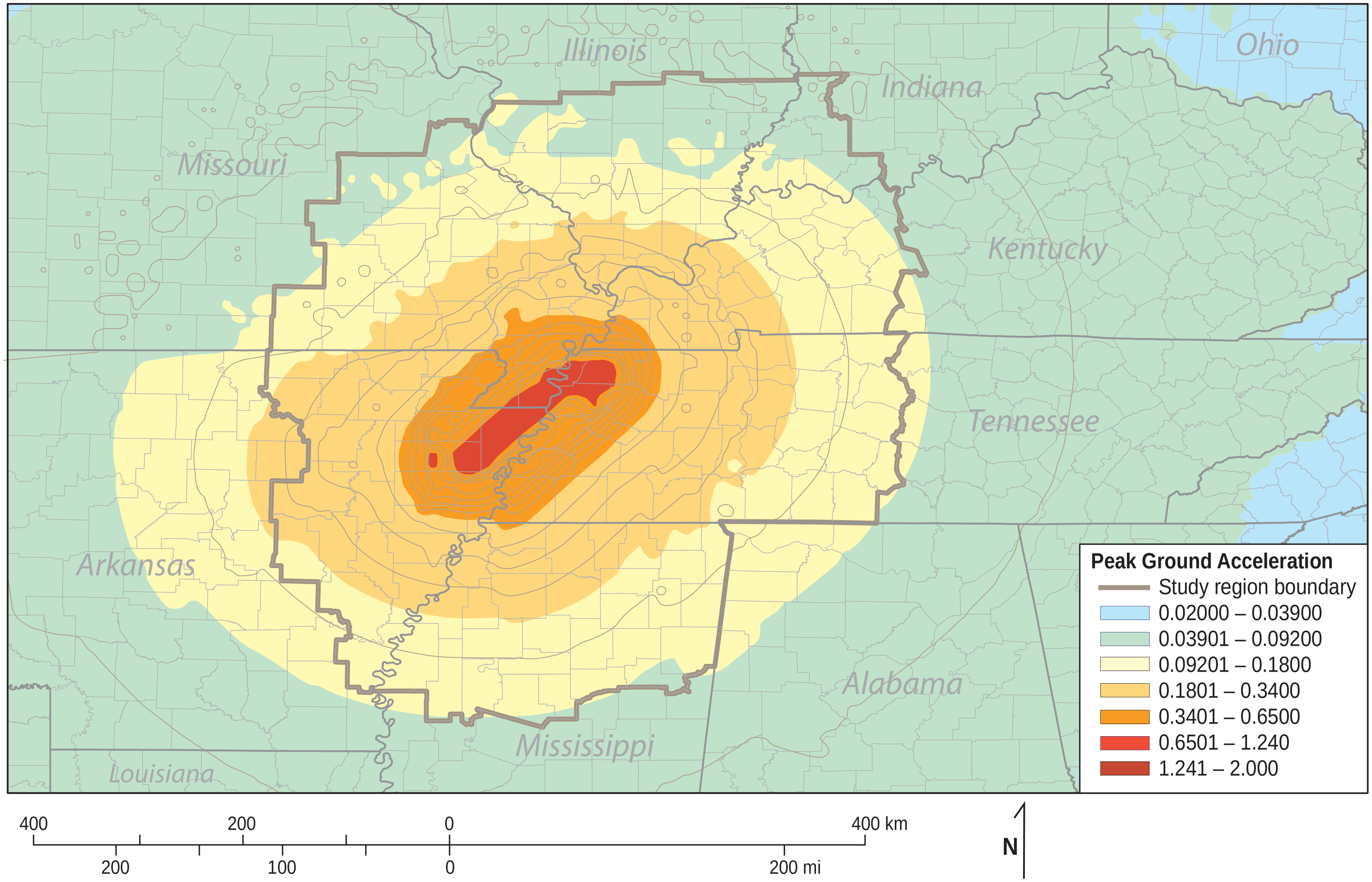


Figure 13. Spectral acceleration at 1.0 s for A 4028 81 10. Scenarios using the A&B 2006 attenuation function consistently resulted in higher ground-motion values and larger contours than models at the same locations and magnitudes using the composite attenuation function, CEUS 2008. For comparison, see Figure 12 for C 4028 81 10.



Peak Ground Acceleration
Study Region: SW Fault 1
Hazard Scenario: 16 December 1811 (New Madrid SW) Fault, M7.7

Figure 14. Peak ground acceleration for SW Fault 1. Ground-motion values and contours from the fault-line scenario differed from those from point-source scenarios at the same location and depth, based on both line versus point geometry and attenuation function effects.

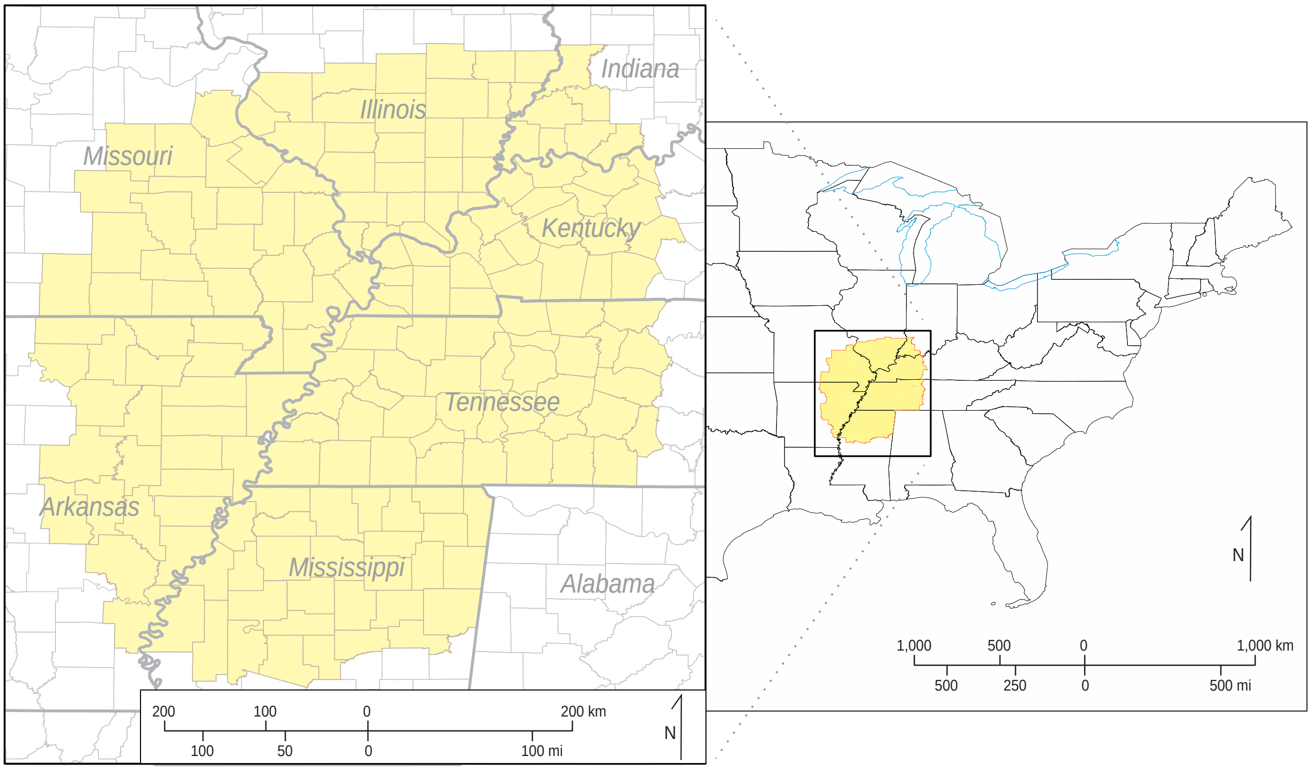


Figure 15. Area for each Hazus-MH economic analysis. See Orton (2014) for a list of states and counties in the study area.

Table 4. Various statistical estimates from the Global Summary Reports for selected Hazus-MH scenarios. Values apply to the entire study region and have not been specified for smaller areas in the study region.

Model ID	*Maximum PGA* (g)	*Maximum SA 1.0* (g)	*Fatalities (range)*	*Income and Capital Stock Losses (million dollars)*	*Transportation and Utility System Losses (million dollars)*	*Total Losses (million dollars)*
A 4028 74 10/20	2.51	4.61	1,282–3,061	67,737.93	9,863.75	77,601.68
C 4028 74 10/20	1.66	1.96	109–244	7,208.23	3,503.92	10,712.15
A 4028 78 10/20	2.91	5.31	6,483–12,002	175,537.60	14,141.99	189,679.59
C 4028 78 10/20	1.94	2.38	403–862	24,406.58	5,492.91	29,899.49
A 4028 81 10/20	3.21	5.73	8,114–14,784	214,421.25	17,809.27	232,230.52
C 4028 81 10/20	2.19	2.65	670–1,482	36,963.08	7,219.36	44,182.44
A 4026 77 10/20	2.81	5.15	5,220–9,892	140,971.33	11,951.64	152,922.97
C 4026 77 10/20	1.85	2.27	364–840	23,309.79	4,623.73	27,933.52
SW Fault 1	1.10	1.14	720–1,176	34,194.85	9,203.49	43,398.34

Report results for the single-fault-line model were incorporated with results for the point-source models. SW Fault 1 results were much closer to those using the CEUS 2008 attenuation function than to results using A&B 2006 for the same location and magnitude event.

The study region of central counties in the New Madrid Seismic Zone has an estimated population of 6,841,567 and 2,074,400 single-family residences. In the best-case scenario, human casualty estimates were as low as 70 deaths, whereas the worst-case estimate was 14,784 deaths. Casualty estimates were almost always higher in the midafternoon, and life-threatening injury estimates were higher in the evening. The lowest casualty and injury estimates occurred during morning hours in every case.

In the best-case scenario, less than 8 percent of single-family residences sustained any damage, and only 1,753 (0.08 percent) were totally destroyed. In the worst-case scenario, however, as much as 67 percent of single-family residences sustained some damage, and 182,782 (8.8 percent) were totally destroyed. For potable water resources, the best-case scenario estimated 20,299 of 2,634,125 households in the region would be without water service on day 1 (less than 1 percent), whereas the worst-case scenario estimated 1,834,583 households (almost 70 percent) would be without water on day 1 and 300,422 (greater than 11 percent) would still be without water service after 90 days.

In the best-case scenario, 95 percent of the region's hospitals (196 of 205) were expected to be at least 50 percent operational on the first day of a modeled earthquake and no hospital was expected to be totally destroyed. The worst-case scenario, though, indicated total destruction of 151 of the 205 hospitals in the region (approximately 74 percent) and an expectation that no hospital would be at least 50 percent functional on the day of the event.

Although no damage was expected to any of the region's highway segments, highway bridges showed a high potential for damage. Of 21,414 highway bridges in the study region, a minimum of 45 were expected to be totally destroyed, and a high estimate of 4,570 (greater than 21 percent) could be completely destroyed in the worst-case scenario.

Economic loss estimates included $1.2 to $46.2 billion in income, $3.5 to $168.2 billion in capital investments (buildings, improvements, and contents), $582 million to $4.7 billion in transportation system infrastructure, and $1.6 to $13.1 billion in utility-system infrastructure for the range of scenarios modeled for this study.

Economic analyses related to the Feb. 7, 1812, scenarios (event ID 4028) are the most important for this study since they relate to the model most likely to adversely affect western Kentucky. Considering only the Global Summary Reports for the two largest scenarios for this historical location (A 4028 81 10/20 and C 4028 81 10/20), the differences were as follows:

- For the modeled magnitude-8.1 earthquake, 670 to 14,784 deaths were estimated, depending on time of day and modeled attenuation function.
- Between 14,102 and 182,782 single-family residences were expected to be completely destroyed over the entire study region, and between 27,447 and 187,554 more were expected to be extensively damaged and therefore uninhabitable.
- Potable water was expected to be unavailable for a minimum of 264,959 households, and potentially for 1.8 million households on day 1 of the event.
- Within 90 days of the original event, 4,864 to 229,429 households across the study region were expected to be still without water service.
- Between 47 and 151 of the region's 205 hospitals were expected to be completely destroyed, and possibly only two would maintain greater than 50 percent functionality on day 1 in the worst-case scenario.
- Of 21,414 highway bridges, at least 421 were expected to be totally destroyed, and 4,368 could be completely destroyed.
- Monetary losses included $9,641.59 to $46,234.31 million in income losses, $27,321.49 to $168,186.94 million in capital investment losses, $179.00 to $297.90 million in transportation system infrastructure losses, and $5,535.56 to $13,100.27 million in utility-system infrastructure losses.

These numbers were not broken down to show specific impacts to western Kentucky.

The 2008 Wenchuan Earthquake

The strong shaking from the Wenchuan earthquake was felt throughout China, as well as in Thailand and Vietnam in Southeast Asia. The quake was felt in Beijing, Shanghai, Taipei, and other major cities more than 1,000 km away. The main event was well recorded by the National Strong Motion Observation Network System of China, which consists of 460 permanent free-field stations and arrays (Li and others, 2008). Ninety-three free-field stations were within rupture distances of 300 km, the closest one about 1.5 km distant (Lu and others, 2010). The largest recorded peak ground acceleration was 0.96 *g* near the epicenter. A preliminary study by Wang and Lu (2011) suggests that the ground-motion attenuation models for the central and eastern United States are similar to those for the Wenchuan area. Figure 16 compares ground-motion observations from the Wenchuan earthquake with ground-motion prediction equations for hard rock for an M 7.9 earthquake in the central and eastern United States (Somerville and others, 2001; Campbell, 2003; Atkinson and Boore, 2006). Thus, in terms of scenario hazard, ground-motion observations of the Wenchuan main shock can be compared with the scenario hazards generated for the New Madrid earthquakes.

Figure 17 is the recorded PGA contour map of the Wenchuan earthquake (Wang and others, 2010). It shows that the recorded PGA in the Wenchuan area ranges from 0.05 to 0.40 *g*, much less than for any scenario ground motion for the New Madrid area (Table 3). As shown in Table 3, the maximum PGA's from the scenario earthquakes are all greater than 1.0 *g*. The lowest maximum PGA is from the SW Fault 1 scenario (Fig. 14), which has much higher PGA over a larger area. Thus, compared with the observations from the Wenchuan earthquake (M 7.9), all scenario hazards for the New Madrid Seismic Zone are overpredicted.

Figure 18 is a Google Maps comparison of the New Madrid and Wenchuan areas. As shown on the maps, the Wenchuan area has a much higher exposure (i.e., the population and built environment), with more than 80 million people living in the Sichuan Basin and more than 7 million people in the city of Chengdu. This is one of the main reasons that more than 87,000 people were killed and 370,000 were injured during the Wenchuan earthquake.

Discussion

General Knowledge of Earthquake Science and Policy Impacts

To establish the range of general knowledge about science and engineering practice in the New Madrid Seismic Zone as well as to identify local concerns in western Kentucky about the impacts of current science practice on public policy and the economy, we interviewed stakeholders in the region. These interviews were intentionally informal and variable in order to create an open forum for participants to express views that could not be adequately addressed with a yes/no questionnaire, but also to avoid predetermined opinions or conclusions. Because not all questions were asked during all interviews, or some questions were asked but not answered, and because not all survey populations were evenly represented among the participants, the responses may not represent a complete view of the issues. Enough information was gathered, however, to begin building a framework for addressing the concerns of this research.

The interviews made clear that although concern for mitigation and safety was important, it was not the only concern of western Kentucky businesspersons and public officials. They were also concerned that the regional earthquake hazard had been either over- or understated, and that there were both safety and economic costs associated with the discrepancy. Engineering and real estate development professionals had some sense that the methods used for creating the national seismic hazard maps do not return realistic results because of uncertainty in the underlying science. Although the participants knew about the national seismic hazard maps, they rarely understood the maps and often did not perceive the maps as an authoritative, trusted source for information about earthquake hazard potential.

On the federal level, there seemed to be little understanding of the impact that the scientific uncertainty has at local levels, although federal employees were admittedly underrepresented, and we are not suggesting that interview results represent the position of the entire federal government. Current map science and methods have been published by the federal government, however, and individuals and communities may use the information at their own discretion. In addition, some tools for earthquake hazard education and analysis and building design information have been developed by various federal agencies and are outlined in publications as well as available online for general use (U.S. Geological Survey, 2008d). Examples include the national seismic hazard maps, earthquake data, shake maps, scenario models, modeling software packages, earthquake probabil-

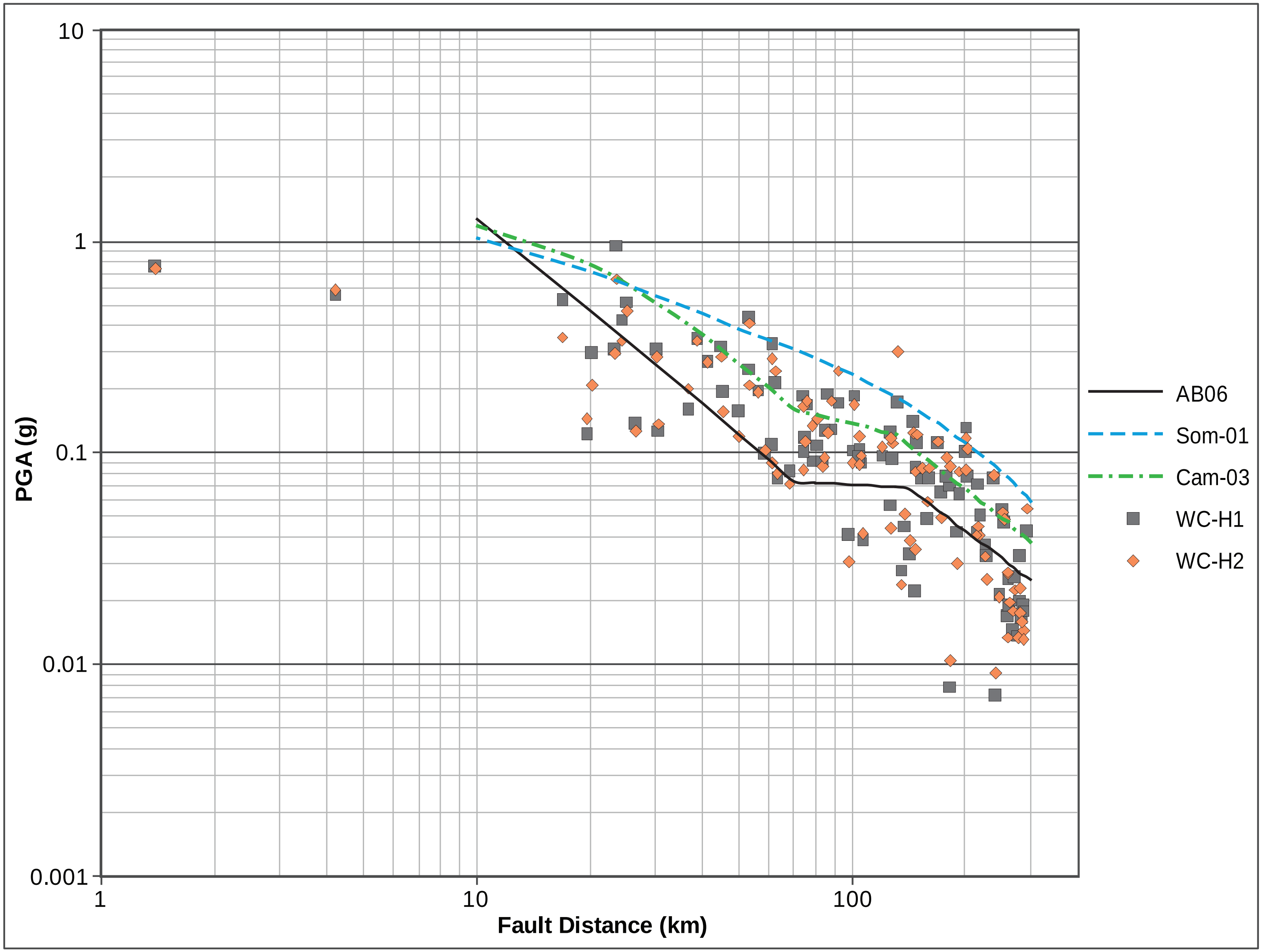


Figure 16. Peak ground acceleration attenuations of Somerville and others (2001), Campbell (2003), and Atkinson and Boore (2006) compared to the recordings from the 2008 Wenchuan earthquake (M 7.9). From Wang, Z., and Lu, M., A short note on ground-motion recordings from the M7.9 Wenchuan, China, earthquake and ground-motion prediction equations in the central and eastern United States, Seismological Research Letters, v. 82, p. 731–733, 2011, ©Seismological Society of America.

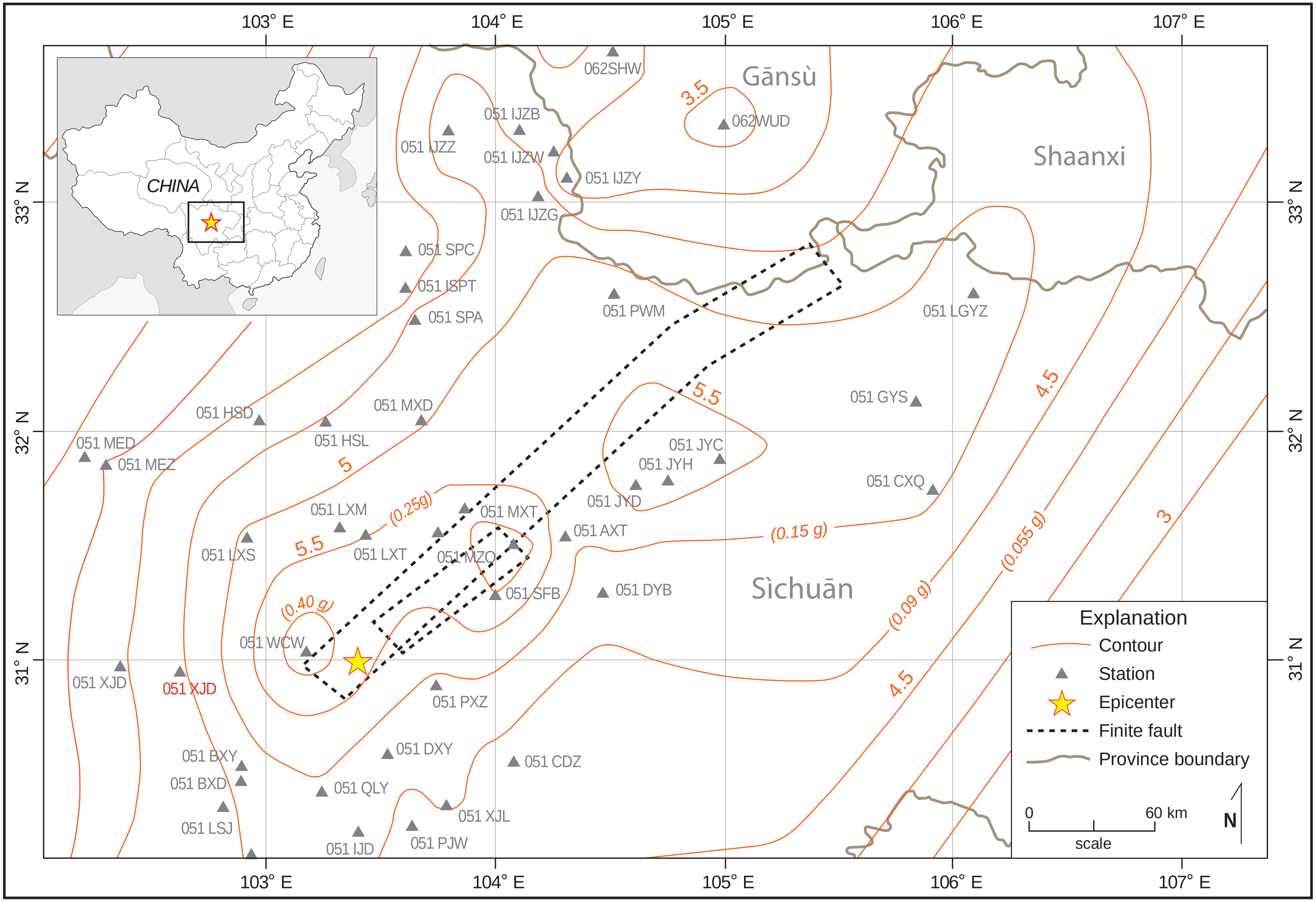


Figure 17. Natural log of peak ground acceleration (ln(PGA) values) for the epicentral area of the 2008 Wenchuan earthquake (in cm/s^2). High values of greater than 5.5 on this map correspond to approximately 0.25 *g* PGA values. Modified from Wang, D., Xie, L., Abrahamson, N.A., and Li, S., Comparison of strong ground motion from the Wenchuan, China, earthquake of 12 May 2008 with the next generation attenuation (NGA) ground-motion models, Bulletin of the Seismological Society of America, v. 100, p. 2381–2395, 2010, ©Seismological Society of America.

ity mapping tools, and a worldwide seismic design values calculation tool. Interview results make clear, however, that not enough of this information is making its way to the end users to allow them to have confidence in the science. Because the stated purpose of the national seismic hazard maps is to inform seismic design provisions for building codes and insurance rates (U.S. Geological Survey, 2008d), the information and data must be used appropriately and the limits of our knowledge must be communicated. Whether the current national seismic hazard maps represent the best current science is debatable, but additional education of engineering professionals, public emergency management, and education personnel would clarify the scientific process, current practices, and uncertainty so that public policy, building codes, education, and planning are appropriate.

A second policy concern is that federal agencies apply different standards, codes, or rules than local and State agencies do. The effect is twofold. First, this double standard may allow the federal government to outsource jobs to out-of-area contractors or labor forces, making these jobs unavailable to local workers. Several participants referred to instances of the U.S. Army Corps of Engineers applying its own standards, not local building codes, and providing its own workforce. This practice is perceived as being both an unfair advantage for project approval ("You can build something we are not allowed to build because of local regulations") and removing local jobs to outside labor pools (labor is performed by nonlocal government employees or contractors). The second effect of different standards for federal agencies is that higher seismic

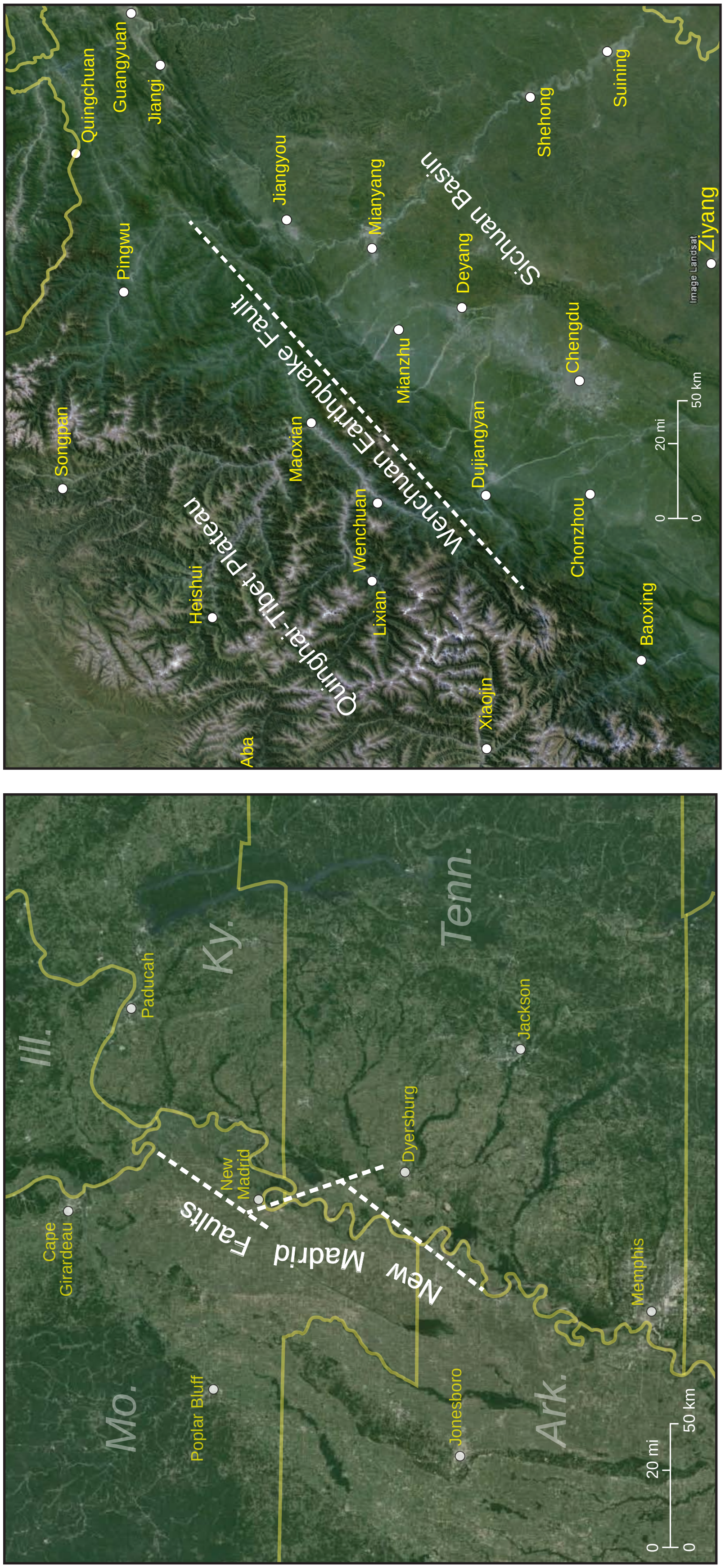


Figure 18. Comparison of the New Madrid Seismic Zone and Wenchuan earthquake areas. Map data ©Google Earth 2015, www.google.com/maps.

standards cause higher project costs, effectively pricing federal projects out of the region. The most well-known example of this is the higher standards required by the U.S. Nuclear Regulatory Commission for the Paducah Gaseous Diffusion Plant and the associated proposed but rejected uranium-enrichment centrifuge. This project to develop a centrifuge at an existing nuclear facility was denied as a direct result of the national seismic hazard maps estimating high seismic hazard for the Paducah area. Local perception is that the cost of building a plant to federal standards in the current location is so much higher than the cost of building elsewhere that the project is not feasible in western Kentucky. The difference between local and federal policies is therefore blamed for the direct loss of more than 1,200 local jobs and the indirect loss of thousands more jobs in support industries and community services.

Scenario Seismic Hazards

The 38 point-source hazard scenarios were based on current scientific understanding of locations, magnitudes, and ground-motion attenuations of great earthquakes in the New Madrid Seismic Zone. These scenarios do not have associated probabilities of occurrence, but are strictly scenario event hazards. They are, in fact, specific cases of the potential earthquakes for the region and cover a range of possible earthquakes. The single-fault-line hazard model is also a scenario for a specific event that was developed by the USGS seismic hazard mapping team and is considered to be similar to the Dec. 16, 1811, earthquake, based on current information.

Table 5 compares the maximum PGA, SA 0.3, and SA 1.0 of minimum and maximum point-source scenarios, the SW Fault 1 scenario, and the Wenchuan earthquake recordings. As shown in Table 5, a large range of ground motions could be produced from combinations of location, magnitude, and attenuation model, and demonstrates the large uncertainties in the scientific input models (parameters). Any ground-motion hazard map produced for the New Madrid Seismic Zone inherits a large uncertainty. Thus, the maps, including all scenarios and the national seismic hazard maps, must be evaluated to determine the level of uncertainty; unfortunately, there is no instrumental record available for this evaluation. Historical intensity observations are available, however. Source parameters, magnitudes in particular, were estimated from intensity observations of historical events (Nuttli, 1973; Johnston and Schweig, 1996; Hough and others, 2000; Bakun and Hopper, 2004; Cramer and Boyd, 2011; Hough and Page, 2011). These historical intensity observations should be used as one of the bases for evaluating ground-motion hazard maps, even though they are subject to subjective interpretation.

The first estimation of the modified Mercalli intensity distributions and magnitudes of the 1811-12 sequence was by Nuttli (1973), based on recorded and reported effects throughout the eastern United States. Figure 19 shows the intensity distribution for the Dec. 16, 1811, earthquake (Nuttli, 1973). A body-wave magnitude of 7.2 was determined for this event (Nuttli, 1973), which is equivalent to a moment magnitude of 7.7. As shown in Figure 19, the maximum modified Mercalli intensity is about X at the epicenter. The same historical records used by Nuttli (1973) have been interpreted several times since 1973, including by Johnston (1996), Johnston and Schweig (1996), Hough and others (2000), Bakun and Hopper (2004), Cramer and Boyd (2011), and Hough and Page (2011). Figure 20 shows the intensity distribution for the Dec. 16, 1811, earthquake, interpreted by Hough and others (2000), and indicates that the maximum modified Mercalli intensity is about VIII at the epicenter. The estimated moment magnitude for the Dec. 16, 1811, event is 7.2 (Hough and others, 2000). Com-

Table 5. Comparison of maximum ground-motion values.

Model ID	*Maximum PGA* (g)	*Maximum SA 0.3* (g)	*Maximum SA 1.0* (g)
A 4026 82 10/20 (M 8.2)	3.308	5.263	5.839
C 4027 71 10/20 (M 7.1)	1.447	1.983	1.628
SW Fault 1 (M 7.7)	1.100	1.380	1.140
Wenchuan (M 7.9)	0.950	2.370	0.360
national seismic hazard maps (2 percent in 50 yr)	1.960	3.520	1.690

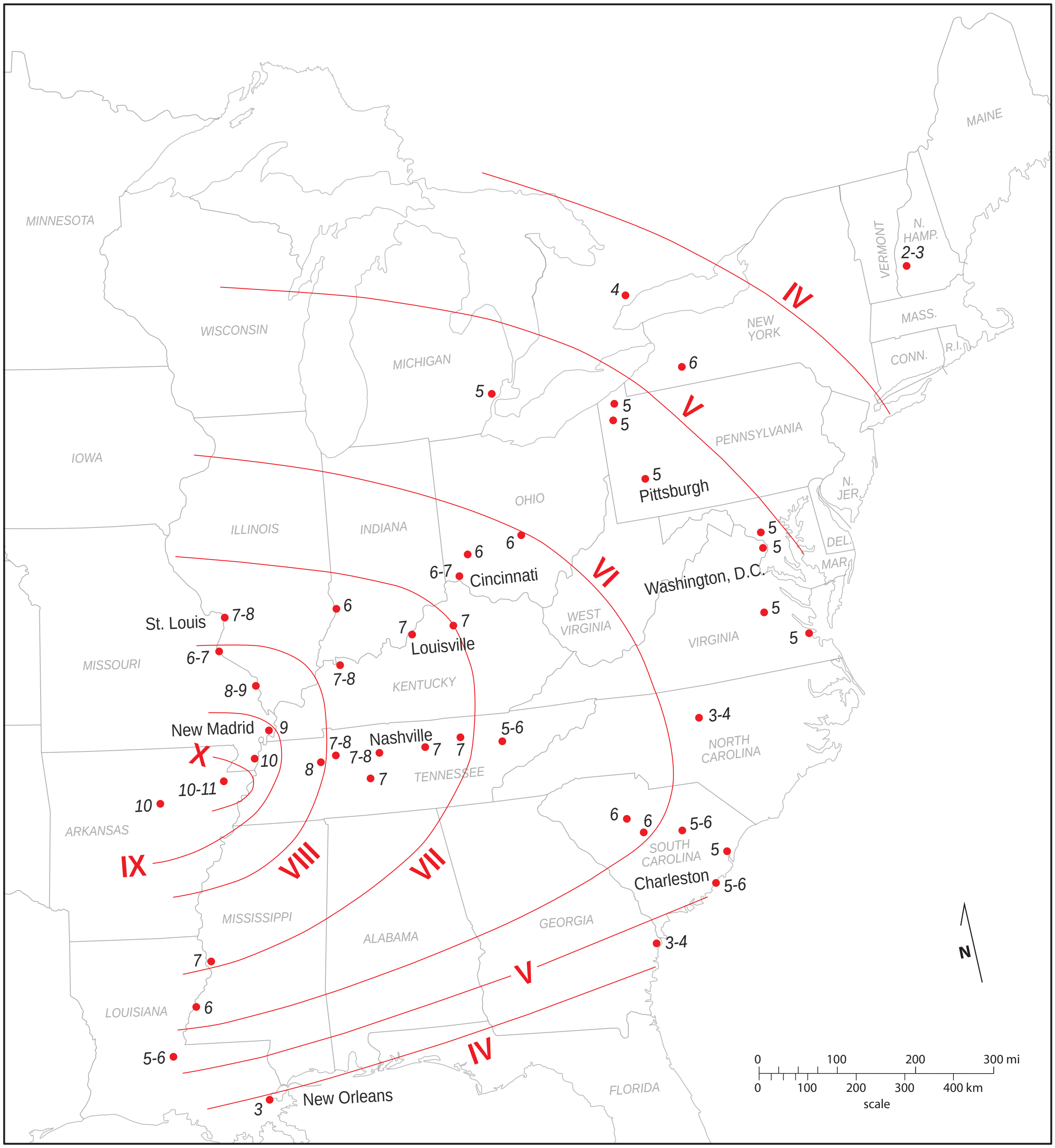


Figure 19. Estimated intensities of the Dec. 18, 1811, New Madrid earthquake. From Nuttli, O.W., The Mississippi Valley earthquakes of 1811 and 1812: Intensities, ground motion, and magnitudes, Bulletin of the Seismological Society of America, 1973, v. 63, p. 227–248, ©Seismological Society of America.

pared with other estimates, those by Hough and others (2000) are at the lower end. The range of all modified Mercalli estimates for the epicentral area is between VIII and X. According to Wald and others (1999), these intensities are equivalent to a PGA range of 0.3 to 1.2 *g* (Table 6). Even though these PGA estimates are rough, they are all lower than those predicted from scenario models (Table 3).

Records and intensity observations from the Wenchuan earthquake can also be used to evalu-

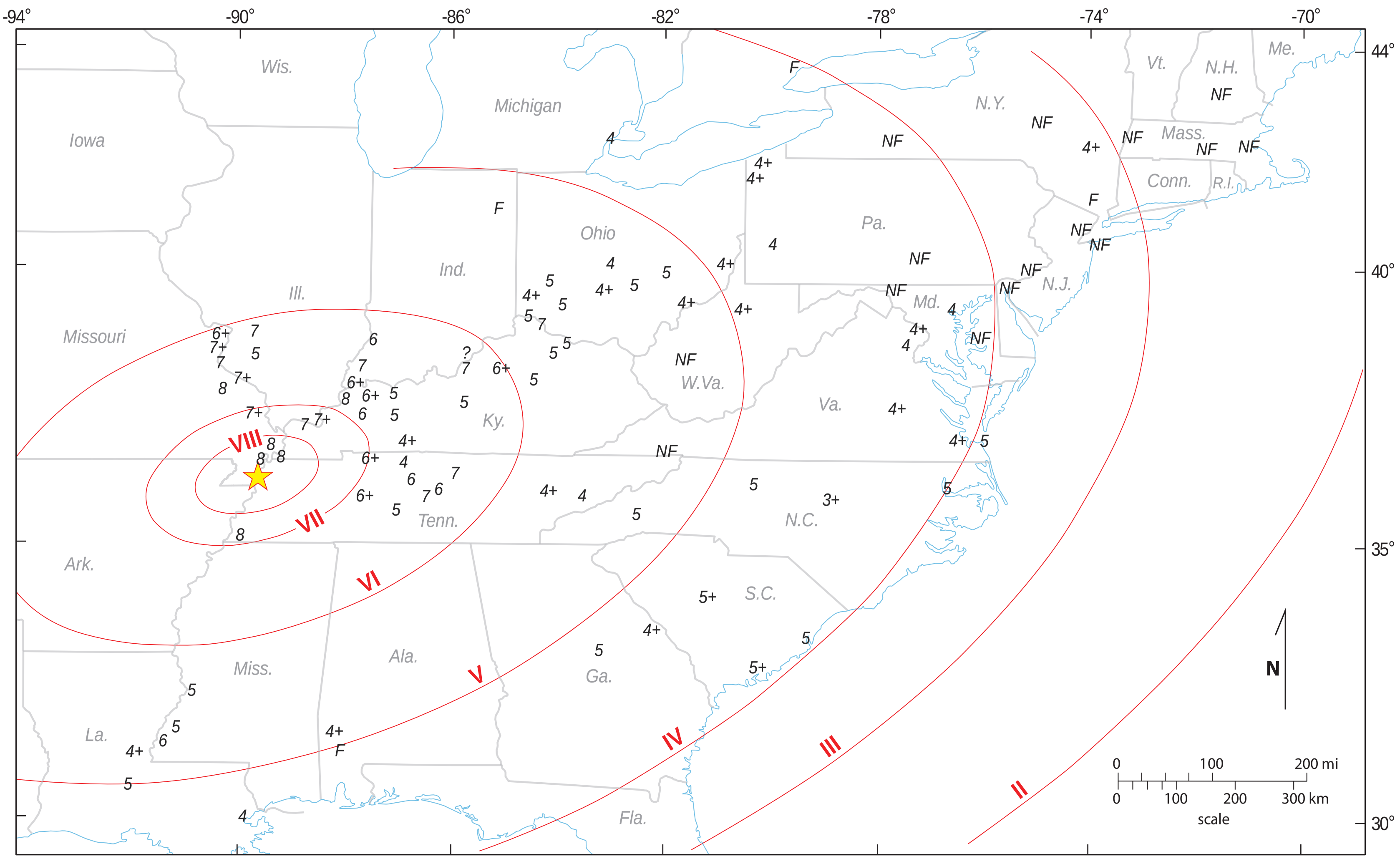


Figure 20. Estimated intensities of the Dec. 18, 1811, New Madrid earthquake. From Hough and others (2000). Used with the permission of the American Geophysical Union.

Table 6. Relationship between modified Mercalli intensity and ground-motion measurement. From Wald and others (1999). ©1999 Earthquake Engineering Research Institute.

Perceived Shaking	not felt	weak	light	moderate	strong	very strong	severe	violent	extreme
Potential Damage	none	none	none	very light	light	moderate	moderate/ heavy	heavy	very heavy
Peak Acceleration (% g)	< 0.17	0.17–1.4	1.4–3.9	3.9–9.2	9.2–18	18–34	34–65	65–124	> 124
Peak Velocity (cm/s)	< 0.1	0.1–1.1	1.1–3.4	3.4–8.1	8.1–16	16–31	31–60	60–116	> 116
Instrumental Intensity	I	II–III	IV	V	VI	VII	VIII	IX	X+

ate the ground-motion hazard maps for the New Madrid Seismic Zone. Wang and Lu (2011) showed that the central and eastern United States and the Wenchuan area have a similar ground-motion attenuation for distances greater than 20 km. Figure 16 shows that all three ground-motion attenuation models (Somerville and others, 2001; Campbell, 2003; Atkinson and Boore, 2006) reasonably predict PGA for an M 7.9 earthquake at a distance greater than 20 km. All three models overpredict PGA at distances less than 20 km (referred to as near-source), however. In general, ground motion increases as magnitude increases, especially for near-source locations. When magnitude reaches 6.5 to 7.0, however, ground motion no longer increases; this is referred to as ground-motion saturation (Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008). Recent research by Pezeshk and others (2011) confirms that the predicted ground motion is much lower when near-source saturation is considered (Fig. 21). Thus, current ground-motion attenuation models overpredict ground motion at near-source locations in the New Madrid Seismic Zone.

Figure 22 shows intensity observations from the Wenchuan earthquake, in which high intensities (greater than IX) are concentrated along the rupture fault (Figs. 8, 17) and in the area with PGA greater than 0.25 *g*. In other words, observed intensities from the Wenchuan earthquake are consistent with recorded ground motions. Thus, intensity observation can be used to infer the corresponding ground motion.

Thus, historical intensity observations and observations from the Wenchuan earthquake indicate that all the scenario ground-motion hazards are overpredicted in the New Madrid area, primarily because of the overprediction of ground motion by currently available models.

National Seismic Hazard Maps

Most stakeholders were unaware of the process for creating the national seismic hazard maps. The maps were produced from a comprehensive consensus process involving many geologists, seismologists, engineers, and others (Frankel and others, 1996, 2002; Petersen and others, 2008). The first step was to build a database that reflects the current scientific understanding of earthquakes. Then input models were developed from the database and used to generate seismic hazard curves on grids across the United States using probabilistic seismic hazard analysis, a mathematical model developed by Cornell (1968). Figure 23 shows 0.2-s response acceleration hazard curves for Memphis, New Madrid, Paducah, and San Francisco from the 2008 national seismic hazard maps (Petersen and others, 2008). These curves provide a range of ground motion, from 0.001 to 5.0 *g* for a range of annual frequencies of exceedance, from 1.0 to 0.00001 per year. The points on the curves corresponding to annual frequencies of exceedance of 0.0004 per year were chosen to produce the national seismic hazard maps (Figs. 2–3) (Petersen and others, 2008).

Although PSHA is the most widely used method for seismic hazard assessment, it is a purely numerical model without a physical or mathematical basis, and its results are artifacts of a mathematical error (Wang, 2011; Wang and Cobb, 2012): In PSHA, the annual probability of exceedance (a

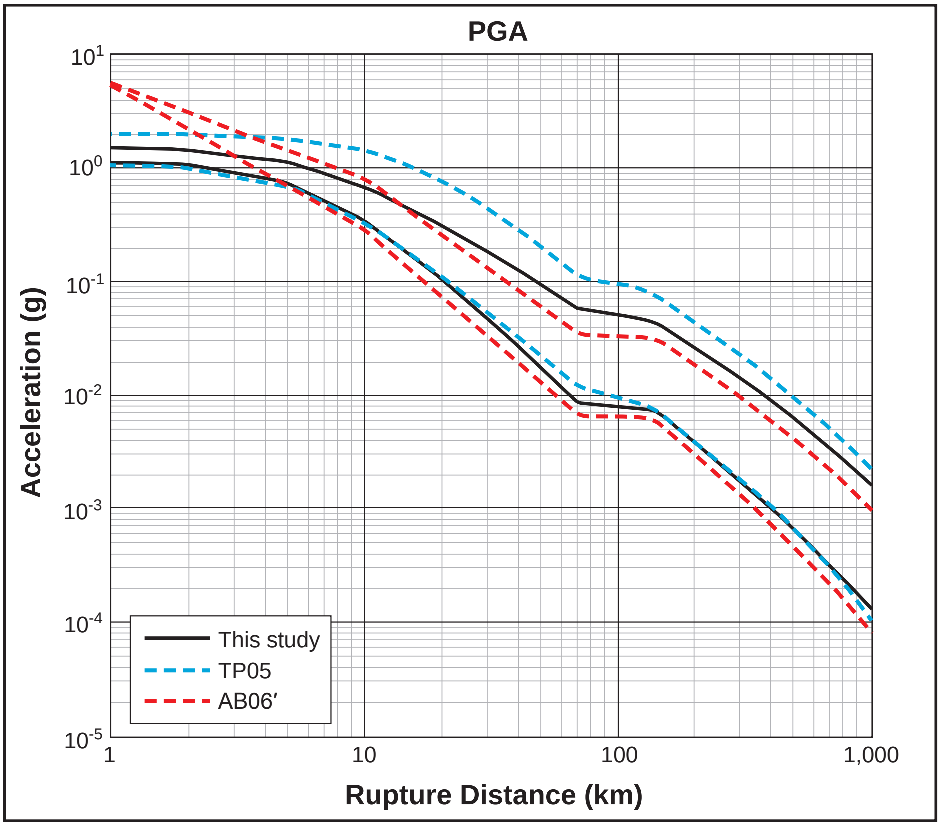


Figure 21. Comparison of PGA on hard rock developed by Pezeshk and others (2011), indicated by black solid line, and ground-motion models developed by Tavakoli and Pezeshk (2005), indicated by blue dashed line, and Atkinson and Boore (2006), indicated by red dotted line, for earthquakes with magnitude 5.0 (lower curve) and magnitude 7.0 (upper curve). From Pezeshk, S., Zandieh, A., and Tavakoli, B., Hybrid empirical ground-motion prediction equations for eastern North America using NGA models and updated seismological parameters, Bulletin of the Seismological Society of America, 2011, v. 101, p. 1859–1870, ©Seismological Society of America.

dimensionless quantity) is equated to the annual frequency or rate of exceedance (a dimensional quantity with the unit of 1/year). This error leads to the so-called ergodic assumption: “treating spatial uncertainty of ground motions as an uncertainty over time at a single point” (Anderson and Brune, 1999, p. 19). Even though the database and input models are scientifically sound, the hazard curves and national seismic hazard maps (Frankel and others, 1996, 2002; Petersen and others, 2008) are inaccurate and difficult to understand and use.

The national seismic hazard maps should be evaluated by comparing them with local historical observations as well as observations in a similar geologic environment, such as the Wenchuan area. As shown in Table 5, the ground-motion values shown on the national seismic hazard maps are quite high, twice as high as observed ground-motion values from the Wenchuan earthquake. The PGA’s (Fig. 3) on the maps are also much higher than those inferred from historical observations in the New Madrid Seismic Zone (Figs. 19–20). Thus, the national seismic hazard maps for the central United States overestimate the hazard.

Using these maps as a basis for the seismic provisions in building codes, insurance rate structures, risk assessments, and other public policies is problematic. The high hazard valuation for the New Madrid Seismic Zone directly contributes to depressed economic development in the area. Increased building costs and insurance rates are a direct result of the high hazard rating. Some businesses are prohibited from building in the area because they cannot meet federally mandated seismic requirements, and other businesses simply choose to go elsewhere to avoid bureaucratic red tape and risk of business loss. Fewer businesses in the area contributes directly to fewer jobs, resulting in a depressed economy in the region.

Much of the problem is about what we do not know. The scope of the uncertainties in the science used to develop the national seismic hazard maps should encourage us to reexamine the map models and hazard rating criteria to see if the science supports the end products: building codes and current public policies regarding seismic design and earthquake risk. Not being able to agree on the size of historical regional earthquakes and a basic attenuation model for the region is indicative of the uncertainty of the current science. When assigning seismic hazard levels, consideration must also be given to the differences in size of geographic area, population densities, magnitudes of ground motion, and recurrence intervals of earthquakes

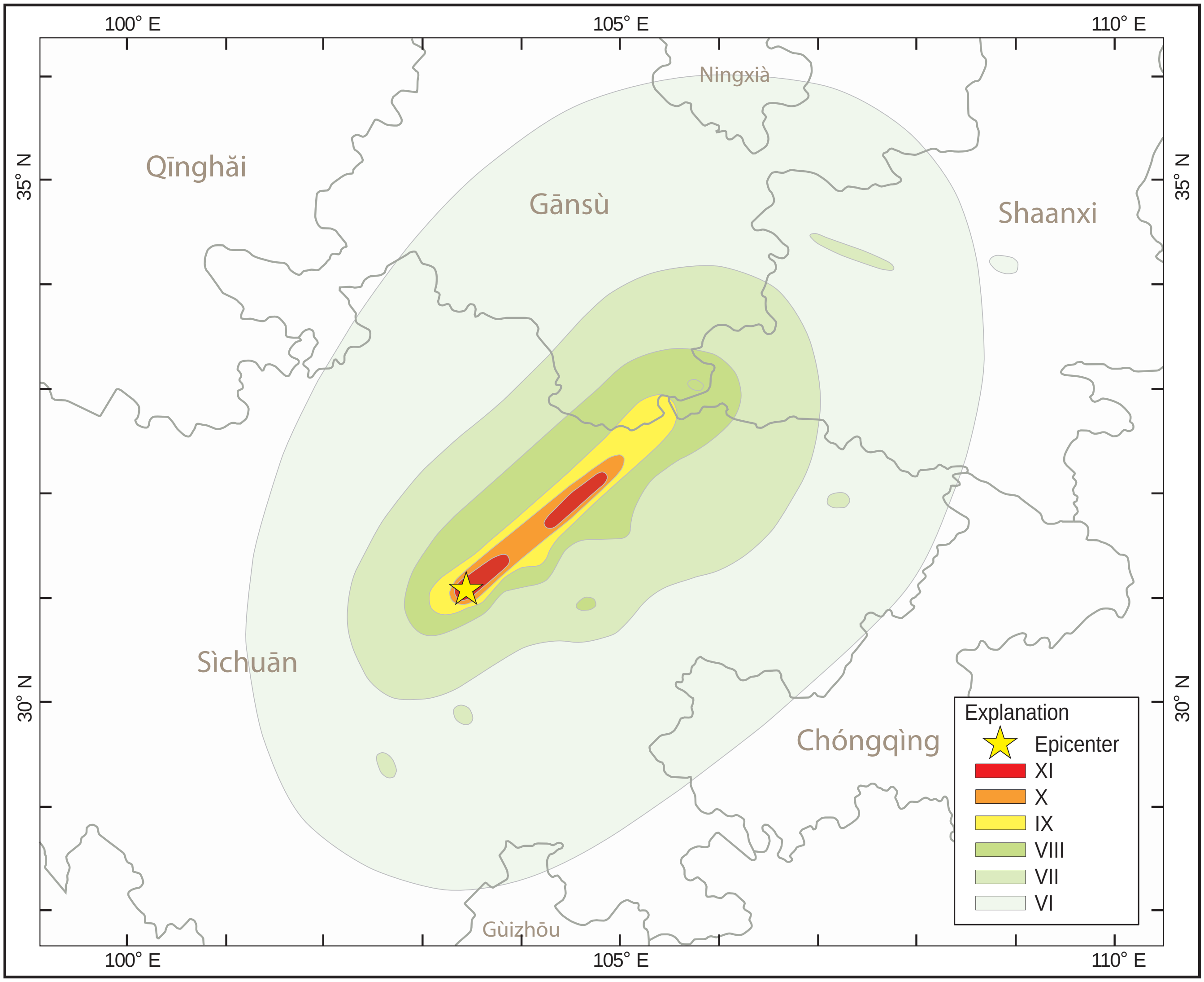


Figure 22. Observed Chinese intensity of the Wenchuan earthquake. From China Earthquake Administration.

between the central United States and California. Even if lower attenuation rates and higher ground-motion magnitudes in the central United States make a single large earthquake a risk to a larger geographic area than one in California, the lower population in the central United States and longer recurrence interval for significant seismic events in the region should offset these factors. A model that considers the complete scope of these variables should reconsider assignment of seismic hazard levels in the New Madrid Seismic Zone to lower levels than those assigned to California.

Ultimately, we cannot prove that a large earthquake will or will not happen or in what timeframe such an event might occur. We do not have conclusive answers. Much of the problem, then, has to do with how the scientific and historical data we have are applied. Many people have looked at the final product—not only the hazard maps but also the derived building codes and emergency management plans—and questioned whether the science actually supports the conclusions that have been drawn and the requirements that are in place. Local residents, businesspersons, and government officials want reassurance that their money, time, and effort are being spent on something that is of real value to their community.

Limited funds require us to choose projects carefully. We cannot protect everyone from everything. At some point, we must decide what is the best we can do at a cost we can afford. Local

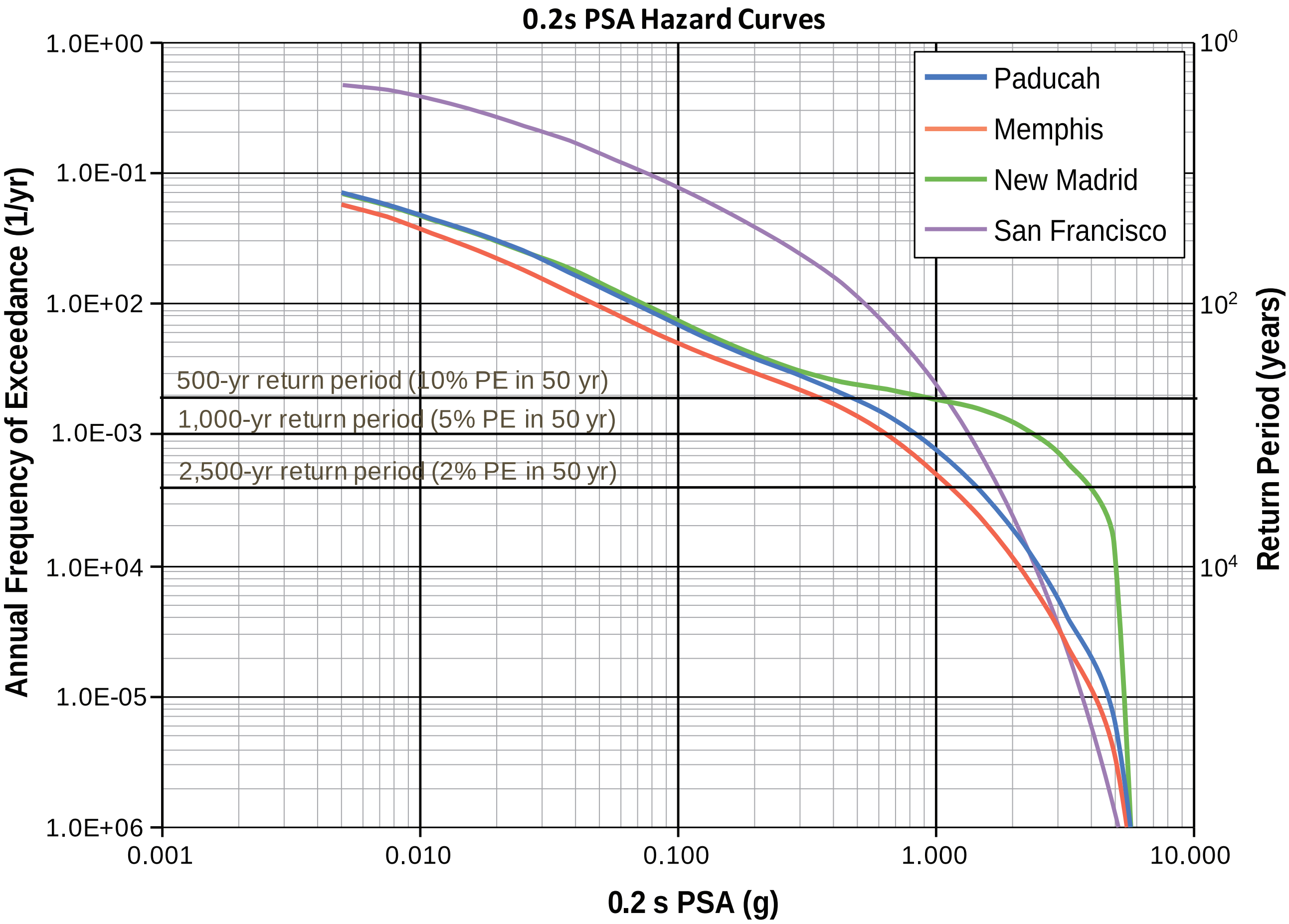


Figure 23. Selected hazard curves from the national seismic hazard maps: 0.2-s response acceleration hazard curves for Memphis (N35.15°/W90.05°), New Madrid (N36.25°/W89.50°), Paducah (N37.10°/W88.60°), and San Francisco (N37.80°/W122.40°). From Petersen and others (2008).

concerns that building code requirements are too costly or that the level of seismic hazard identified by federal agencies is overstated for western Kentucky must be taken into consideration when determining an appropriate response. Also harmful are the differences in local and federal standards, as well as the latitude allowed federal agencies to choose the projects to which to apply seismic standards. What is the level of risk the local community is willing to incur? Is there a consensus? Has there been enough education to ensure that people are making informed decisions? And can the federal government modify its hazard assessment without exaggerating the results either positively or negatively in order to mitigate impacts on local economies?

Economic Impact Analysis

The stated purpose of the Hazus-MH software is "to produce loss estimates for use by federal, state, regional and local governments in planning for earthquake risk mitigation, emergency preparedness, response and recovery" (Federal Emergency Management Agency, 2012c). The software documentation also indicates that "uncertainties are inherent in any loss estimation methodology," and that the range of uncertainty in Hazus-MH is "possibly *at best* a factor of two or more" (Federal Emergency Management Agency, 2012c). Factors contributing to the uncertainty include incomplete assessments of the built environment, changes in demographic databases, and changing economic parameters. These economic-factor uncertainties are in addition to the underlying scientific uncertainties involved in generating ground-motion contour maps discussed above. Using only default Hazus-MH databases, a single soil condition is assumed for all analyses, although local geology may vary widely. All the inherent uncertainties lead to a large range of economic loss estimates for a New Madrid scenario earthquake: from $10 to $230 billion (Table 4). Considering that losses from the Wenchuan earthquake are approximately $110 billion and that New Madrid ground-motion hazards are overpredicted, a more realistic estimate for the New Madrid scenario would be in the range of $10 to $50 billion.

Additional information and studies are needed to improve the associated databases used in seismic hazard assessment. More accurate data will return more accurate results. Data on local soil conditions and specific locations of source faults would be required to minimize the ground-motion uncertainties, and specific physical inventory and demographic information would better constrain economic and damage estimates.

Ongoing economic impacts of mitigation requirements can also be assessed via cost analysis. A long-awaited cost analysis of earthquake-resistant construction in the Memphis, Tenn., area was recently released (National Earthquake Hazards Reduction Program, Consultants Joint Venture, 2013). The report concludes that construction costs to meet current national seismic resistance standards are approximately 3 percent more than standards to resist wind loads, and 1 percent more than current design standards. West Tennessee and western Kentucky are in the same wind zone, Zone IV (Federal Emergency Management Agency, 2012d) and similar seismic ground-motion zones (U.S. Geological Survey, 2012), as well as being in a similar region of the central United States, so many of the cost-analysis principles can be assumed to also be correct for western Kentucky. These costs are very different from the estimates gleaned from this study's interviews with design and building professionals in western Kentucky, however, which indicated 1 to 20 percent cost increases for seismic mitigation requirements. On closer examination, the Memphis report only models costs for construction and does not address indirect building costs such as associated design fees for seismic requirements, additional time required to address permit and inspection requirements, or earthquake insurance over the life of a building's mortgage. This difference likely accounts for the extreme difference in mitigation requirement cost estimates between the Memphis report and the costs estimated by this study. A true cost analysis considering these and other indirect costs of meeting seismic mitigation requirements should be done to complement the Memphis analysis.

China Mitigation Policy

China has a nationally mandated plan in place for seismic design for buildings. It differentiates regions of higher seismic hazard based on locations of faults and frequency of recurrence of earthquakes, as well as for types of building uses and occupancy levels. Critical structures such as hospitals and schools are to be built to higher design standards than single residences or unoccupied structures. Some leeway is given for rural areas where building materials may be limited or where cultural traditions are strong, but whenever possible a better or higher standard than the minimum is encouraged. During the Wenchuan earthquake, the buildings that suffered the most damage were either not built to code requirements—because they predated requirements or were of shoddy construction (Earthquake Engineering Research Institute, 2008)—or were in areas where the earthquake ground-motion effect was much greater than code requirements anticipated (Miyamoto and others, 2009). Before the plan was put in place, implementation of building codes varied greatly and enforcement at local levels was sometimes problematic, particularly during economic boom periods.

In the epicentral area for the 2008 Wenchuan earthquake, the design PGA for most cities is 0.10 to 0.20 *g* (Chinese intensity of VII to VIII) (Table 7, Fig. 24). Figures 17 and 22 show, however, that the observed PGA was greater than 0.3 *g* in the epicentral area. One factor contributing to the failure of structures was that the ground shaking was both much greater and much longer than anticipated (Free and others, 2008). The ground shaking simply exceeded the level of seismic design that was required for construction, so even buildings constructed to code were not strong enough. China's design map is clearly not adequate for this seismically active area.

Table 7. Relationship between expected seismic intensity and acceleration of ground-motion design requirements from the national seismic design code of the People’s Republic of China (Ministry of Construction, People’s Republic of China, 2001).

Chinese Intensity	*VI*	*VII*	*VIII*	*IX*	*X*
Equivalent PGA (g)	0.05–0.10	0.10–0.15	0.20–0.30	0.30–0.40	>0.40

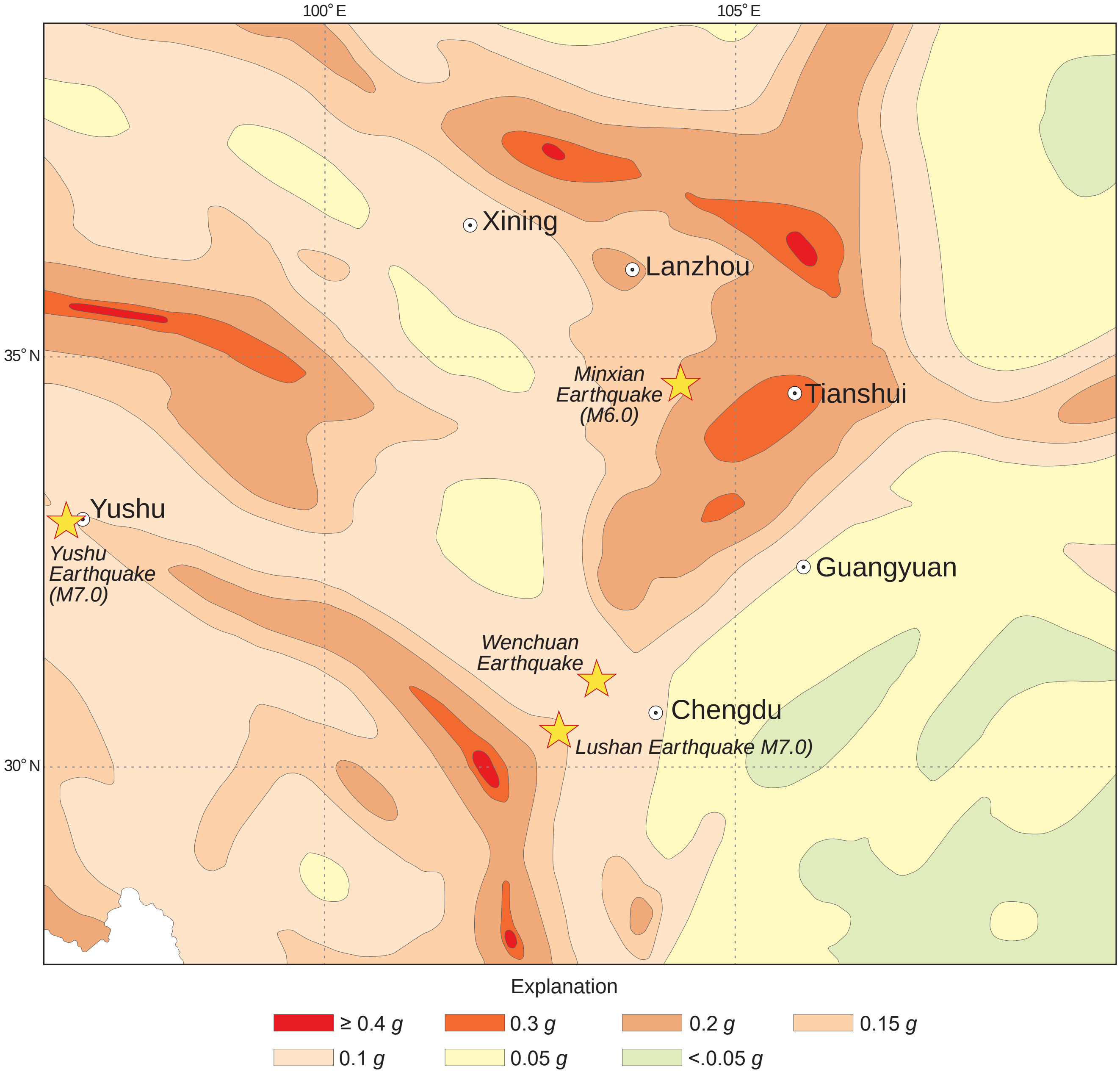


Figure 24. Seismic hazard for the Wenchuan earthquake affected area showing design PGA. Stars indicate approximate locations of recent earthquakes. Modified from People’s Republic of China National Standard (2001).

The Chinese national design ground-motion maps, like the U.S. national seismic hazard maps, were produced using the flawed PSHA (People's Republic of China National Standard, 2001). But the Chinese design ground-motion value is that for a 10 percent probability of exceedance in 50 yr from the hazard curves (compared to a 2 percent probability of exceedance in 50 yr for the U.S. maps). The Wenchuan earthquake, as well as other recent earthquakes in the same region (Fig. 24), have demonstrated that the Chinese design map does not serve the purpose of preventing future earthquake disasters, and may lead to a future disaster by underestimating seismic hazard in some areas.

Although the current seismic standard may not be high enough in the Wenchuan area, any effort to improve a building's ability to withstand seismic force helps prevent collapse and saves lives (Free and others, 2008; Miyamoto and others, 2009). To this end, before the Wenchuan earthquake the Chinese government launched a campaign to promote seismic-resistant homes for farmers in rural areas by providing government subsidies (Wang and others, 2005). Many new homes were built in southeastern Gansu Province as part of this campaign. As illustrated in Figure 25, the seismic-resistant houses suffered little or no damage during the 2008 Wenchuan earthquake, but traditional unreinforced adobe houses suffered severe or total damage. Many communities that built a seismic-hazard–resistant environment through appropriate code requirements coupled with adequate enforcement and use of government assistance programs for particularly at-risk sectors sustained minimal damage.

Conclusions and Recommendations

Whether justified or not, the predicted extreme high ground-motion hazards for the New Madrid Seismic Zone and the resulting stringent seismic design requirements have an impact on communities in the New Madrid area, western Kentucky in particular. The perception in western Kentucky is that overstated seismic-hazard estimates have led to overly stringent building codes and other detrimental public policies, ultimately suppressing economic growth through increased building and insurance costs, general inconvenience, and fear of increased economic and safety risks.

Large uncertainties are inherent in the estimation of earthquake parameters, ground-motion values in particular, for the New Madrid Seismic Zone. These uncertainties have led to a large range of estimates of the ground-motion hazards that could result from future earthquakes in the zone. Thus, any ground-motion hazard estimate or map must be evaluated to determine the level of uncertainty by comparing the estimates to historical observations from the 1811-12 New Madrid earthquakes and observations from similar areas such as the Sichuan Basin of China. This study shows that most of the maximum ground-motion values for the scenario hazard are overpredicted, particularly in the near-source area. These overpredictions are mainly the result of ground-motion attenuation models that do not account for near-source saturation.

Although the national seismic hazard maps (for ground motion with 2 percent probability of exceedance in 50 yr) are not supposed to be the worst-case scenarios, they predict much higher ground-motion values than the best estimates from historical observations in the New Madrid Seismic Zone and recordings from the Wenchuan earthquake. The fundamental problem with the national seismic hazard maps is that they were produced from a scientifically flawed mathematical model: PSHA. In PSHA, the annual probability of exceedance (a dimensionless quantity) is equated to the annual frequency or rate of exceedance (a dimensional quantity with the unit of 1/year), and the results being used inappropriately. PSHA has no scientific basis and results in ineffective, even wrong, mitigation policies. This is clearly demonstrated in the overly stringent seismic design requirements for the New Madrid area and insufficient seismic design for the Wenchuan area.

Caution will also be needed when future social and economic impacts are assessed for earthquake scenarios, because of the large uncertainties inherent in the Hazus-MH hazard scenario, building inventory, and model. As shown in this study, a large range of economic loss estimates of $10 to $230 billion resulted from a range of earthquake models. A more realistic estimate of economic

Figure 25. (a) A traditional adobe house and (b) a recently constructed seismic-resistant house after the Wenchuan earthquake. Traditionally built adobe houses suffered severe damage, but houses built to seismic-resistant standards under the government-subsidized mitigation program sustained little or no damage. Photos © Zhenming Wang. Used with permission.

losses from a large earthquake in the New Madrid Seismic Zone is in the range of $10 to $50 billion.

Development of effective and sound seismic hazard mitigation policies is challenging for the New Madrid Seismic Zone, in light of this uncertainty. The process requires earth scientists, engineers, public officials, and private citizens to work together closely. We recommend the following actions be taken to develop, adapt, and implement effective seismic hazard mitigation:

Research

1. **Continue earthquake monitoring and research.** First and foremost, current monitoring of regional seismicity and research into causative mechanisms and paleoseismic studies must continue in order to increase the knowledge base for the New Madrid Seismic Zone. New directions for research such as recent forays into monitoring and explaining strain through GPS data should continue to be developed to broaden our understanding of geoscience principles. Research into seismic attenuation functions should continue to narrow the uncertainty in ground-motion expectations for modeling purposes.
2. **Continue to improve hazard assessment, as well as seismic risk assessment.** The national seismic hazard maps as currently produced are not scientifically sound. Thus, there is an urgent need to improve the maps and make sure that subsequent versions are based on sound science. Alternative ground-motion hazard maps should also be developed. FEMA's Hazus-MH software for economic analysis should continue to be improved, and documentation and training should be provided for its correct use. Hazus-MH should include more complete databases of soils geology, faults in the central United States, populations, and building types and distributions; improved attenuation models; and less uncertainty in mathematical calculations to reduce the documented overstatement of hazard.
3. **Perform cost-benefit analysis.** At a minimum, a cost analysis considering indirect costs of meeting seismic requirements should be done to complement the recent construction cost-benefit analysis done for Memphis. Indirect costs may include design and permitting costs, additional wages for employee time required to comply with seismic design requirements, and required or desirable insurance.

Education

1. **Improve the transfer of information to the public.** As science becomes more complex, the public must rely more on experts to collect and interpret data and communicate information in an unbiased manner. Federal agencies should improve the level of trust between the public and seismic experts with more transparent communication and more understandable and more available documentation of data, information, methods, and products. Scientists should understand how the data and information affect the public and respond appropriately to concerns about the underlying science.
2. **Provide opportunities for additional education for nonscientists.** Federal, State, and local seismic experts should provide education in layman's terms to the nonscience-based public. Topics should include general earthquake information as well as information specific to geographic regions. Both certainties and uncertainties should be clarified, along with the way in which uncertainties are incorporated into products such as hazard maps, building codes, and emergency preparedness plans. Both likely and worst-case scenarios should be communicated, with emphasis given to explanation of probability.
3. **Provide opportunities for additional education for structural design and construction professionals.** Federal, State, and local experts should provide continuing or targeted education for professionals such as engineers, architects, and builders regarding current science. By working together, experts will better see the range of topics and concerns that might not be obvious when focusing on jurisdictional topics only. Topics should include known and unknown factors, level of certainty of current science, existing tools for seismic analysis, and appropriate uses. This recommendation could be worked into the requirement of some professions for continuing education.

4. **Suggest appropriate emergency response plans and preparation activities.** Although seismic hazard is considered high in western Kentucky, there are few guidelines for hospitals and other care facilities for appropriate response to seismic events. General emergency response plans are in place at all medical facilities, but there is little or no understanding of a realistic scenario for an expected or potential earthquake, and therefore no way to adequately prepare for emergency response. On both State and local levels, providing probable scenarios for the aftereffects of earthquakes of various magnitudes with various sources would be wise. A range of scenarios would allow emergency responders to develop appropriate plans for emergency management and response. The likelihood of aftershocks, the probability of disruption of local utilities or public services, and a realistic expectation of local buildings and infrastructure that would be destroyed or remain functional should all be considered. The U.S. Geological Survey's Great ShakeOut website (www.shakeout.org) has many resources that could be modified for this purpose, but scenarios must be somewhat customized to local conditions for emergency responders to prepare appropriately.

Policy/Application

1. **Revise the New Madrid Seismic Zone earthquake hazard on the national seismic hazard maps.** On the federal level, appropriate changes should be made to the maps for the central and eastern United States to account for uncertainties in the science. Common sense about earthquake magnitudes, locations, and recurrence intervals discredit the current maps, which indicate higher earthquake hazard in the New Madrid Seismic Zone than in the more highly seismic California fault zones. Although map documentation indicates the hazard levels for the central and eastern United States were reduced between the 2002 and 2008 map versions, later revisions have restored the hazard levels to very nearly the same level as on the 2002 maps; neither current nor historic activity supports this analysis, however. If current hazard levels are justifiable, the reasoning must be explained more clearly.
2. **Open a forum for revisions to seismic requirements for State building codes.** State and local building codes are under the jurisdiction of the building code adopted by the commonwealth of Kentucky, which has been modified from the International Building Code. Although the code has been developed by professionals, objections or problems may be encountered during the application of code requirements. A forum for discussing problems and suggested changes to the building code should be established for professionals tasked with implementing code requirements.
3. **Establish assistance for nonprofessionals for individual residential projects.** The commonwealth should help nonprofessionals obtain appropriate permits and approvals for residential construction projects. This recommendation addresses concerns that private homeowners have inadequate access to affordable design services for their building projects. Licensed engineers or other design professionals are reluctant to take on small single-residence projects, or associated fees are considered too high for personal budgets (compared to larger-scale commercial projects with comparatively larger budgets), and local officials run the risk of conflict of interest for advising on individual projects. An avenue is needed to provide necessary advice and services to citizens at affordable rates to maintain residential building.
4. **Customize Hazus-MH for area-specific economic analysis of potential hazards.** In order to help State and local officials prepare for potential large earthquakes, Hazus-MH scenarios should be customized with updated building, populations, and soils databases. Additional scenarios for fault hazards should be developed rather than relying on the minimal point-source hazard scenarios included with the software. Resulting scenario analysis using more specific local data will point out weak areas of local buildings and infrastructure and help State and local agencies determine where best

to assign available funds for reconstruction and emergency preparedness projects.

5. **Be aware of worst-case scenarios, but plan and prepare for likely scenarios.** State and local agencies responsible for emergency planning and response should collaborate with each other and the public to prepare for likely events at all levels. Agencies should consider extreme events, but focus on common-sense self-help expectations for the general public. Public-school elementary programs should include regular instruction on appropriate response to earthquakes.

As one participant stated, ultimately, in order for science to help communities, it must be more than applicable: It must be compelling (L. Peters, Secretary of Energy and the Environment, personal communication, 2013). It is to the benefit of professionals at all levels to make sure current science is both applicable and compelling.

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References Cited

Anderson, G.A., and Brune, J.N., 1999, Probabilistic seismic hazard analysis without the ergodic assumption: Seismological Research Letters, v. 70, p. 19–28.

Atkinson, G.M., and Boore, D.M., 2006, Earthquake ground-motion prediction equations for eastern North America: Bulletin of the Seismological Society of America, v. 96, p. 2181–2205; doi:10.1785/0120050245.

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, v. 94, p. 64–75.

Bazzurro, P., and Cornell, C.A., 1999, Disaggregation of seismic hazard: Bulletin of the Seismological Society of America, v. 89, p. 501–520.

Boore, D.M., and Atkinson, G.M., 2008, Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s: Earthquake Spectra, v. 24, p. 99–138.

Boore, D.M., Joyner, W.B., and Fumal, T.E., 1997, Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work: Seismological Research Letters, v. 68, p. 128–153.

Burchfiel, B.C., Royden, L.H., van der Hilst, R.D., Hager, B.H., Chen, Z., King, R.W., Li, C., Lu, J., Yao, H., and Kirby, E., 2008, A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China: GSA Today, v. 18, p. 4–11; doi:10.1130/GSATG18A.1.

Calais, E., Freed, A.M., Van Arsdale, R., and Stein, S., 2010, Triggering of New Madrid seismicity by late-Pleistocene erosion: Nature, v. 466, p. 608–612; doi:10.1038/nature09258.

Calais, E., and Stein, S., 2009, Time-variable deformation in the New Madrid Seismic Zone: Science, v. 323, p. 1442.

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, v. 93, p. 1012–1033.

Campbell, K.W., and Bozorgnia, Y., 2008, NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s: Earthquake Spectra, v. 24, p. 139–171.

City of Paducah, 2012, A resolution of the city of Paducah recommending the United States Geological Survey to review the national seismic hazard map (NSHM), based upon research by Dr. Zhenming Wang and Dr. James Cobb of the Kentucky Geological Survey at the University of Kentucky: Paducah Board of Commissioners, Feb. 2, 2012, 1 p.

Cornell, C.A., 1968, Engineering seismic risk analysis: Bulletin of the Seismological Society of America, v. 58, p. 1583–1606.

Cramer, C.H., and Boyd, O.S., 2011, Why the New Madrid earthquakes are M7–8 and the Charleston earthquake is ~M7 [abs.]: American Geophysical Union, 2011 fall meeting, San Francisco, Calif., Abstracts, S22A-04.

Csontos, R., and Van Arsdale, R., 2008, New Madrid Seismic Zone fault geometry: Geosphere, v. 4, p. 805–813; doi:10.1130/GES00141.1.

Earthquake Engineering Research Institute, 2008, Learning from earthquakes: The Wenchuan, Sichuan Province, China, earthquake of May 12, 2008: Earthquake Engineering Research Institute, EERI Special Earthquake Report, 6 p.

Federal Emergency Management Agency, 2012a, Hazus-MH 2.1, multi-hazard loss estimation methodology software: Federal Emergency Management Agency, ver. 2.1, February 2012, 1 CD-ROM.

Federal Emergency Management Agency, 2012b, Multi-hazard loss estimation methodology, earthquake model, Hazus-MH 2.1 technical manual: Federal Emergency Management Agency, 718 p.

Federal Emergency Management Agency, 2012c, Multi-hazard loss estimation methodology, earthquake model, Hazus-MH 2.1 user manual: Federal Emergency Management Agency, 863 p.

Federal Emergency Management Agency, 2012d, Wind zones in the United States: www.fema.gov/safe-rooms [accessed 03/2014].

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic hazard maps: Documentation: U.S. Geological Survey Open-File Report 96-532, 69 p.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 update of the national seismic hazard maps: U.S. Geological Survey Open-File Report 02-420, 33 p.

Free, M., Rossetto, T., Eiris, N., Taucer, F., Zhao, B., Koo, R., Wang, J., Ma, X., and Verrucci, E., 2008, The Wenchuan, China earthquake of 12 May 2008: A preliminary field report by EEFIT: Earthquake Engineering Field Investigation Team, Institution of Structural Engineers, 14 p.

Grollimund, B., and Zoback, M.D., 2001, Did deglaciation trigger intraplate seismicity in the New Madrid Seismic Zone?: Geology, v. 29, p. 175–178; doi: 10.1130/0091-7613(2001)029<0175:DDTISI>2.0CO;2.

Holbrook, J., Autin, W.J., Rittenour, T.M., Marshak, S., and Goble, R.J., 2006, Stratigraphic evidence for millennial-scale temporal clustering of earthquakes on a continental-interior fault: Holocene Mississippi River floodplain deposits, New Madrid Seismic Zone, USA: Tectonophysics, v. 420, p. 431–454; doi:10.1016/j.tecto.2006.04.002.

Hough, S.E., Armbruster, J.G., Seeber, L., and Hough, J.F., 2000, On the modified Mercalli intensities and magnitudes of the 1811-1812 New Madrid earthquakes: Journal of Geophysical Research, v. 105, p. 23,839–23,864.

Hough, S.E., and Page, M., 2011, Toward a consistent model for strain accrual and release for the New Madrid Seismic Zone, central United States: Journal of Geophysical Research, v. 116, issue B3; doi:10.1029/2010JB007783.

International Code Council, 2000, International building code: International Code Council, 678 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, v. 126, p. 314–344.

Johnston, A.C., and Schweig, E.S., 1996, The enigma of the New Madrid earthquakes of 1811-1812: Annual Review of Earth and Planetary Sciences, v. 24, p. 339–384; doi:10.1146/annurev.earth.24.1.339.

Klügel, J.-U., 2011, Uncertainty analysis and expert judgment in seismic hazard analysis: Pure and Applied Geophysics, v. 168, p. 27–53; doi: 10.1007/s00024-010-0155-4.

Li, X., Zhou, Z., Huang, M., Wen, R., Yu, H., Lu, D., Zhou, Y., and Cui, J., 2008, Preliminary analysis of strong-motion recordings from the magnitude 8.0 Wenchuan, China, earthquake of 12 May 2008: Seismological Research Letters, v. 79, p. 844–854; doi:10.1785/gssrl.79.6.844.

Lu, M., Li, X.J., An, X.W., and Zhao, J.X., 2010, A comparison of recorded response spectra from the 2008 Wenchuan, China, earthquake with modern ground-motion prediction models: Bulletin of the Seismological Society of America, v. 100, p. 2357–2380; doi: 10.1785/0120090303.

McBride, J.H., Pugin, A.J.M., Nelson, W.J., Larson, T.H., Sargent, S.L., Devera, J.A., Denny, F.B., and Woolery, E.W., 2003, Variable post-Paleozoic deformation detected by seismic reflection profiling across the northwestern "prong" of New Madrid Seismic Zone: Tectonophysics, v. 368, p. 171–191.

Ministry of Construction, People's Republic of China, 2001, National standard of the People's Republic of China: Code for seismic design of buildings: Beijing, China, China Architecture & Building Press, 455 p.

Miyamoto, H.K., Gilani, A.S.J., and Chan, T., 2009, The 2008 Sichuan earthquake: Assessment of damage and lessons learned: Structure Magazine, January 2009, p. 17–19.

National Earthquake Hazards Reduction Program, Consultants Joint Venture, 2013, Cost analyses and benefit studies for earthquake-resistant construction in Memphis, Tennessee: National Earthquake Hazards Reduction Program, Consultants Joint Venture, Report NIST GCR 14-917-26, 249 p.

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, v. 284, p. 619–621.

Nuttli, O.W., 1973, The Mississippi Valley earthquakes of 1811 and 1812: Intensities, ground motion and magnitudes: Bulletin of the Seismological Society of America, v. 63, p. 227–248.

Orton, A.M., 2014, Science and public policy of earthquake hazard mitigation in the New Madrid Seismic Zone: Lexington, University of Kentucky, master's thesis, 189 p.; uknowledge.uky.edu/ees_etds/19 [accessed 07/31/2015].

Paducah Area Chamber of Commerce, 2012, Letter to the United States Geological Survey: Paducah Area Chamber of Commerce, Feb. 21, 2012, 1 p.

People's Republic of China National Standard, 2001, Seismic ground motion parameter zonation map of China: China Standard Press, GB 18306–2001, 2 p.

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: U.S. Geological Survey Open-File Report 2008-1128, 61 p.

Pezeshk, S., Zandieh, A., and Tavakoli, B., 2011, Hybrid empirical ground-motion prediction equations for eastern North America using NGA models and updated seismological parameters: Bulletin of the Seismological Society of America, v. 101, p. 1859–1870.

Pollitz, F.F., Kellogg, L., and Burgmann, R., 2001, Sinking mafic body in a reactivated lower crust: A mechanism for stress concentration at the New Madrid Seismic Zone: Bulletin of the Seismological Society of America, v. 91, p. 1882–1897.

Silva, W., Gregor, N., and Darragh, R., 2002, Development of regional hard rock attenuation relations for central and eastern North America: Pacific Engineering and Analysis, El Cerrito, Calif., 57 p.

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 U.S. Geological Survey: URS Group, Pasadena, Calif., Award 99HQGR0098, 38 p.

Stein, S., 2010, Disaster deferred: A new view of earthquake hazards in the New Madrid Seismic Zone: New York, Columbia University Press, 296 p.

Stein, S., and Wysession, M., 2003, An introduction to seismology, earthquakes, and earth structure: Malden, Mass., Blackwell Publishing, 498 p.

Street, R., Wang, Z., Woolery, E., Hunt, J., and Harris, J., 1997a, Site effects at a vertical accelerometer array near Paducah, Kentucky: Engineering Geology, v. 46, p. 349–367.

Street, R., and Woolery, E., 1997, A seismological/geological evaluation with liquefaction and deformation analyses of Rough River Dam, Breckinridge County, Kentucky: U.S. Army Corps of Engineers Periodic Inspection No. 7, Rough River Dam (supplement), 600 p.

Street, R., Woolery, E., Wang, Z., and Harik, I.E., 1997b, Soil classifications for estimating site-dependent response spectra and seismic coefficients for building code provisions in western Kentucky: Engineering Geology, v. 46, p. 331–347.

Structural Engineers Association of Kentucky, 2002, White paper on review of the 2002 Kentucky residential code [2nd ed.]: Structural Engineers Association of Kentucky Document WP-01-2.1, 66 p.

Tavakoli, B., and Pezeshk, S., 2005, Empirical-stochastic ground-motion prediction for eastern North America: Bulletin of the Seismological Society of America, v. 95, p. 2283–2296; doi:10.1785/0120050030.

Toro, G.R., Abrahamson, N.A., and Schneider, J.F., 1997, A model of strong ground motions from earthquakes in central and eastern North America: Best estimates and uncertainties: Seismological Research Letters, v. 68, p. 41–57.

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, v. 92, p. 2080–2089.

Tuttle, M.P., Schweig, E.S., III, Campbell, J., Thomas, P.M., Sims, J.D., and Lafferty, R.H., III, 2005, Evidence for New Madrid earthquakes in A.D. 300 and 2350 B.C.: Seismological Research Letters, v. 76, p. 489–501; doi:10.1785/gssrl.76.4.489.

U.S. Geological Survey, 2008a, Earthquake Hazards Program magnitude 7.9—Eastern Sichuan, China, earthquake details: earthquake.usgs.gov/earthquakes/eqinthenews/2008/us2008ryan/#details [accessed 02/2014].

U.S. Geological Survey, 2008b, Earthquake Hazards Program magnitude 7.9—Eastern Sichuan, China, summary: earthquake.usgs.gov/earthquakes/eqinthenews/2008/us2008ryan/#summary [accessed 02/2014].

U.S. Geological Survey, 2008c, M7.9 eastern Sichuan, China, felt map: earthquake.usgs.gov/earthquakes/dyfi/events/us/2008ryan/us [accessed 02/2014].

U.S. Geological Survey, 2008d, ShakeMap background: earthquake.usgs.gov/research/shakemap [accessed 03/2014].

U.S. Geological Survey, 2012, Earthquake Hazards Program 2008 NSHM figures: earthquake.usgs.gov/hazards/products/conterminous/2008/maps [accessed 03/2014].

U.S. Geological Survey, 2014, Earthquake Hazards Program seismic design maps & tools: earthquake.usgs.gov/hazards/designmaps [accessed 01/2014].

Van Arsdale, R.B., Stahle, D.W., Cleaveland, M.K., and Guccione, M.J., 1998, Earthquake signals in tree-ring data from the New Madrid Seismic Zone and implications for paleoseismicity: Geology, v. 26, p. 515–518; doi:10.1130/0091-7613(1998)026<0515:ESITRD>2.3CO;2.

Wald, D.J., Quitoriano, V., Heaton, T.H., and Kanamori, H., 1999, Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California: Earthquake Spectra, v. 15, p. 557–564.

Wang, D., Xie, L., Abrahamson, N.A., and Li, S., 2010, Comparison of strong ground motion from the Wenchuan, China, earthquake of 12 May 2008 with the next generation attenuation (NGA) ground-motion models: Bulletin of the Seismological Society of America, v. 100, p. 2381–2395; doi:10.1785/0120090009.

Wang, L., Tao, Y., and Yuan, Y., 2005, Summary of the Seismic Safe Rural Houses Project [in Chinese]: Northwestern Seismological Journal, v. 27, p. 305–311.

Wang, Z., 2007, Seismic hazard and risk assessment in the intraplate environment: The New Madrid Seismic Zone of the central United States: Geological Society of America Special Paper 425, p. 363–373.

Wang, Z., 2011, Seismic hazard assessment: Issues and alternatives: Pure and Applied Geophysics, v. 168, p. 11–25; doi:10.1007/s00024-010-0148-3.

Wang, Z., and Cobb, J.C., 2012, A critique of probabilistic versus deterministic seismic hazard analysis with special reference to the New Madrid Seismic Zone: Geological Society of America Special Papers, v. 493, p. 259–275; doi:10.1130/2012.2493(13).

Wang, Z., and Lu, M., 2011, A short note on ground-motion recordings from the M7.9 Wenchuan, China, earthquake and ground-motion prediction equations in the central and eastern United States: Seismological Research Letters, v. 82, p. 731–733.

Wang, Z., and Woolery, E.W., 2006, Recordings from the deepest borehole in the New Madrid Seismic Zone: Seismological Research Letters, v. 77, p. 148–153.

Wheeler, R., 2011, Reassessment of stable continental regions of Southeast Asia: Seismological Research Letters, v. 82, p. 971–983.

Woolery, E.W., and Street, R., 2002, 3D near-surface soil response from H/V ambient-noise ratios: Soil Dynamics and Earthquake Engineering, v. 22, p. 865–876.

Xie, F., Wang, Z., Du, Y., and Zhang, X., 2009, Preliminary observations of the faulting and damage pattern of M8.0 Wenchuan, China, earthquake: The Professional Geologist, v. 46, p. 3–6.

Xu, X., Wen, X., Yu, G., Chen, G., Klinger, Y., Hubbard, J., and Shaw, J., 2009, Coseismic reverse- and oblique-slip surface faulting generated by the 2008 Mw7.9 Wenchuan earthquake, China: Geology, v. 37, p. 515–518; doi:10.1130/G25462A.1.

Zoback, M.D., Hamilton, R.M., Crone, A.J., Russ, D.P., McKeown, F.A., and Brockman, S.R., 1980, Recurrent intraplate tectonism in the New Madrid Seismic Zone: Science, v. 209, p. 971–976.