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EARTHQUAKE RISK AND DAMAGE FUNCTIONS: AN INTEGRATED PREPAREDNESS AND PLANNING MODEL APPLIED TO NEW MADRID

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16. Abstract (Limit: 200 words)

This study attempts to provide, in an integrated analytical framework, the methodology and the data needed to guide public and private planning and future decision making for earthquake hazard preparedness and risk mitigation. The focus is on the New Madrid Fault region, especially the effect on the St. Louis and Memphis Standard Metropolitan Statistical Areas. An interdependent planning simulation model was developed to tie together statistically the seismic risk or physical damage functions to economic damage functions for potential earthquake risk assessment and impact evaluation for the next 50 years. Several topics are covered: (1) Various seismological risks in the New Madrid region are described and predicted; (2) The surficial materials are documented and ground susceptibility for the region is classified; (3) Populations subject to earthquake risk and the projected populations, 1980 through 2030, are discussed; (4) The development of the physical and economic damage functions and their applications to damage estimation and impact assessment under the "status quo" scenario are presented; and (5) The institutional aspects and policy issues concerning earthquake risk reduction and preparedness are shown.

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I am most grateful for the counsel, insight, and assistance from all the above-mentioned persons and agencies but, as project leader and principal author, must alone accept the responsibility for any errors that may remain in this report.

Sincerely,

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EXECUTIVE SUMMARY

A. Background and Study Objectives

Most earthquakes are related to compressional or tensional stresses built up at the margins of the huge moving lithosphere plates that make up the earth's surface. Since the earth is in constant motion, earthquakes of varying magnitude are common natural phenomena occurring throughout the world thousands of times each year. Although the number of earthquakes occurring in which there is extensive damage or loss of life is comparatively small--approximately 140 earthquakes with Modified Mercalli intensity (M.M.) VI or greater are recorded each year--historically the earth has been marked by a continuing chain of major earthquake disturbances which have caused catastrophic destruction and extensive loss of life. The recent earthquake disasters in Guatemala, Italy, Russia, China, Rumania, and Iran have alerted the entire world to the danger of earthquakes, and people in the United States have been encouraged to accelerate their rate of preparedness in order to reduce the risk and potential damages caused by earthquake and other natural hazards. Passage of the Earthquake Hazards Reduction Act of 1977 and the recent establishment of the Federal Emergency Management Agency (FEMA) vividly signify public awareness of the problem and greater recognition of the need for earthquake risk and hazard mitigation.

In recorded history, the most seismologically dangerous region on the North American continent in terms of earthquake intensity and magnitude has been the New Madrid seismic zone which encompasses portions of eastern Arkansas, southern Missouri, western Tennessee and western Kentucky. In the winter of 1811-1812, the New Madrid seismic zone produced the greatest sequence of earthquakes ever experienced in the United States. The three largest of the nearly 2,000 felt earthquakes that occurred in a 3-month interval in the New Madrid seismic zone had surface-wave magnitudes of 8.2, 8.0, and 7.8 on the Richter scale and intensities between XI and XII on the Modified Mercalli intensity scale. These three earthquakes caused topographic changes over an area covering from 30,000 to 50,000 square miles; the total area shaken by the quakes was at least 2 million square miles, and the three largest shocks were felt from Canada to New Orleans.

Many seismologists agree that the earthquakes in the New Madrid seismic zone are likely to be perceived over areas 10 to 100 times larger than are earthquakes of the same magnitude west of the Rocky Mountains. Despite their record intensities, the 1811-1812 earthquakes in the New Madrid seismic zone did not cause particularly serious structural damage because the epicenters were located in what at that time were rather sparsely populated rural areas. With the development of two major Standard Metropolitan Statistical Areas (SMSA's)--St. Louis about 130 miles north of the northern limit of the New Madrid fault zone and Memphis about 30 miles

east of the southern limit, the damage effect could be disastrous should earthquakes similar to those of 1811-1812 occur today or in the near future under the existing levels of regional preparedness.

In terms of expanding regional preparedness efforts, however, several critical questions must be raised. First, what is the risk to life and property due to earthquakes in the New Madrid seismic zone? Second, is that risk socially and economically acceptable for existing populations subject to the earthquake risk? Third, as these populations grow in size and density, to what degree will earthquakes affect risks to life and property? Fourth, if the risk is not tolerable, how can it be technically reduced to a level socially and economically acceptable? Finally, with our limited knowledge, how can scarce resources be efficiently allocated so as to reduce the risk to such an extent that it would be considered minimal; or how are the marginal social benefits derived from earthquake damage reduction made equal to the marginal social costs, i.e., the amount spent on the last unit of risk reduction and/or protection?

In terms of preparedness, very little information is available to explain and answer the above questions. Despite the fact that three of the great earthquakes in this country occurred in the New Madrid seismic zone, few studies on earthquake risk prediction are available for that region. Studies on potential earthquake risk and economic damage for this region in terms of structural and property damage and human mortality and injury are virtually nonexistent, and the above questions have never been systematically studied and/or fully understood.

The primary objective of this study is to develop a body of information and data essential to a better understanding of earthquake risk, i.e., the social and economic consequences of possibly damaging earthquakes in the New Madrid seismic zone. Due to population growth and continuing urbanization in the region, especially in the St. Louis and Memphis SMSA's, this information is essential so that public policies can be adopted and various protective actions can be taken towards the mitigation and reduction of earthquake risk and hazard. Specifically, the five major objectives of this study are as follows:

- To evaluate the geological conditions and ground susceptibility of the region with respect to potential earthquake hazards;

- To develop and generate isoseismal or intensity maps for the selected epicenters so that intensity values could be related to damage values for a given probability of occurrence;

- To provide a body of updated information on the effects of major damaging earthquakes in the New Madrid seismic zone, especially for the 15 counties selected as case studies, i.e., the St. Louis and Memphis

Standard Metropolitan Statistical Areas (SMSA's) plus Cape Girardeau and New Madrid counties (see Figure S-1 for the study region); and

- To develop and construct a simulation model so that various physical damage functions can be empirically estimated and subsequently converted into economic damage values. In addition, the populations at risk to earthquake damage are projected to the year 2000 and then extrapolated to 2030 to shed some light on the social benefit calculations essential for social cost comparisons;

- To evaluate the existing public programs and policies related to preparedness for and protection from earthquakes and the relief and rehabilitation of earthquake victims in the region.

In summary, the major objective of this study is to provide an integrated analytical framework or model that can be employed for a systematic risk assessment of natural hazards in general and that of earthquakes in particular. The New Madrid quake zone is used as a case study to test the feasibility of such a model.

B. Study Design and Methodology

To accomplish the objectives, major research tasks were designed and completed, including risk population identification, data investigation and collection, as well as the development and simulation of the physical and economic damages functions in an integrated earthquake hazard planning and prediction model. Specifically, the backbone of this study design consists of three essential modules: the physical damage functions, the economic damage functions, and the institutional aspects related to government and community preparedness responses. The physical damage functions are related to earthquake prediction and utilize both probabilistic and deterministic approaches for risk assessment, and the economic damage functions refer to potential damage estimates--human, structural, and others--depending on the occurrence of a certain type of earthquake and the projected population bases at risk. Government and community preparedness is a concomitant investigation; baseline data on the state of awareness of potential risks by the public and private sectors are evaluated for alternative policy simulation in the future.

The extent of economic loss, physical damage, and social disruption caused by major earthquakes is highly susceptible to the quake's geographic location and size of its epicenter, the time of day when the quake occurs, and the region's social and economic characteristics and development. Needless to say, the magnitude, intensity, and duration of the earthquake itself are also critical determinants. Therefore, methodologically the integrated models in this study are characterized by a variety of interdisciplinary approaches pertaining to each component element in the model structure, as follows:

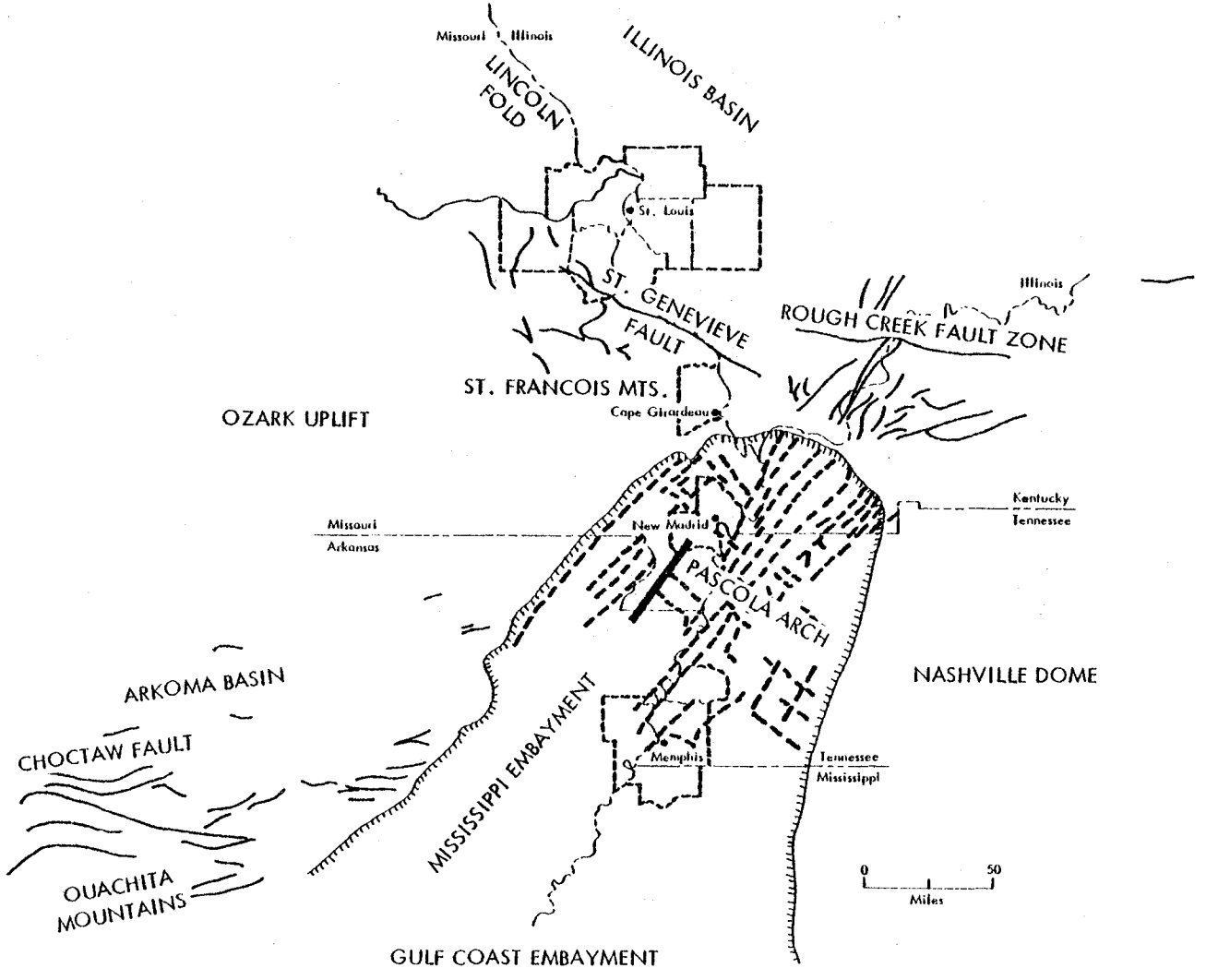


Figure S-1 - Exposed faults, the New Madrid epicenter, and the study region.

1. Earthquake risk analysis: In determining earthquake risk in the study area for the next 50 years, both probabilistic and deterministic approaches were employed. While the deterministic approach must assume an intensity and site-specific epicenter and determine ground motion in the surrounding area using various wave attenuation models, the probabilistic approach takes into account all possible epicenters in the New Madrid fault zone and computes the probability of occurrence of a certain magnitude of quake on the basis of historical data for the period of time under consideration. Isoseismic contour maps of various seismic risks in terms of Modified Mercalli (M.M.) intensity were produced for the central region of the New Madrid Fault Zone.

2. Geological vulnerability analysis: In determining the physical damage functions for different types of earthquake risk receptors, or populations at risk, especially for structural damages, the surface materials and ground conditions and their susceptibility with respect to earthquake shocks were studied. The entire study region, the 15 counties selected as samples in this project, were reclassified and subdivided into six major categories of vulnerability. The ground susceptibility was analyzed, and the vulnerability indexes were developed by an ordinal rank approach, then the output was utilized as the weight factor in the physical damage functions.

3. Populations at risk and population projections: Three categories of populations subject to earthquake risk were identified and quantitatively estimated. They are human populations (diurnal and nocturnal), structures, and personal property. An empirical field study approach was incorporated with the official documents reviewing process for data identification, collection, editing, and organization. The basic data unit was a census tract, and the aggregate level of estimation of population at risk was a county. Included in this study as sample observations were populations in two metropolitan areas. St. Louis and Memphis, and two rural counties, Cape Girardeau and New Madrid. The base year used for this study was 1978, and all monetary values were in constant dollars. For structural populations both the market value as assessed by county assessors and the replacement cost of new construction estimated by a structural engineer were employed to illustrate the range variation. All populations were projected to the year 2030 with a shift-share analysis by taking into account various regional and national growth trends and historical patterns of change and development.

4. Development of physical damage functions: Econometric techniques of linear and log-linear regressions were employed to estimate the functional relationship between physical earthquake damages, the damage ratios, and the M.M. intensity of various earthquakes occurring in the United States. This was done in conjunction with other exogenous determinants such as population density, distribution of the structures, the type of construction material, etc. As pointed out previously, the ground susceptibility indexes were incorporated along with the age of the structure as weighting factors for

the adjustment of the damage ratios. A recursive model of structure damage, property damage, and human mortality and injury was constructed to illustrate the interdependent relationships among these risk receptors. The integrated physical damage model underwent two generations and numerous revisions. Its present and final form for this study is called Model III.

5. Simulation of physical and economic damage functions: Baseline data for 1978 and the projected values of populations were fitted to the entire model to simulate quantitatively the potential damage of various earthquake risks that the study region will face from 1980 to 2030 with virtually no additional hazard mitigation action or risk reduction program implementation. This status quo scenario was adopted primarily for two reasons. First, it is the general conclusion from our survey that there will not likely be any significant changes in attitude toward earthquake hazard mitigation and, consequently, no drastic improvement in earthquake risk reduction investment. The status quo scenario is expectable because of the lack of any incentive and stimulus given, publicly or privately, in the past to this region. Second, the scope of work of this project was limited to the development of such a model methodologically and to the baseline information provision for future comparisons and scenario simulation. In short, the three versions of the earthquake risk planning and mitigation models, namely, Model I, Model II, and Model III, were simulated under a fixed policy impact scenario; but varying scenarios of earthquake risks (M.M. intensities VII to XII) and structural values (market value versus replacement cost approach) were projected. As a result, range estimates in terms of potential earthquake damage for each of the 15 counties were produced from 1980 through 2030 by type and combination of the scenarios.

C. Important Findings and Implications

This study provides determinants of earthquake risk with special application to the New Madrid Fault Zone. As expected, the most important determinants in such a damage study would be the direct seismological risk assessed and estimated, the risk receptors subject to the risk, and the adjustment factors between the risk and risk receptors, such as geological and institutional aspects whose existence may either aggravate the risk or alleviate the potential damage. The findings and implications of these earthquake damage determinants are briefly summarized below.

1. Seismological risk: Based on historical data and the probability of recurrence and other associated factors, it is predicted that the New Madrid seismic zone has a 10.0 percent probability in the next 50 years of experiencing earthquake ground shaking with an M.M. intensity of IX. The metropolitan areas of St. Louis and Memphis would have a 10.0 percent chance of being impacted by a ground shaking with a maximum intensity of VII and VIII, respectively. On the other hand, the deterministic approach

using epicenters at New Madrid and Marked Tree produced seismic risk maps for potential earthquakes ranging from M.M. intensity VII up to XII. For example, should an earthquake like those of 1811-1812 (M.M. intensity XI) recur in the New Madrid epicenter, both SMSA's would be faced with M.M. intensity VIII; should one occur at Marked Tree epicenter, the St. Louis SMSA would be faced with M.M. intensity VII and Memphis with M.M. intensity X. Figure S-2 shows selected earthquake risk maps under alternative assumptions.

2. Ground susceptibility: Surficial materials, ground conditions, and characteristics of land formation in the region were studied with special reference to earthquake resistance. Employing an ordinal scale ranging from I to VI in descending order of vulnerability, the 15-county region was reclassified, and it was found that liquefaction and landslide, among others, are typical problems associated with this study region. While the soil and bedrock in Memphis SMSA, especially the areas along both banks of the Mississippi River and entire Crittenden County, are most susceptible to earthquake (rating ranges from I to II), most areas along both Mississippi River banks in St. Louis SMSA were classified as III. Although the soil and bedrock susceptibility in Cape Girardeau varies (an index range from II to V), susceptibility ratings in New Madrid county were uniquely classified as I's and II's. Figures S-3 through S-6 show various types of susceptibility ratings geographically.

The implication of this ground vulnerability investigation suggests that the entire counties of New Madrid and Crittenden are in the area most vulnerable to earthquake, and the severity of the normal damaging impact of earthquake shock is likely to be very much intensified by the weak resistance of the soil and bedrock in these two countries. In planning future land use and regional development in the two counties, these indexes of various levels of quake susceptibility must be taken into account if the social costs of earthquake damage are to be minimized and the mitigation programs and projects are to be implemented efficiently and effectively. Similarly, zoning and building regulation for the urbanized areas such as those along the banks of the Mississippi River in both the St. Louis and the Memphis SMSA's must be carefully re-examined so that preventive actions can be taken to alleviate or avoid, if possible, the potential yet unnecessary damages resulting from any given type of earthquake.

3. Populations at risk: The three types of population--human, structural, and personal property--subject to earthquake risk considered in this study are all growing in number and value over time. Especially for populations at risk in St. Louis County and Shelby County, the growth rate has been accelerating. In contrast, populations in the cities of St. Louis and Memphis, and New Madrid County are expected to decline continuously or to be stabilized at best. However, structures and buildings are more vulnerable the older they become. As a result of the deterioration or aging effect of the structural population in the central cities and the unplanned

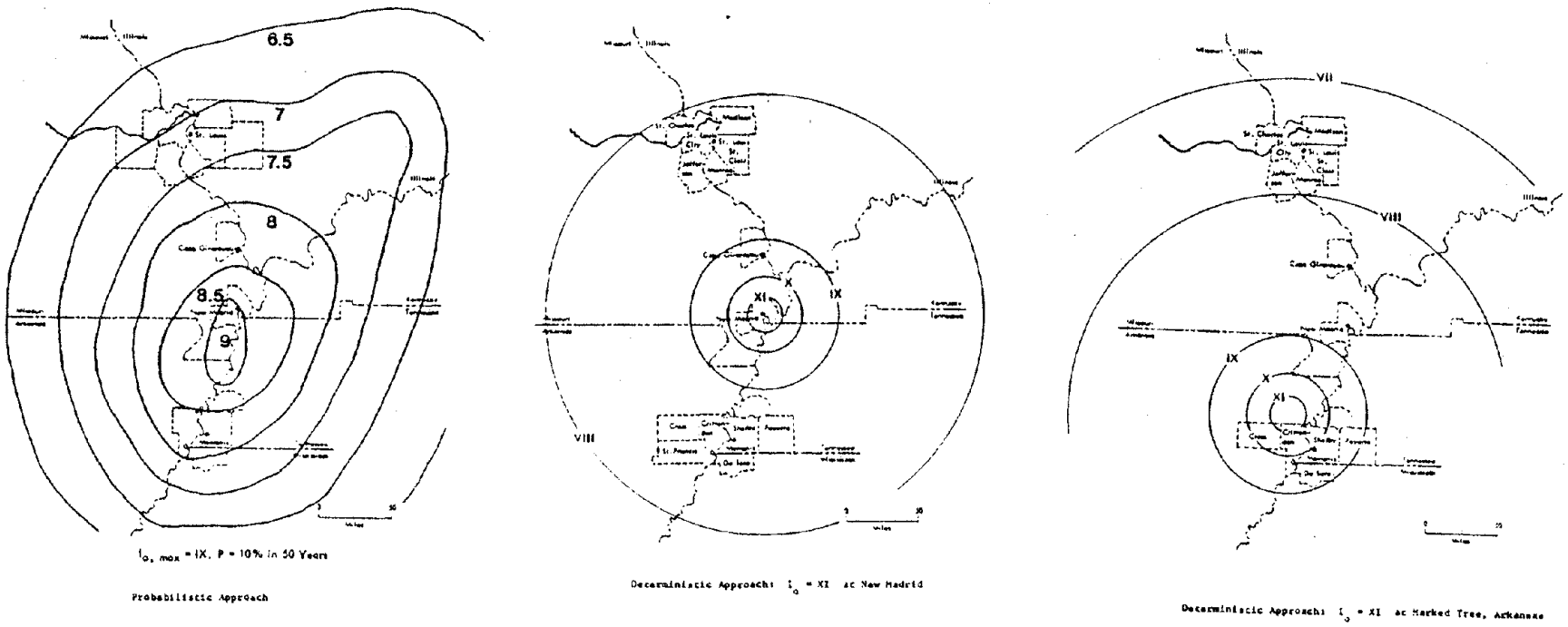


Figure S-2 - Regional seismic risk maps.

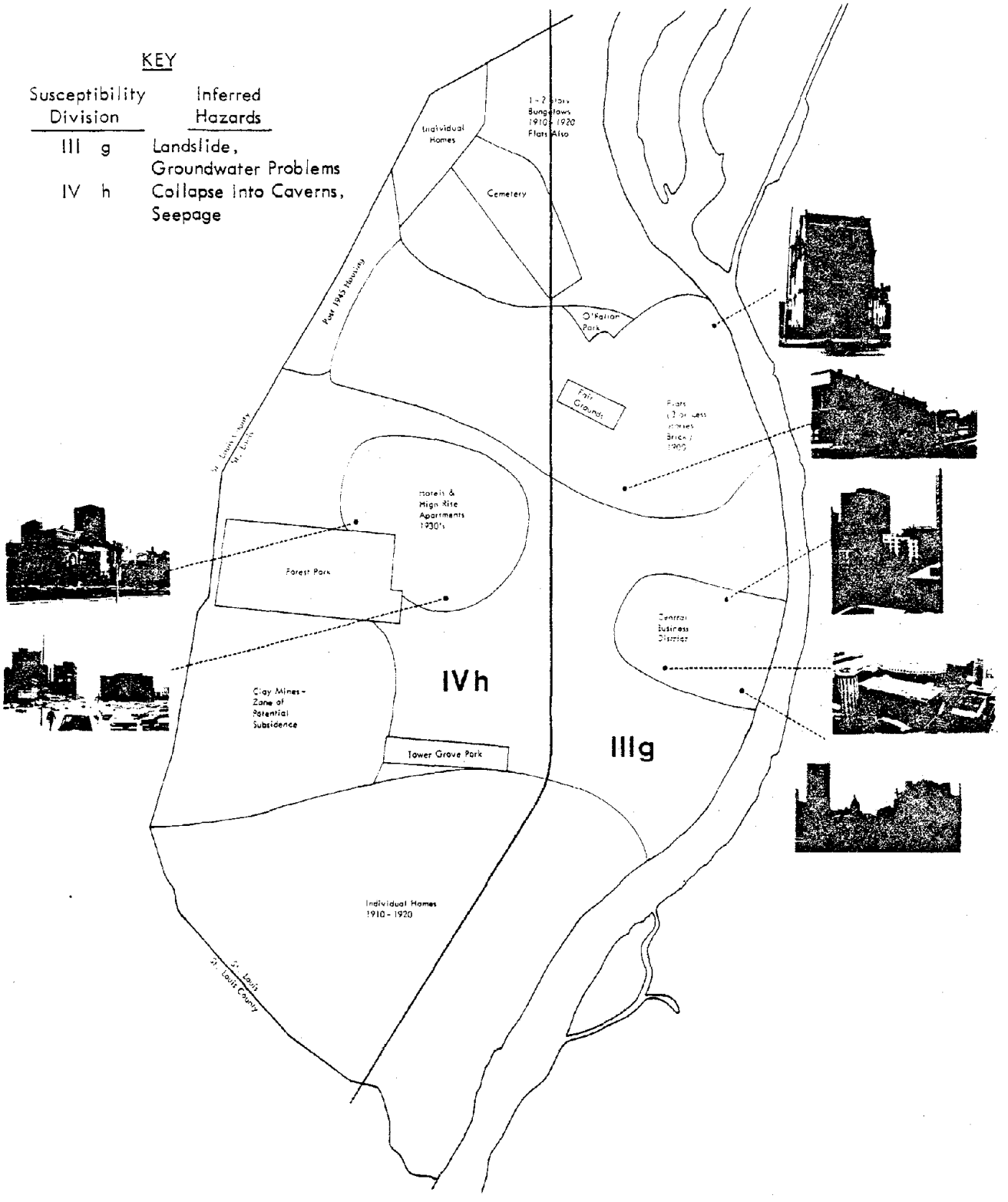


Figure S-3 - City of St. Louis, Missouri, building characteristics and earthquake susceptibility divisions.

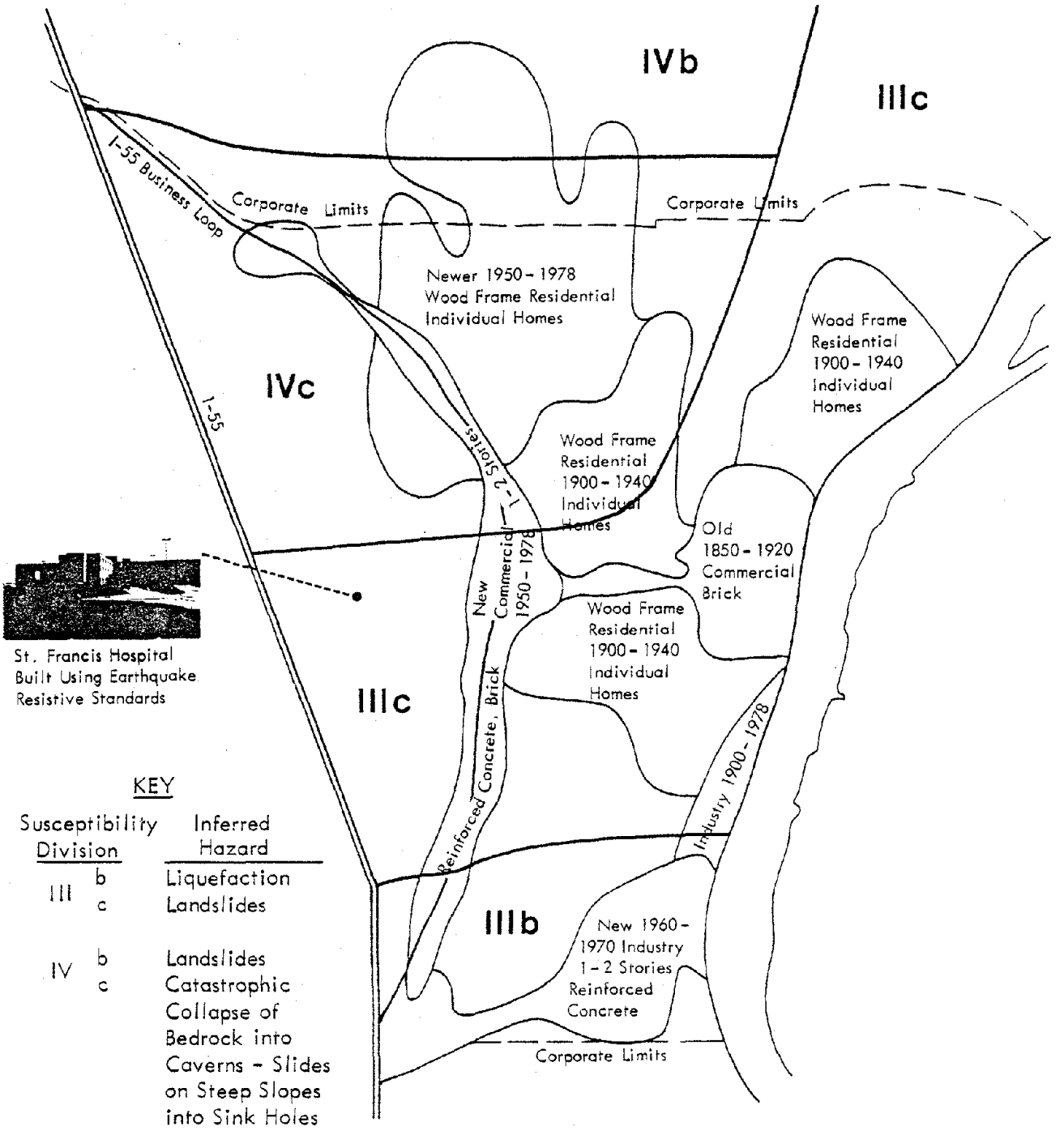


Figure S-4 - City of Cape Girardeau, Missouri, building characteristics and earthquake susceptibility divisions.

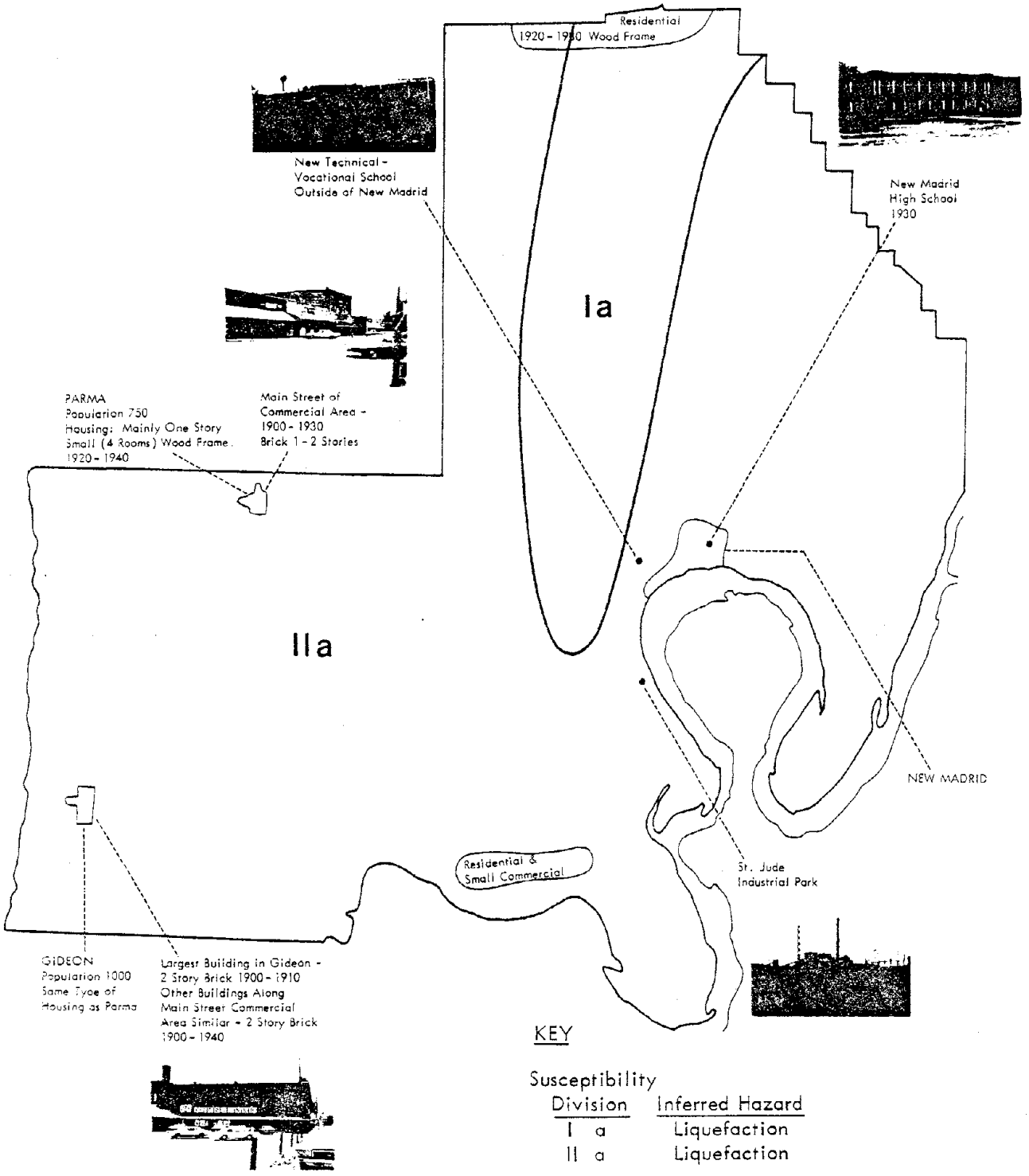
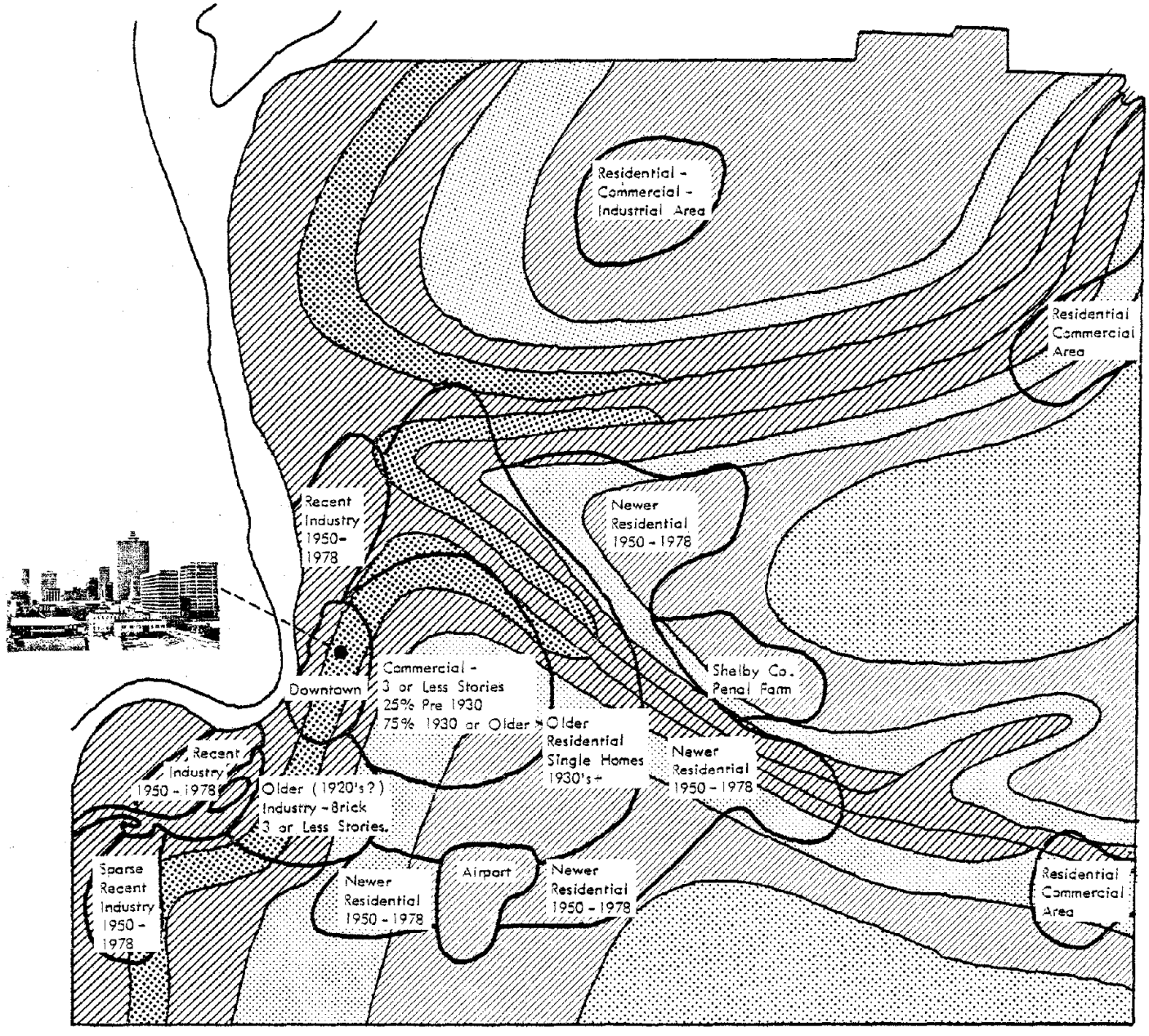


Figure S-5 - New Madrid County building characteristics and earthquake susceptibility divisions.



Susceptibility Division	Inferred Hazard
Ib	Landslides, Liquefaction
IIa	Liquefaction
IIb	Landslides, Liquefaction
IIIa	Landslides, Liquefaction
IVa	Landslides, Liquefaction
Va	Landslides, Liquefaction

Figure S-6 - Shelby County Building Characteristics and Earthquake Susceptibility Divisions

expansion and unbalanced growth in other parts of these two metropolitan areas, apparently there is an ever-increasing population more vulnerable to earthquake risk.

Land utilization patterns and the distribution of residential, commercial, and industrial buildings and associated activities in the study region have had virtually no bearing on the ground susceptibility indexes, much less on the concept of earthquake risk mitigation. This is more true in St. Louis SMSA than in Memphis SMSA. Figures S-3 through S-6 show the present patterns of regional land utilization versus the land susceptibility indexes in the four study areas. Figure S-7 depicts the project land utilization patterns in 2030. Figure S-7 also shows growth both in size and value of populations at risk as projected by the shift-share analysis of the national economy from 1980 to 2030. It indicates that the nearer the predicted earthquake occurs to the year 2030, the greater the resulting damage will be, not only because the risk population base is growing but also because the growth is taking place within the areas that are most susceptible to earthquake risk and yet receive little special consideration of risk mitigation.

4. Structural specification and construction of the damage functions: Structurally, the physical and economic damage functions developed in this study differ from those established by others mainly in the synthesized nature of specification and estimation. In addition to the interdependent relationships among the three types of population at risk, the damage functions developed in this study attempted to tie into one analytical framework the two major uncontrollable determinants--earthquake risk and the value and characteristics of populations at risk--to a more or less controllable determinant with policy implication--land utilization patterns and population distribution.

Aside from various modifications and improvements, the physical damage functions derived in this study indicate that the damage ratios of any given earthquake risk are slightly lower than the existing ones, holding everything else constant. In other words, the damage ratios of a given earthquake are found to be relatively smaller in this than in previous studies of its kind.

A significant difference between this and previous studies lies in the casualty or mortality functions; the casualty rate with respect to any urban earthquake of the same intensity was too high in the previous studies. The assumption that day-time damage always exceeds night-time damage is not necessarily valid. Damage to human populations depends also on population distribution--day-time versus night-time; on the distance of populations from the epicenter (or energy source); on the structures; and on the distribution of these structures in which human populations are housed.

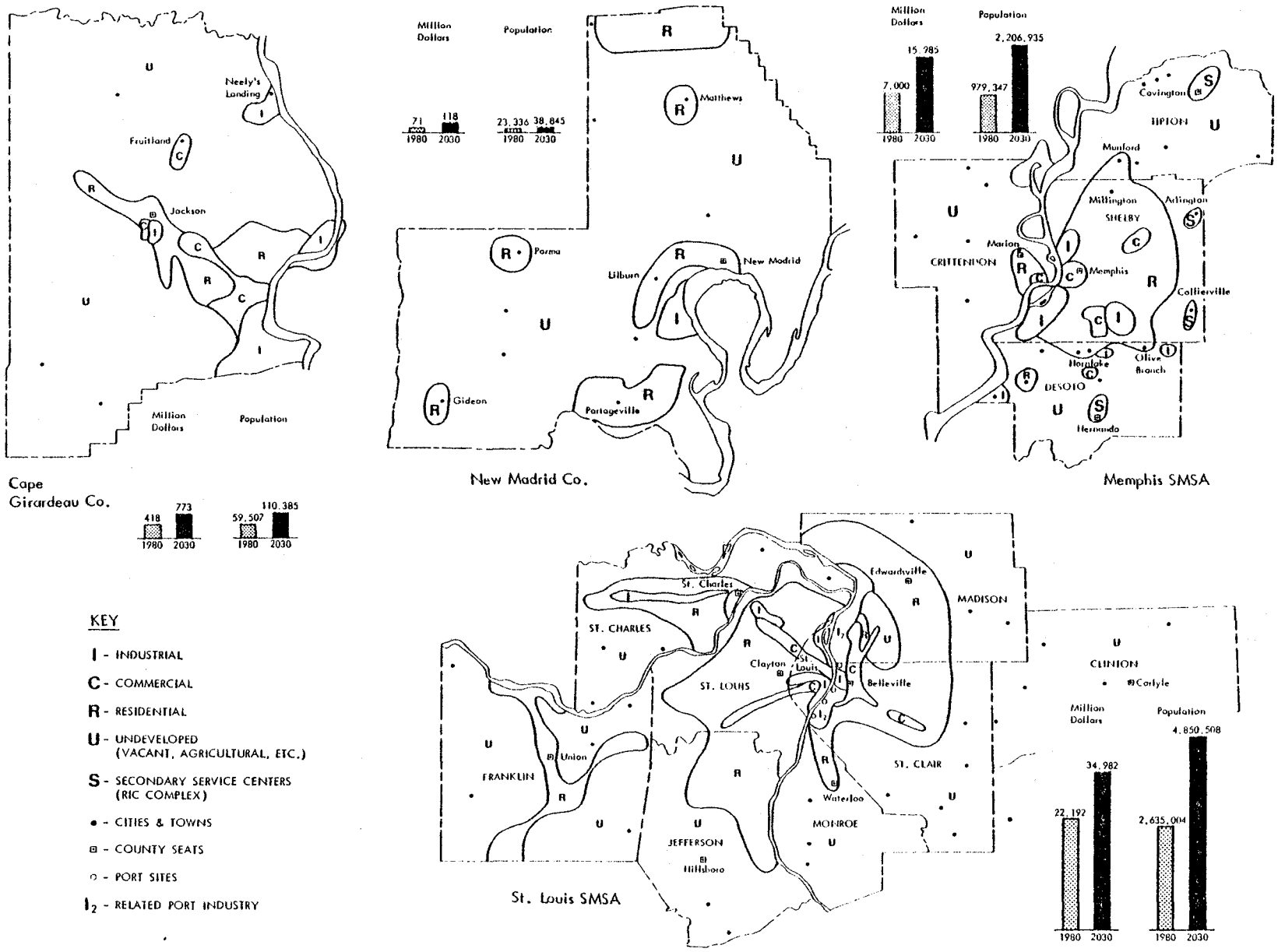


Figure S-7 - Projected land uses, population growth, and estimated values, 1980 and 2030.

The damage ratios for structures and buildings derived in this study are lower than the previous ones, but the differences are not as significant as is revealed in the casualty functions. Another interesting characteristic in our model is that concrete and steel frame structures are in general more vulnerable than masonry structures to smaller earthquakes but more resistant to an earthquake of M.M. intensity VIII or larger. Recent earthquakes in this country tend to support a lower damage ratio. For example, the Gilroy, California, earthquake which occurred on August 6, 1979, registered an estimated magnitude of 5.9 on the Richter scale but only broke windows, cracked walks and pipelines, and caused minor injuries.

The elasticity estimated for earthquake intensity [in terms of (M.M.)] in the day-time mortality equation was about 2.5; and in the night-time mortality equation, 3.2. This difference indicates that the night-time mortality rate is, on the average, about 75.0 percent more sensitive to earthquake intensity than is the day-time mortality rate, holding everything else constant. Restricting earthquake risk to an M.M. intensity of VI and greater, all elasticities with respect to earthquake estimated in the structural physical damage function were highly elastic; values ranged from 2.2 to 2.7, indicating that damage would be from 2.0 to 3.0 percent higher for every incremental level of quake risk exceeding M.M. intensity VI. Figure S-8 depicts physical damage functions between structural damage and quake intensity by type of building.

5. Simulated damages: The simulation of earthquake damages has been performed under two quake risk predictions, the probabilistic approach and the deterministic approach from two epicenters (New Madrid and Marked Tree). While all three versions of the simulation models were tested with varying scenarios, the results shown in this section are those of Model III under the scenario of status quo. The results indicate that considerable damage would result in the study area if it were to experience the motion which has a 10 percent probability of occurring in 50 years.

Figure S-9 illustrates the simulated damage by selected receptor, i.e., human mortality, buildings, and personal property, under the probabilistic approach, 1980 through 2030. Figure S-10 depicts the simulated structural and property damages by intensity, 1980 to 2030, with the deterministic approach. Figure S-11 portrays simulated human casualties, also with the deterministic approach.

Among the significant findings were:

a. if the 10 percent probability that in 50 years motion should occur in the region in 1980, our model shows that the structural damage, primarily to buildings in terms of constant 1978 market value, would range from $173 million estimated by the deterministic approach with New Madrid as the epicenter to $1.2 billion estimated by the probabilistic

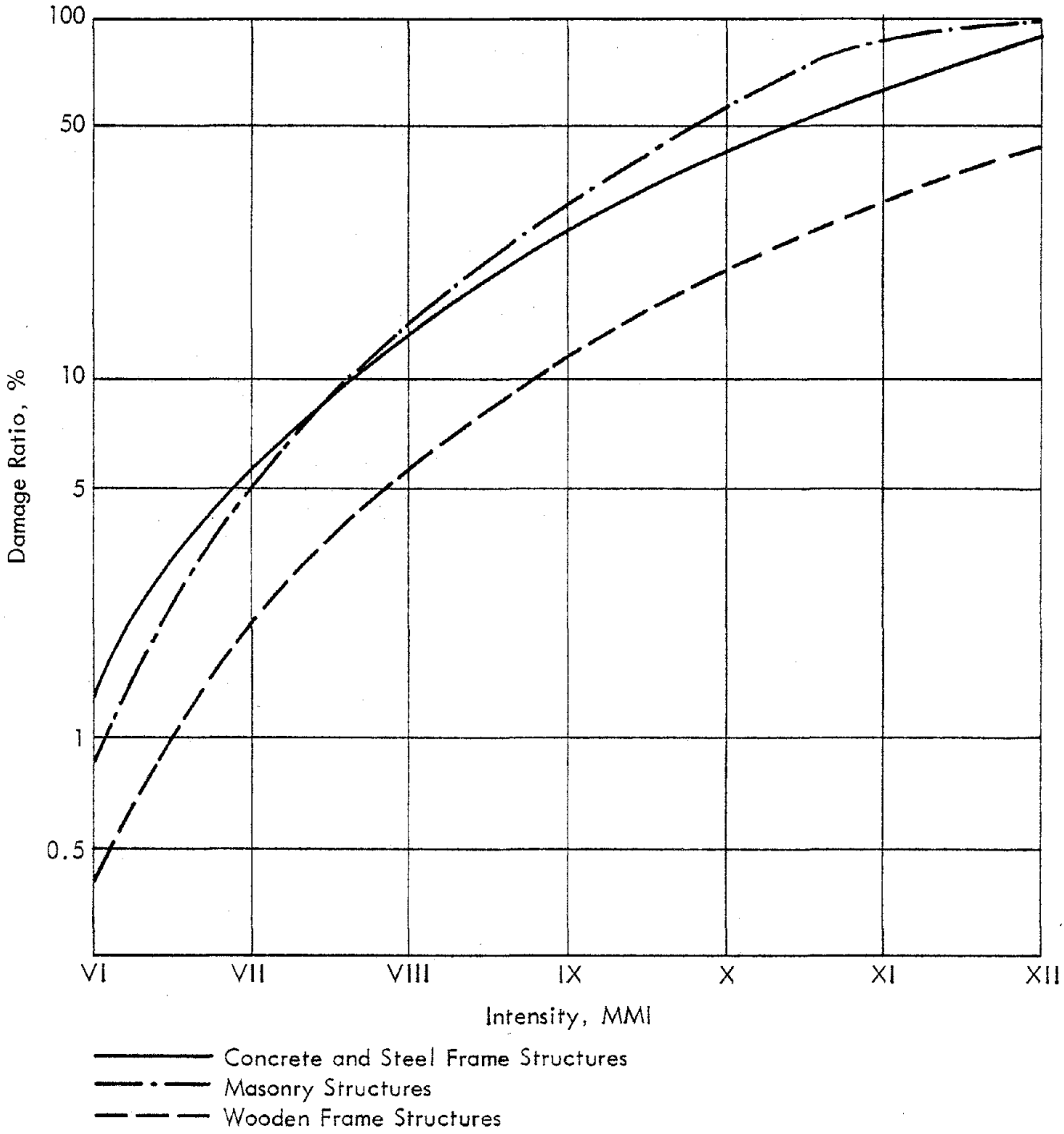


Figure S-8 - Physical damage functions for structures.

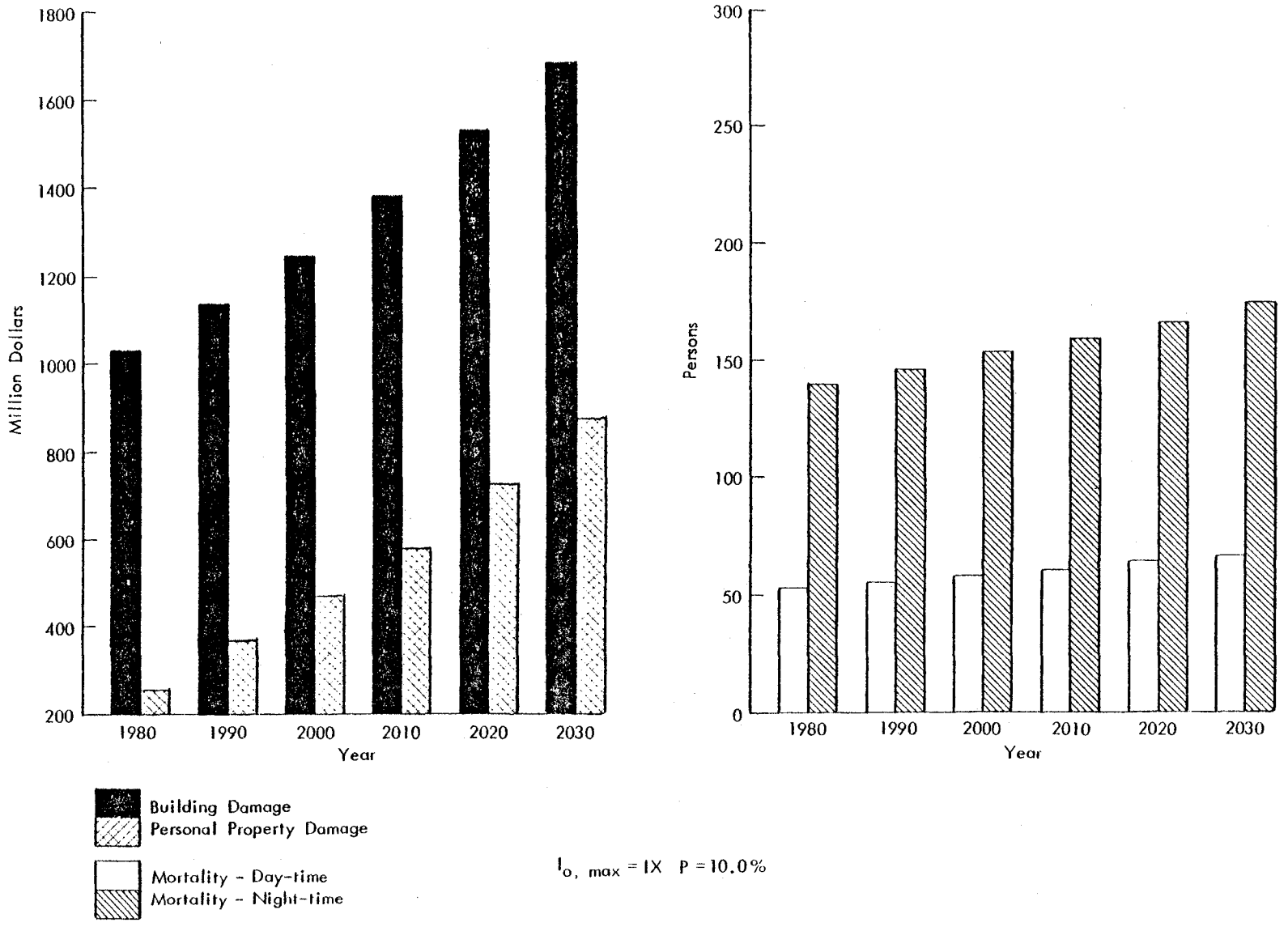


Figure S-9 - Simulated earthquake damages by receptor, 1980-2030.

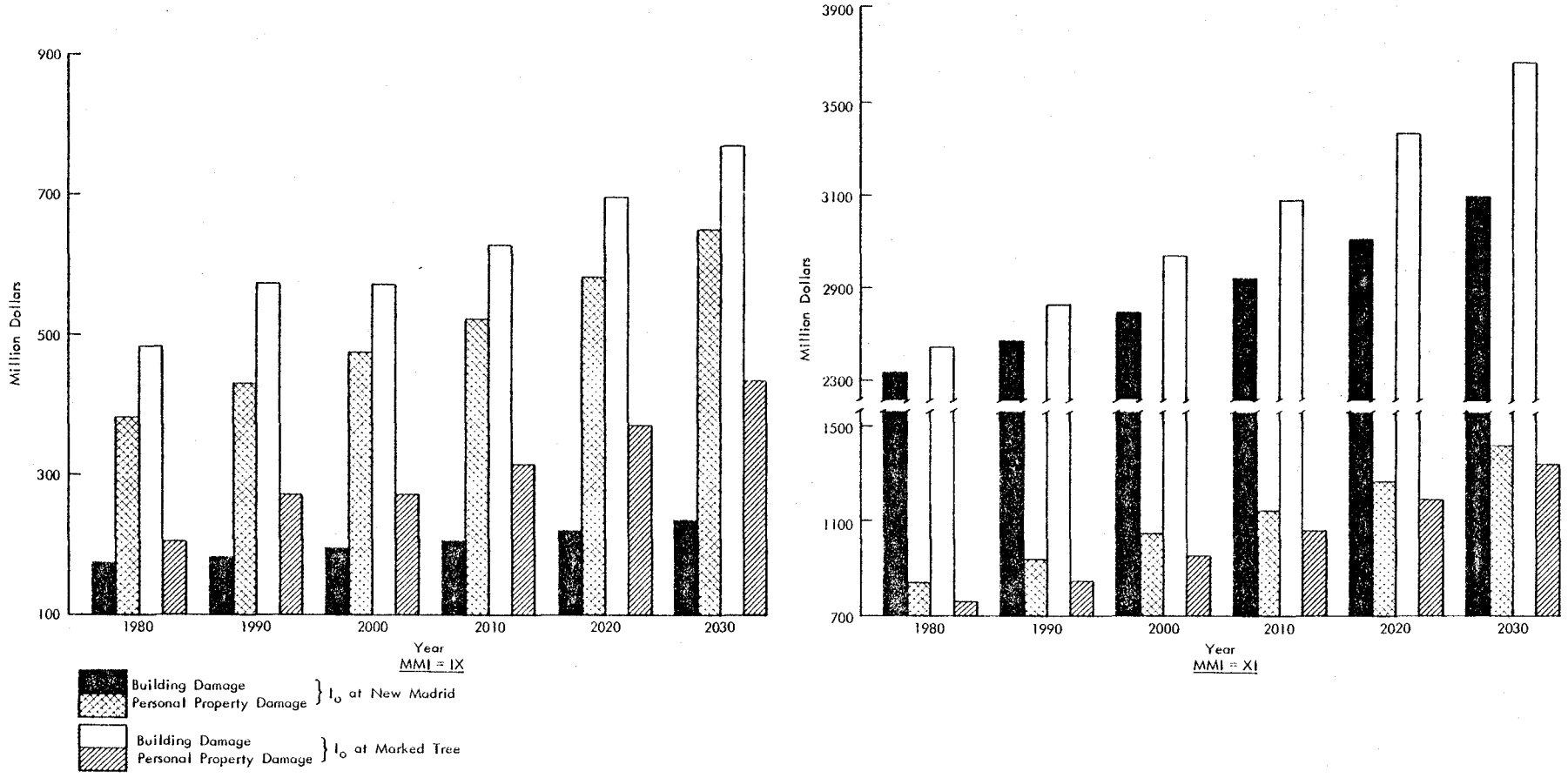


Figure S-10 - Structural and property damages by intensity, 1980-2030 (deterministic approach).

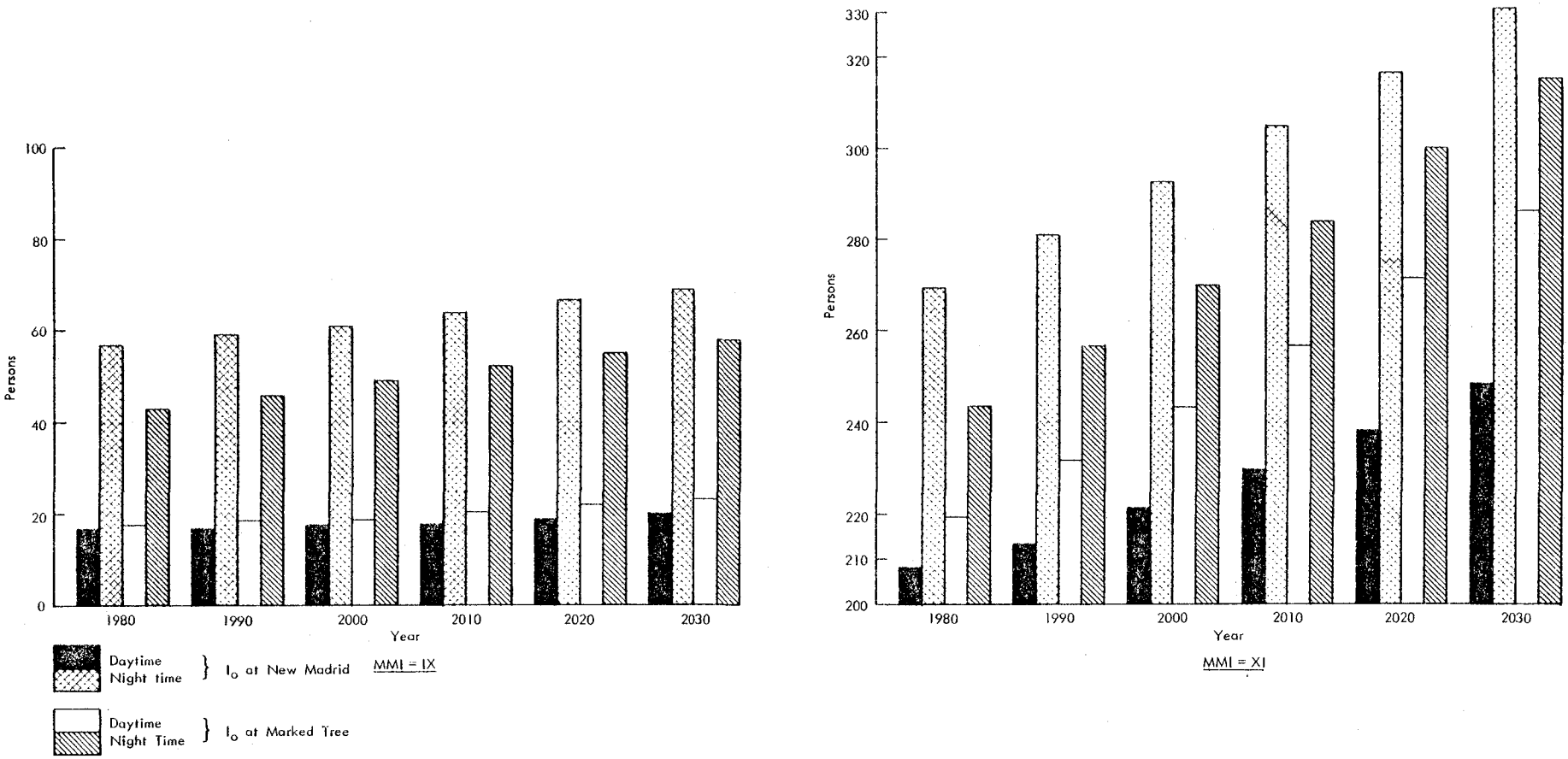


Figure S-11 - Simulated human casualties by intensity, 1980-2030 (deterministic approach).

approach. The corresponding human casualties would be between 15 and 53 persons during the day-time, and the night-time death toll would be about 4 times higher. The low human casualty estimates are assumed to be balanced by the high injury rates employed in this study. The corresponding injuries are estimated to range from 1,700 to 5,270 during the day-time, and from 4,350 to 14,000 during the night-time. As expected, the damage would be higher the nearer to 2030 the quake would hit the region. The estimated structure damage would range from $231 million to $1.7 billion, and the estimated casualties would increase by some 50 percent if the same event were to occur 50 years later. It should be noted that the actual damage would actually be much greater than this since geographically we have included in our study only a portion (15 counties) of the total area within each isoseismal region.

b. The New Madrid earthquakes that occurred in 1811-1812 might have had a maximum M.M. intensity equivalent to XI, and the return period is estimated to be from 500 to 1,000 years. However, should such an earthquake hit the region again in 1980, the model indicates structural damage in the 15 counties being studied would range from $2.3 to $2.5 billion depending on whether the epicenter is located in New Madrid or Marked Tree, and a death toll of between 200 and 300 persons depending on whether the quake takes place during the day or at night.

c. The personal property damage caused by such earthquakes would also be substantial. For an earthquake of M.M. intensity IX occurring in the night-time, the property loss value would range from $205 million to $640 million in 1980 and in 2030 from $436 million to $1,104 million. Should an earthquake similar to those of 1811-1812 with an estimated Modified Mercalli intensity of XI recur in the year 1980, the 15 counties being studied would suffer a personal property loss from about $745 to $841 million.

d. The damage results estimated in this study, although substantial, are much smaller than the estimates made by Mann and others for the Memphis SMSA alone. Our estimates may be considered conservative. Conservative estimates, however, are useful for decisionmakers in making mitigation policies and preparing for future earthquakes since the minimum damages are basically the baseline estimates required for many policy issues, e.g., zero base budgeting. Another reason for obtaining relatively smaller estimates is that continuous scientific and technological improvement has generally increased public awareness of public policies on natural hazard prevention and mitigation over the past decades, and this has to a certain extent reduced the potential earthquake risk. A recent example of possibly reduced earthquake damage may be the August 6 earthquake in Gilroy California registering 5.8 or 5.9 on the Richter scale, but resulting in little structural damage.

The potential earthquake damages estimated from Model III are presented in Table S-1. While sections (A) through (C) in the table show the damage estimates for a ground motion of Modified Mercalli intensity of IX, the damage estimates of the recurrence of the 1811-1812 quakes are shown in sections (D) and (E).

D. Suggestions and Recommendations

Although our extrapolated historical relationships between various types of damage and earthquake intensities attempted to account for the simultaneity of our model in explaining the interactive relationships among mortality, building damages, and personal property damages, and our log-linear model may represent a certain type of dose-response relationship and thus may provide a more convincing measurement of the potential damage of various types of earthquake risks for different types of populations, the results should still be considered tentative. Because of the diversity of our damage estimates, which are a function not only of the time of earthquake occurrence but also of the intensity, distance, and other determinants or estimation procedures, the results must be interpreted carefully. It should be noted again that the estimations are for the 15 counties within the New Madrid seismic zone only, not for the entire region within the damaging seismic contour of an earth motion of M.M. intensity VI or above.

There are of course many areas in our model that could be further improved when additional research opportunity materializes. The physical damage functions should be further refined and disaggregated by types of risk population, by structural frames and materials of construction, etc. For example, the age, present condition, level of use and maintenance, among other building characteristics, are also important determinants in the physical damage function. These attributes could be incorporated in the model for determining structural damage ratios with respect to intensity.

The research approach in this study, however rudimentary it may be, combines the efforts of an interdisciplinary team consisting of a seismologist, geologist, construction engineer, economist, and systems analyst. The methodology presented in this study has demonstrated its feasibility in constructing the potential earthquake risk for the New Madrid seismic zone and may be replicated and retested for other earthquake-prone regions so that from more reliable earthquake risk estimates more efficient emergency management decisions can be made.

In addition to model improvement and methodological refinement, additional research on finer risk population estimations is by all means warranted. A more detailed survey on the existing inventory and characteristics of various risk populations in this and other earthquake-prone areas

TABLE S-1

SUMMARY OF POTENTIAL EARTHQUAKE DAMAGES: MODEL III

	Building Damage ($M)			Personal Property Damages ($M)-Night			Mortality (persons)						Injuries (persons)					
							Day			Night			Day			Night		
	1980	2000	2030	1980	2000	2030	1980	2000	2030	1980	2000	2030	1980	2000	2030	1980	2000	2030
(A) Probabilisitc Approach: $I_{o,max}$ = IX (P = 10.0%)																		
St. Louis SMSA	614	662	740	408	490	615	17	18	19	72	77	84	1,680	1,794	1,947	7,201	7,718	8,429
Cape Girardeau	28	33	43	14	19	27	5	5	6	9	11	12	456	509	573	949	1,065	1,209
New Madrid	6	7	9	8	8	11	5	6	6	9	9	10	545	560	629	851	875	990
Memphis SMSA	576	682	917	211	281	451	26	29	34	50	56	68	2,590	2,886	3,423	4,987	5,616	6,764
Total	1,224	1,385	1,709	641	798	1,104	53	57	66	140	153	174	5,272	5,748	6,574	13,987	15,275	17,391
(B) Deterministic Approach: I_o = IX at New Madrid, Missouri																		
St. Louis SMSA	117	127	144	270	326	411	2	2	2	31	33	36	348	373	408	3,096	3,341	3,673
Cape Girardeau	6	7	7	8	11	15	1	1	1	3	3	4	65	73	82	310	348	395
New Madrid	10	11	14	10	10	15	12	12	14	13	14	16	1,177	1,209	1,358	1,350	1,389	1,571
Memphis SMSA	40	48	64	97	130	210	0	1	1	10	11	13	108	122	148	942	1,072	1,303
Total	173	193	231	385	477	651	15	16	18	57	61	69	1,698	1,777	1,996	5,698	6,150	6,942
(C) Deterministic Approach: I_o = IX at Marked Tree, Arkansas																		
St. Louis SMSA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cape Girardeau	2	2	3	6	9	12	0	0	0	2	2	2	21	24	27	181	203	230
New Madrid	0	0	0	3	3	5	0	0	0	1	1	2	16	16	18	130	134	151
Memphis SMSA	481	570	763	196	261	419	16	19	23	40	45	55	1,719	1,908	2,257	4,035	4,537	5,456
Total	483	572	766	205	273	436	16	19	23	43	48	59	1,756	1,948	2,302	4,346	4,874	5,837
(D) Deterministic Approach: I_o = XI at New Madrid, Missouri																		
St. Louis SMSA	1,695	1,838	2,071	600	725	917	75	80	88	163	176	193	7,459	8,036	8,798	16,281	17,570	19,307
Cape Girardeau	43	50	65	17	23	32	10	11	13	14	16	18	1,030	1,148	1,294	1,411	1,584	1,797
New Madrid	25	28	36	11	14	19	100	103	116	43	44	50	10,014	10,285	11,557	4,297	4,420	5,001
Memphis SMSA	574	682	921	213	285	461	23	26	32	50	56	69	2,333	2,637	3,175	4,952	5,636	6,856
Total	2,337	2,598	3,093	841	1,047	1,429	208	220	248	270	292	330	20,836	22,106	24,824	26,941	29,210	32,961
(E) Deterministic Approach: I_o = XI at Marked Tree, Arkansas																		
St. Louis SMSA	629	683	770	414	500	633	18	19	21	75	81	89	1,794	1,933	2,116	7,535	8,131	8,935
Cape Girardeau	28	33	43	14	19	27	5	5	6	9	11	12	456	509	573	949	1,065	1,209
New Madrid	5	6	7	7	8	10	3	3	4	7	7	8	335	344	386	684	704	796
Memphis SMSA	1,789	2,119	2,847	310	418	684	193	215	255	151	170	205	19,328	21,511	25,515	15,129	17,046	20,546
Total	2,451	2,841	3,667	745	945	1,354	219	242	286	242	269	314	21,913	24,297	28,590	24,297	26,946	31,486

is urgently needed for government quake hazard reduction in general and for future damage model simulation in particular. Biased or inaccurate information on potential earthquake risk and damage estimates is often brought about by the lack of a correct risk population inventory, which in turn causes inefficient allocation of resources.

According to the interviews conducted during our study period, there are virtually no earthquake preparedness plans included in the industrial development and land utilization plans for the St. Louis SMSA and the two rural counties, let alone mitigation and emergency or disaster relief programs specifically designed for coping with earthquake hazard. No continuous or permanent educational programs for the improvement of public awareness of the potential damage of earthquake were found. Consequently, no significant risk reduction plans were observed in the study region. Specific building and zoning codes for earthquake hazard reduction were nonexistent in almost all counties.

It is well recognized that the lack of concern about earthquake risk in this region is due to the fact that people are not aware of the potential damage that could be caused by earthquakes. It is hoped that the results reported in this study will provide the public and private agencies affected by the New Madrid seismic zone with the kind of information required for making future policy decisions on earthquake preparedness and risk reduction. It is desirable from the social point of view that the estimated damage results and other pertinent information derived from this study be broadly disseminated to the people in this 15-county region so that subsequently their awareness and responsiveness to earthquake damage in general and their reaction to damage mitigation in particular can be studied.

Furthermore, it would also be appropriate to suggest that a reexamination of land use planning, especially long-range planning, be considered jointly by all regional planning agencies. Since most of the commercial and industrial plans and blueprints have evolved with little or no consideration of earthquake risk in general and ground susceptibility in particular, this reexamination and, consequently, redesigning of future land use patterns will be likely to reduce considerably the earthquake risk potential. In light of the potential damages simulated in this study, for the region, the social benefit of this risk reduction and hazard mitigation work would seem to be enormous.

CHAPTER I

INTRODUCTION

A. An Overview of Earthquakes and Earthquake Damages

Historically, the earth has been marked by a continuing chain of major earthquake disturbances which have caused catastrophic destruction and extensive loss of life. It is estimated that in the past 4,000 years, over 13 million deaths have been caused by earthquakes (New Columbia Encyclopedia, 1975.)

Most earthquakes are related to compressional or tensional stresses built up at the margins of the huge moving lithosphere plates that make up the earth's surface. The immediate cause of most shallow earthquakes is the sudden release of stress along a fault or fracture in the earth's crust, resulting in movement of the opposing blocks of rock past one another. The earth is in constant movement, and earthquakes in varying magnitude are common natural phenomena that occur throughout the world thousands of times each year. Since shocks of magnitude 2.5 (Richter scale, see Table I-1) are usually felt in settled areas, and reported, it is estimated that perceptible shocks number about 150,000 annually on a worldwide basis, not counting the aftershocks and series of smaller shocks. The total number of true earthquakes that occur throughout the world each year may be on the order of a million or more. However, the number of earthquakes reported that are associated with extensive damage and loss of life is comparatively small--140 earthquakes of magnitudes of 6 or greater are recorded each year (Gutenberg and Richter, 1945).

The extent of physical damages, economic loss, and social disruption caused by major earthquakes is strongly related to the quake's geographic location and size of its epicentral region, the time of day when the quake occurs, the region's social and economic characteristics and development, and the magnitude, intensity, and duration of the quake itself. The March 2, 1933, earthquake in Japan which recorded a magnitude of 8.9 (Richter scale), was one of the most intense earthquakes recorded since the turn of this century; it caused 2,990 deaths. The earthquake in Agadir, Morocco, on February 29, 1960, with a magnitude of 5.8 (Richter scale) caused 12,000 deaths; and the Tangshan, China, earthquake on July 28, 1976, with a magnitude of 8.2 (Richter scale), caused 655,000 deaths (World Almanac and Book of Facts, 1978). In contrast, the New Madrid, Missouri, earthquakes on December 16, 1811, January 23, 1812, and February 7, 1812, considered among the major earthquakes in world history and the most extensive quakes ever experienced in the United States, caused few deaths and little property damage primarily because the region was sparsely settled at the time. This fact points up that earthquake risk is largely an urban problem,

and earthquake occurrence, even at its worst, may have little effect on sparsely populated regions.

While much of the world sustains earth shocks of varying degrees, earthquakes are not spread randomly throughout the earth. They are concentrated in specific regions (Gutenberg and Richter, 1954). The principal geographic areas of major seismic shocks are shown in Figure I-1 and including the following regions:

1. The Circum-Pacific, with many branches and subdivisions: The area sustains a large majority of the shallow quakes recorded, a still larger fraction of intermediate shocks, and all the deep shocks.

2. The Mediterranean and trans-Asiatic zone, with the Alpide belt: The area accounts for most of the remaining shallow shocks and includes nearly all of the major shallow shocks outside of the Pacific belt. The Alpide belt sustains all of the remaining intermediate shocks.

3. Other narrow belts, including only shallow shocks: One of these extends through the Arctic and Atlantic Oceans. There is another with several imperfectly known branches through the Indian Ocean.

4. Rift zones internal to their stable masses: The greatest and most seismic of these is that of East Africa, which some authors associate with the Palestine rift zone. The Hawaiian Islands mark an active rift zone interior to the Pacific mass.

5. Active areas marginal to the continental stable masses: These are usually near seacoasts, but some are inland, as in Central India.

6. Minor seismic areas: These are extensive regions mostly characterized by older orogenies lying between the stable continental nucleus and the active belts of the first three groups.

7. Stable masses: These include the continental nuclei of old rocks, but the great areas of the north and central Pacific also belong to this category. Very small shocks occur even in these regions.

In the United States there are very few areas which have not experienced earthquakes. Figure I-2 indicates the epicenters of earthquakes which have recorded an intensity of V or greater on the Modified Mercalli Scale. (See Table I-1 for the Modified Mercalli Intensity Scale.) This map suggests that death and destruction from earthquakes may be registered almost everywhere. The need to mitigate the destructive effects of earthquake damage today is, therefore, not a problem restricted only to the most earthquake-prone areas of the western United States. Earthquakes occurring in the eastern United States have caused damage over wider areas and

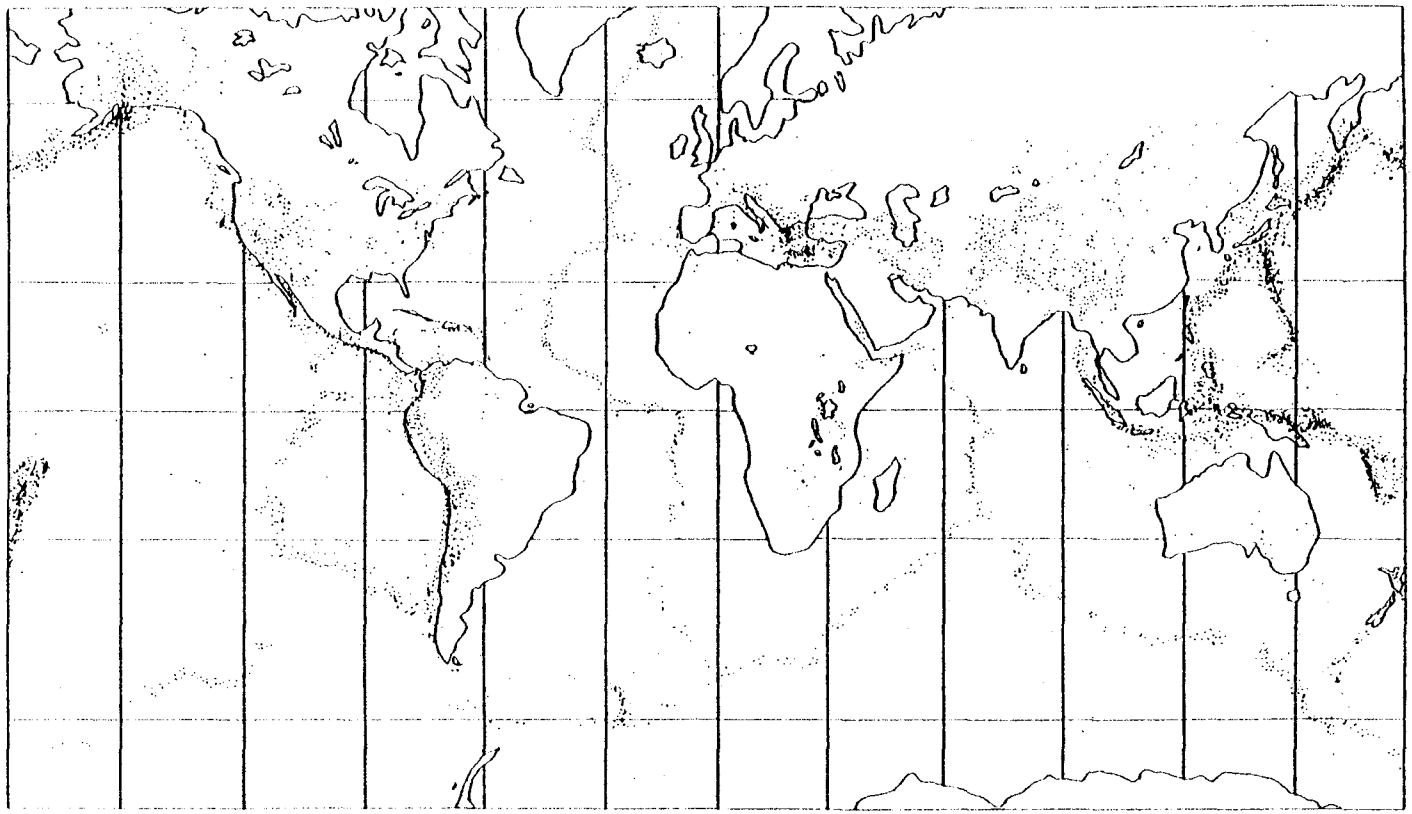


Figure I-1 - Worldwide patterns of earthquake activity recorded during a recent 10-year period.

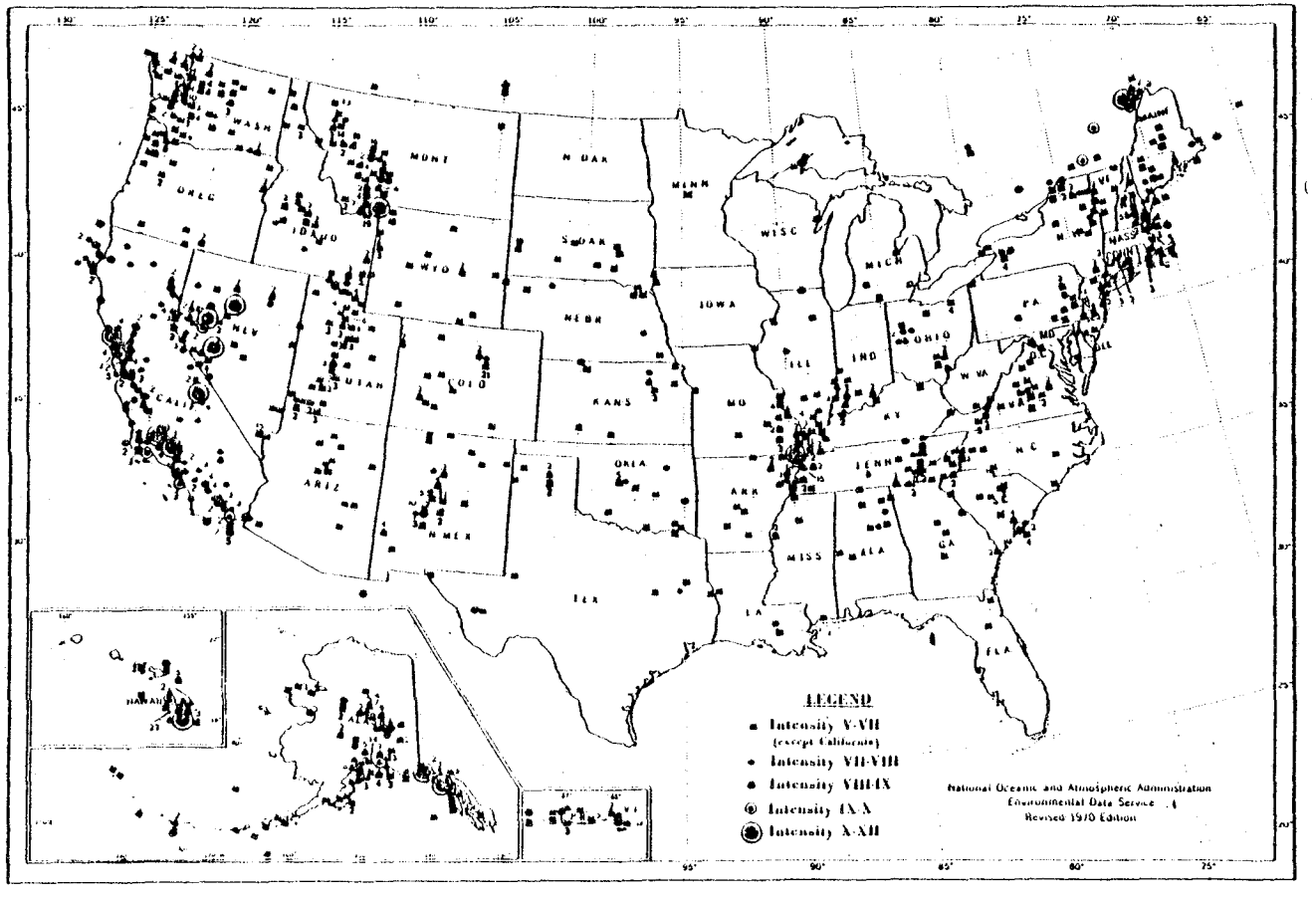


Figure I-2 - Earthquakes of Modified Mercalli intensity V and above in the United States through 1970.

are perceptible over greater distances than earthquakes occurring west of the Rocky Mountains.

About 36 percent of the people in the United States (nearly 80 million) in the areas west of the Rocky Mountains live with a considerable risk to their lives and property from earthquakes. But 56 percent (about 123 million) living east of the Rockies are exposed to a moderate, but not negligible seismic risk. Only about 8 percent of the American population can safely ignore earthquake hazards (National Academy of Sciences, 1975).

B. Major Earthquakes and Their Damage Estimates

In the history of the United States, there have been approximately 1,300 deaths and $4 billion (then-current) worth of property damage resulting from earthquakes. More than half of the deaths occurred in San Francisco in 1906, and most of the dollar losses occurred in three quakes: San Francisco 1960; Alaska, 1964; and San Fernando, 1971. However, future losses of life and property will probably be much greater because many more people and more extensive facilities are now concentrated in the cities subject to earthquake risk.

Interior nonmountainous portions of continents are usually less subject to earthquakes than any part of the earth except the flat beds of some oceans. But this is not the case for the central United States encompassing the region between the Appalachian Mountains and the Rocky Mountains and from Canada to the Gulf of Mexico. The upper Mississippi and Ohio valleys are regions of frequent earthquakes. The three great quakes in the New Madrid seismic zone in 1811-1812 were among the 20 great earthquakes of known history and had more effect on the region's topography than any known earthquake on the North American continent (Moneymaker, 1954; Penick, 1976).

The New Madrid seismic zone has remained active since the 1811-1812 earthquakes and continues to be highly unstable. Since 1909 the seismograph network at Saint Louis University has chronicled a continuing record. If only this record is considered, the region is of minor seismic importance. It is the great events of 1811 and 1812 and the geological evidence later unearthed as a result that have led seismologists to conclude that the New Madrid region is "one of the relatively few in the United States in which there is a probability of major destructive earthquakes" (Heck, 1974).

Notable earthquake disturbances have been categorized in various ways (magnitude of earthquake, deaths, or physical damage caused). (See Table I-1, "Selected Scales of Earthquake Intensity," p. 21.)

In terms of magnitude of energy released, representative earthquakes which are ranked 8.0 or above on the Richter scale could be classed as major disturbances. The following are among the most intensive quakes since 1755.

Date	Place	Magnitude (Richter Scale)
November 1755	Lisbon, Portugal	8.75
December 1811	New Madrid, Missouri	8.2
January 1812	New Madrid, Missouri	8.0
February 1812	New Madrid, Missouri	7.8
June 1897	India	8.7
August 1897	Japan	8.7
September 1897	Mindarao, Indonesia	8.6 - 8.7
September 1899	Alaska	8.6
August 1902	Sinkiang, China	8.6
April 1905	Indiana	8.6
July 1905	Mongolia	8.7
January 1906	Colombia	8.9
April 1906	San Francisco, California	8.3
August 1906	Valparaiso, Chile	8.6
June 1910	New Hebrides	8.7
January 1911	Tien-Shan	8.7
June 1911	Ryukyu	8.7
November 1914	Mariana Islands	8.7
May 1917	Kermadec	8.6
June 1917	Samoa	8.7
December 1920	Kansu, China	8.6
September 1923	Tokyo, Japan	8.2
May 1927	Nan-Shan, China	8.3
March 1929	Aleutians	8.6
March 1933	Japan	8.9
January 1934	Bihar-Nepal, India	8.4
February 1938	Banda Sea	8.6
November 1938	Alaska	8.7
January 1939	Chilla, Chile	8.3
December 1939	Celabes	8.6
June 1941	Andaman Islands	8.7
August 1942	Peru	8.6
December 1946	Honshu, Japan	8.4
August 1950	Assam, India	8.7
August 1950	Tibet, China	8.7
November 1958	Kunile Islands	8.7
May 1960	Southern Chile	8.3
March 1964	Alaska	8.5
May 1968	Japan	8.6
July 1976	Tanshan, China	8.2

In terms of deaths, the following earthquakes recorded more than 50,000 fatalities.

Date	Place	Deaths
May 526	Antioch, Syria	250,000
1268	Cilcia, Asia Minor	60,000
September 1290	Chilli, China	100,000
January 1556	Shensi, China	830,000
November 1667	Shemaka, Caucasia	80,000
January 1693	Catania, Italy	60,000
December 1730	Hakkaodi, Japan	137,000
October 1737	Calcutta, India	300,000
November 1755	Lisbon, Portugal	60,000
December 1908	Messina, Italy	83,000
September 1923	Tokyo, Japan	99,330
May 1927	Nan-Shan, China	200,000
December 1932	Kansu, China	70,000
May 1970	Northern Peru	66,794
July 1976	Tangshan, China	655,235

The following earthquakes are examples of extensive physical damage:

Date	Place	Damages
1755	Lisbon, Portugal	City damaged extensively
1906	San Francisco, USA	Approximately 28,000 homes destroyed and great damage to the business district.
1963	Skopje, Yugoslavia	90 percent of the city destroyed.
1964	Alaska, USA	Devastated several cities, particularly Anchorage.
1968	Hokkaido and North Honshu, Japan	2,000 dwellings destroyed.
1971	Los Angeles, USA	$500 million damage to Los Angeles area.
1972	Managua, Nicaragua	City almost totally destroyed.
1976	Tangshan, China	City nearly half destroyed.

In the central United States, although most of the earthquakes have occurred near river valleys, there have been small numbers of isolated quakes in other places throughout the region. Between 1811 and 1943, there were at least 17 major earthquakes in the central United States which had an intensity of 8 to 10 on the Rossi-Forel scale:

Date	Location	Rossi-Forel Intensity Scale
December 1811	New Madrid, Missouri	10
January 23, 1812	New Madrid, Missouri	10
February 1812	New Madrid, Missouri	10
January 1843	Memphis, Tennessee	9
April 1867	Kansas	8
October 1882	Arkansas	8
January 1891	Rusk, Texas	8
October 1895	Charleston, Missouri	8 - 9
January 1906	Manhattan, Kansas	8
May 1906	Keewenaw Peninsula, Michigan	8 - 9
May 1906	Illinois	8
July 1909	Illinois	8
September 1909	Indiana	8
October 1923	Arkansas	8
September 1931	Anna, Ohio	8
March 1937	Western Ohio	8
March 1937	Western Ohio	8

C. The New Madrid Earthquakes and the Study Background

In recorded history, the most seismically active region in North America has been the so-called New Madrid seismic zone. This zone, which lies north-northeasterly by south-southwesterly, has a northern limit about at the confluence of the Mississippi and Ohio rivers and a southern limit at a point in eastern Arkansas approximately at the latitude of Memphis, Tennessee. Algermissen's seismic risk map puts this area in seismic Zone 3, the highest possible risk zone (Figure I-3) (Algermissen, 1969).

As noted earlier, during the winter of 1811-1812, the New Madrid seismic zone produced the greatest sequence of earthquakes ever experienced in the United States (Fuller, 1912; Richter, 1958; Nuttli, 1973a). The more than 1,000 earthquakes that occurred in a 3-month period equaled the size and number of all earthquakes that occurred in the southern half of the state of California in the 40-year interval from 1932 to 1972 (Nuttli, 1977).

The three earthquakes of 1811 and 1812 caused topographic changes over an area of 30,000 to 50,000 square miles; the total area shaken by the quakes covered at least 2 million square miles. The most seriously affected area was characterized by raised and sunken lands, fissures, sinks, sand blows, and large landslides. The area of great physiographic change extended from Cairo, Illinois, to Memphis, Tennessee, and from Crowley's Ridge to

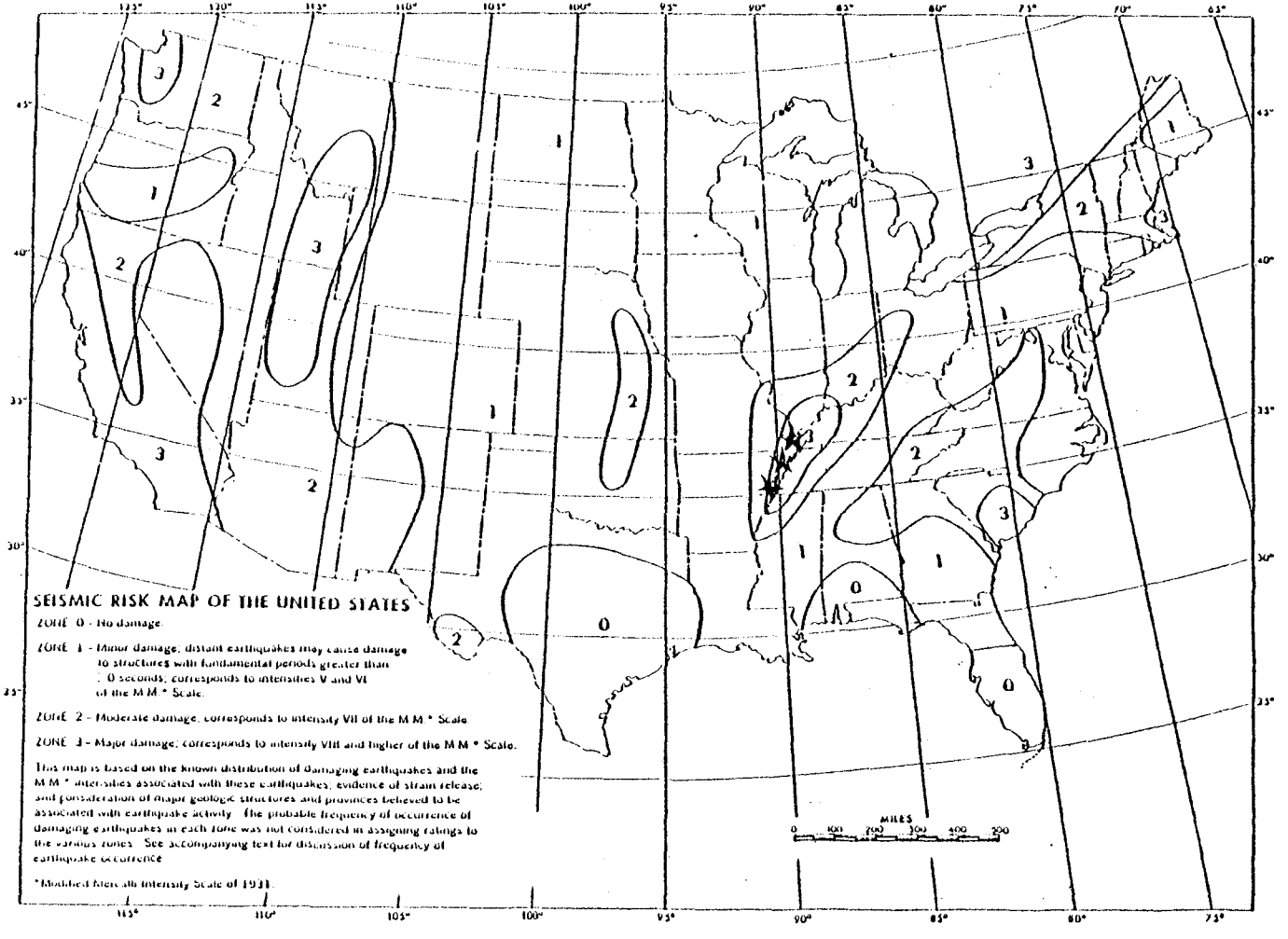


Figure I-3 - Seismic risk map by Algermissen (1969).

Chickasaw Cliffs. Cave-ins of river banks occurred as far away as Vicksburg, Mississippi. The shock was felt from Canada to New Orleans and from the headwaters of the Missouri River to the Atlantic seacoast including Boston, 1,100 miles away. About 1 million square miles, or half of the area, was so shaken that vibrations were felt distinctly. The extent of this shock far exceeded in land area any other known earthquake on this continent.

While the quakes were all classed as intensity 10 on the Rossi-Forel scale, the damage was very slight for such a great earthquake due primarily to the light population in and around the epicenter. Records show that at New Madrid only one life was lost through falling buildings. Several persons fell into the river and drowned when banks caved in, and a number of boatmen were lost when their boats sank.

The New Madrid is notable for the large areas over which earthquakes cause damage and over which they are perceptible. This is a phenomenon common to all earthquakes in the United States east of the Rocky Mountains; that is, the damage and perceptible areas are 10 to 100 times larger for earthquakes east of the Rocky Mountains than those of the same magnitude to the west (Nuttli, 1972). (Figure I-4 compares the damage and perceptibility areas of the December 16, 1811, New Madrid earthquake (M_S = 8.0) with that of the great April 18, 1906, San Francisco earthquake (M_S = 8.3).) A point of great significance in this study is that whereas large California earthquakes will cause damage over an area of several counties, large central United States earthquakes will cause damage over an area comprising several states. Thus, in terms of injury, loss of life, and property damage, an earthquake east of the Rocky Mountains may have a much greater impact than one occurring in the western part of the United States (Nuttli, 1973b, 1974).

The seismic activity of the New Madrid zone is not confined to the great sequence of 1811-1812. On January 4, 1843, an earthquake whose epicenter lay near the southern end of the New Madrid seismic zone caused notable damage in Memphis and also as far south as northern Mississippi. On October 21, 1895, there was another large earthquake at the northern end of the New Madrid seismic zone which caused damage as far north as St. Louis. Since 1811, the City of St. Louis suffered earthquake damage from 13 earthquakes whose epicenters were located in the New Madrid seismic zone, in the seismic zone of southern Illinois to the east, or in the seismic zone of eastern Missouri to the south.

The frequency of earthquakes of magnitude greater than or equal to 2.5 which have occurred in the region from 1962 to 1974 has also been studied by Nuttli, as shown in Figure I-5. From the figure it can be seen that there is an extremely high concentration of earthquake activity in the region. Furthermore, a recent study by Algermissen and Perkins also shows that this region has the highest earthquake shaking hazard among all regions in the eastern two-thirds of the United States (Figure I-6) (Algermissen and Perkins, 1976; Department of the Interior, 1976).

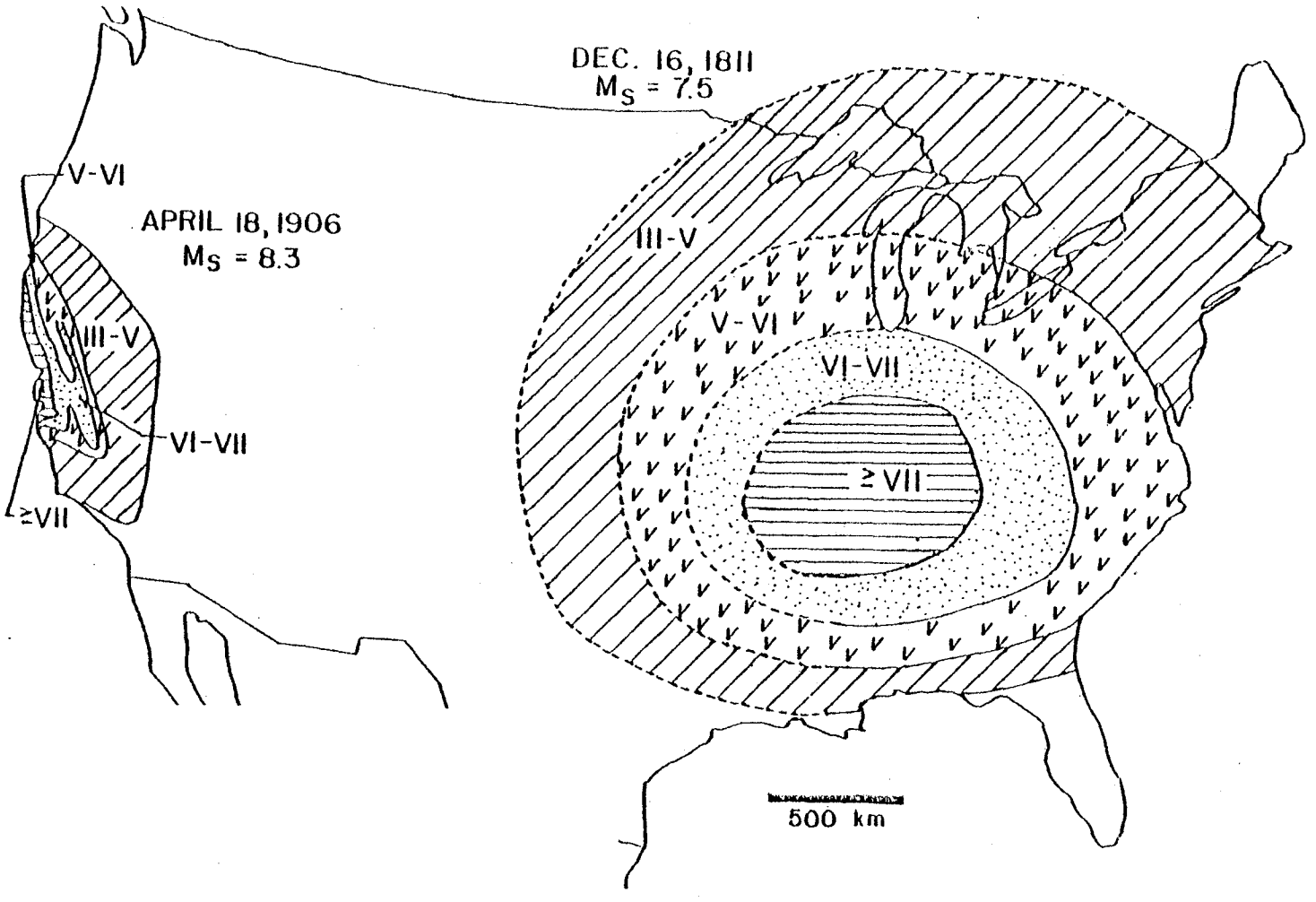


Figure I-4 - Intensity maps for the San Francisco earthquake of April 18, 1906, and the Mississippi Valley earthquake of December 16, 1811. (The damage areas would correspond to those of M.M. intensity VII and greater).

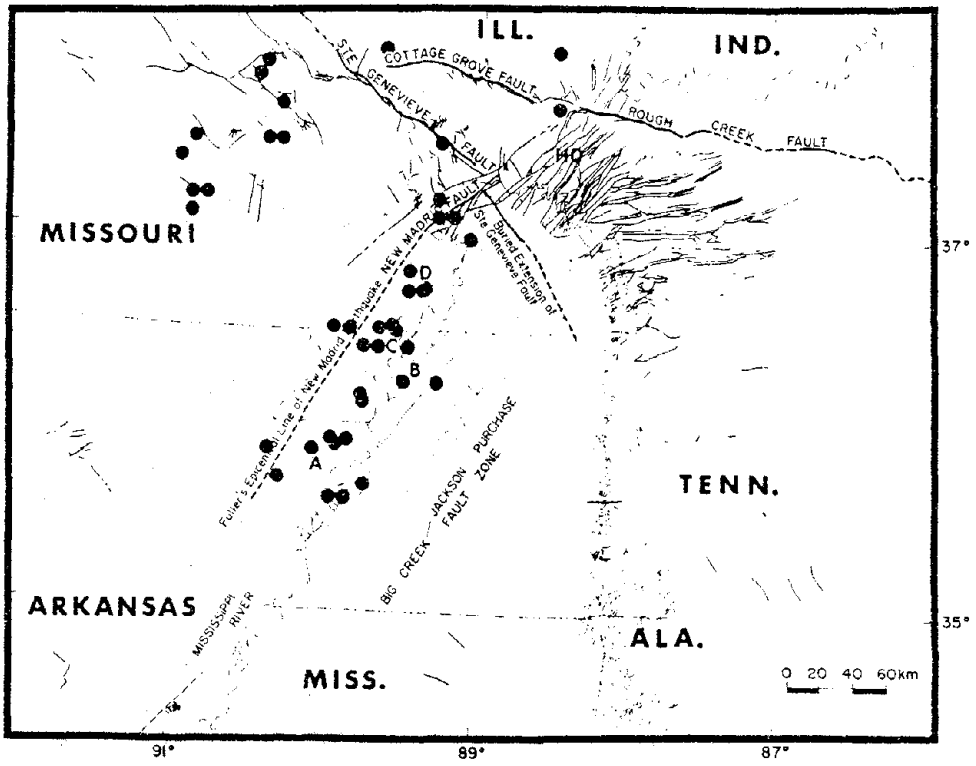


Figure I-5 - Epicenters and faults along the New Madrid seismic zone in the Central United States. Many of the faults in the Mississippi embayment are inferred and are shown as dotted lines. Solid circles are earthquakes reported by the U.S. Geological Survey from 1961 to 1974. Note the similarity in trends between these and the line of epicenters determined by Fuller for the New Madrid earthquakes of 1811-1812. The segments A-B, B-C, and C-D are zones of high activity defined by W. H. Stauder and his colleagues in 1976 using a recently installed seismic network. (From Fletcher and others, 1978).

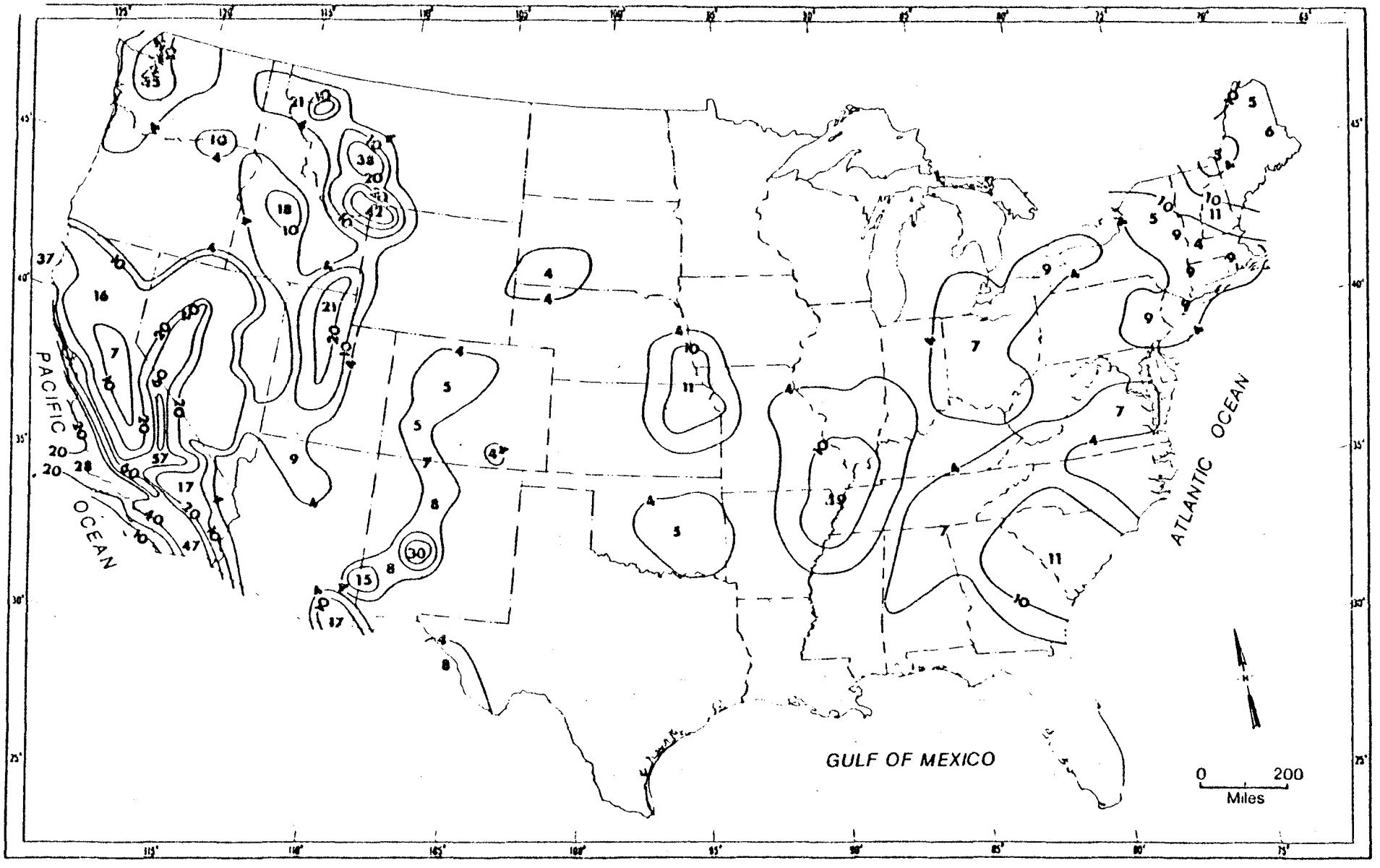


Figure I-6 - Expected levels of earthquake shaking hazards. (Maximum horizontal acceleration [in percentage of g] which has a 10 percent probability of being exceeded in 50 years.)

D. The Objectives and the Scope of the Study

Recent earthquake disasters in Guatemala, Italy, Russia, China, Rumania, and Iran have alerted the entire world to the danger of earthquakes. In the United States, people have been encouraged to accelerate their rate of preparedness in order to reduce the risk of earthquake-related damages.

For example, the Disaster Relief Act of 1974 (PL 93-288) amending the Disaster Relief Act of 1970 (PL 91-606) revised and broadened the scope of the previous legislation and encouraged the development of comprehensive plans for disaster preparedness and assistance, programs, and organizations by state and local government. Passage of the Earthquake Hazards Reduction Act of 1977 signifies political awareness of the problem and, consequently, greater recognition of the need for solutions, i.e., earthquake risk and hazard mitigation. In response to the Earthquake Hazards Reduction Act of 1977 (PL 95-124), the President specifically listed milestones and actions for the next several years for earthquake damage reduction, including the formation of a new Federal Emergency Management Administration and the establishment of the National Earthquake Prediction Evaluation Council by the U. S. Geological Survey.

In order to make their assistance more effective and equitable, federal agencies such as the National Science Foundation and the U. S. Geological Survey have also recognized the need for expanding preparedness efforts. In fact, over the past 6 years the U. S. Geological Survey has been conducting a research program designed to mitigate the disastrous effects of earthquakes, and the National Science Foundation has also increased its funding of Earthquake Engineering Programs and has expanded the scope of research to cover socioeconomic planning and hazard investigation.

In terms of expanding regional preparedness efforts, however, several critical questions have been raised. First, what is the risk to life and property due to earthquakes in any given region? Second, is that risk socially and economically acceptable and tolerable at the present level of the three populations subject to earthquake risk (human, structural, and nonstructural)? Third, with the growth and density of population that accompanies the urbanizing process, how much will the risk of life and property due to earthquakes change over time? Fourth, if the risk is not tolerable, how can it be technically reduced to a level that is socially and economically acceptable? Finally, within our limited knowledge, how can our scarce resources be efficiently allocated so as to reduce the risk to such an extent that it would be considered minimal; or, how are the marginal social benefits derived from earthquakes damage reduction made equal to the marginal social costs spent on the last unit of risk reduction and/or protection.

In terms of preparedness, very little information is available for answering the above questions about the Midwest. Despite the fact that three of the great earthquakes in this country occurred in the central region, fewer studies on earthquake prediction are available for this region than for both coasts. Studies on potential earthquake risk and economic damage for this region by damage receptors and population classes are virtually nonexistent. Furthermore, the five questions listed above, particularly the last one, have not ever been systematically studied.

The urgent need for an earthquake risk study in this region was highlighted and called for by Nuttli (1973a):

> The earthquakes of 1811 and 1812 provide convincing evidence of the differences in ground motion to be expected for large-magnitude earthquakes in the Mississippi Valley seismic region, as compared to those which occur in the Western United States. The combination of poor soil conditions in the epicentral area and of low attenuation of surface-wave energy produced damage and fault areas about 100 times greater than those of western North American earthquakes of the same magnitude.
>
> Fortunately, the frequency of recurrence of earthquakes of the size of those in 1811 and 1812 is low. None of that magnitude have occurred since, although there is a continuing minor to moderate seismic activity in the area, which indicates that large-magnitude earthquakes can be expected there some time in the future.

On the basis of the historical seismicity described above and the latent earthquake problem in the region, a study was undertaken of hazard reduction and the socioeconomic effects of earthquakes in the New Madrid seismic zone. The primary objective of this study was to develop a body of information and the data essential to better understand earthquake risk and the social and economic impacts of possible damaging earthquakes in the major damage zone of the New Madrid. Due to population growth and continuing urbanization in the region, this information is urgently needed so that public policies can be adopted and protective actions taken towards mitigation and reduction of the risk and hazard of earthquakes.

Prior to establishing public policies on earthquake protection such as land-use planning and construction regulations, emergency disaster rescue, mandatory insurance programs, and mitigation and other national public assistance as reflected in the Disaster Relief Acts of 1970 and 1974, the risk and social costs of earthquakes must be estimated for the region. Thus, an initial objective of this study was to determine the risk of earthquakes in the region under consideration; in other words, to specify

the locations, the magnitude, and the intensity distribution of the earthquakes likely to occur in the region surrounding the epicenters within the next 50 years, to the year 2030, and to estimate their probability of occurrence and other technical aspects related to the uncertainty of earthquakes and the consequences of such an occurrence.

The second objective of the study was to develop a simulation model to physically quantify the direct damages from earthquakes to human beings, structures, and property given the intensity and the probability of earthquake risk. Projection models incorporating various growth assumptions were developed for projecting future populations at risk in the region, important in determining the physical bases upon which social benefits and costs of the protection programs can be quantitatively evaluated over the next 25 years. The results were extrapolated for another 25 years, or to the year 2030.

The third objective of this study was to develop economic damage function(s) for quantitative measurement of various damages derived and estimated from the physical damage functions. How much damage to buildings, property, and human resources is to be expected? What can be done to ameliorate the damages? How much protection cost is justifiable?

To reach an efficient decision on resource allocation and distribution, a social welfare model requires that marginal social costs be equal to marginal social benefits. Thus, to reach an optimal level of protection, a balance must first be struck between what society is willing to invest in protection against earthquakes and the magnitude of economic and social disaster it is willing to tolerate. Then the willingness to pay for the investment must be evaluated against the incremental costs of damages or risk beyond the toleration level. For tangible, direct, physical, and natural risks, comparisons on project efficiency have to be made between benefits and costs converted into dollar values. The monetary damage function developed in this study will be used for these evaluations when damage estimates in terms of loss of life and property are empirically established.

With sufficient information on earthquake risks and intensity, and on physical damage functions and economic values subject to the potential earthquake damages, decision analysis methods can be applied to public decisionmaking related to protective and preventive measures, emergency relief programs, and treatment and rehabilitation plans for victims. Based on the information collected, recommendations and suggestions can be deduced on building codes and hazard elimination ordinances, land utilization patterns, and needed future research.

In summary, the primary objectives of this study were the following:

1. To provide a body of updated information on major damaging earthquakes in the New Madrid Region, especially for the 15 counties selected as case studies, i.e., the St. Louis and Memphis Standard Metropolitan Statistical Areas (SMSA's) plus Cape Girardeau and New Madrid counties;

2. To develop and generate isoseismal or intensity maps for the selected epicenters so that intensity values can be related to damage values for a given probability of occurrence; and to study the surficial materials and ground conditions so that the geological susceptibility in the region can be better analyzed;

3. To develop and construct a simulation model so that various physical damage functions can be empirically estimated and converted into economic damage values. In addition, the populations at risk to earthquake damage were projected to the year 2000 and extrapolated to 2030 in order to shed light on social benefits experienced through continued, rapid urban expansion and industrial development, which are essential for social cost comparisons; and

4. To evaluate the existing public programs and policies related to preparedness for and protection from earthquakes and the relief and rehabilitation of earthquake victims in the region.

To accomplish these objectives, six major research tasks were completed:

1. Literature review and data preparation;

2. Earthquake prediction and ground susceptibility assessment;

3. Identification and estimation of populations at risk;

4. Development and estimation of physical and economic damage functions;

5. Regional damage simulation; and

6. Policy recommendations and suggestions for effective pre-disaster planning in general and for earthquake risk preparedness in particular.

Results of the six tasks are presented in a stepwise manner in the following six chapters; Figure I-7 depicts the systematic approach and organization of this study. While Chapter II provides a seismological analysis and geological risk estimation with isoseismic contour maps, Chapter III documents ground materials, geological susceptibility, and earthquake risk vulnerability classification. The populations in the 15 counties which

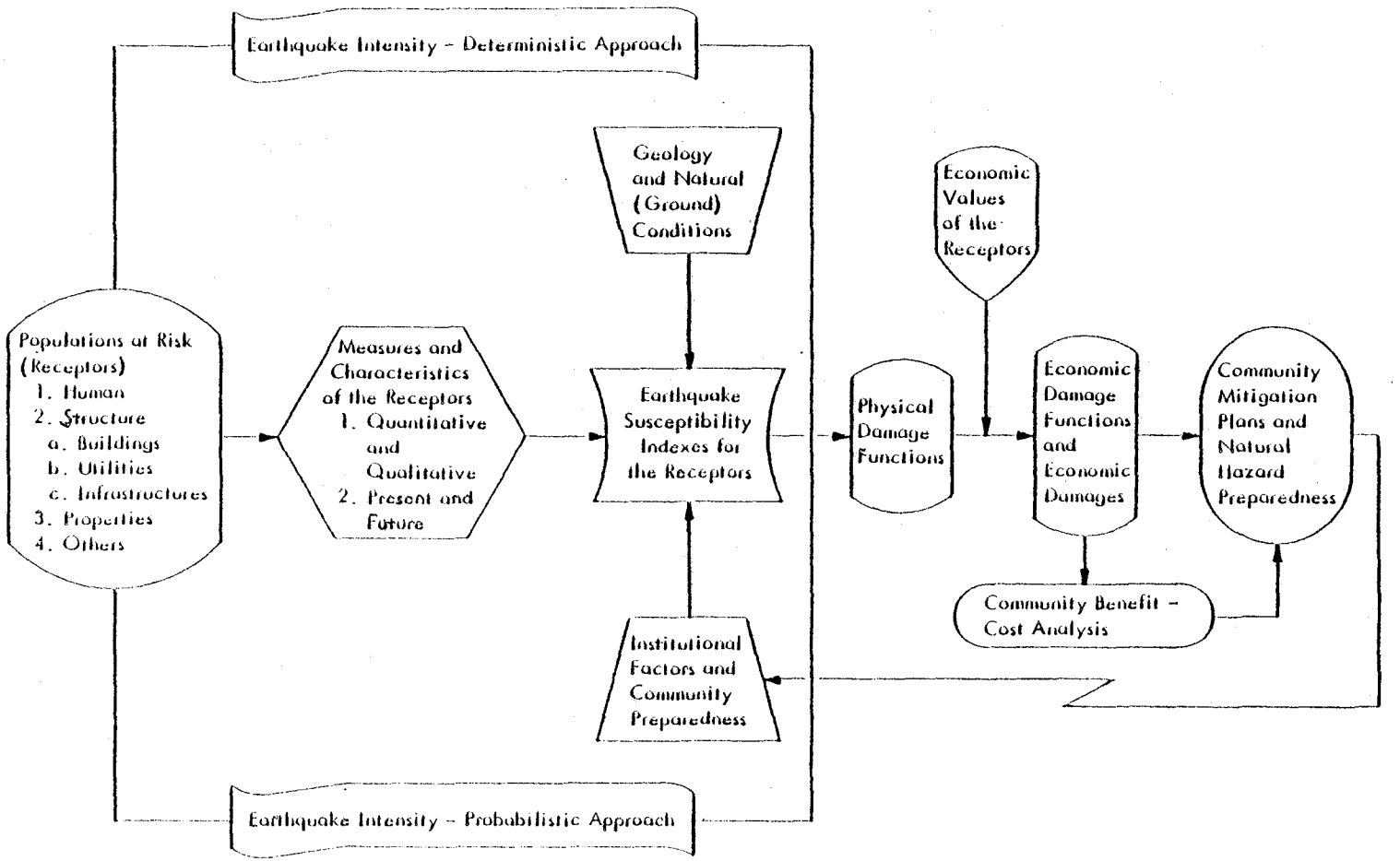


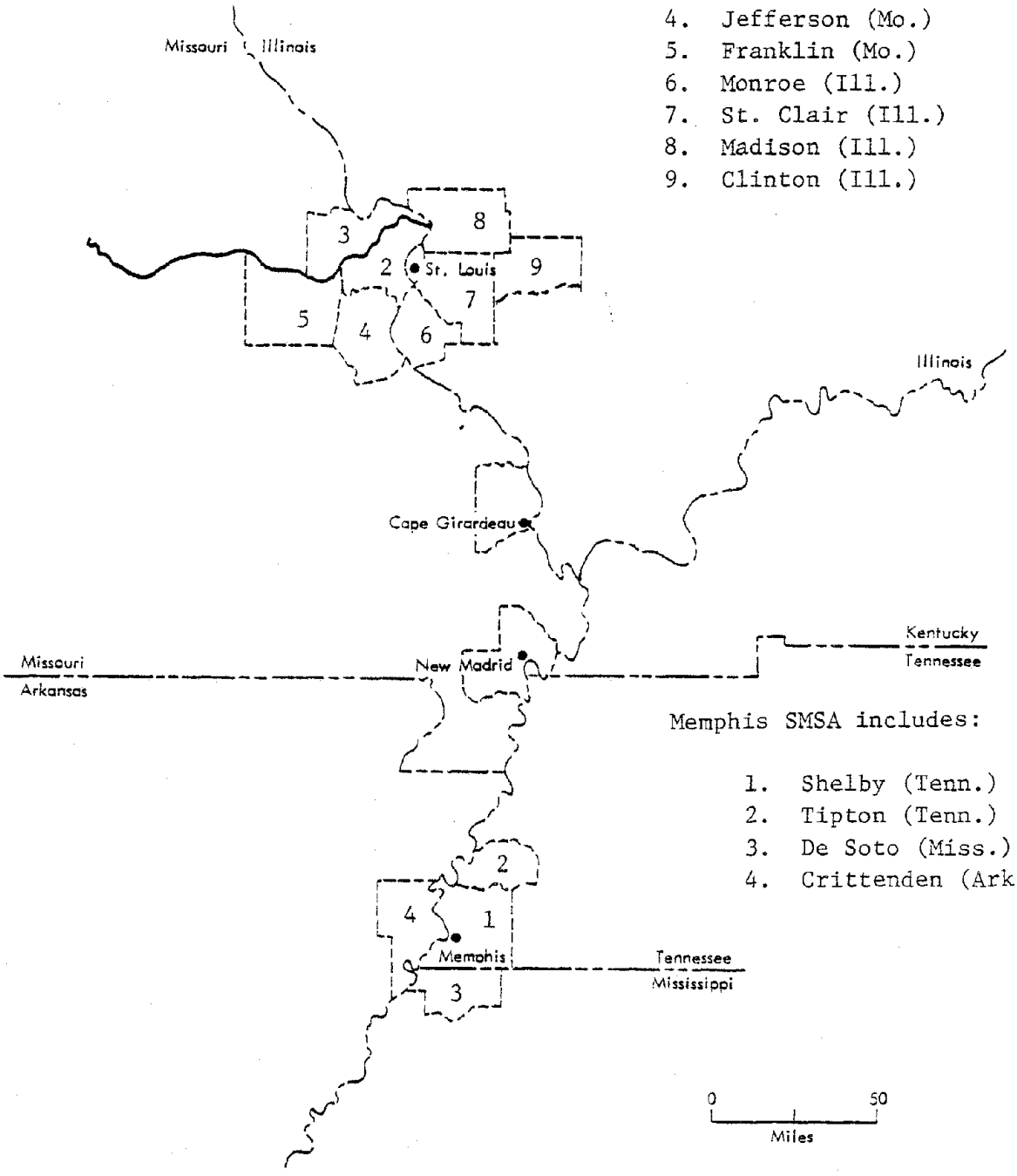
Figure I-7 - The integrated model for earthquake study.

are subject to earthquake risk are delineated in Chapter IV together with projections from 1980 to 2030. The physical and economic damage functions are developed in Chapter V, and Chapter VI contains simulated damage results under various scenarios. Chapter VII deals primarily with the institutional aspects and public agencies which are either practically involved with or strongly interested in risk mitigation and damage reduction in the region. Summary and recommendations are presented in the last chapter.

In essence, the study provides an integrated preparedness and planning simulation model for the New Madrid seismic region--15 counties including the St. Louis and Memphis SMSA were samples selected in this study for purpose of illustration. Figure I-8 shows the 15-county study region geographically. The model consists of three essential modules: the physical damage functions, the economic damage functions, and the government and community preparedness responses. While the physical damage functions are related to earthquake prediction and utilize both the probabilistic and the deterministic approaches, the economic damage functions refer to potential damage estimates--human, structural, and others--depending on the occurrence of a certain type of earthquake. Government and community preparedness is the consequence or impact assessment in response to simulated earthquake damages.

St. Louis SMSA includes:

1. St. Louis City (Mo.)
2. St. Louis (Mo.)
3. St. Charles (Mo.)
4. Jefferson (Mo.)
5. Franklin (Mo.)
6. Monroe (Ill.)
7. St. Clair (Ill.)
8. Madison (Ill.)
9. Clinton (Ill.)



Memphis SMSA includes:

1. Shelby (Tenn.)
2. Tipton (Tenn.)
3. De Soto (Miss.)
4. Crittenden (Ark.)

Figure I-8 - The four study regions.

TABLE I-1

SELECTED SCALES OF EARTHQUAKE INTENSITY
(Richter, Rossi-Forel, Modified Mercalli Scales)

A. Richter Scale: A determination of earthquake size as measured on a logarithmic scale in which each higher number represents a 10-fold increase in amplitude measured in ground motion and an energy increase of some 30 to 50 times. An earthquake of 8.0 magnitude does not cause twice the ground movement as one of 4.0 magnitude, but rather 10 x 10 x 10 x 10 times as large. A correlation between magnitude readings of the Richter scale and possible intensity is:

Magnitude	Intensity (Probable Effects)
1	Detectable only by instruments.
2	Barely perceptible, even near epicenter.
4.5	Detectable within 20 miles of epicenter. Possible slight damage within a small area.
6	Moderately destructive.
7	A major earthquake.
8	A great earthquake.

B. Rossi-Forel Scale:

Intensity	Description of Earthquake Size
1	Microseismic shock.
2	Extremely feeble shock.
3	Very feeble shock.
4	Feeble shock.
5	Shock of moderate intensity.
6	Fairly strong shock

TABLE I-1 (Continued)

Intensity	Description of Earthquake Size
7	Strong shock.
8	Very strong shock.
9	Extremely strong shock.
10	Shock of extreme intensity.

C. Modified Mercalli Scale of Earthquake Intensities:

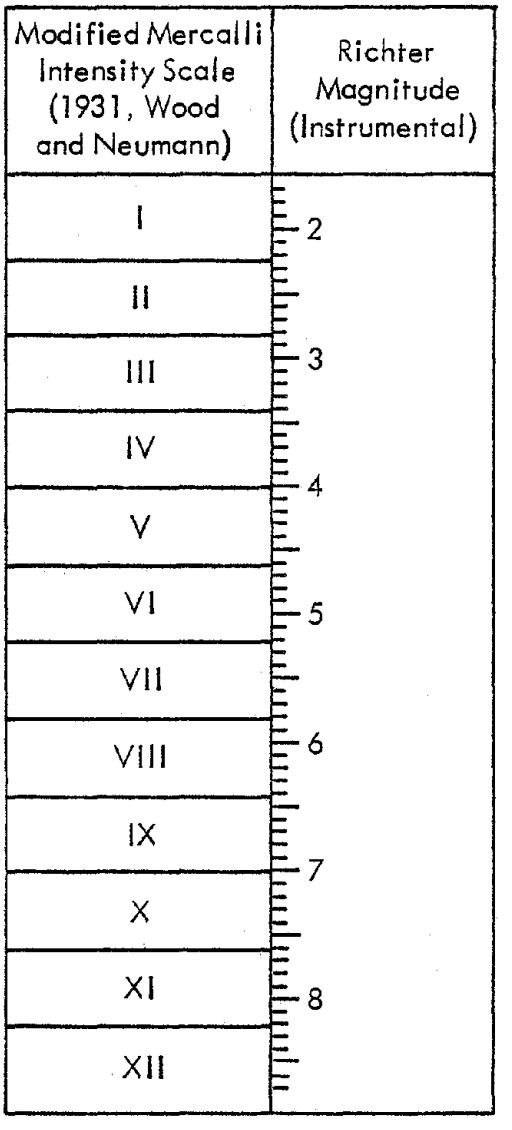
Intensity	Description of Effects
I	Not felt by persons except under particularly favorable circumstances.
II	Detected indoors by a few persons, particularly on upper floors of a multistory building and by sensitive or nervous persons.
III	Detected indoors by several persons, usually as a rapid vibration but which may not be recognized as an earthquake immediately. Vibration is similar to that from a passing, lightly loaded truck or of a heavily loaded truck from some distance.
IV	Detected indoors by many persons and outdoors by a few persons. Dishes, windows, and doors rattle; hanging objects swing.
V	Detected indoors by practically everyone and outdoors by most everyone. Buildings tremble throughout; trees and bushes shake lightly.
VI	Detected by everyone, indoors and outdoors. Awakens all sleepers. Plaster falls in small amounts; heavy furniture moves.

TABLE I-1 (Continued)

Intensity	Description of Effects
VII	People find it difficult to stand. Large church bells ring. Bricks and stones are dislodged; weak chimneys break.
VIII	Trees shake vigorously. Solid stone walls crack and break seriously. Factory stacks and towers twist and fall.
IX	Panic is general. Ground cracks conspicuously. Damage is considerable in masonry structures; some collapse.
X	Ground, especially when loose and wet, cracks up to widths of several inches; most masonry and frame structures and their foundations are destroyed.
XI	Disturbances in ground are many and widespread; damage is severe to wood frame structures; railroad rails bend greatly; pipelines buried in earth are pulled completely out of the earth.
XII	Damage is total. Practically all works of construction are damaged greatly or destroyed. Landslides, rockfalls, and slumps in river banks are numerous and extensive.

TABLE I-1 (Concluded)

D. Suggested Comparison Between Modified Mercalli Intensity and Richter Magnitude Scale:



Source: Van Nostrand's Scientific Encyclopedia, 1976; U. S. Coastal and Geodetic Survey, Earthquake History of the United States Part I - Continental United States by N. H. Heck, 1974 (revised); and The Journal of Kansas Geological Survey, Vol. 1, No. 3 (Summer 1979), p. 6.

CHAPTER II

SEISMOLOGICAL ANALYSIS AND GEOLOGICAL RISK ESTIMATION

The most significant determinant in any natural hazard study is obviously the source, magnitude, and type of the hazard itself. This chapter will discuss in detail the seismological aspects in New Madrid, including its historical background. In addition, predicted earthquake risk over the next 50 years will be presented.

A. Technical Issues of the New Madrid Earthquakes

There is a tendency for people to ascribe earthquakes to a variety of causes. In his book based on newspaper accounts and personal narratives, Penick (1976) describes various likely causes of the 1811-1812 New Madrid earthquakes. The generally accepted sea floor spreading hypothesis does not seem to be applicable in this case. According to this hypothesis, an active global rift system--mostly on ocean floors--is the source of new surface material that moves away from the rifts and eventually sinks again into the mantle beneath the earth's crust. The lithosphere, the strong surface layer, moves in plates away from the rifts. These plates are bounded by the ocean ridges, island chains, and continental perimeters that constitute the great earthquake belts of the world. The sea floor spreading movement thus causes earthquakes.

However, the earthquakes in the New Madrid region were abnormal because the region is not associated with any of the great belts of the ocean ridges or margins, and because the number of shocks, the continuity of the disturbance, the area affected, and the severity of the earthquake sequence were different from other quakes recorded in the history of the North American continent (Fuller, 1912; Mateker, 1968; National Academy of Sciences, 1969; Heck, 1965; Davison, 1936; Richter, 1958). The causes of those quakes are far from being ascertained even today. There are numerous speculations on the existence of faults in the region.

According to Penick (1976), Jared Brooks counted 1,874 shocks between December 16, 1811, and March 15, 1812; and William Pierce counted 89 shocks between the 16th and 23rd of December 1811, on the Mississippi below New Madrid. Pierce described 17 of these shocks individually as severe, very severe, long and violent, and great and awful. Even after the period of intense activity had ended in March 1812, disturbances continued. Slight shocks were still felt every 24 hours as late as December 1812, and periodically for years thereafter. It is possible that the New Madrid series even triggered activity in neighboring faults, e.g., the 1804 earthquakes in southern Illinois near Kaskaskia.

Technically speaking, the potential damaging effects of the largest earthquake of the New Madrid series might have been as great or greater than that of such modern earthquakes as the San Francisco quake in 1906 and the Anchorage quake in 1964. In terms of area affected, number of large aftershocks, and duration, the New Madrid earthquakes are most noteworthy.

By correlating instrumental seismographic data with the distribution of isoseismals for the November 9, 1968, Southern Illinois earthquake, Nuttli developed a method to determine earthquake magnitude from the isoseismal map. He applied this method to estimate the magnitude of the 1811-1812 earthquakes. For these earthquakes he obtained the distribution of isoseismals from a study of the contemporaneous newspaper accounts of the earthquakes. Figure II-1 presents his generalized isoseismal map for the earthquake which occurred on December 16, 1811. The numbers on the map represent various levels of intensities at individual sites. According to Nuttli's estimates, the area with an M.M. intensity of VII or greater encompassed some 600,000 square kilometers, or an area about 20 times as large as that of the 1906 San Francisco earthquake; and the ground movements of the quake were powerful enough to be felt by nearly everyone within 2,500,000 square kilometers.

It has also been reported that later shocks in the series could be felt over a comparable area. No other earthquakes recorded on the North American continent can approach this effect, and similar examples elsewhere in the world are extremely rare. Reports Nuttli (1973a):

> At distances less than 100 km the attenuation of surface waves is controlled by geometric spreading rather than absorption, so that the attenuation of surface waves in the near field region does not vary much with the surface geographic area. Thus, it is not low attenuation, but rather surficial geology which was responsible for the severity of damage in the epicentral region of the 1811 and 1812 earthquakes. There is a thick cover of alluvium, containing a layer or layers of water-saturated sand, which resulted in large surface displacements and blows, fissures, and landslides.

Recently, Gupta and Nuttli reassessed the maximum M.M. intensity of the 1811-1812 series with additional data on spatial alternation of intensities and concluded that the maximum M.M. intensity should be revised upward to XI for the December 16; X-XI for the January 23; and XI-XII for the February 7 earthquakes (Gupta and Nuttli, 1976).

Seismologists have consistently pointed out that (1) not only the 15-county New Madrid region under consideration in this study, but also the 5 states neighboring St. Louis (Missouri, Arkansas, Tennessee, Kentucky, and Illinois) are in an active seismic zone, once the scene of unprecendented

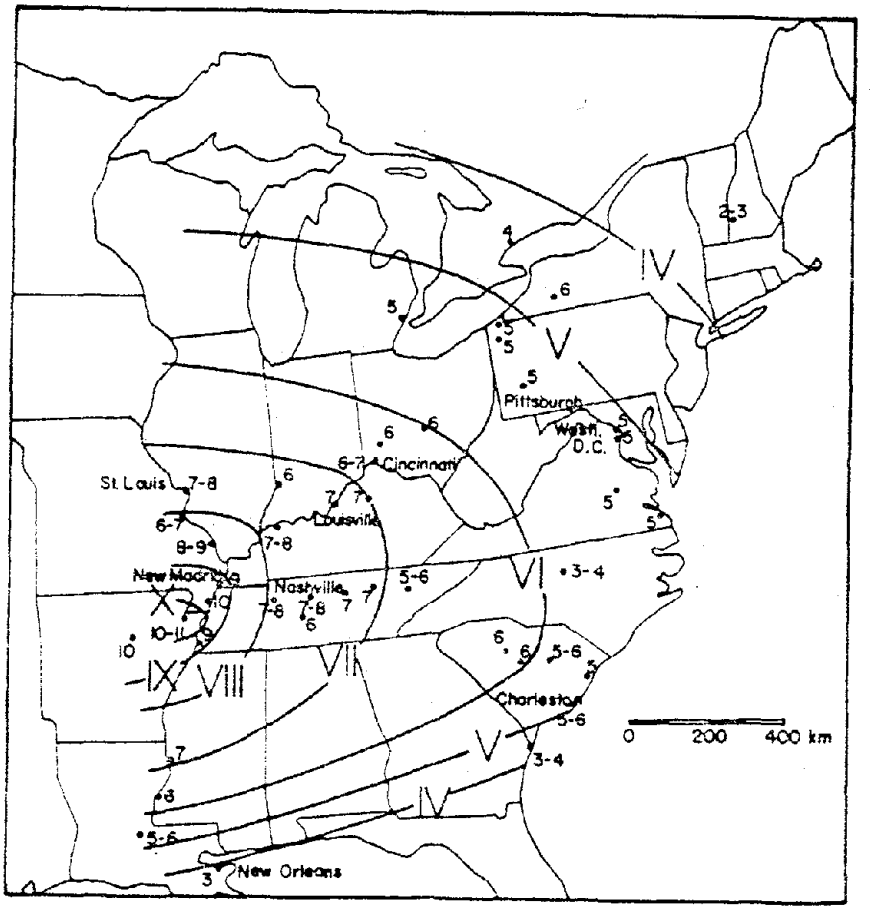


Figure II-1 - Generalized isoseismals, December 16, 1811, earthquake.

Note: Arabic numerals refer to intensities at individual points.
Source: Otto W. Nuttli, "The Mississippi Valley Earthquakes of 1811 and 1812: Intensities, Ground Motion, and Magnitudes," Bulletin of the Seismological Society of America 63:1 (February 1973):230. Provided by The John Crerar Library, Chicago, Illinois.

earthquakes, and (2) that the major disaster of 1811-1812 might recur at any time. Pierce (Penick, 1976) found traces of prior eruptions and believed that the Mississippi River itself was formed by some great earthquakes. It is certain that some earthquakes with a magnitude comparable to the 1811-1812 series had occurred previously in southeastern Missouri or northeastern Arkansas. Faulting in the young rocks of the region indicates that earthquakes of significant magnitude occurred for several thousand years; clastic dikes and fissures of old earthquakes filled with sand have been discovered in widely scattered localities in the region.

Myron Fuller (1912) found that at least part of the Tiptonville Dome was uplifted before 1811 and that bayous sunk by a prior earthquake had cypresses that were several hundred years old growing in them. Over a period of several thousand years, numerous violent earthquakes have occurred in the region, but the 1811-1812 quakes are the earliest to be recorded (Mateker, 1968). Berlin Moneymaker (1954), who catalogued many of the shocks of the 19th century, reported an earthquake on October 31, 1895. The epicenter was near Charleston, Missouri, and had an intensity measure of IX on the M.M. intensity scale.

Since 1909 the seismograph network at Saint Louis University has continuously chronicled shocks in the region. It registered shocks of magnitude 5.5 in 1968 and 5.0 in 1976. As pointed out by Penick (1976), this region has been subject to minor seismic risk only as far as the records since 1909 are concerned. However, the great quakes of 1811-1812, the geological evidence, and the continuously unstable ground lead seismologists to believe that the New Madrid is one of the few regions in this country highly subject to major, destructive earthquakes in terms of populations at risk and intensity.

There is no doubt that earthquakes will happen again in the region. What remains uncertain is whether they will occur in such large numbers, with such severity, and over such a long period of time as they did in 1811-1812. According to the probability approach they have employed and based on historical data developed since 1906, Saint Louis University seismologists found that there is a 10 percent chance that a maximum M.M. intensity of IX will occur in this region within the next 50 years.

B. Seismic Risks in New Madrid

The seismicity of the New Madrid region has been intensively studied in recent years by many seismologists including Cornell (1968, 1971, 1974); Cornell and Merz (1974); McGuire (1976); Nuttli (1973b, 1973c, 1974); Gupta and Nuttli (1976); Schaefer and Herrmann (1977); and Stauder et al. (1976). Although the region has not recorded any earthquakes of the same magnitude as those which occurred in 1811-1812, seismologists

generally agree that the region is one of the most seismically active regions in the eastern United States. The region of greatest activity includes portions of the five states--Missouri, Arkansas, Tennessee, Kentucky, and Illinois--and is centered around the New Madrid region.

Two approaches have been employed to study the seismic risk of any given region. One is called the probabilistic approach and the other, deterministic. The former estimates the earthquake risk by computing the distribution of seismic intensity which has a specified probability of occurring in a selected time interval, based on historical data including maximum intensity and return period, as well as attenuation and other considerations affecting the intensity. Sophisticated seismic models are developed to define the source zones and to assign the potential earthquakes their maximum intensity. These are used to generate isoseismic contour plots of a certain site intensity expected for a certain risk probability. For instance, one of the earthquake risk estimates employed in this study is the result of a probabilistic approach carried out by Schaefer and Herrmann (1977). For different source configurations, different contour plots are available for a risk level of 10.0 percent over 50 years. This study employs the latest version, with finer maximum intensity breakdowns for four source zones.

The deterministic approach estimates the intensities for selected epicenters. With the assumed epicentral location and epicentral intensity, one may evaluate the intensity at the selected point if the attenuation of earthquake intensity in the region is known. The attenuation of seismic body waves as well as surface waves in the region east of the Rocky Mountains is thought to be smaller than that west of the Rockies (Everden, 1967; Nuttli, 1973b, 1973c; Mitchell, 1973). As a consequence, an earthquake in the East will be perceived over a much larger area and will cause more damage than an earthquake of the same magnitude or epicentral intensity occurring in the West. Gupta and Nuttli have attempted to describe some relationships between the attenuation and distance of M.M. intensity for the central United States (considered to be the area east of the Rocky Mountains and west of the Appalachians). With the attenuation of seismic body waves as well as surface waves, it is then possible to design earthquakes for a given site, such as New Madrid (Missouri) or Marked Tree (Arkansas) shown in the following section. According to Gupta and Nuttli, the spatial attenuation of intensities can also be useful in estimating the epicentral intensity of an earthquake whose maximum intensity is not reliably known.

1. Earthquake risk estimated by the probabilistic approach: The seismic risk map makes use of the historic record of earthquake activity in a given region. In addition, it requires knowledge of how the ground motion decreases with increasing distance from the earthquake source region and an estimate of the "maximum" earthquake to occur in a region. The

probabilistic method of estimating earthquake risk was developed by Cornell and was recently applied by Algermissen and Perkins (Cornell, 1968; Algermissen and Perkins, 1976) to the United States for an estimate of maximum horizontal acceleration.

Because of a lack of instrumental seismographic data for a sufficent period of time for the central Mississippi Valley, Nuttli (1974) used M.M. intensity rather than horizontal ground acceleration as a measure of the ground motion at a particular site. He compiled a catalog of earthquakes in the central Mississippi Valley that have occurred since 1800. The catalog includes the date, location, and maximum intensity of all known earthquakes large enough to be felt. From this catalog Schaefer and Herrmann (1977) divided the central Mississippi Valley into five source regions. For each source region they estimated the intensity in the epicentral region of the largest earthquake to occur, which is greater than or equal to the largest epicentral intensity of historical earthquakes.

Other required information to complete the probabilistic approach is the activity rate for each source region $\emptyset$ defined as the mean number of earthquakes per year with epicentral intensity equaling or exceeding an assigned minimum M.M. intensity (selected as V for this study) and the slope b and intercept a of the intensity recurrence relation:

$$\log_{10} N(I_o) = a - b\, I_o \qquad \text{(II-1)}$$

where N is the cumulative number of earthquakes per year occurring in the source region which are epicentral intensity I_o or greater. The values of $\emptyset$, a, and b are determined from the catalog of earthquakes developed by Nuttli.

Schaefer and Herrmann considered three models of the central Mississippi Valley source regions. Their third model, which geologically is the most reasonable, is shown in Figure II-2. The five source zones are labeled 1', 1, 2, 3, and all the remaining area (background) between latitudes 34° and 42°N and longitudes 86° and 94°W. For these regions they obtained from the historical record the following values of $I_{o,\,max}$ $\emptyset$, and b:

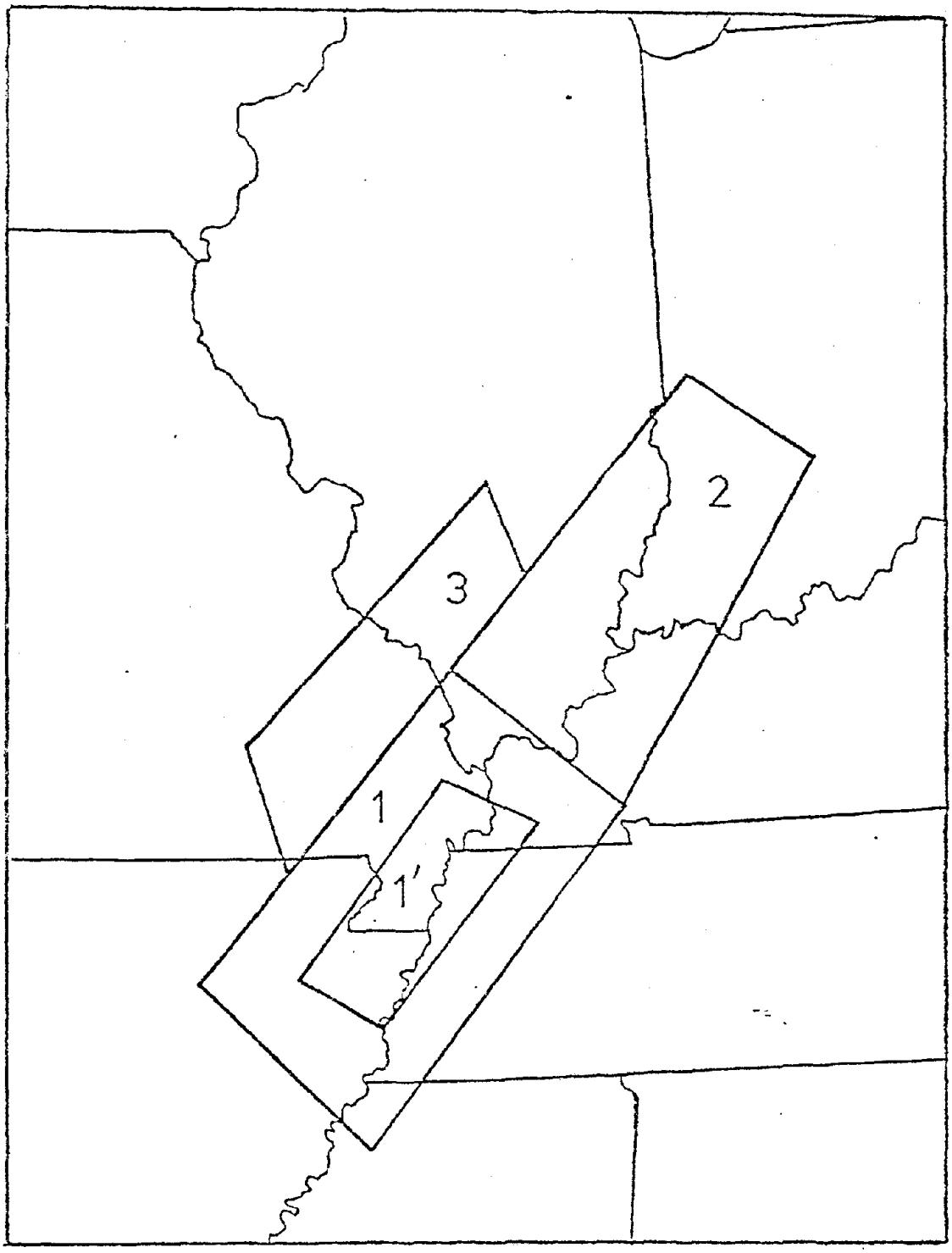


Figure II-2 - Source configuration 3.

Source Zone	$I_{o,\,min}$	$I_{o,\,max}$	$\emptyset$ (year^{-1})	b
1'	V	XI-XII	0.35	0.45
1	V	IX-X	0.15	0.47
2	V	IX-X	0.20	0.37
3	V	VIII-IX	0.20	0.47
background	V	VIII	0.004[a/]	0.47

[a/] Number of earthquakes per year per 10,000 square kilometer area greater than $I_{o,min}$.

The data in the preceding table were used as input to compute the risk analysis using a computer program written by McGuire (1976). A brief summary of the theory underlying the computer program follows.

Consider a source region (the number of source regions is arbitrary) of n small areas or blocks. Let the number of earthquakes of epicentral intensity I_o likely to occur in the intensity range ΔI_o for each small block of the source region be $N_{\Delta I_o/n}$. Given the distribution of earthquakes likely to occur in each small block of the source region (we assume a uniform or constant distribution throughout an individual source region, such as 1'), the effect at each site (dots in the figure) due to the occurrence of earthquakes in each small block of the source can be computed using a suitable intensity-attenuation formula. An intensity-attenuation formula is an equation or set of equations which gives the fall-off of M.M. intensity with increasing epicentral distance. The equations used in this study were those developed by Gupta and Nuttli (1976). The equations are:

$$I(R) = \begin{cases} I_o & \text{for } R \leq 20 \text{ km} \\ I_o + 3.7 - 0.0011R - 2.7 \log R & \text{for } R \geq 20 \text{ km} \end{cases} \qquad \text{(II-2)}$$

where R is epicentral distance in kilometers and I(R) is the site intensity at a distance R corresponding to a source intensity of I_o.

From the distribution of intensity at each site, the expected number of times a particular intensity i is likely to occur in a given number of years at given site can be determined. From this the maximum site intensity in a given number of years for any selected level of probability can be calculated. Call this extreme probability $F_{max,t}(i)$. It is calculated for all points of the grid considering the contributions of all the source zones or regions, and then the values of i at all the grid points are contoured so that the results can be given as a map.

Call $F(i)$ the probability that an observed site intensity I is less than or equal to the selected value i, given that an earthquake with epicentral intensity I_o greater than a selected $I_{o,min}$ has occurred. The expression $F(i)$ is equal to

$$F(i) = \frac{\text{expected number of occurrences with } I \leq i \text{ and } I_o \geq I_{o,min}}{\text{total expected number of occurrences } (I_o \geq I_{o,min})} . \qquad \text{(II-3)}$$

Assume there are N independent earthquakes where N is a Poisson-distributed variable with mean rate γ. Then Algermissen and Perkins show that

$$F_{max}(i) = \exp\lambda \left\{ -\lambda \left[1 - F(i)\right]\right\}. \qquad \text{(II-4)}$$

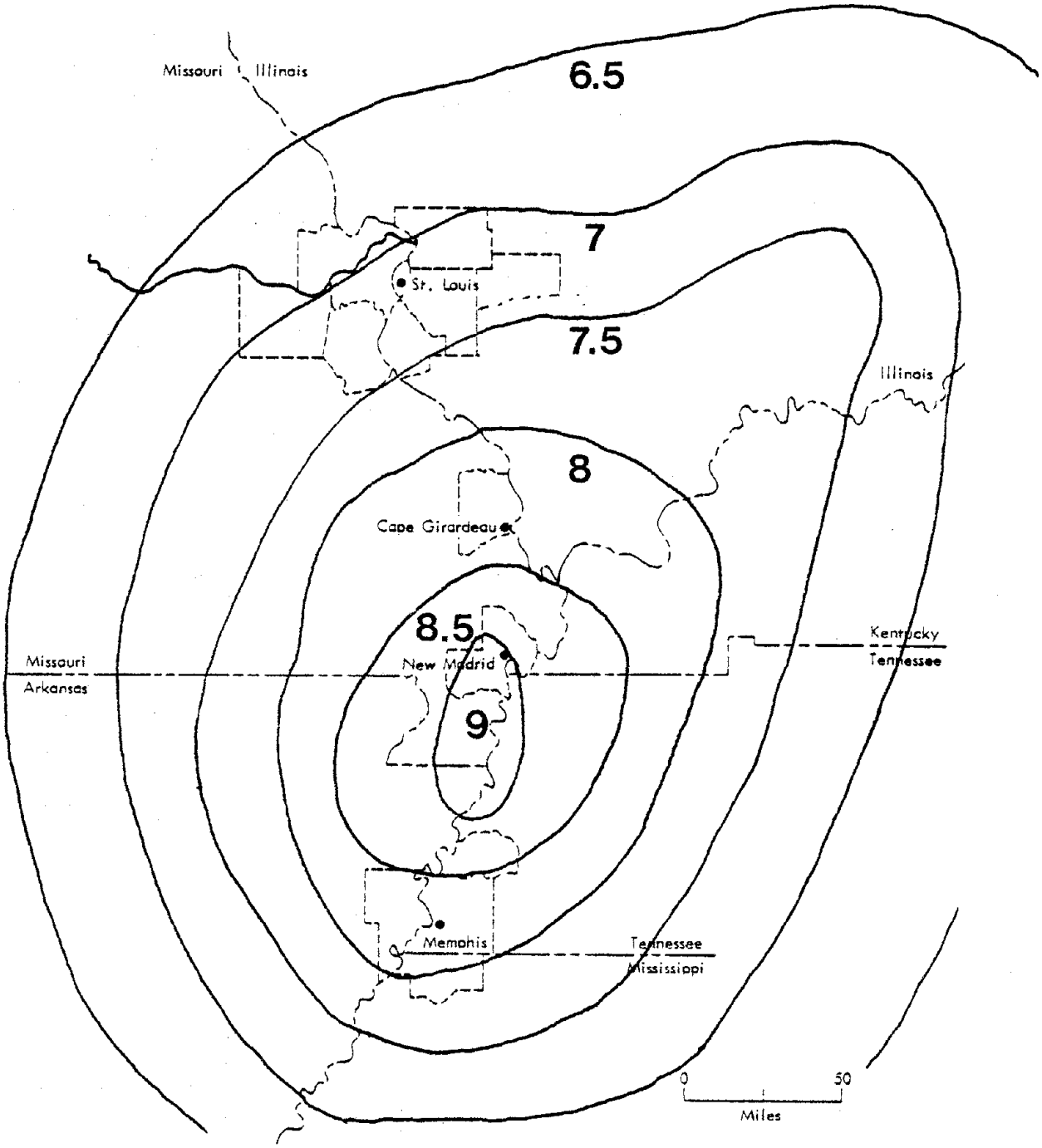
If $\gamma = \emptyset t$, where $\emptyset$ is the mean rate of occurrence of earthquakes of $I_o I_{o,min}$ per year and t is the number of years in a period of interest

$$F_{max,t}(i) = \exp \left\{ -\emptyset t \left[1 - F(i)\right]\right\}. \qquad \text{(II-5)}$$

A table of i versus $F(i)$ can be constructed from the historical data, and $F_{max,t}(1)$ can be calculated for an assigned t. From this the contour map of site intensities with an assigned probability of not being exceeded in an assigned number of years can be constructed. Such a map, produced by Schaefer and Herrmann, is shown in Figure II-3.

Figure II-3 is to be interpreted as follows. The numbers which are contoured are the M.M. intensity values (customarily written in Roman numerals) which have a 10 percent probability of being equaled in a 50-year time period. Because 50 years is chosen as the study period and it does correspond approximately to the average lifetime of an ordinary building, this would mean that the ordinary structure in St. Louis has a 10 percent probability of experiencing a maximum M.M. intensity of VII in its lifetime. In Memphis the corresponding 10 percent, 50-year maximum M.M. intensity would be slightly greater than VIII, while in New Madrid County the 10 percent, 50-year maximum M.M. intensity would be between VIII and IX.

It should be noted that Figure II-3 represents only the maximum likelihood of the estimated earthquake risk for the next 50 years with the probability being 10.0 percent. The earthquake maximum risk estimation by the probabilistic approach is different from any of the earthquake predictions with greater certainty; it should be interpreted only as a possible, potential maximum risk to the study region rather than as a "sure event of recurrence."



$I_{,max}$ = IX, P = 10% in 50 Years

Figure II-3 - Probabilistic approach.

2. Earthquake risk estimated by the deterministic approach: An alternative approach to earthquake risk is to make deterministic estimates of intensity. By this method, one must assume an epicentral location and an epicentral intensity to evaluate the intensity at the selected site. Furthermore, the attenuation of earthquake intensity in the region must also be known.

In analyzing the data from central U.S. earthquakes, Gupta and Nuttli (1976) have shown that "particle velocity" rather than acceleration correlates directly with intensity. For distance outside the near-field region, the largest particle velocity of the sustained maximum surface wave motion is caused by waves of periods of about 3 seconds. Observational data from four earthquakes in the Mississippi Valley have yielded an average value for the coefficient of an elastic attenuation ($\gamma = 0.10$) per degree for waves with a maximum particle velocity in the period range 3 to 12 seconds. According to Nuttli, the spatial attenuation of 3- to 12-second period rayleigh waves may be described by the following relationship:

$$\left(\frac{A}{T}\right)_{max} (\Delta) = K^{-1/2} (\sin\Delta)^{-1/2} \exp(-0.10\Delta) \qquad \text{(II-6)}$$

where $(A/T)_{max}(\Delta)$ is the maximum value of A/T at the epicentral distance, Δ, in degrees, A is the amplitude of the ground motion due to surface wave of period T, and K is a constant. Note that particle velocity is equal to $2\pi x(A/T)$ so that A/T is a measure of the particle velocity. Since the error introduced by assuming $\sin\Delta = \Delta$ is less than 1 percent for Δ about 2,000 kilometers, equation (II-6) may be replaced by:

$$\left(\frac{A}{T}\right)_{max} (\Delta) = \frac{K}{\Delta} \exp(-0.10\Delta). \qquad \text{(II-7)}$$

It can be expected that there will be small regional departures from the assumed value of $\gamma = 0.10$ per degree, which represents an average for the central United States. Such differences in the value of γ will principally affect A/T only at larger distances, say beyond 100 kilometers.

Although the theoretical as well as observed curves of log (A/T) versus log Δ are not linear, data from the November 9, 1968, earthquake of southern Illinois indicate that, for M.M. intensity of IV and larger, an approximately linear relationship may exist between log (A/T) and M.M. intensity. A linear relationship between $I_o - I(\Delta)$ and log (A/T), where I_o is the epicentral intensity and $I(\Delta)$ the intensity at an epicentral distance, Δ, may be derived from equation (II-7) as:

$$I(\Delta) = I_o - C_1 - C_2 \ (0.1\Delta \text{Log } e + \log\Delta) \qquad \text{(II-8)}$$

where C_1 and C_2 are empirical constants.

Assisted by the November 9, 1968, earthquake in southern Illinois and the December 16, 1811, New Madrid earthquake, M.M. intensity and distance from the epicentral in four directions were fitted to equation (II-8) through the least squares method to estimate C_1 and C_2.

There is a problem in assigning maximum intensities to the earthquakes of December 16, 1811, and January 23 and February 7, 1812. Not only was the region sparsely populated and communications primitive, but the closeness in time of the three earthquakes often made it difficult to separate the accounts of one from the other. For this latter reason, Nuttli used only contemporary newspaper accounts that clearly distinguished the earthquakes from one another when assigning intensity values for the three earthquakes (Nuttli, 1973a, 1974). In this way he arrived at a maximum M.M. intensity of X-XI for the December 16, 1811, event. However, on the basis of earth slumps and land slips in soft ground (M.M. intensity XI) and of waves seen on ground surfaces (M.M. intensity XII), the maximum intensity for this earthquake was conservatively revised upward to M.M. intensity XI.

The values of C_1 and C_2 with their associated standard deviations were found to be:

$$C_1 = 1.827 \pm 0.079$$
$$C_2 = 2.710 \pm 0.076 \qquad \text{(II-9)}$$

The standard deviations are rather small, about 4.3 percent in C_1 and about 2.7 percent in C_2.

Substituting these values of C_1 and C_2 into equation (II-8), one obtains, for $I(\Delta) \geq IV$ (M.M. intensity), the following:

$$I(\Delta) = I_o - 1.8 - 0.12 - 2.7 \log\Delta \qquad \text{for } \Delta \geq 0.2^\circ \qquad \text{(II-10)}$$

If the epicentral distance is expressed as R km, equation (II-10) yields

$$I(R) = I_o + 3.7 - 0.0011R - 2.7 \log R \text{ for } R \geq 20 \text{ km} \qquad \text{(II-11)}$$

The spatial attenuation of M.M. intensity for various epicentral intensities described by equation (II-11) has shown fairly good agreement with isoseismals of many large earthquakes in the central United States. The relationship developed by Gupta and Nuttli, based on Nuttli's earlier studies suggesting an average value for the anelastic attenuation coefficient ($\gamma = 0.10$) per degree for this region, can be useful in providing estimates of spatial attenuation and hence of design earthquakes and seismic risk at a given site for any sites specific deterministic application.

Figures II-4 through II-7 are earthquake risk estimates developed by Nuttli under the deterministic approach for two sites, New Madrid and Marked Tree, for two different M.M. intensities, VIII and XII, respectively. For example, Figure II-5 assumes the largest possible earthquake, one of epicentral intensity XII, occurring right on site at New Madrid, Missouri. The circles on the map represent outer bounds of given intensities. For example, the intensity would be IX between the circles IX and X. Figure II-7 is similar to Figure II-5 except that the epicenter is moved to Marked Tree, Arkansas, near the southern edge of the New Madrid fault zone. As a result, the isoseismal contour maps in terms of M.M. intensities and distance from the center vary considerably. Figures II-4 and II-6 are displays similar to Figures II-5 and II-7 except that the epicentral intensity is VIII rather than XII.

The return period of an earthquake of epicentral intensity XII occurring <u>somewhere</u> between the epicenters in Figures II-4 and II-7 is approximately 1,000 years. That is, there is a 63 percent probability that an earthquake having an epicentral intensity XII will occur somewhere in the New Madrid fault zone between New Madrid and Marked Tree in a 1,000-year interval. For any 50-year interval, the probability of occurrence becomes much smaller, about 4.9 percent; and for any 1-year interval, it is 0.10 percent. The return period of an earthquake of epicentral intensity VIII is approximately 50 years. Thus, there is also a 63 percent probability that an earthquake having an epicentral intensity VIII will occur somewhere between New Madrid and Marked Tree in a 50-year interval; and for any 1 year, the probability of occurrence is reduced to 2.0 percent. These epicentral intensities VIII and XII correspond to body-wave magnitudes of 5.8 to 6.2 and 7.0 to 7.4, respectively. The body-wave magnitude in the range 6.2 to 6.6 would be IX, and its recurrence time would be about

125 years. The probability of occurrence of an earthquake of that size somewhere in the New Madrid seismic zone is 33.0 percent for a 50 year interval and 0.80 percent for any 1-year.[1/]

The intensity distribution in Figures II-4 through II-7 are averages. They do not take account of the effects of thick unconsolidated soil layers (which would increase the intensity) or of hard rock at the earth's surface (which would decrease the intensity). Nor do they take into account the unequal azimuthal radiation of energy which is characteristic of actual earthquakes but which is difficult to predict for an area such as the New Madrid fault zone.

1/ The probability of occurrence (p) is computed as follows:

$$p = 1 - e^{(-t/T)}$$

Where T is the return period and t is the study interval or period in years. For example, $p = 1 - e^{(-50/125)} = 1 - e^{-0.4} = 1 - 0.67 = 0.33$ for M.M. intensity IX in this region.

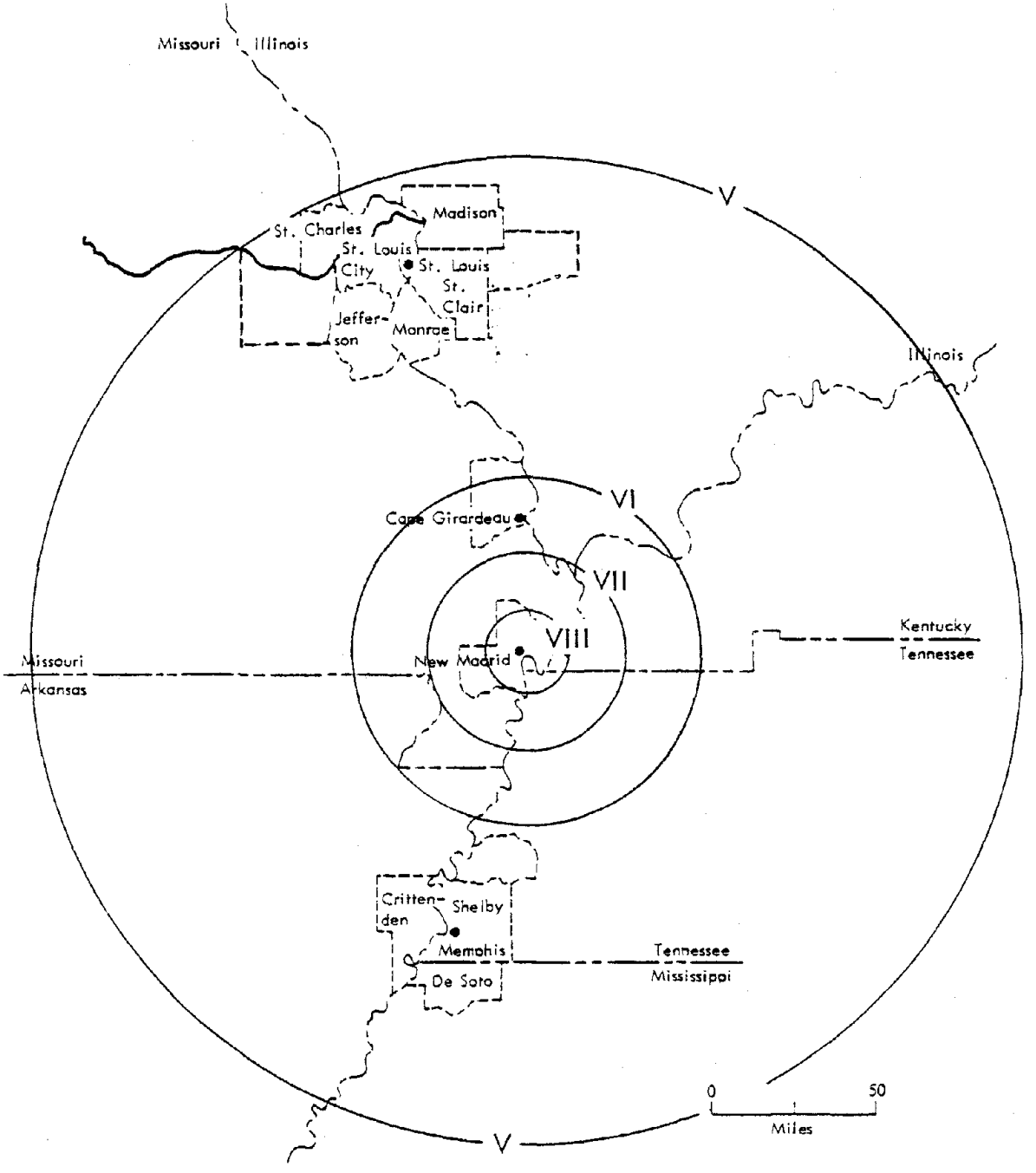


Figure II-4 - Deterministic approach: I_o = VIII at New Madrid, Missouri.

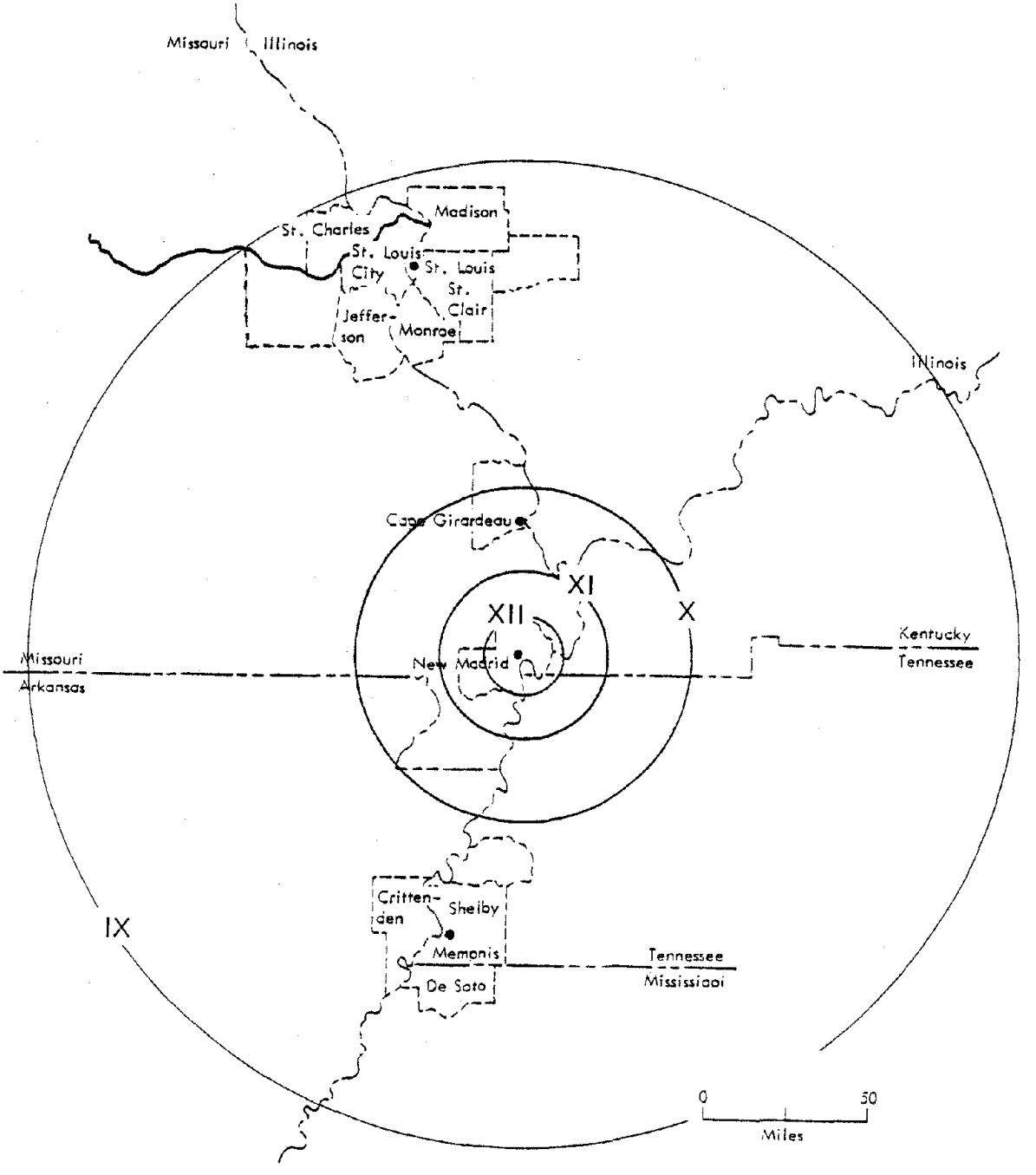


Figure II-5 - Deterministic Approach: I_o = XII at New Madrid, Missouri.

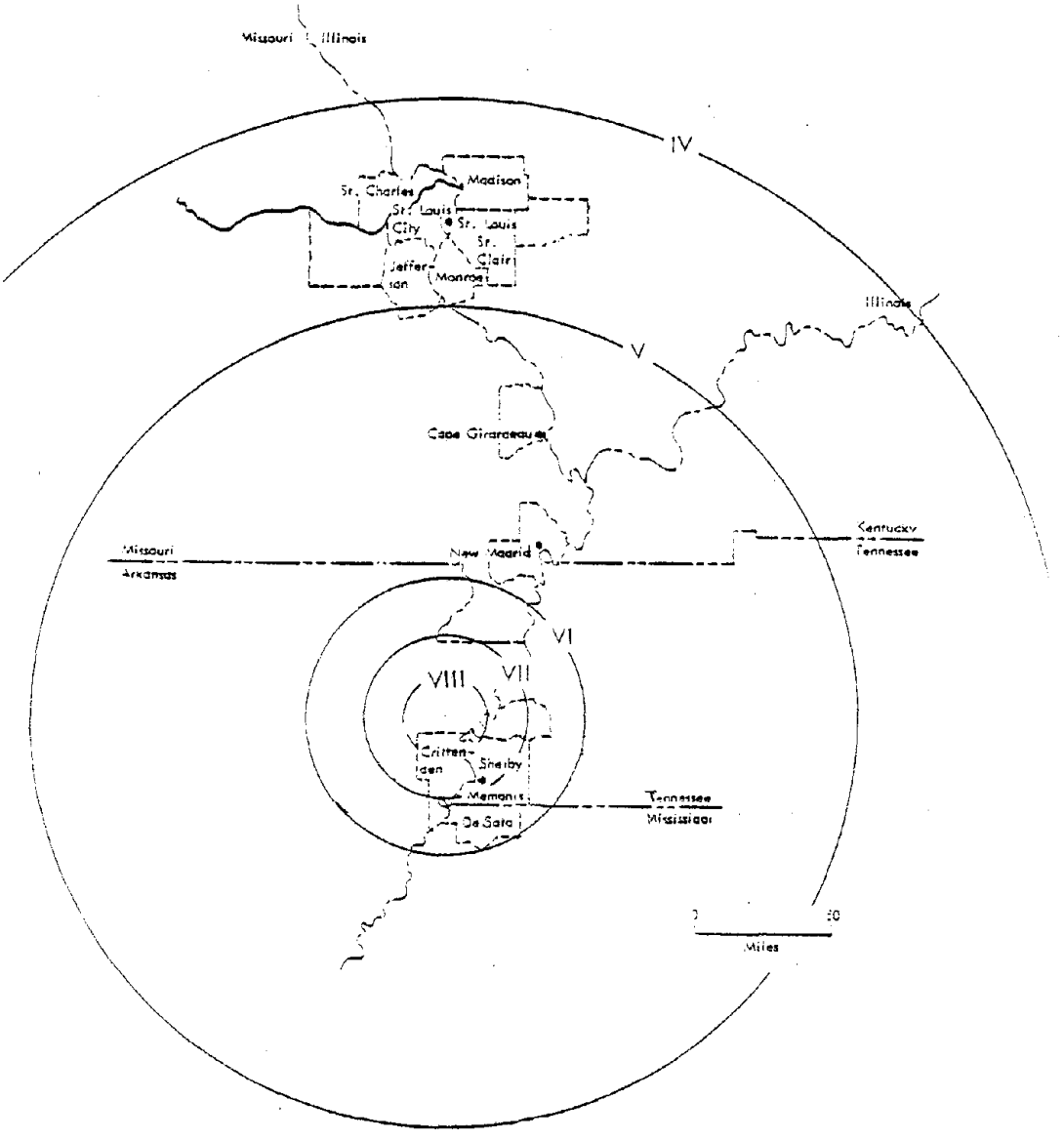


Figure II-6 - Deterministic approach: I_o = VIII at Marked Tree, Arkansas.

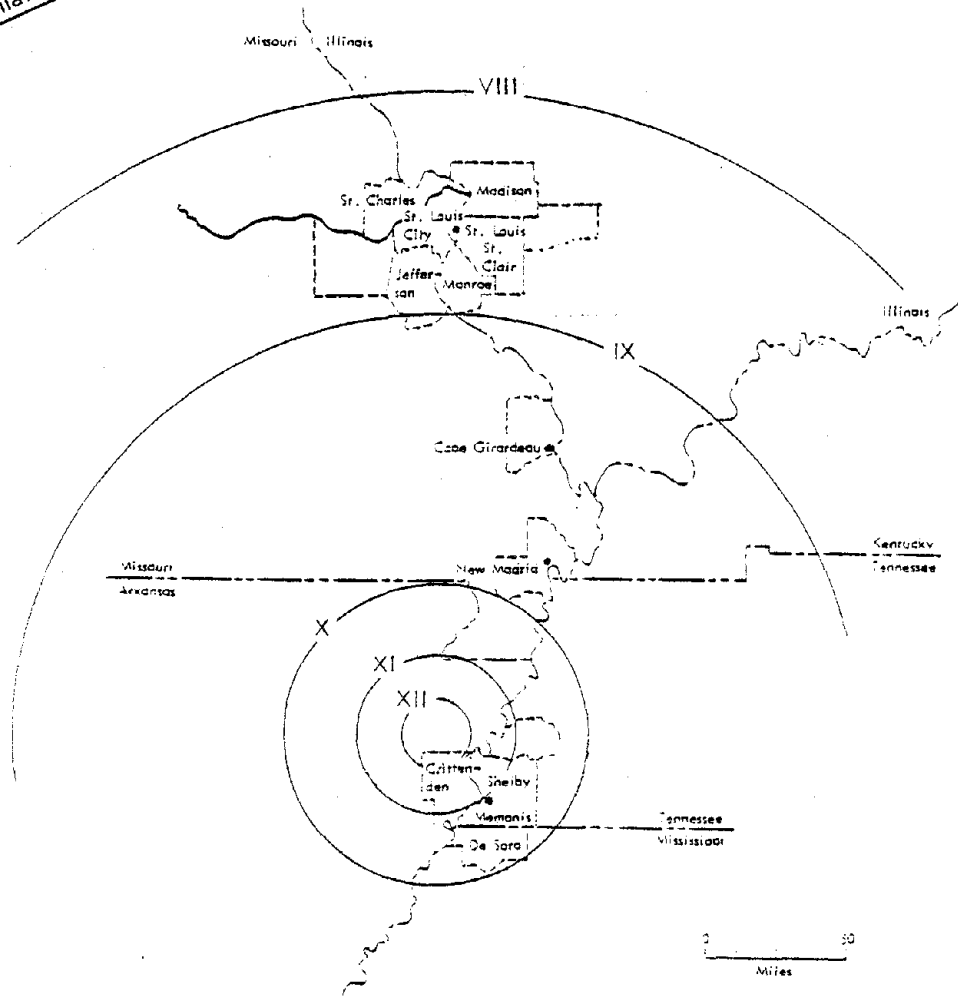


Figure II-7 - Deterministic approach: I_o = XII at Market Tree, Arkansas.

CHAPTER III

SURFICIAL MATERIALS AND GEOLOGICAL SUSCEPTIBILITY ANALYSIS

The damaging effect of an earthquake depends not only on the magnitude and intensity of the quake itself, but also on the ground conditions and the characteristics of the quake receptors as well. Various predictions and risk estimations based on seismological analysis have been discussed in the preceding chapter. This chapter delineates the ground conditions and the geological vulnerability of the study region. This chapter also analyzes the areal extent and physical properties of the surficial materials and bedrock in the four study areas. Information on a particular soil type and its associated bedrock is presented first in Section A, while Section B examines many of the potential hazards associated with each soil type if it were subjected to shaking by a major earthquake. Finally, by combining the surficial materials, bedrock, and other information developed in Sections A and B, the four study areas--St. Louis and Memphis SMSA's and Cape Girardeau and New Madrid counties--have been reclassified according to earthquake hazard susceptibility.

A. Types of Surficial Materials (Soils)

Surficial materials (commonly called soils by engineering geologists) comprise all the fragmented, unconsolidated, or semiconsolidated materials which overlie bedrock including the organic and mineral materials that compose "rock" in the traditional agricultural concept and the deeper materials lying above solid rock. The thickness of these materials varies greatly, being nil in some areas where erosion has kept pace with rock weathering but reaching as much as a few hundred feet where there has been extensive redeposition or *in situ* accumulation of rock debris. The nature of surficial materials that have formed *in situ* from the weathering of bedrock is largely a function of bedrock composition, whereas materials redeposited by water, glacial ice, or wind bear no relation to the bedrock upon which they rest.

Residual materials slowly creep downslope under the influence of gravity and slope wash. Such material in the process of migration to valley bottoms is called colluvium; it is thickest at the base of a slope. Understandably, the composition of colluvium may be quite complex because more than one type of surficial material is commonly intermixed.

Brief descriptions of the major types of surficial materials are included in the following pages and include two major categories:

- Transported soils (materials redeposited by water, glacial ice, or wind).

  Alluvium;

  Loess; and

  Glacial deposits

- Residuals soils (formed in situ by the weathering of bedrock).

  Chert-clay residual and colluvial soils; and

  Silt-clay residual and colluvial soils

1. Transported soil: Alluvium is rock debris that has been transported and sorted to various degrees by streams. By the sorting action of running water, alluvium is segregated into more or less distinct gravel, sand, silt, and clay deposits.

The alluvium occurs as valley fill of the major rivers and as the cover formation of the Mississippi embayment area or alluvial plain, excluding Crowley's Ridge. The Mississippi embayment is 100 miles wide at Memphis, Tennessee, and the thickness of alluvium there exceeds 200 feet. The Mississippi River alluvial plain is about 10 miles wide at St. Louis, but from that point to where the plain widens near Cape Girardeau to become the Mississippi embayment, the plain is 4 to 5 miles wide. Here the alluvial fill is from 100 to 200 feet thick. A thickness of over 200 feet has been recorded underlying the floodplain near St. Louis. Significant thicknesses of alluvium underlie the valleys of the larger tributary streams of the Mississippi River. The Meramec River Valley has deposits of alluvium 60 feet thick which do not thin measurably 75 miles upstream from its mouth. Over 125 feet of alluvium has been recorded from test borings in the Kaskaskia River Valley. The Missouri River alluvial plain averages about 1-1/2 miles wide, and the maximum thickness of alluvium exceeds 120 feet at the confluence of the Missouri and Mississippi rivers.

Alluvium is largely unrelated to local bedrock geology and has for the most part been transported long distances from upstream sources. The floodplains of the Missouri and Mississippi rivers are underlain mostly by sand with some gravel at the base near the bedrock surface. A mantle of clay and silt forms the top several feet. In the Mississippi embayment, alluvium is not confined to a valley; rather, in recent epochs of the geologic past, major river channels have migrated laterally many miles, leaving a broad blanket of alluvium across the lowland. Crowley's Ridge comprises remnants of a higher land which escaped destruction by lateral channel cutting. A former river channel separates segments of the ridge from the Ozark Plateau. Alluvium in the Mississippi embayment is somewhat thicker than in the Mississippi or Missouri River valleys.

Loess is an unconsolidated, porous silt, commonly yellowish brown but may also sometimes be gray, yellow, brown, or red. Loess is characterized by a lack of stratification and the tendency to stand in vertical walls along road cuts and banks undercut by streams. It commonly shows a crude columnar structure formed by erosion along vertical cracks or joints. Loess is essentially a silt. The average sample of loess studied in the laboratory has 60 percent of the material in the 1/16- to 1/32-millimeter grade size range, which would be classified as coarse silt. It contains very little sand or clay. The siliceous minerals quartz and feldspar predominate. Common accessory minerals are hornblende, zircon, garnet, tourmaline, and epidote.

The source of the loess is generally believed to be the broad valleys of the Missouri and Mississippi rivers. During the late stages of glacial retreat, the northwest winds picked up silt and clay from the sediment-choked valleys of these major rivers and redeposited this material as a broad blanket on the uplands over most of the area. Because the winds were generally from the northwest, the loess deposits are thicker on the uplands south and east of the main river valleys. From 50 to more than 100 feet of this windblown silt caps the bluffs adjacent to the Missouri and Mississippi rivers. Away from the major rivers, the cover of loess on the uplands thins rapidly to less than 4 feet thick in places in the study area that are farthest from the Missouri and Mississippi rivers.

Erosion of the loess has exposed bedrock in some of the upland areas, but a thick blanket of it remains, masking the bedrock and other types of surficial deposits in most of the area. Where loess blankets a steep slope, it is moved downward by mass wasting and sheet erosion and accumulates at the base as colluvium. Only after close examination can loess in place be distinguished from loess in secondary transport. On slopes, the true thickness of a loess sheet is almost impossible to measure accurately except by test drilling methods.

Glacial deposits are derived from continental glaciers which moved southward into the area during the relatively recent Pleistocene epoch. Huge volumes of sediments were incorporated into the ice of these glaciers during their southward movement from ice accumulation centers in Canada. Ahead of the advancing ice, meltwater streams carried clay, silt, sand, and gravel into the preglacial valleys of northern Missouri and Illinois, filling them with more or less poorly sorted debris. Ice subsequently overrode these outwash deposits leaving an irregular, unsorted deposit of till that consisted of a heterogenous mixture of clay, sand, and boulders of both local and exotic rocks. Drainage was sometimes interrupted by the ice, forming temporary bogs or shallow lakes in which silt and clay accumulated. Deposition of the various glacier-related sediments was controlled by the complex preglacial topography and by many local irregularities of ice movement. Accordingly, the relationships among these sediments are complex and their thickness is highly variable, but the glacial

materials attain thicknesses of over 100 feet in many areas. The alluvium underlying the floodplains of the Missouri-Mississippi River is largely derived from glacial deposits by the winnowing and sorting action of the running water which transported these sediments to their site.

The silt and clay that formed extensive deposits of loess are the finer grained constituents of these glacial deposits carried by melt-waters and deposited on the floodplains of the major rivers. Later these fine materials were picked up and carried by wind to be deposited as loess on the adjacent highlands.

The transported soil category also includes stream-deposited lenses of coarse sand and gravel that were deposited on bedrock before the alluvial fill of the major river valleys. These deposits are exposed on Crowley's Ridge in Cape Girardeau County and along the Mississippi River bluff in the vicinity of Memphis.

2. Residual soil: Chert-clay residuum and colluvium are types of surficial deposit derived primarily from cherty limestones and dolomites. Limestone and dolomite, collectively known as carbonates, form the bedrock in much of Cape Girardeau County and the St. Louis area under study. Carbonates are slowly dissolved by groundwater both at the bedrock surface and deep in the cavern systems. The calcium and magnesium bicarbonates are removed in solution, but particles of clay, grains of sand, and nodules of chert are far less soluble than the enclosing carbonate rock and thus accumulate at the bedrock surface as residuum. Large fragments of chert in clay-rich residuum stabilize the finer particles, but surficial materials of this type, particularly those high in clay content, have a tendency to slump on steep slopes.

Silt-clay residuum and colluvium are formed from the weathering of bedrock composed predominantly of shale, claystone, or sandstone. Residual materials developed on bedrock of this type are relatively thin (seldom over 30 feet thick) because they are easily eroded by slope wash. Slope wash is more pronounced in areas underlain by impermeable bedrock of shale or clay. From downslope movement, clay and silt sometimes accumulate at the base of hills to form thick deposits of colluvium.

The residual soil category also includes soils that have been derived from bedrock of variable composition; for example, chert-clay and silt-clay residual soils in variable amounts.

B. Earthquake Hazards Associated with Surficial Materials

During an earthquake, the degree of shaking that is necessary to initiate failure of surficial materials is dependent on a variety of factors including soil and bedrock types, slope, and water saturation. The main types of surficial material failure that can be expected in the

study area if it is subjected to a major earthquake are (1) liquefaction of alluvium, and (2) landslides. Fluctuation of water levels and an increase in turbidity in wells can also be expected. Fissuring and collapse of soils into underground caverns in areas of karst topography would be a likely consequence as well.

1. Liquefaction of thick alluvium: The physical properties of the alluvium that underlies most areas of the Mississippi embayment and floodplains of the Missouri and Mississippi rivers are of utmost importance when considering the effects of a major earthquake with an epicenter in the central interior United States. The alluvium is characterized by a thin top stratum of clay and silt from a few feet to several feet thick. Beneath this top stratum is a massive sand and gravel substratum ranging in thickness from 50 to over 200 feet. Under normal conditions, the water table lies about 10 to 20 feet below the land surface, and the zone of groundwater saturation corresponds to the sand and gravel substratum. The thin top stratum of clay and silt forms a much more cohesive deposit than the underlying sand and gravel. The downward-coarsening, cohesive-noncohesive sequence is a significant factor in response to earthquakes by these alluvial deposits.

Unconsolidated sandy alluvium in areas with high water tables has been observed to liquefy during major earthquakes in all parts of the world (Seed, 1970). The liquefaction of the cohesionless layer of sand results from the collapse of the structure by shock and strain translated by seismic earth waves. This is a rapid and often catastrophic failure of predominantly cohesionless material that is generally at or near full saturation. The effect is a temporary transformation of the loosely packed sediment into a fluid mass.

The tendency of the saturated cohesionless materials to compact must be accompanied by an increase in pore water pressure in the soil and a resulting movement of water from the voids. Water is thus caused to flow upward to the ground surface where it emerges in the form of "sand spouts" and "sand boils." The development of high pore water pressures due to ground vibration and the upward flow of water turns the sand into a liquefied condition essentially similar to quicksand. Fragments of the disrupted cohesive layer may briefly float on a layer of liquefied sand.

During the Niigata, Japan, earthquake in 1964, automobiles, structures, and other objects gradually settled into the resulting quicksand. Many structures settled more than 3 feet, and settlement was accompanied by severe tilting. In several cases, lightweight structures that had been buried, such as storage tanks, floated to the surface. The emergence of water and sand at the surface and the accompanying land subsidence resulted in considerable flooding (Seed, 1979).

During the New Madrid earthquakes of 1811-1812, subsidence was 14 feet at New Madrid and 5 to 20 feet at Reelfoot Lake (Fuller, 1912). Geological effects of the New Madrid earthquake series of 1811-1812 in the upper portion of the Mississippi embayment included land subsidence, uplift or doming, bank caving, fissures, and sand blow phenomena. Fissures resulting from the liquefaction of sand are widespread in the alluvial valley and offer the greatest potential for definitively assessing the effects of major earthquakes on thick alluvial deposits. Sand blows, fissures, and related phenomena caused by liquefaction of shallow subsurface sand and its extrusion to the surface are unquestionably the most widespread and significant effects correctly attributable to the New Madrid earthquake (Saucier, 1977).

Liquefaction during the New Madrid earthquakes caused features ranging from single low circular mounds a few tens of feet in diameter to linear ridges thousands of feet long. Farmland near New Madrid was buried beneath several feet of sand in 1811-1812. Sheets of extruded sand which is now being spread by plowing and wind is still clearly visible in some counties. Work presently being conducted by the U.S. Army Corps of Engineers is focused on sand blows, fissures, and related phenomena caused by the liquefaction of shallow subsurface sand and its extrusion to the surface. These features are being classified and mapped at the surface and in the subsurface to establish recognition criteria. Their distribution and morphology are being related to surface geology, soil types, drainage patterns, and topography to determine relative susceptibilities of various deposits to liquefaction during earthquakes.

The density and character of sand blows and fissures are highly dependent on local geology. The overwhelmingly dominant factor is the thickness of the cohesive top stratum. Areas of greatest sand blow and fissure development appear to coincide with areas of thinner substratum. Widespread flooding may be anticipated when large quantities of water and sand are extruded to the surface. Drainage ways are blocked by bank caving and extruded sand.

Detailed mapping of liquefaction phenomana from aerial photographs by Saucier (1977) has revealed their essentially continuous presence over an area of about 4,000 square miles. According to Saucier (1977):

> When looking at the size and nature of the entire area, it is not difficult for one to question whether this may be the most intense and widespread case of earthquake-induced liquefaction in the entire world. It is clear that hundreds of millions of cubic yards of sand were extruded to the surface.

The tendency for the alluvium to fail by liquefaction appears to have been the major cause for the widespread effects of the New Madrid earthquakes of 1811 and 1812 as shown by the intensity maps prepared by Stearns and Wilson (1972). This area corresponds to the region lying within the Roman numeral XII isoseismal line (Modified Mercalli scale) of maps by other workers that appear in the present study.

If liquefaction occurs in or under a sloping soil mass, the entire mass will flow laterally to the unsupported side in a phenomenon termed a flow slide (Seed, 1970). Variation in the relief of the Mississippi River alluvial plain is slight. Most areas are flat and featureless, consisting of natural levees, depressions of former stream channels, and slack-water areas. The highest points on the alluvial plains, excluding structural features, are natural levees that are 25 to 35 feet above the normal stage of the river. A gradient of over 10 percent has been recorded on some of the older natural levees near Memphis. Natural levees interbedded with lenses of cohesionless sand may fail by liquefaction, form flow slides into the watercourses, and cause flooding. Man-made dikes in the New Madrid area have been constructed to a height of 40 or 50 feet. The collapse of these dikes into the extensive system of drainage canals would cause widespread flooding.

Considerable discussion has been devoted to the depths to which liquefaction in sands might occur in surficial materials other than alluvium. In most areas along the Mississippi River, the uplands are rugged to gently rolling hills developed in thick loess deposits. In the Memphis, Tennessee, area, the loess is underlain by several feet of unconsolidated sand and gravel. An earthquake of intensity IX would probably liquefy fine and very fine sands underlying the loess or other surficial materials, causing damage to constructions through loss of bearing capacity (Parks and Lounsburg, 1975).

Marcuson and Gilbert (1972) have investigated the liquefaction potential of the foundation material at the Patoka Dam site in Indiana. Alluvium similar in physical characteristics to that of the major river valleys of this study underlies the dam site. Results obtained from a number of tests indicate the foundation at the Patoka Dam site to be subject to liquefaction if an earthquake of magnitude 6.5 occurred with a peak acceleration of 0.17 g or greater. It is recommended that similar studies be made, particularly at construction sites where large structures may someday be built.

Open to speculation is the degree to which the substratum sands may be densified as a result of having been liquefied during the New Madrid earthquake. The possibility exists that the soils are more dense and hence less susceptible to further liquefaction after a major earthquake. Nevertheless, building on unconsolidated deposits, in particular alluvium that becomes unstable or shakes easily during an earthquake, is more hazardous than building on bedrock.

2. Slope failure: Steep bluffs over 100 feet high in places rise above the floodplain of the Mississippi River at St. Louis and are continuous along both sides of the river to the vicinity of Cape Girardeau where the Mississippi River Valley widens to become the Mississippi alluvial plain or embayment, the northern extension of the Gulf coastal plain. Southward from Cape Girardeau to Memphis and beyond, the bluffs on the east side of the Mississippi River are over 50 feet high.

The bluffs along the Mississippi River in many places have slopes that range from steeply rolling to vertical cliffs.[1/] The upland areas, including the bluffs, are dissected by numerous tributary streams. The result is that a gently rolling to steep, hilly topography has developed; much of the area slopes 10 percent or more. Over 30 percent of St. Charles County has slopes with grades of 10 percent or more (Missouri Department of Natural Resources, 1975). The composition of surficial materials and bedrock in the area along the major waterways is highly variable.

Landslides are the most common type of mass movement to be expected from earthquake shocks along river bluffs and steep, hilly areas inland from the major rivers.

- Types of landslides:

(1) Falls: Loosened material breaking clear and moving to a lower level without seriously disturbing the surface between (Office of Emergency Preparedness, 1972). Rock falls can be expected in cliffed areas eroded in bedrock along the major rivers and in steeply excavated highway excavations, especially in areas where the joints or cracks in the bedrock are parallel to the vertical face of the cliff or excavation.

(2) Slides: There are two types of slides:

. Rotational: This type of slide occurs in slope material that is homogeneous. The rock material will move as a block or spall along a curved plane. This type of slump typically involves a backward rotation of the slice or spall. Rotational slides are commonly developed in loess or glacial till, especially where the weight is increased by water saturation. At Memphis, Tennessee, slumps occur, especially in wet weather, along the high loess bluffs facing the Mississippi River Valley. Mass movements could also be triggered by vibrations during earthquakes (Parks and Lounsberg, 1975).

1/ The following values pertaining to slope are used in this report (Lutzen and Rockaway, 1974): nearly level, 0-2 percent slopes; gently rolling, 2-5 percent slopes; rolling, 5-9 percent slopes; and steeply rolling and hilly, greater than 10 percent slopes.

. Translation or slab slides: In this type of landslide, the slope materials have directions of weakness such as clay layers. The materials move downslope as a unit or slab along a glide plane developed at the base of the material. This type of slide is common in soils or bedrock that are underlain or intercalated with a thin layer of clay. There is a greater potential for a slide to occur when the rock materials are saturated with water that has seeped downward to move laterally along the top of the clay layers, thus building a fluid pressure along the glide plane. An example of a translation of slide would be an area where a thick deposit of loess, residual soil, or glacial till overlying a bedrock of shale or claystone has moved downslope along the slide plane developed on the sensitive clay layer.

(3) Flows: These are mass movements of unconsolidated material that exhibits a plastic or semifluid behavior resembling that of a viscous fluid. Many flows begin as slides, but as the acceleration increases and the material moves downslope, the slide or spall is broken into numerous fragments that exhibit a continuity of motion such as in fluids. Flows may be dry or wet, but water-soaked soils consisting predominantly of fine particles on steep slopes are most likely to become unstable and flow downslope or lose their bearing capacity, allowing structures built on these to sink with minimal lateral movement. Unconsolidated surficial materials such as loess and glacial deposits commonly move as flows.

3. Groundwater problems: The water level and the quality of water in wells of midcontinent United States are affected by earth tremors that occur thousands of miles away. The 1964 Alaska earthquake caused water levels to fluctuate and the water to become turbid in observation wells throughout Missouri (Missouri Geological Survey, 1964a). The Alaskan earthquake affected static water levels in 28 of the 38 observation wells monitored by the Missouri Geological Survey in 30 counties of the state. In 15 wells, the fluctuations were more than a foot (Missouri Geological Survey, 1964b).

4. Soil and bedrock collapse in karst areas: Karst is a type of terrain characterized by solution features such as sinkholes, caves and gullies, enlarged joints, and pinnacled bedrock surfaces. Karst terrains develop by weathering and solution of carbonate bedrock, in particular limestone and dolomite. Areas of karst terrain are shown in Figures III-1 and III-2 (as shown on pp. 55 and 56). Karst areas have numerous sinkholes and little or no surface drainage into streams. The sinkholes are the surface expression of subsurface collapse resulting from the chemical removal of sizable amounts of bedrock by groundwater solution. Karst topography generally occupies upland areas of low relief usually lacking in well-defined surface drainage. The sinkholes act as natural funnels for surface drainage. In places, semiconsolidated chert-clay residuum forms a "bridge" over solution cavities in the underlying carbonates. Failure of this poorly consolidated residuum by the shaking produced by seismic waves could be a major problem in areas of karst topography.

Various types of sanitary facilities have been built in karst areas in places where the lower reaches of the sinkholes have been blocked by clay and rock debris. The contamination of groundwater supplies by leakage from sewage lagoons and related sanitary facilities is always a potential hazard in karst regions. Structural damage to the residual materials that form a "seal" at the bottom of these facilities by prolonged earthquake shocks could result in effluent from sewage lagoons and sanitary landfills being funneled underground in the karst area and then resurging in springs at a lower level or becoming part of the underground supply. Table III-1 presents some suggested relationships between earthquake susceptibility and different types of soil and bedrock.

C. Geological Vulnerability and Spatial Earthquake Susceptibility Analysis

The susceptibility of the soil and bedrock materials to fail in the study region during an earthquake has been analyzed in detail and is shown in Figures III-1 through III-4.

The susceptibility of earth materials to fail, producing the hazards of landslides, liquefaction, etc., is determined by many interrelated variables. Two of the most important are the soil and bedrock type and the slope. The study area has been subdivided into six zones based on these two variables. Each zone is designated by a Roman numeral. The area where the earth materials are most susceptible to the hazards produced by earthquake shocks are designated by Roman numeral I; the least susceptible areas are assigned Roman numeral VI. Each area designated by a Roman numeral is further subdivided by letters of the alphabet. The lettering system, however, is not intended to indicate degrees of susceptibility. For example, areas designated Ia and Ib are considered to be equally susceptible to the hazards produced by an earthquake. The lettering system is used to call attention to the various combinations of soil, bedrock, and slope that exist in the study area. All areas are considered to have been subjected to earthquake shocks of equal magnitude and duration.

The New Madrid earthquakes of 1811-1812 were located in the northern part of the Mississippi embayment, commonly called the Mississippi structural trough. It is a spoon-shaped depressed area extending north from the Gulf coastal embayment. The structural axis of the trough approximates the course of the Mississippi River. Along this line, crustal movements associated with the development of the embayment or trough began in the Late Cretaceous epoch, almost 100 million years ago. The Mississippi embayment, which extends as far north as Cairo, Illinois, and includes southeastern Missouri, western Kentucky, western Tennessee, and eastern Arkansas, received large amounts of sediment in the Late Cretaceous and early Tertiary as the basin formed by downwarping of the crustal rocks. The sediments comprise beds of predominantly sandstone and claystone and have a combined thickness of almost 3,000 feet in some parts of the embayment.

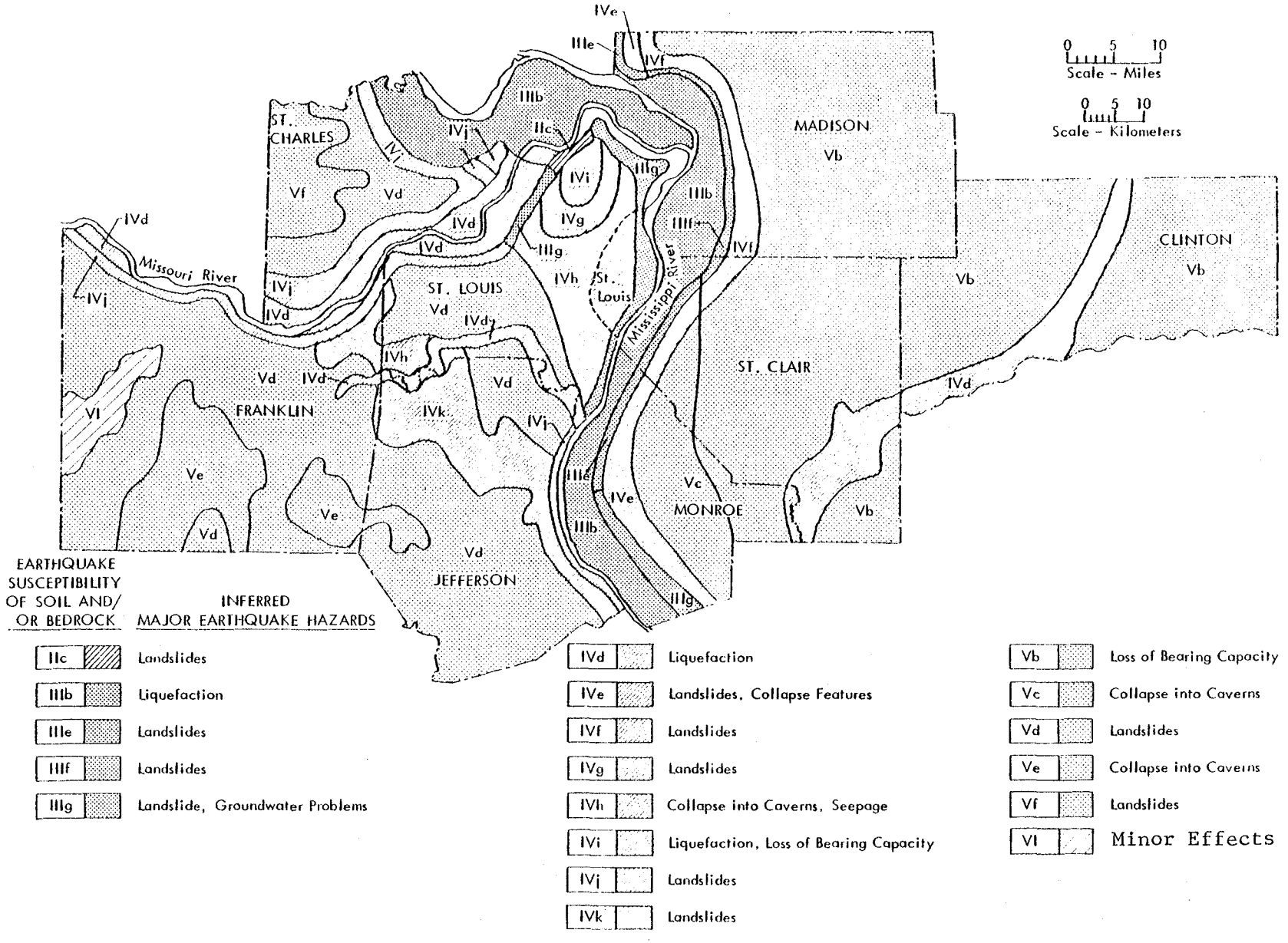
TABLE III-1

EARTHQUAKE SUSCEPTIBILITY SCALE FOR SOIL AND BEDROCK

Susceptibility	Soil Type and Bedrock	Inferred Major Earthquake Hazards
Ia	Very thick alluvium over thick poorly consolidated bedrock.	Liquefaction: Sand "boils," mud "spouts," subsidence, uplift, fissuring, bank caving, slides, failure of fills on weak foundations; for example, collapse of man-made levees that dam canals causing flooding.
Ib	Thick loess overlying unconsolidated lenses of sand and gravel over thick poorly consolidated bedrock.	Instability of soils on steep slopes, slides and flows, liquefaction of thin water soaked sand lenses under loess resulting in various landslides and loss of soilbearing capacity.
IIa	Thick alluvium over thick poorly consolidated bedrock.	Same as Ia but to a lesser degree.
IIb	Thick loess soil over sand lenses over poorly consolidated bedrock.	Same as Ib but to a lesser degree.
IIc	Very thick loess over cyclic sedimentary bedrock.	Slides, flows, instability of surficial materials on sensitive clay layers.
IIIa	Thick to medium thickness loess over sand lenses over poorly consolidated bedrock.	Same as IIb but to a lesser degree.
IIIb	Thick alluvium over massive predominately carbonate bedrock.	Liquefaction.
IIIc	Thin loess soil and residual soil over carbonate bedrock with shale layers.	Instability of soils and bedrock on steep slopes and cliffs; slides and falls.
IIId	Poorly consolidated clays, sands and gravels.	Liquefaction, landslides.
IIIe	Thick loess soil over thin glacial soil over karst bedrock.	Slides, flows in steeply rolling to cliffed areas; collapse of bedrock; slides down slopes into sinkholes, groundwater problems.
IIIf	Thick loess soil, thin to thick glacial soil over cyclic sedimentary bedrock.	Slides, flows in steeply rolling to cliffed areas, liquefaction of water saturated sand lenses in thick glacial soil; slides developed on sensitive clay layers.
IIIg	Thick loess on karst bedrock.	Slides and flows on steeply rolling terrain, groundwater problems.
IVa	Thin loess soil over sand lenses and poorly consolidated bedrock.	Slides along larger streams where slope is steep.
IVb	Residual soil and thin loess soil on carbonate bedrock with some shale.	Instability of slopes on steeply rolling terrain.
IVc	Residual soils of variable thickness on karst.	Collapse of bedrock into caverns, gently rolling upland but slides on steep slopes into sinkholes.
IVd	Medium to thick alluvium over massive to predominately carbonate bedrock.	Liquefaction.

TABLE III-1 (Concluded)

Susceptibility	Soil Type and Bedrock	Inferred Major Earthquake Hazards
IVe	Medium thickness loess soil over karst bedrock.	Collapse of soil into caverns.
IVf	Medium to thick loess soil, thick to thin glacial soil overlying cyclic sedimentary bedrock.	Slides in steeply rolling areas, liquefaction of water saturated sand lenses in thick glacial soils.
IVg	Medium to thin loess over cyclic sedimentary bedrock over karst.	Gently rolling, 2 to 5 percent slopes but slides where slopes are steep.
IVh	Thin to medium thickness loess soil over karst.	Mostly gently rolling, 2 to 5 percent slopes but collapse of residual soil into caverns; slides into sinkholes, groundwater problems.
IVi	Thick loess on carbonate bedrock.	Slides, falls, flows in steeply rolling and cliffed areas.
IVk	Medium to thin loess over residual soil over carbonate bedrock with some shale.	Slope instability where thick shale is present; slides, falls on cliffs along lower reaches of major streams.
Va	Thin loess over sand and gravel over poorly consolidated bedrock.	Loss of bearing capacity of soil.
Vb	Thin to medium loess soil, thin to thick glacial soil over cyclic sedimentary bedrock.	Loss of bearing capacity on thick loess with sand lenses; minor slides on gently to almost flat slopes.
Vc	Medium to thin loess soil over karst.	Minor slides on gentle to almost flat slopes; collapse of bedrock and soil into caverns.
Vd	Medium to thin loess soil over residual soil over carbonate bedrock.	Slides along major stream valleys where terrain is steeply rolling; seepage problems in permeable bedrock.
Ve	Residual soil over sandstone bedrock.	Roof collapse where sandstone is underlain by cavernous carbonates.
Vf	Medium to thin loess soil over thin glacial soil over carbonate bedrock.	Gentle (2 to 5 percent) to rolling (5 to 10 percent) slopes but slides on sensitive clay lenses may develop.
VI	Thin loess soil over cyclic and carbonate bedrock.	Soil bearing problems in ancient clay-filled sinkholes.



EARTHQUAKE SUSCEPTIBILITY OF SOIL AND/ OR BEDROCK	INFERRED MAJOR EARTHQUAKE HAZARDS
IIc	Landslides
IIIb	Liquefaction
IIIe	Landslides
IIIf	Landslides
IIIg	Landslide, Groundwater Problems
IVd	Liquefaction
IVe	Landslides, Collapse Features
IVf	Landslides
IVg	Landslides
IVh	Collapse into Caverns, Seepage
IVi	Liquefaction, Loss of Bearing Capacity
IVj	Landslides
IVk	Landslides
Vb	Loss of Bearing Capacity
Vc	Collapse into Caverns
Vd	Landslides
Ve	Collapse into Caverns
Vf	Landslides
VI	Minor Effects

Figure III-1 - Earthquake susceptibility of soil and bedrock, St. Louis, Missouri, area.

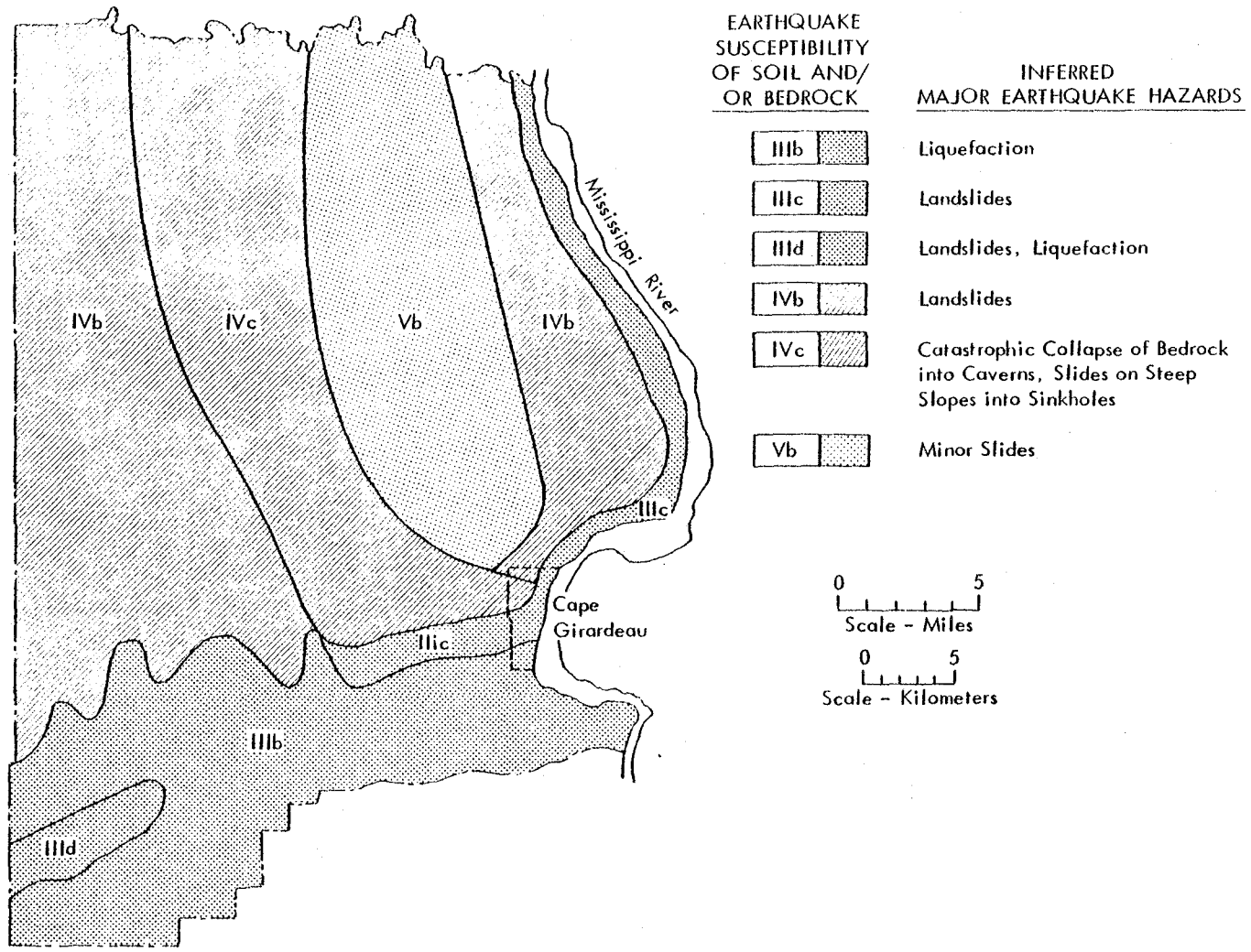


Figure III-2 - Earthquake susceptibility of soil and bedrock, Cape Girardeau County, Missouri.

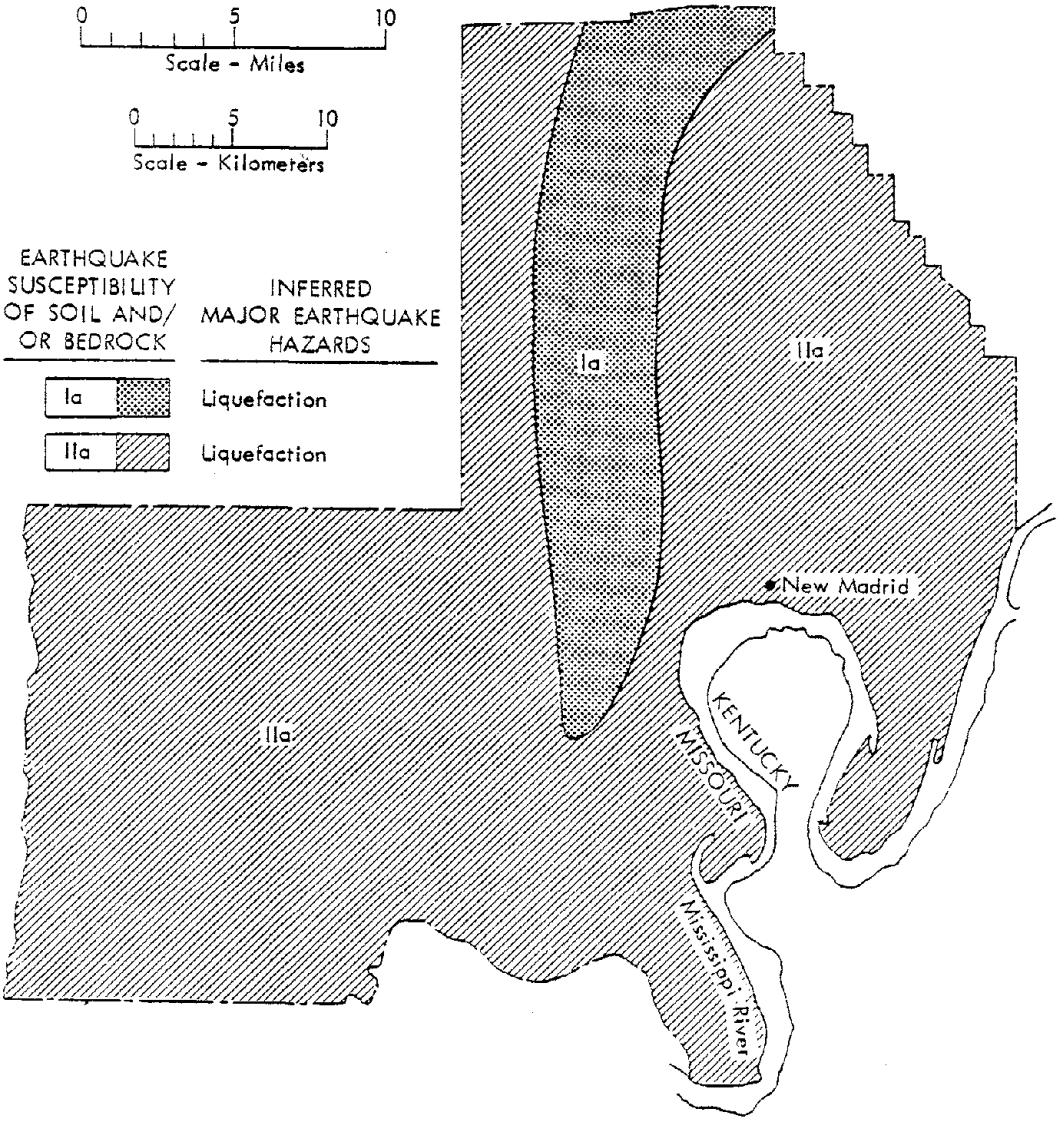


Figure III-3 - Earthquake susceptibility of soil and bedrock, New Madrid County, Missouri.

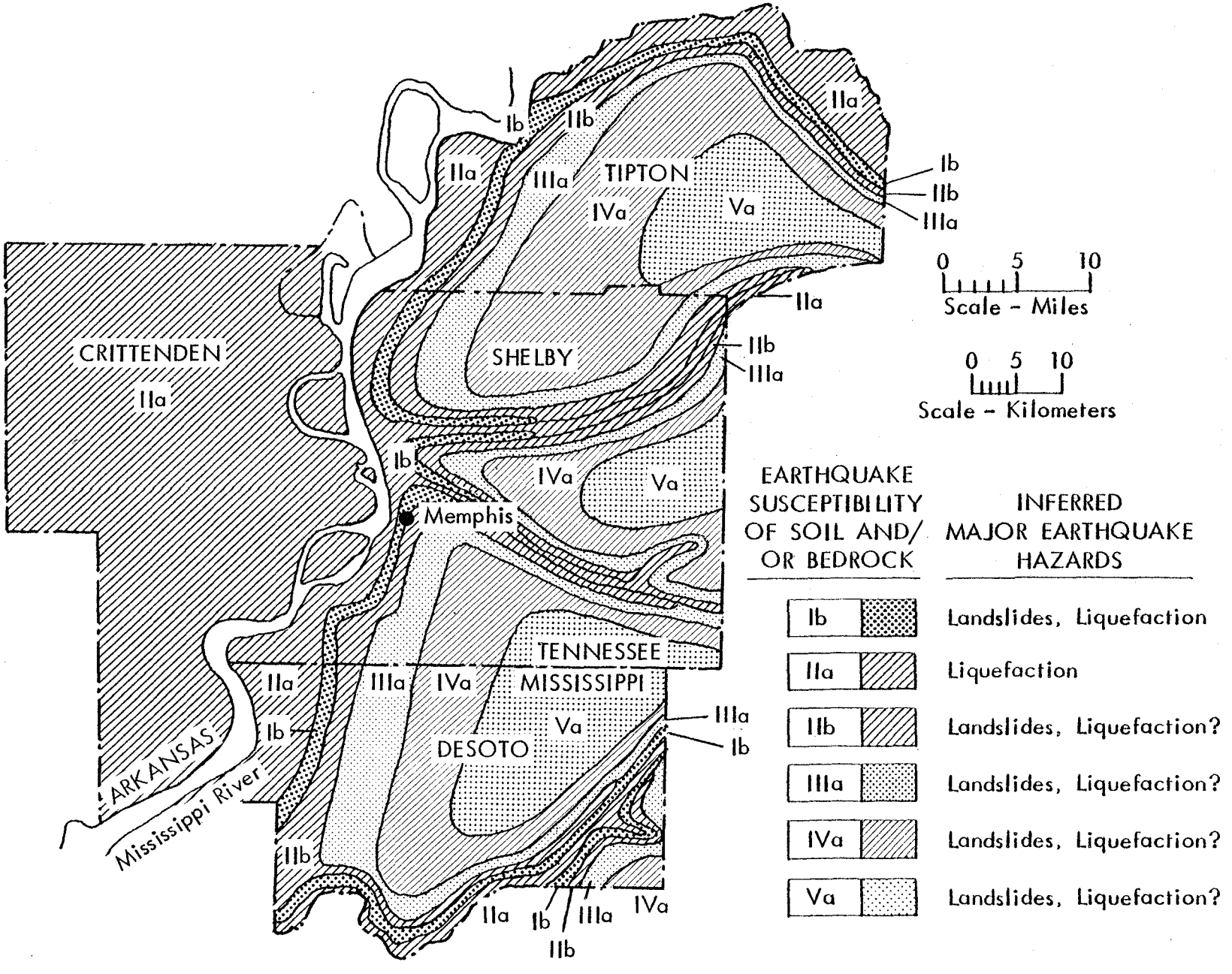


Figure III-4 - EARTHQUAKE SUSCEPTIBILITY OF SOIL AND BEDROCK MEMPHIS, TENN. AREA

The strata on the western side of the embayment in Missouri and Arkansas dip at very low angles to the east. In southern Illinois, they dip at very low angles to the south. On the east, in western Kentucky and Tennessee, they dip at very low angles to the west. Thus, the attitude of these strata form a spoon-shaped structure with the structural axis dipping to the south. Many earthquakes have occurred along the axis of the Mississippi embayment, including the New Madrid earthquakes of 1811-1812 that centered in the northern part of the embayment. These earthquakes are evidence that earth movements are still occurring in the embayment.

Most earthquakes are the result of shock waves created by the sudden release of slowly accumulated stress in rigid bedrock. The release of stress results in the rocks sliding along fractures called faults. On either side of the fault, the rock is offset. The sliding relieves the stress for a time; but continued stress accumulation often leads to recurrent, sudden slippage on the fault, and more earthquakes are the result.

There is little direct evidence of structural attitudes of the downwarped and possibly faulted bedrock that underlies the alluvium. The faults are not easily mapped at the surface because of burial by mud from the many streams and lack of good exposure in soft alluvial sediments. But this is not the case in areas adjacent to the Mississippi embayment where faults are exposed at the surface in the consolidated, resistant bedrock formations. Information concerning the subsurface rocks of the Mississippi embayment is derived mainly from test drilling and geophysical methods.

Faulting at the surface has not been unequivocally established for the New Madrid earthquakes of 1811 and 1812, but the available evidence strongly suggests that faulting did occur. Historic accounts mention the formation of both barriers and waterfalls across the Mississippi River near New Madrid. One of the waterfalls was estimated to be 6 feet high (indicating vertical slippage of adjacent rock masses (Fuller, 1912). This fault extends below the surficial sediments, and borings show a vertical displacement of 40 feet in Eocene beds 160 feet below the surface (Army Corps of Engineers, 1950). Other areas that sank or rise during the earthquake also may be bounded by faults, but no direct information about this is available.

Fuller (1912) placed the series of New Madrid earthquakes of 1811-1812 along a line extending from west of the town of New Madrid to a point a few miles north of Parkin, Arkansas. He believed this line might be along a deep-seated fault in the pre-Cretaceous rocks of the embayment or trough. Nuttli placed the focal depth between 5 and 20 kilometers and the fault plane or planes having a north-northeast, south-southwest strike direction, which is more or less parallel to the Mississippi River. Lines of small earthquakes indicate a series of northeast-southwest trending faults

are active at some depth in the northwest corner of the state of Tennessee. The foci of the earthquakes are several kilometers deep, indicating that they originated in much older rigid rocks underlying soft sediments exposed at the surface (Stearns and Miller, 1977).

The degree of susceptibility of earth materials plotted on the maps, in Figures III-1 through III-4, is based on interpretations made from a variety of published sources listed in the bibliography; the interpretations should be considered general. Appendix A contains a glossary of terms employed in this chapter.

CHAPTER IV

STRUCTURAL AND NONSTRUCTURAL POPULATIONS AT RISK

Chapter II estimated earthquake risk in the study area, and Chapter III described the ground conditions and physical susceptibility of the areas. This chapter deals primarily with the fundamental input information needed in simulating the physical and economic effects of earthquakes on the study area, i.e., an inventory of the populations at risk at present through the year 2030. Given the paucity of data and limited sources of information, this chapter will involve investigations of and projections on the following receptors:

- Socioeconomic setting and number of characteristics of populations at risk including density and distribution patterns of human populations at risk, migration patterns, and the forming of new households;

- Present and expected socioeconomic structures and industrial and community development characteristics including development and construction trends, land utilizations patterns, public policy regarding growth management, and rate of labor force growth and capital formation;

- Populations of buildings by class and structure and nonstructure inventory of properties under risk.

The subject of zoning and regulations for natural hazard protection and emergency preparedness in general and for earthquake damage investigation in particular, including policy issues at all levels of government, are discussed in Chapter VII.

The results of the investigation of populations at risk will provide basic information needed to set up the data base for model simulation. In this chapter three types of major earthquake receptors--structures, human beings, and personal property--are investigated and described for the study area. Special problems encountered during the investigation and projection are discussed, and the potential benefits of earthquake hazard mitigation are presented on the basis of land utilization patterns in terms of "commercial" "industrial," "residential," and "undeveloped," (or "other").

A. Land Utilizations Patterns and Characteristics

Geographically, this project selected two very urban metropolitan areas and two rural counties, St. Louis Standard Metropolitan Statistical Area (SMSA), Memphis SMSA, and Cape Girardeau and New Madrid counties, or a total of 15 counties as samples for study.

To better and more easily assess the damage resulting from any significant earthquake, the populations at risk in the 15 counties under study were investigated separately for each county according to each land use category, "residential," "commercial," "industrial," and "other." The four categories were then further studied on a census tract basis and verified with a field survey and personal interviews.

1. Land utilization patterns and characteristics--1970

a. St. Louis SMSA: With respect to risk populations in the St. Louis SMSA, data were taken from land use maps provided by the East-West Gateway Coordinating Council and derived from information released by "Land Use 2000" (population figures, employment, industry, commuting, housing, farmland acreage) (East-West Gateway Coordinating Council, 1977). Data were verified by a field survey. Figure IV-1 shows the land use patterns by county in the St. Louis SMSA. This map was generalized for the best visual fit; substantiated with additional information, such as the Census of Population and Housing, 1972b; and developed on the basis of general housing information for each census tract.

Eight counties comprise the St. Louis SMSA: St. Charles, Franklin, Jefferson, and St. Louis in Missouri; and Monroe, Madison, St. Clair and Clinton in Illinois. Most of these counties are divided into the four land use classifications except Clinton and Monroe, which were included in the "other" category because they are primarily rural. Information for Clinton County, newly added to the St. Louis SMSA, came from the General Social and Economic Characteristics of Illinois (Census of Population, 1972a). Data dealing with population, percentage working in the county, employment, occupation, housing and percentage rural and urban were used.

Of the eight counties in the St. Louis SMSA, four have vast agricultural land and only small cities, with populations between 500 and 10,000. These counties are Clinton, Monroe, Franklin, and Jefferson. On the other hand, Madison County has a relatively large residential area that follows the Mississippi River, a commercial district along a major trafficway, and a small industrial district on the banks of the Mississippi which runs south into St. Clair County. St. Clair and St. Louis counties also have large residential communities which serve the St. Louis central business district as suburbs and have commercial areas which follow major roads and highways. In St. Louis County, the industrial areas are scattered and generally smaller than those in the City of St. Louis. St. Charles County has enjoyed rapid growth in the past two decades, not only with substantial expansion in residential areas in the county near the City of St. Louis, but also with commercial and industrial developments spilling over from St. Louis County.

The City of St. Louis is completely developed urban area. It has an industrial zone which parallels the industry on the Illinois side

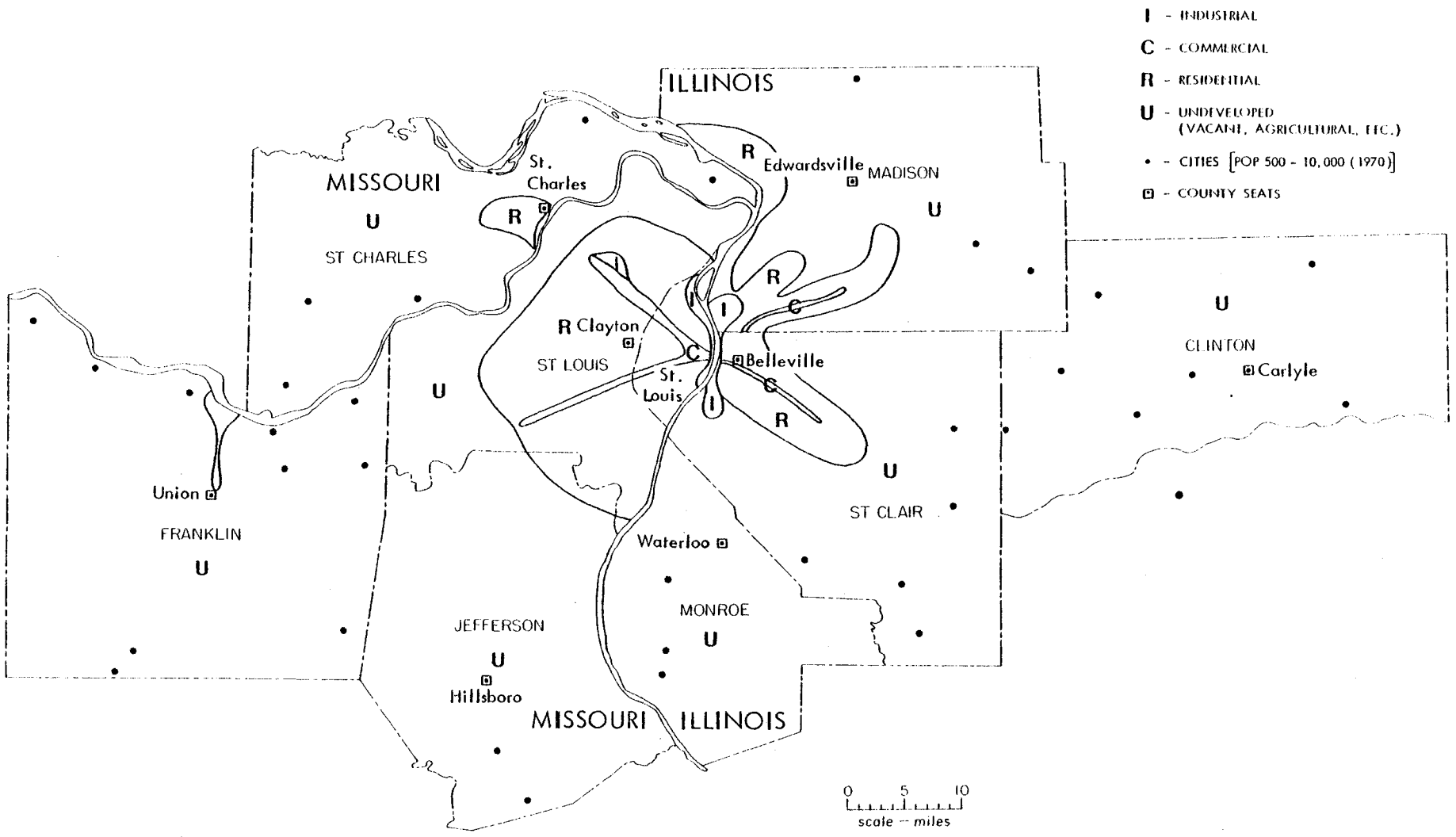


Figure IV-1. St. Louis SMSA: 1970 Land Use.

of the Mississippi River, a commercial area branches out from the central business district along the river in the heart of the city. The rest of the City of St. Louis is residential.

The land use patterns and the size distribution of these uses for each county were roughly estimated on the basis of zoning maps obtained from the city planning departments. Table IV-1 shows, in matrix form, on pp. 65 and 66, land use purposes and distribution patterns. For example, it was estimated that only about 75 percent of all residential areas classified for the City of St. Louis in 1970 were really residential. The remaining 25 percent of the land was used for "commercial" and "other." In a like manner, we estimated that only about 78 percent of the land classified as "commercial" in St. Louis County was really used for that purpose; 15.0 percent was "residential"; 2.0 percent, "industrial"; and 5.0 percent, "other." Since earthquake damage mitigation policy would depend on land utilization patterns, a general assessment of the land use distribution by census tract was not only desirable but deemed essential to damage estimation.

b. Memphis SMSA: Four counties comprise the Memphis SMSA: Shelby and Tipton in Tennessee; Crittenden in Arkansas; and De Soto in Mississippi. Most information for the Memphis SMSA land use classification was taken from the planning commission studies and publications of the 1970 census. In Shelby County, for example, industrial areas were identified from land use maps for Memphis and Shelby counties, then generalized for best visual fit, and revised and finalized after the field trip investigation. For the SMSA's census tracts were used; and for the rural counties, enumeration districts. These units were then divided into four use categories, and distribution matrices were made.

The idea behind this is that some commercial and residential areas are found within industrial boundaries and industrial areas can be found within residential, commercial, and even "other" boundaries. Therefore, percentages of divisions within categories, e.g., the percentages of "residential," "commercial," and "other" within "industrial," were roughly approximated. These approximations were more or less subjectively arrived at and should not, therefore, be considered precise. However, this was followed by a field trip undertaken for the purpose of verifying and revising the classifications, again subjectively.

As seen in Figure IV-2, industrial areas in Shelby County follow the Mississippi River. The commercial areas of the Memphis central business district and environs lie mostly between industrial and residential developments. Information concerning the location of commercial areas, i.e., wholesale/retail trade, services, and financial institutions, was taken from the housing information in the Census Tract for the Memphis SMSA (Census of Population and Housing, 1972a).

TABLE IV-1

LAND USE INFORMATION - 1970

County	Purpose	Land Distribution Patterns			
		Resident	Commerce	Industry	Other
St. Louis SMSA					
Franklin (Mo.)	Resident	0.740	0.050	0.010	0.200
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.200	0.010	0.010	0.780
Jefferson (Mo.)	Resident	0.680	0.010	0.010	0.300
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.200	0.010	0.000	0.790
St. Charles (Mo.)	Resident	0.830	0.010	0.010	0.150
	Commerce	0.100	0.900	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.100	0.010	0.010	0.880
St. Louis (Mo.)	Resident	0.820	0.050	0.030	0.100
	Commerce	0.150	0.780	0.020	0.050
	Industry	0.020	0.050	0.830	0.100
	Other	0.050	0.010	0.020	0.920
St. Louis City (Mo.)	Resident	0.750	0.150	0.000	0.100
	Commerce	0.200	0.730	0.020	0.050
	Industry	0.020	0.050	0.0830	0.100
	Other	0.000	0.000	0.000	0.100
Clinton (Ill.)	Resident	0.000	0.000	0.000	0.000
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.050	0.010	0.000	0.940
Madison (Ill.)	Resident	0.720	0.030	0.050	0.200
	Commerce	0.300	0.700	0.000	0.000
	Industry	0.150	0.050	0.700	0.100
	Other	0.050	0.010	0.010	0.930
Monroe (Ill.)	Resident	0.000	0.000	0.000	0.000
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.050	0.010	0.000	0.940

TABLE IV-1 (Concluded)

County	Purpose	Land Distribution Patterns			
		Resident	Commerce	Industry	Other
St. Clair (Ill.)	Resident	0.880	0.010	0.010	0.100
	Commerce	0.200	0.800	0.000	0.000
	Industry	0.100	0.010	0.740	0.150
	Other	0.070	0.010	0.000	0.920
Cape Girardeau (Mo.)	Resident	0.670	0.030	0.000	0.300
	Commerce	0.150	0.870	0.000	0.050
	Industry	0.050	0.020	0.530	0.400
	Other	0.080	0.005	0.001	0.914
New Madrid (Mo.)	Resident	0.590	0.010	0.000	0.400
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.800	0.200
	Other	0.010	0.001	0.003	0.986
Memphis SMSA					
Shelby (Tenn.)	Resident	0.800	0.030	0.020	0.150
	Commerce	0.350	0.550	0.050	0.050
	Industry	0.100	0.100	0.500	0.300
	Other	0.180	0.030	0.130	0.660
Tipton (Tenn.)	Resident	0.560	0.200	0.000	0.240
	Commerce	0.150	0.800	0.000	0.050
	Industry	0.000	0.000	0.000	0.000
	Other	0.170	0.020	0.000	0.810
Crittenden (Ark.)	Resident	0.560	0.200	0.000	0.240
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.167	0.017	0.000	0.816
De Soto (Miss.)	Resident	0.560	0.200	0.000	0.240
	Commerce	0.150	0.800	0.000	0.050
	Industry	0.000	0.000	0.000	0.000
	Other	0.170	0.020	0.000	0.810

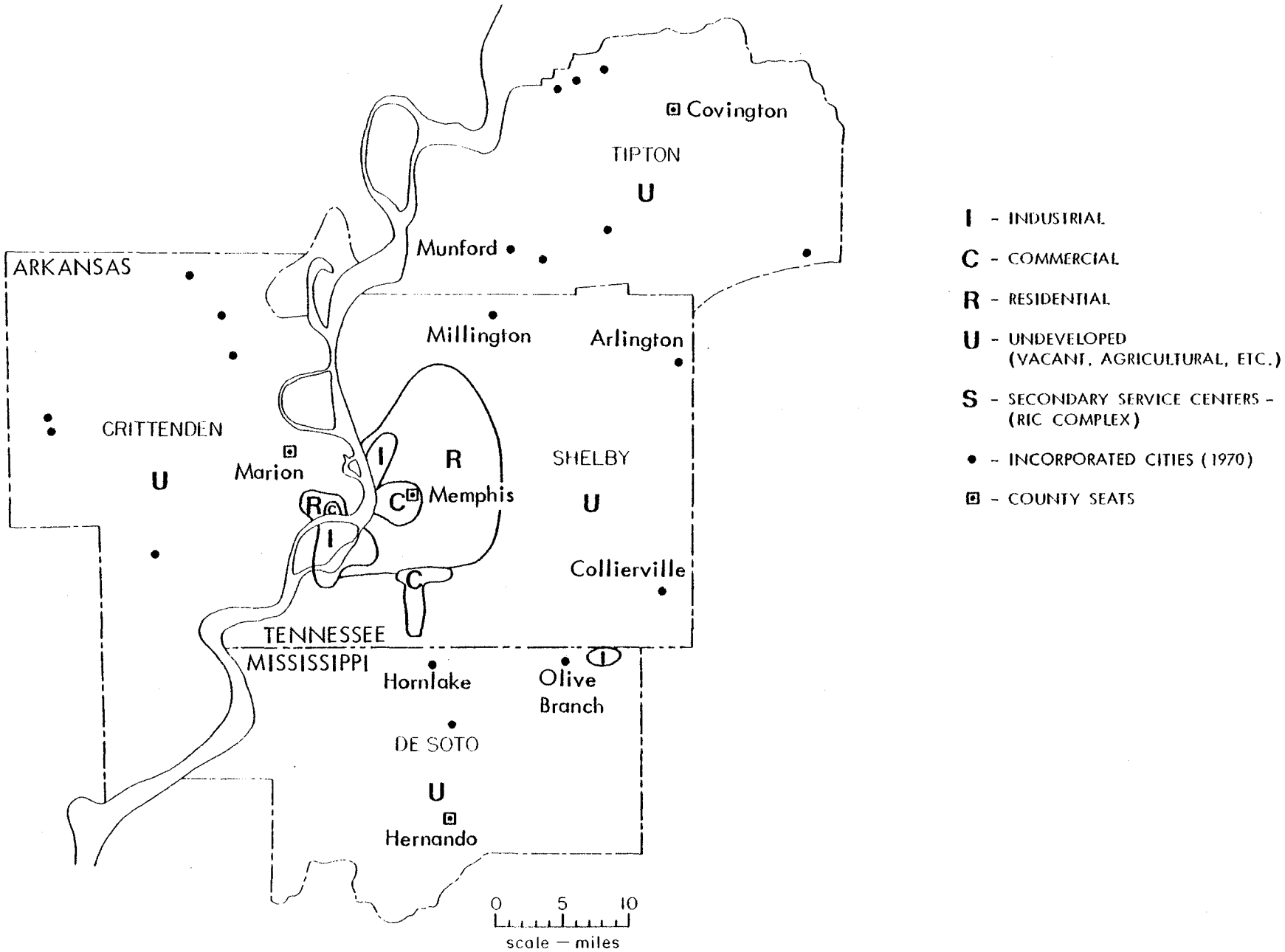


Figure IV-2. Memphis SMSA: 1970 Land Use.

Commercial tracts showed a relative dearth of housing units. The housing unit figures within the supposed commercial area were contrasted with those within the known residential areas. The residential areas, which are characterized by high housing unit figures, outlines the commercial district and bulges near Frayser/Raleigh. This information was substantiated by planning commission studies. The "other" classification effectively makes up the difference and represents agricultural, park, and vacant land. The predominant portion of Shelby County is in the "other" category.

Of the counties other than Shelby in the Memphis SMSA, only Crittenden was included in 1970. And the only developed part of Crittenden County is West Memphis, which lies across the Mississippi River from Memphis and has only residential and commercial districts. There is no true industrial district there although some industry may exist. The other areas of Crittenden County are rural, agricultural, or vacant.

De Soto and Tipton counties are basically rural, each with a small residential area serving the Memphis area. Information concerning Tipton and De Soto counties was taken primarily from the General Social and Economic Characteristics of Tennessee and Mississippi, respectively, published in 1970 Census of Population (1972b, 1972c). Table IV-1 shows the land use patterns and the distribution of the uses by county for the Memphis SMSA.

Unlike the Memphis and St. Louis SMSA's, information on the rural counties Cape Girardeau and New Madrid could not be obtained from census tracts. Instead it was taken from planning commission information, from some general countywide data in the Census, General Social and Economic Characteristics, and from computer printouts of enumeration district data. The planning commissions of both counties included existing land use maps in their studies. These land use maps were then generalized for our study, again with a best visual fit and field observation.

Cape Girardeau County contains two developed areas--Jackson and the city of Cape Girardeau. An indistrial park south of Cape Girardeau along the Mississippi houses most of the county's industry. With the exception of these two cities, the county is mostly agricultural with scattered small communities serving the needs of the rural population.

Like Cape Girardeau, New Madrid is primarily a rural county with three small residential groupings: New Madrid, Portageville, and Sikeston. But the residential density in these areas is much lighter than in Cape Girardeau and Jackson. Most housing in New Madrid County follows the major roads, and the interstitial land is agricultural or vacant. South of New Madrid city is the St. Jude Industrial Park, but there is no true commerical center or district.

Figures IV-3 and IV-4 present the land use classifications and Table IV-1 (pp. 65-66) contains the distribution information by use category for the two rural counties--Cape Girardeau and New Madrid.

2. Land utilization patterns and characteristics--2000: Because of population growth and changes in other social and economic factors, it is likely that land utilization patterns and characteristics of the study counties will be different in the future. Consequently, the value of structures at risk for each use category will undoubtedly change also. The investigation of future land utilization patterns and characteristics for the 15 counties under study was conducted separately for St. Louis and Memphis SMSA's and Cape Girardeau and New Madrid counties.

a. St. Louis SMSA: The data used for projecting the future land utilization patterns and characteristics were based on the information released by "Land Use 2000" (East-West Gateway Coordinating Council, 1977) and are compiled and plotted into Figure IV-5. As these data indicated, two rural counties of the SMSA, Clinton and Monroe, will retain the same status from 1970 to the end of the century. Another county with vast agricultural land and small cities in 1970, Franklin, will gain more business and industrial establishments. The residential area, commercial district, and industrial district in Madison County is likely to be enlarged in 2000, and so will the residential community and commercial areas of St. Clair and St. Charles counties. St. Louis County will experience moderate expansion in its residential area, but its southern neighbor, Jefferson, is expected to establish a large-scale residential community, especially in the area adjoining St. Louis County.

The City of St. Louis itself will become more industrialized as the central portion of the city, the area once designated as residential or commercial, is gradually converted to industrial use. Table IV-2 (on pp. 74-75) shows the land use purpose and the expected pattern of their distribution in 2000. For example, in Jefferson County the residential use of the "other" category is expected to go from 20 percent to 36.5 percent. In St. Clair and St. Charles counties the increase will more than double (from 7 to 15 percent of "other" in St. Clair County and from 10 percent to 21 percent in St. Charles county).

b. Memphis SMSA: The projection was based on the information supplied by the Memphis Regional Planning Commission. (Memphis and Shelby County Planning Commission, 1974, 1976, 1977). These data are summarized in Figure IV-6. It is expected that a substantial portion of the "other" category will be developed for residential purposes in three outlying counties--Crittenden, Tipton, and De Soto. In Shelby County, the portion of "commercial" used for commercial purposes will be expanded, and the "residential" reduced. The rezoning of the residential area will also increase the share of "other" in the commercial category.

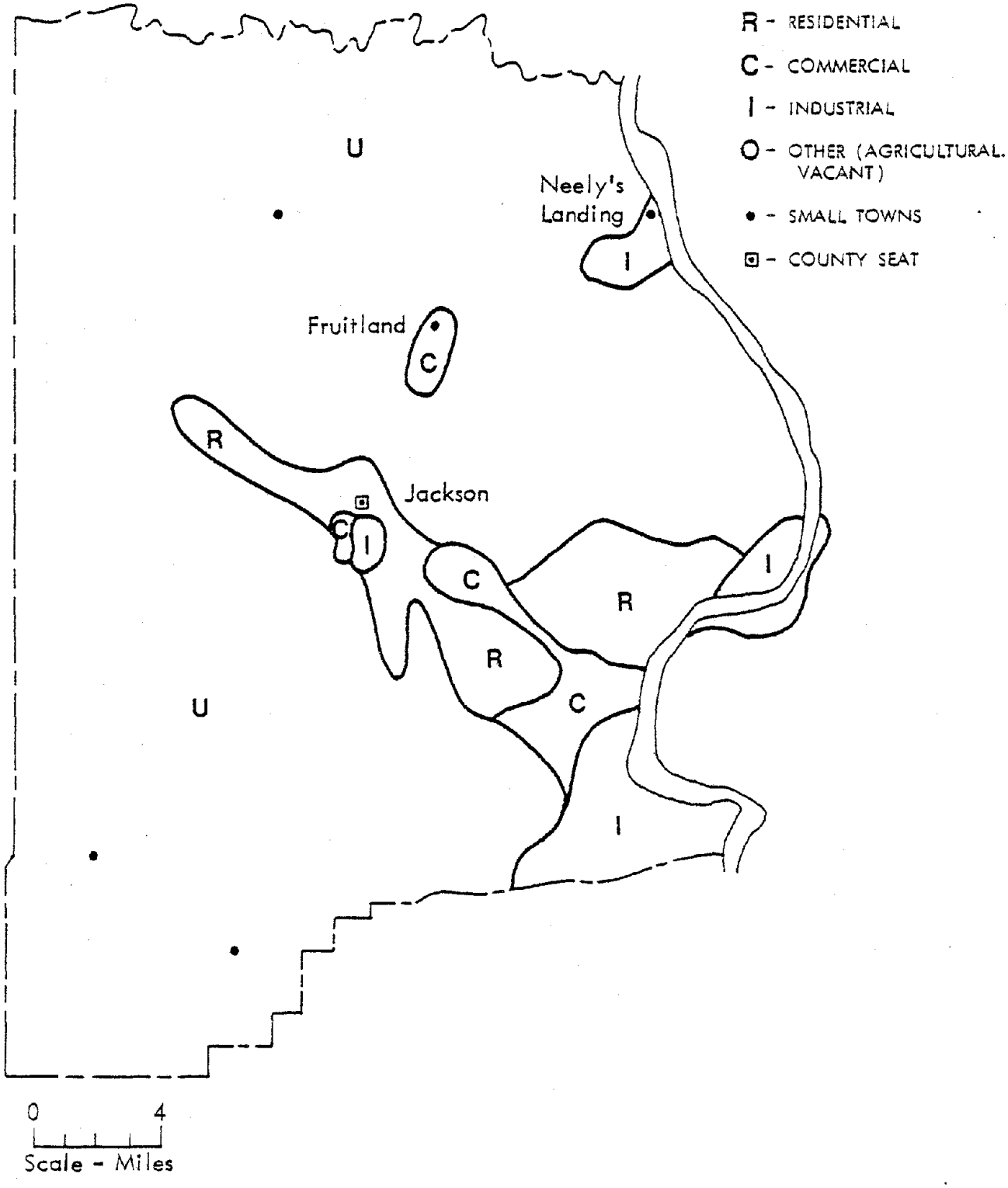


Figure IV-3. Cape Girardeau County Land Use.

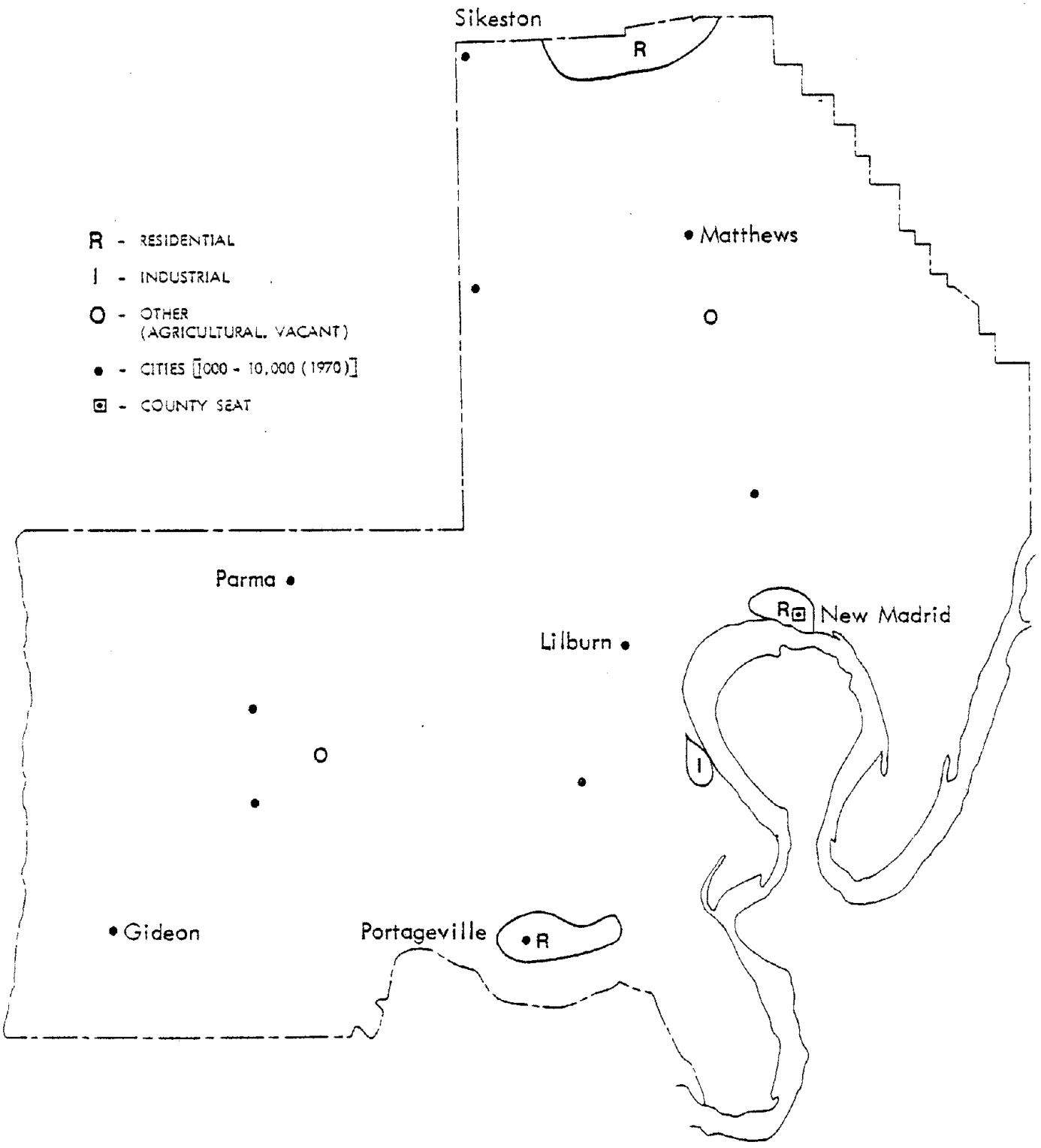


Figure IV-4. New Madrid County Land Use Present.

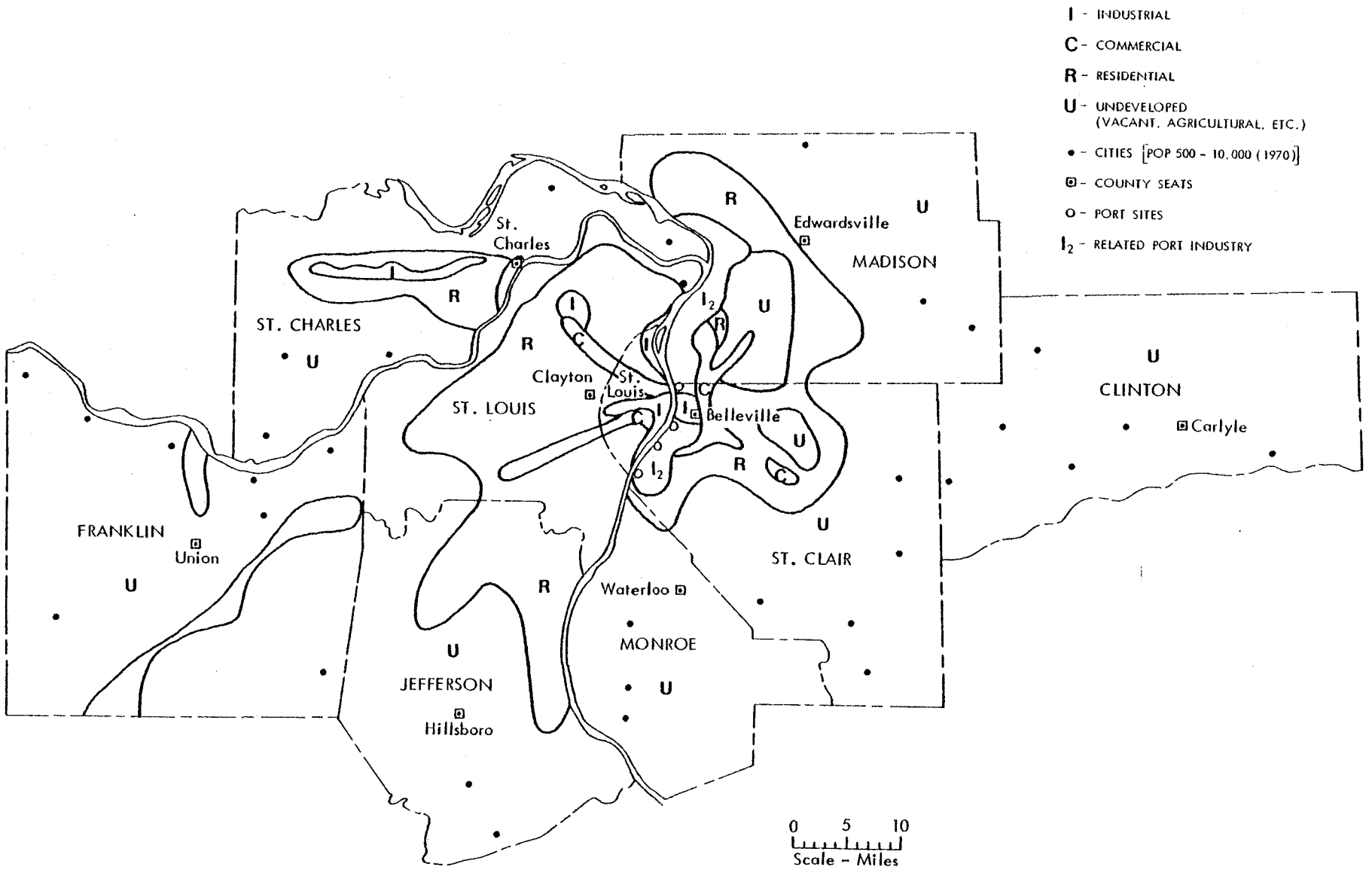


Figure IV-5. St. Louis SMSA: 2000 Land Use.

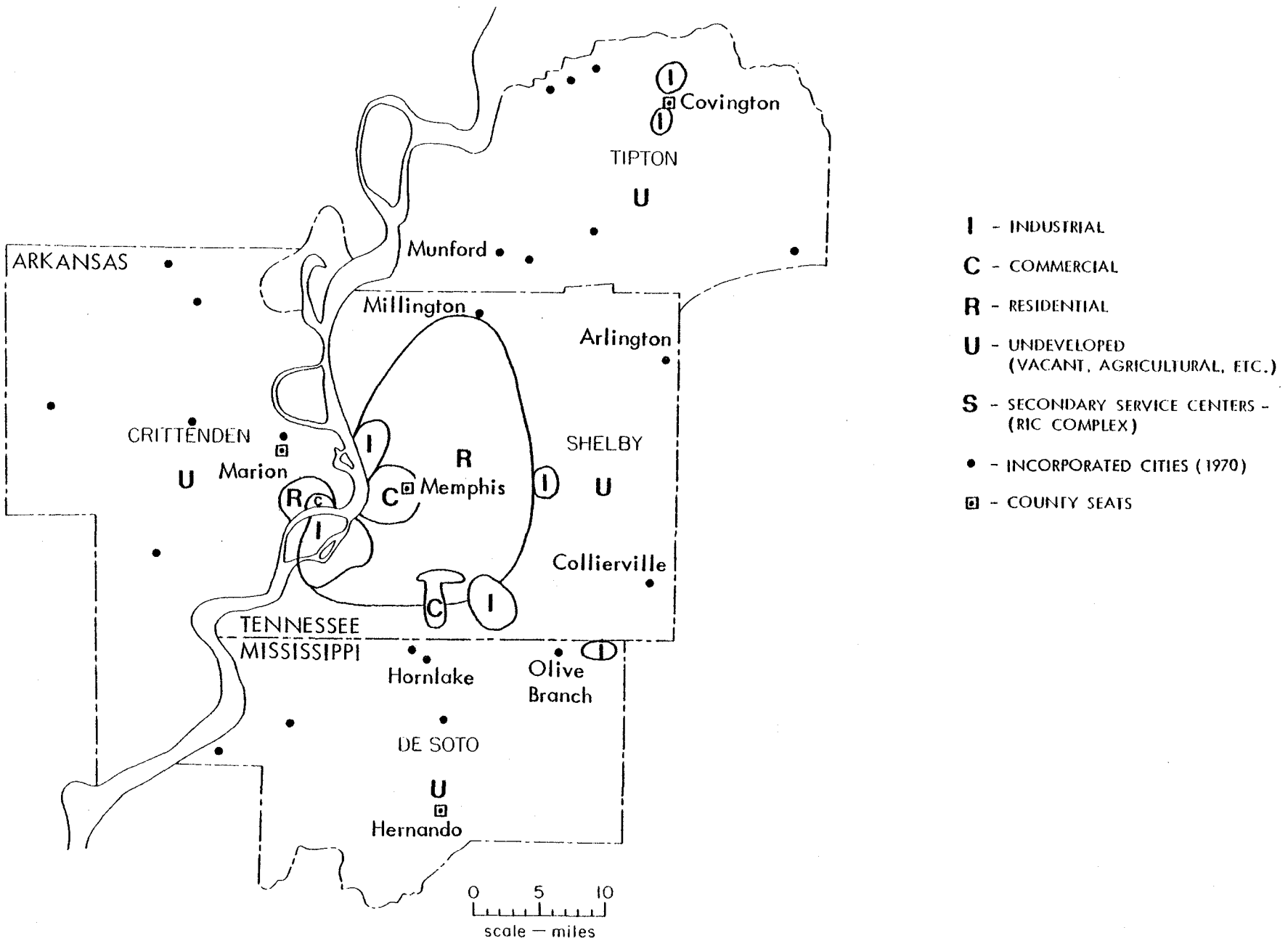


Figure IV-6. Memphis SMSA: 1990 Land Use.

TABLE IV-2

LAND USE INFORMATION - 2000

County	Purpose	Land Distribution Patterns			
		Resident	Commerce	Industry	Other
St. Louis SMSA					
Franklin (Mo.)	Resident	0.695	0.040	0.015	0.250
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.300	0.020	0.010	0.670
Jefferson (Mo.)	Resident	0.630	0.030	0.040	0.300
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.365	0.030	0.010	0.595
St. Charles (Mo.)	Resident	0.600	0.100	0.050	0.250
	Commerce	0.100	0.900	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.210	0.047	0.027	0.716
St. Louis (Mo.)	Resident	0.780	0.050	0.020	0.150
	Commerce	0.150	0.750	0.050	0.050
	Industry	0.100	0.200	0.650	0.050
	Other	0.050	0.020	0.050	0.880
St. Louis City (Mo.)	Resident	0.700	0.250	0.000	0.050
	Commerce	0.300	0.600	0.050	0.050
	Industry	0.150	0.200	0.600	0.050
	Other	0.000	0.000	0.000	1.000
Clinton (Ill.)	Resident	0.000	0.000	0.000	0.000
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.050	0.010	0.000	0.940
Madison (Ill.)	Resident	0.650	0.050	0.050	0.250
	Commerce	0.150	0.700	0.050	0.100
	Industry	0.200	0.150	0.550	0.100
	Other	0.100	0.050	0.010	0.840
Monroe (Ill.)	Resident	0.000	0.000	0.000	0.000
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.000	0.000
	Other	0.050	0.010	0.000	0.940

TABLE IV-2 (Concluded)

County	Purpose	Land Distribution Patterns			
		Resident	Commerce	Industry	Other
St. Clair (Ill.)	Resident	0.770	0.020	0.010	0.200
	Commerce	0.200	0.800	0.000	0.000
	Industry	0.100	0.050	0.750	0.100
	Other	0.150	0.030	0.010	0.810
Cape Girardeau (Mo.)	Resident	0.750	0.040	0.010	0.200
	Commerce	0.100	0.850	0.010	0.040
	Industry	0.030	0.020	0.600	0.350
	Other	0.090	0.005	0.001	0.904
New Madrid (Mo.)	Resident	0.690	0.010	0.000	0.300
	Commerce	0.000	0.000	0.000	0.000
	Industry	0.000	0.000	0.850	0.150
	Other	0.010	0.001	0.005	0.984
Memphis SMSA					
Shelby (Tenn.)	Resident	0.780	0.030	0.020	0.070
	Commerce	0.300	0.620	0.050	0.030
	Industry	0.100	0.100	0.500	0.300
	Other	0.140	0.030	0.130	0.700
Tipton (Tenn.)	Resident	0.690	0.170	0.000	0.140
	Commerce	0.150	0.800	0.000	0.050
	Industry	0.000	0.000	0.000	0.000
	Other	0.050	0.010	0.000	0.940
Crittenden (Ark.)	Resident	0.690	0.170	0.000	0.140
	Commerce	0.150	0.800	0.000	0.050
	Industry	0.000	0.000	0.000	0.000
	Other	0.050	0.010	0.000	0.940
De Soto (Miss.)	Resident	0.690	0.170	0.000	0.140
	Commerce	0.150	0.800	0.000	0.050
	Industry	0.000	0.000	0.000	0.000
	Other	0.050	0.010	0.000	0.940

The study of future land utilization patterns for Cape Girardeau and New Madrid counties was primarily based on the information provided by the Regional Planning Commission, (Yersak, 1976; Hunt et al., 1975; Balsam et al., 1977). Changing patterns in these counties were drafted and mapped in Figure IV-7 and IV-8. There are no drastic changes expected. The land utilization patterns in these two counties for 1990 to 2000 largely reflect the population growth trend. Their distributions are estimated and reported in Table IV-2.

B. Estimated Population at Risk

The earthquake contour maps in Chapter II clearly indicate that a much larger population than that in the 15 counties will be subject to earthquake risk regardless of which approach is employed for earthquake risk estimation. However, this report discusses only the populations at earthquke risk in these 15 counties because the study scope was limited to these two urban metropolitan areas and two rural counties in the New Madrid seismic zone.

1. Population and employment growth--1940 to 1970: In order to better project the population and employment growth in the 15 counties for the year 1980 through 2030, a historical trend analysis in urban development and economic structural change was made. Decennial data on population and employment from 1940 to 1979 were collected from the various publications of the Department of Commerce for both the 15 counties and the functional economic areas (FEA) to which they belong. FEA is a regional definition of many contiguous counties of considerable similarity in terms of economic base, structure, activity, and performance. As of 1972, the entire country was divided into 173 FEA's, and projections for each on income, employment, and other economic variables were made available for 1980 through 2020 (1972). Since a shift-share analysis will be performed later for the projection on populations at risk for the 15 counties being studied, population and employment growth patterns both in the 15 counties and the FEA's are delineated in the section.

Table IV-3 shows the populations and population growth rates from 1940 to 1970. The study region had 2.1 million people in 1940, and the number of human population under earthquake risk had grown to 3.3 million in 1970. Although St. Louis SMSA accounted for more than two-thirds of the total, Memphis SMSA experienced the highest rate of population growth, mostly in Shelby County.

During this period, the population in Memphis SMSA grew by 83.0 percent, but Shelby County doubled its population. While Cape Girardeau has had a very stable population increase, New Madrid County has consistently lost population. On the whole, the two urbanized metropolitan areas seem to

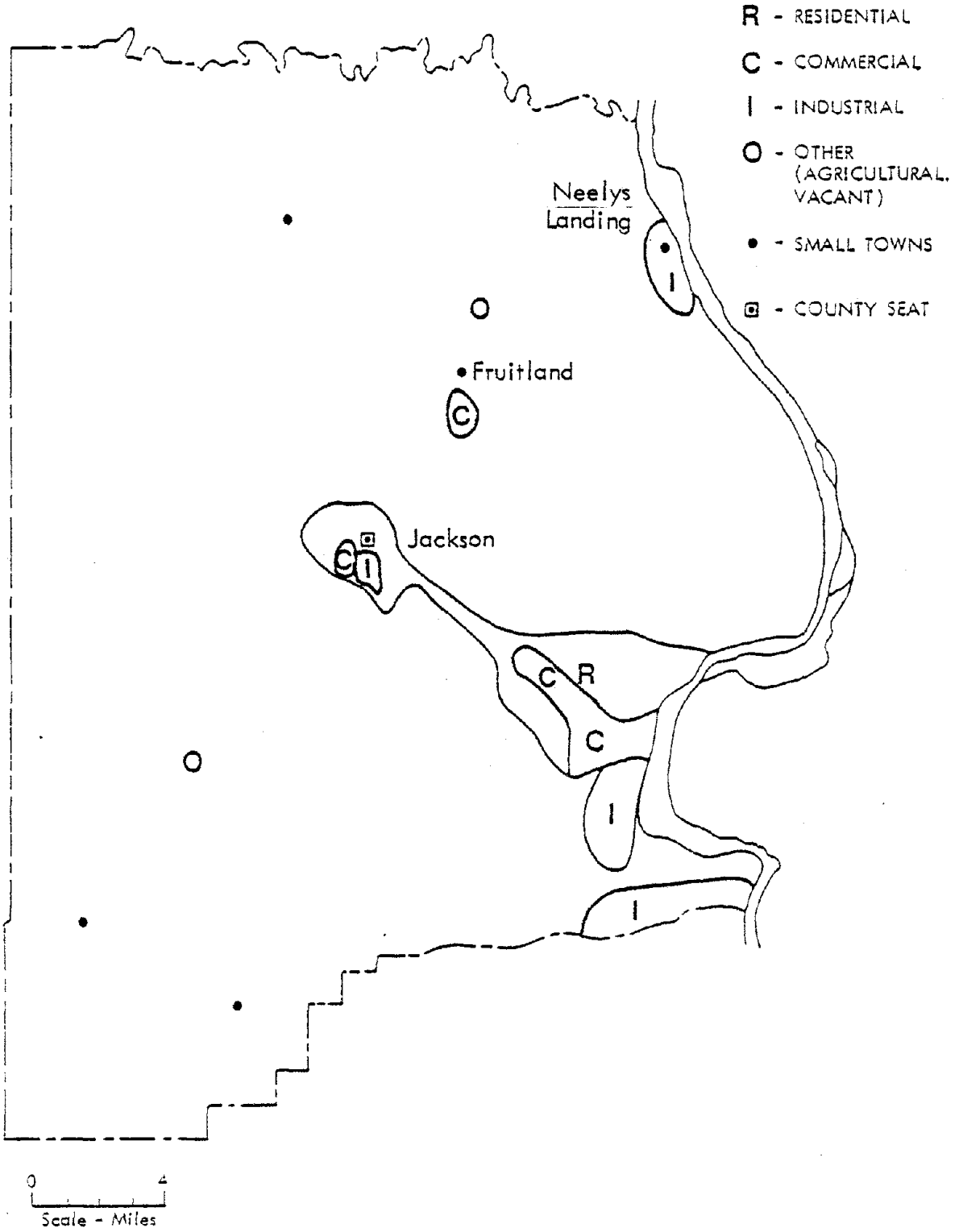


Figure IV-7. Cape Girardeau County Land Use 1990(5).

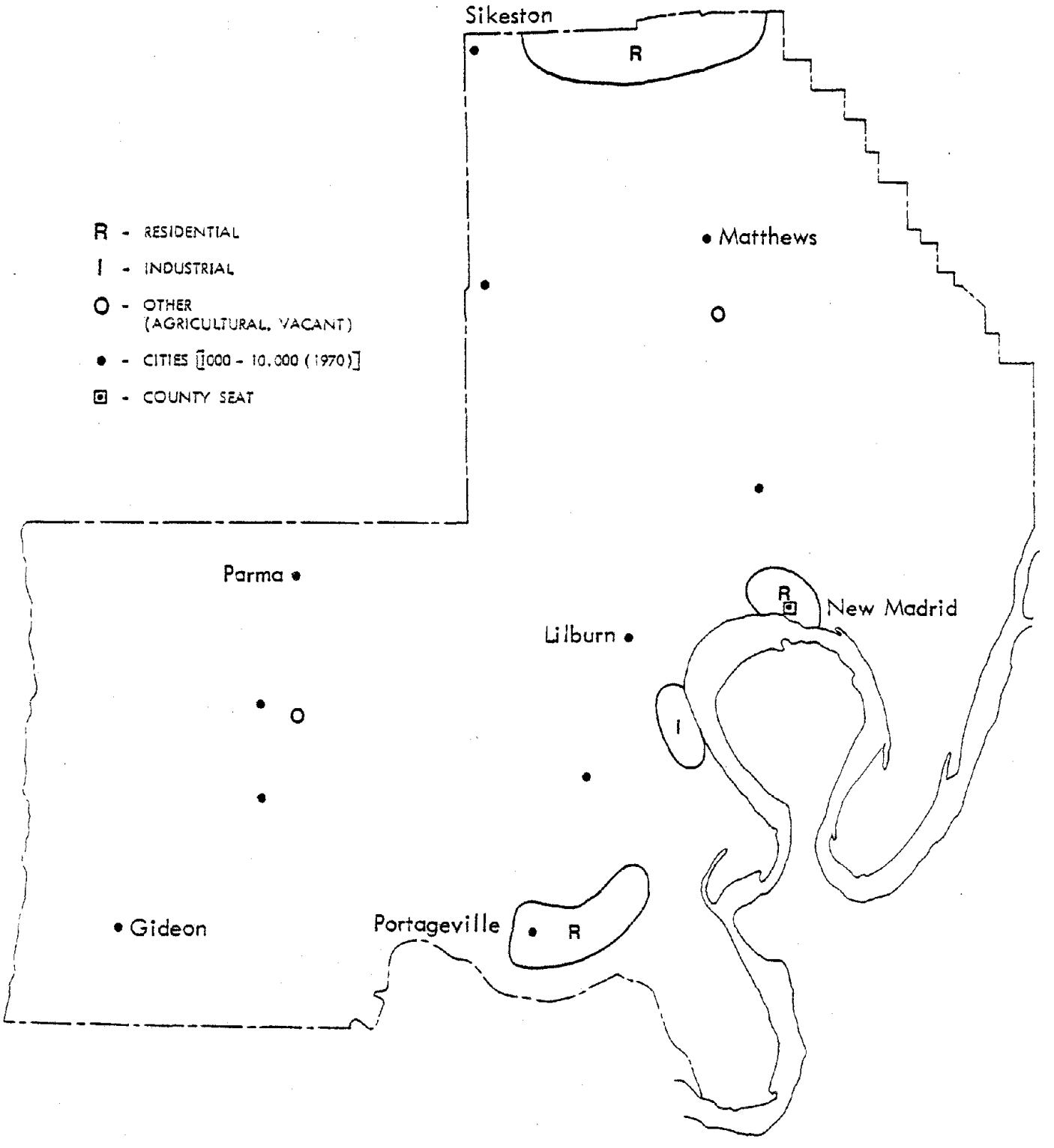


Figure IV-8. New Madrid County Land Use Future (1995-2000).

TABLE IV-3

POPULATION AND POPULATION GROWTH - 1940-1970

St. Louis SMSA	Population 1940	Population 1950	Population 1960	Population 1970	Growth Rate 1940-1950	Growth Rate 1950-1960	Growth Rate 1960-1970
St. Louis City	815,996	856,796	750,026	622,236	5.0	-12.5	-17.0
St. Louis County	274,190	406,349	703,532	951,353	48.2	73.1	35.2
St. Charles	24,708	28,834	52,970	92,954	16.7	77.5	75.5
Jefferson	32,019	38,007	66,377	105,248	18.7	74.6	58.6
Franklin	33,878	36,046	44,566	55,116	6.4	23.6	23.7
Madison	149,310	182,307	224,689	250,934	22.1	23.2	11.7
St. Clair	166,933	205,995	262,509	285,176	23.4	27.4	8.6
Monroe	12,759	13,282	15,507	18,831	4.1	16.8	21.4
Clinton	22,915	22,594	24,029	28,315	-1.4	6.4	17.8
Total SMSA	1,532,708	1,709,210	2,144,205	2,410,163	16.8	19.8	12.4
FEA 114	2,367,341	2,588,961	2,908,573	3,253,579	9.3	12.3	11.8
Memphis SMSA							
Shelby	358,124	482,393	627,019	721,973	34.7	30.0	15.1
Tipton	28,043	29,782	28,564	28,001	6.2	-4.1	-2.0
Crittenden	42,473	47,184	47,564	48,106	11.1	0.8	1.1
De Soto	26,651	24,599	23,891	35,885	-8.7	-2.9	50.2
Total SMSA	455,291	583,98	727,038	833,965	28.3	24.5	14.7
FEA 46	1,468,309	1,584,126	1,590,532	17,702,867	7.9	0.4	7.1
Cape Girardeau Co.	37,792	38,397	42,020	49,350	1.6	9.4	17.4
New Madrid Co.	39,802	39,444	31,350	23,420	-0.9	-20.6	-25.3
FEA 115	658,391	628,998	573,248	559,253	-4.5	-8.9	-2.5

Source: U.S. Bureau of the Census

have enjoyed a faster rate of population growth than the respective FEA regions to which they belong. In other words, this higher rate of growth subjects more people to earthquake hazards if there are no corresponding mitigation plans and programs to alleviate the potential damage.

Another variable to look at in this study is employment. Growth in the number of employed in this region means a more economically productive population that would be subject to earthquake hazards and a greater concentration of economic activities in the study counties as compared to the FEA's to which they belong. The rationale is that the greater the economic base, the greater the potential damage. Furthermore, the employment structure changes, which follow the general urbanization trends and a decline in agriculture employment, not only increases the vulnerability of the region, but also creates additional adverse interactive effects in the case of damaging earthquakes.

Table IV-4 shows the growth in employment in the 15 counties over time. The counties experienced rapid population growth and also enjoyed a faster rate of employment growth than did the FEA as a whole. The most noteworthy counties in the study region are St. Louis, Jefferson, and St. Charles in St. Louis SMSA and Shelby and De Soto in Memphis SMSA.

2. Population and employment projections: The projection of population growth is implemented by using OBERS projection (1972) based on historical census data for the FEA's. Taking the projection of population growth of the St. Louis SMSA as an example, we can illustrate the shift-share projection procedure.

As shown in Table IV-3, St. Louis SMSA is included in FEA 114. Population enumerations before 1970 and population projections through 2020 for this FEA are as follows:

1940 - 2,367,341
1950 - 2,588,961
1959 - 2,908,573
1962 - 3,001,759
1965 - 3,075,448
1969 - 3,221,478
1970 - 3,253,579
1980 - 3,677,000
1990 - 4,143,900
2000 - 4,622,200
2010 - 5,169,400
2020 - 5,777,900

TABLE IV-4

EMPLOYMENT AND EMPLOYMENT GROWTH - 1950-1970

St. Louis SMSA	Employment 1950	1960	1966	1970	Growth Rate 1950-1960	1960-1966	1966-1970
St. Louis City	366,524	294,000	256,659	231,765	-19.8	-12.7	-9.7
St. Louis County	156,526	263,200	335,925	384,409	68.2	27.6	14.4
St. Charles	11,629	18,359	28,230	34,811	57.9	53.8	23.3
Jefferson	13,683	21,462	31,123	37,563	56.9	45.0	20.7
Franklin	13,994	16,735	18,838	20,240	19.6	12.6	7.4
Madison	69,665	80,757	88,240	93,229	15.9	9.3	5.7
St. Clair	72,573	85,859	91,956	96,020	18.3	7.1	4.4
Monroe	5,239	5,827	6,452	6,869	11.2	10.7	6.5
Clinton	8,317	8,043	8,958	9,568	-3.3	11.4	6.8
Total SMSA	718,150	794,242	866,381	914,474	10.6	9.1	5.6
FEA 114	1,005,812	1,080,584	1,173,767	1,235,909	7.4	8.6	5.3
Memphis SMSA							
Shelby	208,115	222,585	248,560	265,876	6.9	11.7	7.0
Tipton	9,397	8,230	8,229	8,228	-12.4	0.0	0.0
Crittenden	-	13,289	13,855	14,232	-	4.3	2.7
De Soto	7,723	6,932	9,657	11,474	-10.2	39.3	18.8
Total SMSA	-	251,036	280,301	299,810	-	11.7	7.0
FEA 46	546,185	537,616	613,001	630,060	-0.4	13.8	8.1
Cape Girardeau Co.	15,979	15,917	18,110	19,572	-0.4	13.8	8.1
New Madrid Co.	11,313	8,272	7,151	6,404	-26.9	-13.6	-10.4
FEA 115	203,096	182,460	195,522	195,739	-10.2	7.2	0.1

Source: U.S. Bureau of the Census.

In addition to the population projections for FEA 114, OBERS (1972) also provided information on the share of FEA 114 population represented by the St. Louis SMSA; the percentages from 1940 through 2020 at 10-year intervals by each county in the St. Louis SMSA are listed in Table IV-5 below. Multiplying the projected population by these projected percentages, we derived the population for the 1978-2020 period for each county in the St. Louis SMSA. These findings are reported in Table IV-6. The average growth rate during the period 1978 to 2020 was selected to extrapolate the population projection for the 2021 and 2030 period, the final decade of our projection period.

Applying the same procedure used for the St. Louis SMSA to the information on FEA 46, in which the Memphis SMSA is included, and to the information on FEA 115, in which New Madrid and Cape Girardeau counties are included, we made population projections for the four counties in the Memphis SMSA and in New Madrid and Cape Girardeau counties. The relevant FEA information for making such projections is presented in Table IV-7, and the projected population data for the 15 counties by the above procedures are reported in Table IV-8.

Projection of employment trends for the study area was similar to projection of population growth. Information provided by OBERS was used and projected employment for FEA 46, FEA 114, and FEA 115 were the foundations for shift-share analysis and projection. The percentage share of each study county in its corresponding FEA, as reported in Table IV-9, was first applied to derive the projected employment for the 1980 to 2020 period, which in turn was used to derive the projection for the 2020 to 2030 period as reported in Table IV-10.

These projections are by no means final, and they should only be considered as gross estimates for the purpose of this study. But the changing distribution of the structures may be hypothesized to follow those of the OBERS projections (1972) since the distributions of population, employment, and the associated socioeconomic and demographic factors of each county, FEA, and the nation as a whole do not take into account such factors as migration patterns, regional industrial and economic development, local zoning and regulations, etc. Thus, these projections may formulate as good a data base as any other for simulting the potential damages by earthquake to subject populations.

C. Personal Property Value Estimation

Another category of reception exposed to earthquake risk is personal property. For most of the study counties, the current value of personal property was obtained through the county assessor's office. For those counties without personal property information, estimation was based on the value of personal

TABLE IV-5

POPULATION SHARES OF ST. LOUIS SMSA IN FEA 114, 1940-2020

	1940	1950	1960	1970	1980	1990	2000	2010	2020
St. Louis City	34.50	33.20	24.46	19.12	15.5	14.0	12.75	11.7	11.0
St. Louis County	11.60	15.74	23.88	29.24	28.5	27.73	26.14	25.0	24.0
St. Charles	1.04	1.12	1.80	3.7	4.44	5.0	5.0	5.19	5.37
Jefferson	1.35	1.47	2.25	3.23	4.2	4.6	4.7	4.8	4.9
Franklin	1.43	1.40	1.51	1.69	1.85	2.19	2.43	2.65	2.9
Madison	6.31	7.10	7.63	7.71	7.9	7.27	7.01	6.9	6.8
St. Clair	7.06	8.00	8.91	8.76	8.5	8.16	7.78	7.4	7.0
Monroe	0.54	0.51	0.53	0.58	0.64	0.69	0.71	0.72	0.73
Clinton	0.97	0.87	0.82	0.87	0.87	0.86	0.85	0.86	0.86
Total	64.7	69.2	72.7	74.1	71.7	70.2	67.7	65.6	64.0

Source: U. S. Bureau of the Census.

TABLE IV-6

PROJECTED POPULATIONS FOR ST. LOUIS BY COUNTY - 1980-2020

	1980	1990	2000	2010	2020
St. Louis City	570,000	580,000	589,330	604,820	635,569
St. Louis County	1,047,945	1,149,103	1,208,243	1,292,350	1,386,696
St. Charles	136,049	183,989	231,000	268,300	310,000
Jefferson	154,434	200,565	230,648	266,224	306,229
Franklin	68,025	90,751	112,319	136,989	167,559
Madison	290,483	301,262	324,016	356,689	392,897
St. Clair	312,545	338,142	359,607	382,535	404,453
Monroe	23,533	28,500	33,000	37,220	42,179
Clinton	31,990	35,638	39,289	44,457	49,690
Total SMSA	2,635,004	2,907,950	3,127,452	3,389,584	3,695,272
Total FEA 114	3,677,000	4,143,900	4,622,200	5,169,400	5,777,900

TABLE IV-7

POPULATION SHARES OF MEMPHIS SMSA IN FEA 46 AND CAPE GIRARDEAU AND NEW MADRID IN FEA 115, 1940-2020

	1940	1950	1960	1970	1980	1990	2000	2010	2020
Memphis SMSA									
Shelby	24.39	30.45	38.77	42.40	44.87	45.54	47.13	48.57	49.97
Tipton	1.91	1.88	1.77	1.64	1.74	1.80	1.86	1.92	1.98
Crittenden	2.89	2.98	2.94	2.83	2.88	2.92	2.97	3.02	3.07
De Soto	1.82	1.55	1.48	2.11	2.70	3.30	3.90	4.50	5.00
Total SMSA	31.01	36.86	44.96	48.98	52.19	53.56	55.86	58.01	60.02
Total FEA 46 Population Projection					1,876,600	2,113,200	2,385,000	2,723,000	3,116,000
Cape Girardeau Co.	5.74%	6.10%	7.35%	8.82%	10.20%	11.00%	11.30%	11.60%	11.90%
New Madrid Co.	6.05%	6.27%	5.49%	4.19%	4.00%	4.10%	4.20%	4.30%	4.40%
Total FEA 115 Population Projection					583,400	617,900	669,300	735,500	811,200

Source: U.S. Bureau of the Census.

TABLE IV-8

PROJECTED POPULATION FOR STUDY REGION
BY COUNTY, 1980-2030

County	1980	1990	2000	2010	2020	2030
St. Louis SMSA						
Franklin	68,025	90,751	112,319	136,989	167,559	209,315
Jefferson	154,434	200,565	230,648	266,224	306,229	379,203
St. Charles	136,049	183,989	231,000	268,300	310,000	394,506
St. Louis	1,047,945	1,149,103	1,208,243	1,292,350	1,386,696	1,495,829
St. Louis City	570,000	580,000	589,330	604,820	635,569	638,111
Clinton	31,990	35,638	39,289	44,457	49,690	55,598
Madison	290,483	301,262	324,016	356,689	392,897	429,711
Monroe	23,533	28,500	33,000	37,220	42,179	49,581
St. Clair	312,545	338,142	359,607	382,535	404,453	433,654
Total	2,635,004	2,907,950	3,127,452	3,389,584	3,695,272	4,085,508
Cape Girardeau Co.	59,507	67,969	75,631	85,318	96,533	110,385
New Madrid Co.	23,336	25,334	28,111	31,626	35,693	38,845
Memphis SMSA						
Shelby	841,940	962,555	1,124,050	1,322,900	1,557,065	1,816,005
Tipton	32,704	38,112	44,400	52,295	61,697	72,241
Crittenden	54,040	61,705	70,835	82,255	95,661	109,714
De Soto	50,663	69,736	93,105	122,566	155,800	208,975
Total	979,347	1,132,108	1,332,300	1,580,016	1,730,003	2,206,935
15-County Total	3,697,194	4,133,361	4,563,494	5,086,544	5,557,501	6,441,673

TABLE IV-9

PROJECTED EMPLOYMENT SHARES OF ST. LOUIS SMSA, MEMPHIS SMSA, CAPE GIRARDEAU AND NEW MADRID COUNTIES, 1980-2020

	1980	1990	2000	2010	2020
St. Louis SMSA					
St. Louis City	16.3	14.7	13.1	11.9	11.1
St. Louis County	30.0	29.0	28.0	27.0	26.0
St. Charles	3.7	4.5	5.1	5.2	5.3
Jefferson	4.0	4.9	5.1	5.2	5.3
Franklin	1.8	2.2	2.6	2.7	2.9
Madison	7.8	7.4	7.1	6.9	6.8
St. Clair	8.4	8.3	7.9	7.4	7.0
Monroe	0.6	0.7	0.7	0.7	0.7
Clinton	0.8	0.9	0.9	0.9	0.9
Total SMSA	73.3	72.6	70.2	67.7	66.0
Total FEA 114 Employment	1,420,400	1,593,800	1,826,700	2,066,400	2,319,300
Memphis SMSA					
Shelby	44.50	46.00	47.50	49.00	50.50
Tipton	1.34	1.40	1.46	1.52	1.58
Crittenden	2.12	2.05	2.02	2.00	1.98
De Soto	3.10	4.00	4.80	5.50	6.10
Total SMSA	51.06	53.45	55.78	58.02	60.16
Total FEA 46 Employment	722,500	811,200	944,000	1,092,800	1,755,900
Cape Girardeau Co.	11.2	12.0	12.3	12.6	12.9
New Madrid Co.	3.0	3.1	3.2	3.3	3.4
Total FEA 115 Employment	217,000	229,500	254,400	283,000	314,700

TABLE IV-10

PROJECTED EMPLOYMENT

County	1980	1990	2000	2010	2020	2030
St. Louis SMSA						
Franklin	25,850	35,393	44,928	54,796	67,024	85,127
Jefferson	56,816	78,220	92,259	106,490	122,492	155,283
St. Charles	52,555	71,721	92,400	107,320	124,000	159,972
St. Louis	426,120	462,202	511,476	557,928	603,018	659,521
St. Louis City	230,774	234,823	238,600	244,871	257,321	262,776
Clinton	11,363	13,899	15,716	17,783	19,876	22,998
Madison	110,384	117,492	129,606	142,582	157,712	175,250
Monroe	8,943	11,157	13,200	14,888	16,872	20,207
St. Clair	118,767	131,875	143,843	152,914	161,781	179,593
Total	1,041,572	1,156,782	1,282,028	1,399,572	1,530,096	1,720,727
Cape Girardeau Co.	24,304	27,540	31,291	35,696	40,596	46,974
New Madrid Co.	6,510	7,115	8,141	9,349	10,700	11,855
Memphis SMSA						
Shelby	321,513	393,152	448,400	535,472	634,230	754,353
Tipton	9,682	11,357	14,349	16,611	19,843	23,673
Crittenden	15,317	16,630	18,880	21,856	24,867	27,796
De Soto	22,398	32,448	45,312	60,104	76,610	112,100
Total	368,910	433,587	526,941	634,043	755,550	917,922
15-County Total	1,441,296	1,625,024	1,848,401	2,078,660	2,336,942	2,697,478

property and structures in another county where physical conditions were similar to the one being studied. For example, Monroe County is similar to Franklin County in terms of its socioeconomic functions in the St. Louis SMSA. The value of personal property in Monroe County, which was not available, was derived primarily based on the per capital data on personal property values in Franklin County, where both the per capita values of structures and personal property were available.

The personal property information for the study area in 1978 dollars is reported in Table IV-11. Projections on personal property were accomplished by using population growth rates in each county as the rates of personal property growth. The results are shown in Table IV-12.

D. Estimated Value of Buildings and Structures

The last category of population subject to earthquake risk is probably the most vulnerable and significant of the three major populations under consideration; namely, buildings and other structures. For earthquake damage simulation, buildings and structures must be valued and any increase in value and improvements made over the next five decades estimated or projected. This section provides data on the existing and projected structure populations in the 15-county area. These data are employed as the basic inputs to the damage simulation that is addressed in the following two chapters.

1. Gross value of structures in 1978: Market values of all structures in the 15-county region were obtained individually from each county assessor's office or school district office. Based on the rate and year of the last assessment, all values were updated to reflect the full 1978 market value. Further, these market values of structures were separated into the four land use types, "residential," "commercial," "industrial," and "other," in accordance with the land utilization patterns discussed earlier. Table IV-13 summarizes all estimated structure values by county and by use.

A total of $29 billion worth of structures are expected to be subject to earthquake hazards, of which $23.6 billion are residential houses and buildings. Geographically, St. Louis SMSA seems to be the most significant in terms of volume of risk population, and Memphis SMSA the most vulnerable in terms of the distance to the risk source, or the epicenter.

Another approach for estimating the value of buildings and structures that are subject to earthquake risk is the so-called replacement cost estimation. According to William R. Park, consulting structural engineer, total replacement costs of the buildings and structures in the 15-county region would amount to $94.6 billion in 1978 dollars. Table IV-14 presents

TABLE IV-11

ESTIMATED VALUE OF
PERSONAL PROPERTY BY COUNTY
(in 1978 dollars, thousands)

County	Value
St. Louis SMSA	
Franklin	71,670
Jefferson	163,398
St. Charles	160,832
St. Louis County	1,648,105
St. Louis City	574,038*
Clinton	262,104*
Madison	411,051*
Monroe	82,039*
St. Clair	401,792*
Total	3,775,029
Cape Girardeau Co.	61,746
New Madrid Co.	11,274
Memphis SMSA	
Shelby	259,025
Tipton	5,768
Crittenden	103,667
De Soto	98,000
Total	466,460
15-County Total	4,314,509

Note: Property values marked with (*) are estimated; for details see text.

TABLE IV-12

PROJECTED VALUE OF PERSONAL PROPERTY
(in 1978 dollars, millions)

County	1980	1990	2000	2010	2020	2030
St. Louis SMSA						
Franklin	75	100	123	151	184	230
Jefferson	176	229	263	304	350	433
St. Charles	174	235	295	342	395	503
St. Louis	1,680	1,842	1,937	2,072	2,223	2,398
St. Louis City	564	574	583	599	629	632
Clinton	269	299	330	373	417	467
Madison	423	439	472	520	572	626
Monroe	86	104	120	136	154	181
St. Clair	409	443	471	501	530	568
Total	3,856	4,265	4,594	4,998	5,454	6,038
Cape Girardeau Co.	64	73	81	92	104	119
New Madrid Co.	11	12	14	15	17	19
Memphis SMSA						
Shelby	267	305	357	420	494	576
Tipton	6	7	8	10	11	13
Crittenden	106	121	139	162	188	216
De Soto	105	145	194	255	324	435
Total	484	578	698	847	1,017	1,240
15-County Total	4,415	4,928	5,387	5,952	6,592	7,416

TABLE IV-13

MARKET VALUE OF ALL STRUCTURES
(in 1978 dollars, Millions)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	209	13	3	85	310
Jefferson	438	11	12	247	708
St. Charles	791	35	22	200	1,048
St. Louis	7,219	1,003	505	1,124	9,851
St. Louis City	1,549	1,165	439	278	3,431
Clinton	51	10	--	963	1,024
Madison	1,394	175	435	530	2,534
Monroe	16	3	--	309	328
St. Clair	1,366	559	244	270	2,439
Total	13,033	2,974	1,660	4,006	21,673
Cape Girardeau Co.	254	33	7	108	402
New Madrid Co.	38	1	6	25	70
Memphis SMSA					
Shelby	3,452	1,166	548	895	6,061
Tipton	102	49	--	55	206
Crittenden	164	49	--	102	315
De Soto	91	42	--	48	181
Total	3,809	1,306	548	1,100	6,763
15-County Total	17,134	4,314	2,221	5,239	28,908

Note: The sign (--) indicates that the value is less than $1 million.

TABLE IV-14

RECONSTRUCTION COST OF ALL STRUCTURES
(Millions of 1978 dollars)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	563	261	79	859	1,762
Jefferson	1,093	508	153	1,668	3,422
St. Charles	1,021	474	143	1,558	3,196
St. Louis	8,499	3,952	1,187	12,972	26,610
St. Louis City	4,657	2,166	650	7,108	14,581
Clinton	304	178	54	871	1,407
Madison	2,552	1,496	449	7,312	11,809
Monroe	192	112	34	550	888
St. Clair	2,870	1,682	505	8,223	13,280
Total	21,751	10,829	3,254	41,121	76,955
Cape Girardeau Co.	474	221	66	723	1,484
New Madrid Co.	215	100	30	328	673
Memphis SMSA					
Shelby	6,277	3,612	1,085	2,052	13,026
Tipton	257	148	44	84	533
Crittenden	425	190	57	295	967
De Soto	396	202	61	267	926
Total	7,355	4,152	1,247	2,698	15,452
15-County Total	29,795	15,302	4,597	44,870	94,564

Source: W. R. Park, Consulting Engineer.

Note: Residential structures include single family and all other residential buildings; commercial structures include office, other commercial, institutional, and all other nonresidential buildings; other include all nonbuilding constructions.

the structure value by county and type of use estimated by this approach. It is worth noting that the replacement cost estimates are much higher than the market values inflated from the assessed values. However, the distribution of these estimates by region and by type of use does agree. For instance, it is still the St. Louis SMSA and the residential housing sector which are esimated with the greatest risk, while nonstructural risks such as utility communication and transportation net worth are by and large disregarded in the "other" category in Table IV-13. Table IV-14 has taken some of these risks into account in its "other" category. As a result, information in the "other" categories of the two tables are not strictly comparable.

2. The projected structure values: The projections on the values of different types of structures were made under various assumptions concerning several important determinants over the period being studied. Those determinants include, but are not limited to, the trend of population growth and urbanization, the development tendency of the study area, the overall structural changes in the regional economy, etc. However, not all data on these factors are available for projection, and it was only possible to include two factors in the computer simulation model developed in this study.

The first factor represents the growth trend of the population. Clearly, there will be an increase in the number of structures to meet the demand for a growing population. For the same reason, the employment trend is also a good determinant for adjusting the structure growth trend. However, population growth may have a heavier impact on residential construction than on other types. On the other hand, the direct impact of an increasing rate of employment may be seen in construction booms in the "commercial," "industrial," and "other" sectors. Therefore, in this study, the population growth rate has been selected as the proxy for the residential structure growth rate and the employment growth trend has been used to adjust growth of the other three types of structures. Because the growth rate of either population or employment for any county is not uniquely distributed over a period of time, the criterion for adjustment will be better if it can reflect this in the projection. Since our projections are valued in constant 1978 dollars, it would not be necessary to take into account the influences of inflation during the projection period.

Thus, the projected values of the four types of structures for 1980 and the next five 10-year intervals from 1980 to 2030 follow directly the population and employment growth rates in each county, and we have:

(a) for residential structures

$$V_{k,t} = V_{k,1978}(1+RP_{k,\ell})^{t-1978} \qquad \text{(IV-1)}$$

and (b) for commercial, industrial, and other structures

$$V_{k,t} = V_{k,1978} \cdot (1+RE_{k,\ell})^{t-1978} \qquad \text{(IV-2)}$$

where

$V_{k,1978}$ = the 1978 value of each type of structure for county k.

$V_{k,t}$ = the value of each type of structure for county k in the year t.

$RP_{k,\ell}$ = the population growth rate of county k at the ℓth time interval.

$RE_{k,\ell}$ = the employment growth rate of county k at the ℓth time interval.

The population and employment growth trends $RP_{k,\ell}$, and $RE_{k,\ell}$ are derived from the projected population and employment figures as discussed in Section B of this chapter.

The gross values of the structures as projected were then adjusted by the changing pattern of the land utilization plan for the study area. As emphasized above, any land may include the land used for all four purposes--"residential," "commercial," "industrial," and "other." Changes in land use patterns in the future will naturally cause redistribution of the land use among the four purposes. To adjust the values of the structures in the project period according to land utilization patterns and their changes, we have

$$V^*_{i,t} = \sum_{j=1}^{4} V_{j,t} \cdot P_{i,j,t} \qquad \text{(IV-3)}$$

where

$V^*_{i,t}$ = the redistribution adjustment value of the structures for the ith purpose at year t,

$V_{1,t} = V_{k,1978} \cdot (1+RP_{k,\ell})^{t-1978}$, is the projected value of residential structures for county k at year t,

$V_{j,t} = V_{k,1978} \cdot (1+RE_{k,\ell})^{t-1978}$, for j = 2 to 4 are the projected values of commercial structures (j = 2), industrial structures (j = 3), and other structures (j = 4) for county k at year t.

The value of $P_{i,j,t}$ is the changed rate of land use for the ith purpose in the jth zone as derived in Section A of this chapter.

The values of the four types of structures for the years 1980, 1990, 2000, 2010, 2020, and 2030 generated by the procedures described above are reported in Tables IV-15 through IV-20. These projected values provide the foundation for potential building damage estimation resulting from earthquake risk during the study period.

Another set of projections on structure values was completed by William R. Park, our consulting engineer. For this study, the value of structures at risk were projected by the following procedures.

The first step was to estimate the "reproduction cost new" of all structures in place in 1978 by counties within each SMSA. The reproduction cost new, while not a measure of current market value, does represent the actual cost to rebuild an area in total, were it destroyed completely.

The current population characteristics and numbers of households were the basis for estimating the total number of residential units in each county included in the study area. The average cost per housing unit in each state, then, as reported by the U. S. Department of Commerce, was applied to the number of housing units within the county to obtain the reproduction cost new of these existing residential structures.

The resulting figures represent the total cost to rebuild all residential structures employing current materials, designs, technologies, and construction methods for all inhabitants of each county.

Residential construction is known to comprise a specific proportion of total construction, with data available on a state-by-state basis for each type of construction from the Commerce Department's Bureau of Defense Services Administration (BDSA). In the form of a multiplier, data from this source were then applied to the total reproduction cost new of all residential structures to obtain the total reproduction cost new of <u>all</u> structures--including commercial, industrial, and institutional buildings; public works projects; utilities of all types; and all other structures. In this step, the supporting structures are lumped together into just two categories: nonresidential buildings and nonbuilding (or engineered) construction.

The second step in the methodology consisted of breaking down the total values from step 1 into the major types of structures. This was accomplished by simply applying the percentages of total construction put in place reported for each category of structure to the total reproduction cost new of all structures in each area.

TABLE IV-15

MARKET VALUE OF ALL STRUCTURES - 1980
(Millions of 1978 Dollars)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	217	14	4	89	324
Jefferson	472	13	14	266	765
St. Charles	837	45	26	223	1,131
St. Louis	7,338	1,025	507	1,175	10,045
St. Louis City	1,534	1,165	432	268	3,399
Clinton	53	11	--	996	1,060
Madison	1,429	187	444	552	2,612
Monroe	17	3	--	326	346
St. Clair	1,385	585	255	285	2,510
Total	13,282	3,048	1,682	4,180	22,192
Cape Girardeau Co.	265	35	8	110	418
New Madrid Co.	39	1	6	25	71
Memphis SMSA					
Shelby	3,548	1,223	568	930	6,269
Tipton	106	51	--	56	213
Crittenden	171	49	--	102	322
De Soto	99	45	--	52	196
Total	3,924	1,368	568	1,140	7,000
15-County Total	17,510	4,452	2,264	5,455	29,681

Note: The sign (--) indicates that the value is less that $1 million.

TABLE IV-16

MARKET VALUE OF ALL STRUCTURES - 1990
(millions of 1978 dollars)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	286	17	6	125	434
Jefferson	607	23	27	342	999
St. Charles	1,018	106	56	350	1,530
St. Louis	7,923	1,127	508	1,443	11,001
St. Louis City	1,596	1,218	411	236	3,461
Clinton	65	13	--	1,219	1,297
Madison	1,446	230	444	610	2,730
Monroe	22	4	--	407	433
St. Clair	1,448	659	284	354	2,745
Total	14,411	3,397	1,736	5,086	24,630
Cape Girardeau Co.	314	41	11	111	477
New Madrid Co.	44	1	7	25	77
Memphis SMSA					
Shelby	3,974	1,489	658	1,091	7,212
Tipton	131	57	--	60	248
Crittenden	210	52	--	103	365
De Soto	144	61	--	68	273
Total	4,459	1,659	658	1,322	8,098
15-County Total	19,228	5,098	2,412	6,544	33,282

Note: The sign (--) indicates that the value is less that $1 million.

TABLE IV-17

MARKET VALUE OF ALL STRUCTURES - 2000
(millions of 1978 dollars)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	349	20	8	161	538
Jefferson	690	35	42	387	1,154
St. Charles	1,136	190	95	500	1,921
St. Louis	8,211	1,231	501	1,689	11,632
St. Louis City	1,657	1,270	388	202	3,517
Clinton	73	15	--	1,378	1,466
Madison	1,516	288	457	696	2,957
Monroe	26	5	--	481	512
St. Clair	1,487	729	311	425	2,952
Total	15,145	3,783	1,802	5,919	29,649
Cape Girardeau Co.	361	48	14	107	530
New Madrid Co.	51	1	8	25	85
Memphis SMSA					
Shelby	4,553	1,871	788	1.313	8,525
Tipton	162	66	--	66	294
Crittenden	259	54	--	105	418
De Soto	203	80	--	85	368
Total	5,177	2,071	788	1,569	9,605
15-County Total	20,734	5,903	2,612	7,620	36,869

Note: The sign (--) indicates that the value is less that $1 million.

TABLE IV-18

MARKET VALUE OF ALL STRUCTURES - 2010
(millions of 1978 dollars)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	420	23	10	203	656
Jefferson	785	49	61	436	1.331
St. Charles	1,154	287	140	651	2,232
St. Louis	8,651	1,344	491	1,985	12,471
St. Louis City	1,736	1,336	368	168	3,608
Clinton	83	17	--	1,559	1,659
Madison	1,622	357	471	805	3,255
Monroe	29	6	--	543	578
St. Clair	1,519	787	332	501	3,139
Total	15,999	4,206	1,873	6,851	28,929
Cape Girardeau Co.	421	56	18	103	598
New Madrid Co.	61	1	10	25	97
Memphis SMSA					
Shelby	5,240	2,334	940	1,582	10,096
Tipton	200	75	--	70	345
Crittenden	322	56	--	107	485
De Soto	281	102	--	103	486
Total	6,043	2,567	940	1,862	11,412
15-County Total	22,524	6,830	2,841	8,841	41,036

Note: The sign (--) indicates that the value is less that $1 million.

TABLE IV-19

MARKET VALUE OF ALL STRUCTURES - 2020
(millions of 1978 dollars)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	506	26	14	257	803
Jefferson	891	66	84	489	1,530
St. Charles	1,143	408	196	833	2,580
St. Louis	9,138	1,461	474	2,320	13,393
St. Louis City	1,863	1,439	354	136	3,792
Clinton	93	19	--	1,743	1,855
Madison	1,736	439	484	930	3,589
Monroe	33	7	--	615	655
St. Clair	1,541	845	353	581	3,320
Total	16,944	4,710	1,959	7,904	31,517
Cape Girardeau Co.	492	65	23	96	676
New Madrid Co.	71	1	12	25	109
Memphis SMSA					
Shelby	6,017	2,885	1,112	1,901	11,915
Tipton	248	86	--	75	409
Crittenden	399	58	--	105	562
De Soto	375	125	--	119	619
Total	7,039	3,154	1,112	2,200	13,505
15-County Total	24,546	7,930	3,106	10,225	45,807

Note: The sign (--) indicates that the value is less that $1 million.

TABLE IV-20

MARKET VALUE OF ALL STRUCTURES - 2030
(millions of 1978 dollars)

County	Residential Structures	Commercial Structures	Industrial Structures	Other	Total
St. Louis SMSA					
Franklin	623	30	19	332	1,004
Jefferson	1,091	95	121	594	1,901
St. Charles	1,211	616	292	1,164	3,283
St. Louis	9,700	1,603	456	2,707	14,466
St. Louis City	1,920	1,494	329	97	3,840
Clinton	107	21	--	2,017	2,145
Madison	1,847	533	496	1,068	3,944
Monroe	39	8	--	736	783
St. Clair	1,591	950	393	682	3,616
Total	18,129	5,350	2,106	9,397	34,982
Cape Girardeau Co.	580	77	30	86	773
New Madrid Co.	81	1	13	23	118
Memphis SMSA					
Shelby	6,855	3,573	1,320	2,269	14,017
Tipton	304	97	--	79	480
Crittenden	487	58	--	97	642
De Soto	526	167	--	153	846
Total	8,172	3,895	1,320	2,598	15,985
15-County Total	26,962	9,323	3,469	12,104	51,858

Note: The sign (--) indicates that the value is less that $1 million.

The final step was to project the current (1978) values to the years 1990, 2000, and 2025. This step relied primarily upon population projections developed by the various local and regional planning agencies for each SMSA. New residential units were assumed to be added at their approximate historical rate as the population changed, with related supporting structures constructed along the same lines and in the same proportions experienced in the past.

The projections, therefore, assume that approximately the same relative mix of structures of all types will be built in the future as have been built in the past. While it is recognized that these proportions do change over time, the change is gradual and the probability of error is far greater if one attempts to anticipate the nature of such change than if one assumes the proportions will remain relatively constant.

For buildings of all types, the substructures represent from 6.0 to 12.0 percent of the total building cost; the cost of substructure ranges from 50.0 to 75.0 percent of the total building cost; and building utilities (plumbing, heating, ventilation, air conditioning, electrical, and communications) make up the remaining 15.0 to 35.0 percent. Most of the engineered construction lies in or on the ground and can be classified as substructure for the purpose of assessing susceptibility to earthquake damage.

Table IV-21 projects the total 1978 structure replacement values for each of the 15 counties to the years 1990, 2000, and 2025. These figures, expressed in 1978 dollars, reflect increases attributable to regional growth and do not include the impact of cost or price inflation. The market value projections obtained from the first approach were employed to generate further breakdowns by type of projected new construction costs.

The values of all types of structures estimated and projected by Park with new construction costs are considerable higher than the results calculated in terms of market values converted from the information provided by county assessors' offices. For example, Park's projection for the St. Louis SMSA indicates a total structure amount at $97.5 billion for reconstruction in year 2000, while the market value approach produced a corresponding figure of $26.6 billion, less than 30 percent of what Park projected. The values of structures of the total study area in the year 2000 were projected to be $125 billion and $37 billion, respectievely, with these two approaches. Park's estimation, thus, might be utilized as the upper boundary for building damage estimation.

However, only 1978 estimates were broken down into the four categories of building uses and all projected values were available at the aggregate level for each county. As a result, we have assumed that the percentage distribution of each building category in 1978 for any county will remain the same throughout the projection period. The damage estimations so derived, thus, should be used for reference only.

TABLE IV-21

RECONSTRUCTION COST NEW OF ALL CONSTRUCTION
(millions of 1978 dollars)

	1978	1990	2000	2025
St. Louis SMSA				
Franklin	1,762	2,545	3,132	4,502
Jefferson	3,422	5,459	5,893	8,365
St. Charles	3,196	5,204	6,533	9,871
St. Louis	26,610	30,729	32,306	38,003
St. Louis City	14,581	14,454	14,910	15,239
Clinton	1,407	1,747	2,038	2,668
Madison	11,809	13,671	14,716	17,623
Monroe	888	1,288	1,732	2,575
St. Clair	13,280	15,267	16,261	19,242
Total	76,955	90,364	97,521	118,088
Cape Girardeau Co.	1,484	1,848	2,128	2,772
New Madrid Co.	673	715	743	813
Memphis SMSA				
Shelby	13,026	17,878	21,113	29,200
Tipton	533	640	711	888
Crittenden	967	1,164	1,302	1,638
De Soto	926	1,111	1,241	1,556
Total	15,452	20,793	24,367	33,282
15-County Total	94,564	113,720	124,759	154,955

E. Summary

This chapter discussed the procedures for establishing the data base for three major populations--structures, human beings, and personal property--that are subject to risk of earthquake in the study period, 1980 to 2030. The procedures took into account the available information on those social and economic factors such as land utilization patterns, interregional migration trends, and national economic and industrial development. The procedures of projecting populations at risk have also been incorporated into the computer simulation program to simulate the physical and economic damages of potential earthquakes in the future. The established data base on projected populations will be employed as the basic input for damage simulation in Chapter VI.

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CHAPTER V

PHYSICAL AND ECONOMIC DAMAGE FUNCTIONS

Although many impact studies on geophysical hazards have demonstrated the use of systematically developed mathematical models, to date there is still no satisfactory model that can be readily used to analyze the risk of potential earthquakes and the associated economic impacts, especially for the major seismic zone, the New Madrid. In this chapter, we briefly review the state of the art and then develop an integrated model which will not only be able to simulate potential earthquake damages in the New Madrid zone, but also will be flexible enough to extend its applicability to other regions.

A. Background and Methodological Review

Potential earthquake damage to structures, human beings, and personal property has been the focus of numerous studies. So far, different approaches have been employed to estimate earthquake casualties and damages. These approaches have combined in various ways the important input or determinant factors, including data from relevant historical damaging earthquakes, theoretical foundations of seismological and geological aspects, and personal judgments of structural engineers.

Perhaps the earliest work in this subject area may be traced to Freeman's (1932) study on earthquake damage and its value for determining earthquake insurance. His approach of deriving the damage ratio to wood and other structures with a single ground factor adjustment was followed and expanded on by several later researchers. Not until the 1960's however, did earthquake information become available that enabled researchers to analyze the physical damage ratio of various types of structures for earthquakes that had occurred previously. Representative studies of this nature may be found in Martel's (1965) investigation of damages caused by the March 10, 1933, earthquake in Long Beach, California, to a group of buildings designated as Class C in many of the older building codes and as Type III in the Uniform Building Code. Similar studies have been conducted by Richter (1958) and by Steinbrugge and his associates (1954, 1968, 1969, 1971, and 1973). Results of some of their investigations were improved upon by other researchers, and some gross damage or loss ratios have been formulated for each type of structure for various earthquake intensities.

Improved work in damage function development can be seen in Whitman et al. (1973, 1974) and Page et al. (1975). The damage rations reported in their studies have recently been synthesized and refined to derive another series of damage functions for finer building structures (Mann, 1974; Friedman, 1975; and Rinehart, et al. 1976).

Some researchers, on the other hand, have selected an engineering approach in establishing the functional relationship between earthquake damage and building structures. For example, the works by Culver et al. (1975) and Ewing et al. (1979) typify the engineering approach. Recently, Laird and his associates (1979) have even attempted to compute average damage ratios based on the damage costs per acre per event.

All the above-mentioned methodologies are either too specific to apply to any aggregate regional study area such as this one for the New Madrid earthquake zone or too general to consider all the important factors essential to the physical damage function estimation. In our opinion, two factors, i.e., ground susceptibility and age of structures, should definitely be included simultaneously in the estimation of a physical damage function for earthquake hazard.

The importance of ground conditions in earthquake damage estimation was recognized by Freeman in 1932. And since then, several studies have incorporated the impact of geologic materials in determining the damage effect of earthquake on structures. For example, studies by Friedman (1975), Perkins and Olmstead (1978), Borcherdt et al. (1979), and Algermissen et al. (1978, 1979), among others, have more or less stressed the variability of earthquake susceptibility depending on geologic materials and their role in quake intensity. To the best of our knowledge, the incremental damage estimation method adjusted by quake intensity is by far the most popular approach available. However, the adjustment for quake intensity may lead to a biased estimation of the damage function if factors other than ground conditions are not considered.

Another factor in the determination of physical damage, whose importance has not been adequately noted by many researchers, must be taken into account if the function is to be conceptually sound. This factor, namely, the age and other characteristics of the structure, was considered critical to building damage even at an earlier stage in the history of earthquake study. Although the earliest work dealing with structure age may be traced to the study of Wailes and Honer (1933), full recognition of the importance of this variable was finally given by Steinbrugge and Schader (1973) in their study of the February 9, 1971, San Fernando, California earthquake. The influence of structure age on demand ratios also appear to be significant in the estimations by Rinehart (1976), Paté (1978), and Wiggins et al. (1978).

Although all the studies cited seem to have established a framework for earthquake damage studies, they all fail to take into account the interdependent relationships among earthquake intensity, structure conditions, ground factors, and age influence in general and the synergistic effect between geology and building age in particular. It thus becomes necessary to develop a more complex physical damage function so that not only the

most important variables are included in the function, but also the interactive influence among them can be better measured and more accurately evaluated and, as a consequence, more reliable earthquake damage estimates can result.

The relationship between quake intensity and human mortality or injury rate has not been as thoroughly studied as have the structures. In most of the damage studies, mortality resulting from earthquake is simply a linear function of the building damage ratio based primarly on records of past damage. The recent works of Wiggins et al. (1978) and Hirschber et al. (1978) did relate the number of lives lost in past events to dollar losses for these events. Their estimations, however, did not include the intensity as a variable but assumed that the population trend (implied by a time variable) and building destruction are the factors determining life loss. Almost without exception, the injuries were then estimated by correlating a rather arbitrarily fixed ratio with the mortality rate. Typical works of this nature are also found in Mann (1974) and Bowden and Kates (1974). Seldom have damage studies been concerned heretofore with damage to personal property because of the paucity of data in general.

All the studies mentioned above, except that of Mann for MATCOG/MDDD, covering the Memphis SMSA, and that of Wiggins et al., which includes a general discussion covering all major earthquake zones of the entire nation, focus on earthquake damage estimation in California or other parts of this country. To our knowledge virtually no study has attempted to provide an adequate account of potential earthquake damages in the New Madrid region between St. Louis and Memphis. Because of the geographical coverage of our study, Mann's work is of special interest. The physical damage functions developed in his study are discussed in detail in this chapter, and they serve as a foundation for methodological departure. However, a sophisticated physical damage function model is developed also in this chapter. In this model, a chain relationship among building damages, casualties, and personal property losses is examined in its recursive form more thoroughly; and the impacted receptors or the damage functions are explained more accurately.

B. An Integrated Model for Damage Assessment

This so-called integrated model consists of three submodules: earthquake risk prediction; the land form and ground susceptibility study; and damage functions relating both physical and economic damages to earthquake risk, ground susceptibility, and total population at risk. In mathematical form, our model looks as follows:

$$D_{ij} = f_i \left[(R_j, S_j, PC_j); PE_j; O_j\right] \qquad \text{(V-1)}$$

where D_{ij} = damage estimate for the ith type of damage in region j.

R = predicted earthquake risk in Modified Mercalli Intensity (MMI), with a certain probability of recurrence or determination.

S = topographic and ground susceptibility to earthquake.

PC = population characteristics that are vulnerable to earthquake.

PE = population volume or number exposed to earthquake risk.

O = other exogenous factors than those listed that also affect the damage, such as damage mitigation policies, etc.

Because of the paucity of historical information on all factors expressed in equation model (V-1) for each type of damage, the physical and economic functions will be discussed separately to derive the best possible relationship for each individual damage category. The results of these relationships then will be incorporated into the projected earthquake information to retain the integrity of the model.

1. An evaluation of structural damages: The first damage estimate of our investigation is the potential damage to structures due to earthquakes, which is usually represented by a ratio of damage value to the total value of the structure. Such a damage ratio has been the focus of several previous studies. (Martel, 1965; Steinbrugge, 1968; Weigel, 1970; MATCOG/MDDD, 1974; Culver et al., 1975). Perhaps the most thorough study is the one by Page et al. (1975) They derived two series of building damage ratios for M.M. intensities VI to X, one for wooden frame structures and another for all non-wooden structures, as shown in Table V-1.

TABLE V-1

POTENTIAL DAMAGE RATIO OF BUILDINGS

Modified Mercalli Intensity	Damage Ratio (%) for Wood Frame Dwelling	Damage Ratio (%) for Other Buildings
VI	0.2	1.0
VII	2.0	5.0
VIII	5.0	15.0
IX	8.0	35.0
X	12.0	50.0

Although historical data did support the division of damage potential between wooden frame and nonwooden structures exposed to earthquakes, historical records also revealed significant differences among various structures of the nonwooden category. In aggregate, there are at least three categories: masonry, concrete, and steel frame. To account for these differentiations, Paté (1978) has suggested another set of damage ratios, which classifies structures in four categories that separate wooden frame structures from masonry or concrete wall, steel or reinforced concrete with fire resistance, and steel or reinforced concrete with less fire resistance. The results of Paté's study are summarized in Table V-2.

TABLE V-2

MEAN DAMAGE RATIO PER TYPE OF STRUCTURE BY EARTHQUAKE INTENSITY a/

Type of Structure	Modified Mercalli Intensity				
	VII	VIII	IX	I	XI
Steel or reinforced concrete with fire resistance	1.75	9	17.5	29	45
Steel or reinforced concrete with less fire resistance	2	12.5	25	45	55
Masonry or concrete wall	2	12.5	35	50	65
Wood frame	1.5	6.5	13.5	25	37.5

a/ The ratios are the average of the damage ratios of the pre-1940 group and the post-1940 group for each type of structure. The average ratio is used for comparing to those suggested by Page et al. (1975) and for deriving the damage ratios used in our study.

Most related studies have adopted one of these two sets of physical damage series for estimating the potential physical damage to various types of structures for earthquake intensities equal to or greater than M.M. intensity VI. In our study, however, we treat these two sets or series as a partial observation and use also the building damages data that have been collected during the past century on various types of structures (see Appendix D).

That is, instead of using any previously derived damage ratio series, we have developed a set of functional relationships to estimate the potential damage to three types of structures--wooden frame, masonry, and concrete and steel frame--in terms of earthquake intensity via the regression technique.[1] The results are as follows:[2]

For wooden frame structures:

$$\ln(DR) = -5.58 + 2.46 \ln(MMI-5) \qquad R^2 = 0.935 \qquad (V\text{-}2)$$
$$(0.17)^* \quad (0.15)^* \qquad F = 258.79$$
$$S.E. = 0.3346$$

For masonry structures:

$$\ln(DR) = -4.83 + 2.65 \ln(MMI-5) \qquad R^2 = 0.914 \qquad (V\text{-}3)$$
$$(0.24)^* \quad (0.20)^* \qquad F = 180.11$$
$$S.E. = 0.3589$$

For concrete and steel frame structures:

$$\ln(DR = -4.36 + 2.18 \ln(MMI-5) \qquad R^2 = 0.871 \qquad (V\text{-}4)$$
$$(0.24)^* \quad (0.21)^* \qquad F = 107.69$$
$$S.E. = 0.4484$$

where DR is the damage ratio; the figures in the parentheses are the standard errors of the estimated coefficients; R^2 is the coefficient of determination normally used to measure the strength of the regression equation relationship; F is the overall test of the goodness of fit of the regression equation; and MMI = Modified Mercalli Intensity. Coefficients marked with asterisks are statistically significant at the 5.0 percent level.

1/ Wiggins et al. (1978) suggested the regression estimation approach to derive the damage ratio for dwelling and industrial or commercial structures. However, in their estimation the parameters of the equation were estimated for several sets of M.M. intensity ranges. Because there are no appropriate criteria for determining the cutoff points in terms of M.M. intensity between any two levels and its partial impact on the structural damage ratio, their approach must be modified.

2/ See Table B-1 in Appendix B for complete listing of sample observations employed to generate these functions.

Because the damages will likely be insignificant for any earthquake with intensity V or less and the maximum intensity will never be higher than XII, the equations suggested above are subject to restrictions of the upper boundary of MMI being equal to XII and DR equal to 1.0, and the lower boundary of MMI equal to V and DR equal to 0.0[1/]

Based on the physical damage functions generated above, three series of damage ratios for three types of structures used in this study were developed and are presented in Table V-3. See Mann (1974) for construction class definitions and earthquake loading zonation.

TABLE V-3

ESTIMATED DAMAGE RATIO PER TYPE OF STRUCTURE IN EACH RANGE OF INTENSITY

Modified Mercalli Intensity	Damage Ratio for Wooden Frame Structures	Masonry Structures	Concrete and Steel Frame Structures
VI	0.0038	0.0080	0.0130
VII	0.0209	0.0503	0.0588
VIII	0.0564	0.1475	0.1421
IX	0.1144	0.3165	0.2658
X	0.1979	0.5721	0.4321
XI	0.3097	0.9280	0.6427
XII	0.4522	1.0000	0.8989

1/ Another set of equations that used ln MMI instead of ln(MMI-5) as the independent variable has also been tested. The results of these equations are:

For wooden frame structures:

$$\ln(DR) = -17.88 + 7.13 \ln MMI \qquad R^2 = 0.892$$
$$(1.22)^* \ (0.58)^* \qquad F = 148.48$$

For masonry structures:

$$\ln(DR) = -17.25 + 7.30 \ln MMI \qquad R^2 = 0.881$$
$$(1.38)^* \ (.065)^* \qquad F = 126.37$$

For concrete and steel frame structures:

$$\ln(DR) = -15.35 + 6.35 \ln MMI \qquad R^2 = 0.863$$
$$(1.33)^* \ (0.63)^* \qquad F = 100.79$$

Because the model using ln(MMI-5) as the independent variable yielded better results as reflected by a higher value of R^2, and reduced the possibility of deriving out-of-range damage ratios (i.e., DR > 1.0) the results of this specification are selected and employed in this study.

The damage ratios reported in Table V-3 are considerably different from those estimated by Mann. (1974) For example, wooden frame structures are expected to sustain less damage than Mann's results for M.M. intensity IX or lower indicate, but more damage when earthquakes of M.M. intensities exceeding IX occur. For masonry structures, our estimation is closer to Mann's estimation for high quality masonry; and for concrete and steel frame structures, our estimation coincides quite well with Mann's estimation for class A construction with Zone 3 earthquake loading (NOAA, 1973). The results of the damage ratio estimations are reported in Table V-3, and those ratios suggested by Mann are plotted in Figure V-1 to V-3 for comparison.

The damage ratios estimated above, however, do not take into account one critical factor with regard to structure. The impact of the age of the structure or the number of years since the structure was completed on the potential damage to the structure may be considerably different because of natural deterioration, changes in the construction code, innovative construction techniques, invention of new construction materials, etc. Historical records have supported this relationship between building damage and building age. For example, the statistics of the field survey after the 1971 San Fernando earthquke revealed that the average pre-1940 dwellings suffered 18.15 percent damage while the overall average of damage to all dwellings was only 10.12 percent. This factor, which was not accounted for by Mann in estimating the potential building damage due to earthquake in the MATCOG/MDDD study, is, in fact, incorporated into some damage estimation models developed recently by Paté (1978) and Wiggins et al. (1978).

While the impact of the age of the structure on the potential damage to the structure itself due to earthquakes is clear, the magnitude of this factor is extremely difficult to estimate.

In both Paté's and Wiggins' models, the damage ratios were estimated separately in terms of age groups. For example, Paté separated all buildings into two groups, with the year 1940 as the cutoff point; in Wiggins' model the cutoff point was 1933. Such an arbitrary criterion does not seem to reflect the deteriorating condition of a building adequately. The ideal way would be to investigate on-site, building-by-building to determine the potential impact of building age on damage. However, it was not possible financially, nor was there time for such a survey. To optimize available resources, we incorporated the information on housing age obtained from the decennial Census of Housing of the Department of Commerce into our model.

According to the 1970 Census of Housing, the residential structures of each county are classified into six age groups--denoted as IY1 to IY6. For these six age groups, we may extrapolate the residential structures' age distribution pattern by the following relationships:

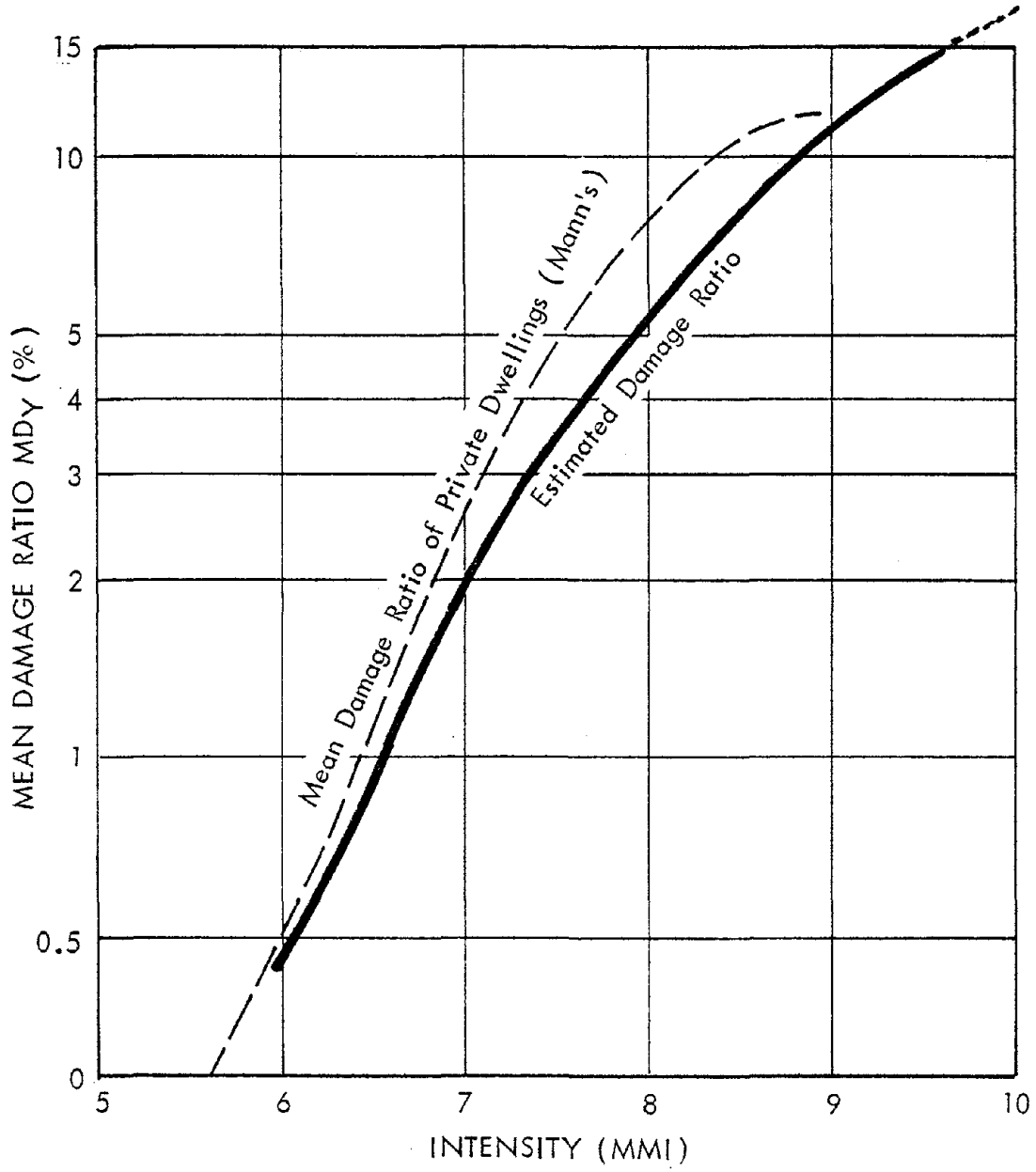


Figure V-1. Estimated Damage Relations:
Wooden Frame Structures

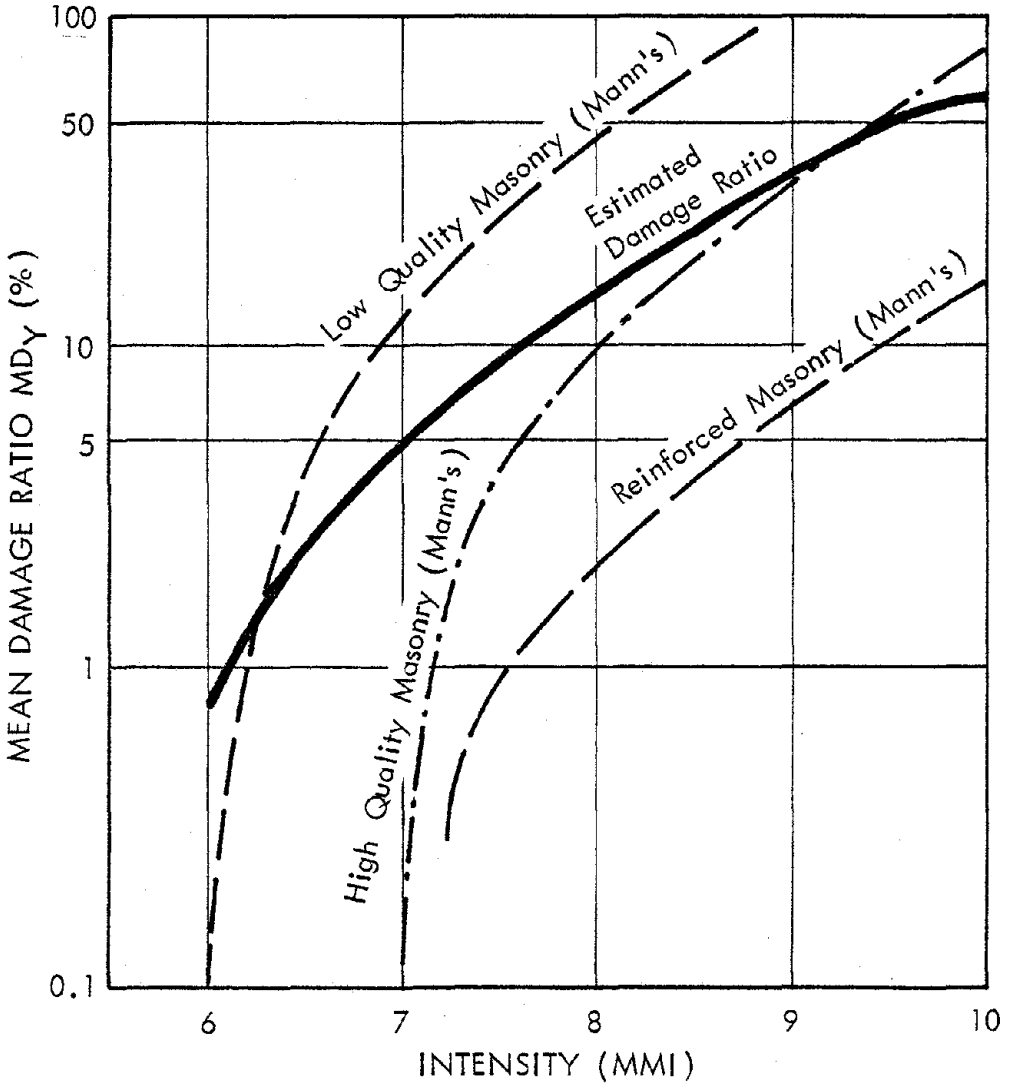
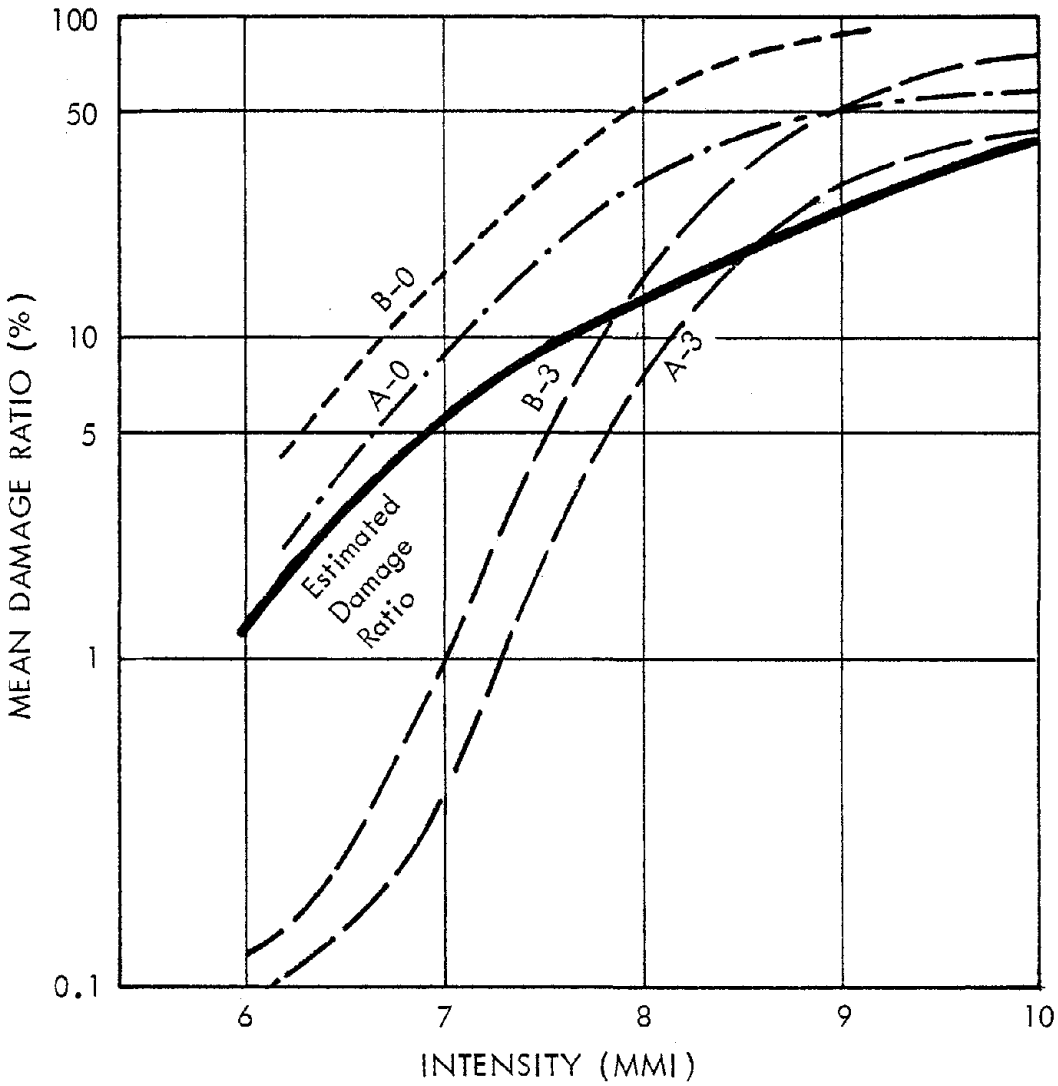


Figure V-2. Estimated Damage Relations: Masonry Structures



Note:

B-0 = Class B with No Earthquake Loading (Mann's)
A-0 = Class A with No Earthquake Loading (Mann's)
B-3 = Class B with Zone 3 Earthquake Loading (Mann's)
A-3 = Class A with Zone 3 Earthquake Loading (Mann's)

Figure V-3. Estimated Damage Relations:
Concrete and Steel Frame Structures

$$IY1 = a_1 + b_1 \text{ TIME} + C_1 X \qquad \text{(V-5)}$$
$$IY2 = a_2 + b_2 \text{ TIME} + C_2 X$$
$$\vdots$$
$$IY6 = a_6 + b_6 \text{ TIME} + C_6 X$$

$$\text{subject to: } \sum_{i=1}^{6} a_i = 1; \quad \sum_{i=1}^{6} b_i = 0; \quad IC = 0$$

Where TIME is the time variable with the value "1" for the start period, value "2" for the next period, etc.; X is the column vector of all other factors affecting the rate of change in the age distribution pattern; C_i is the coefficient of variable X; I is a 1 x 6 unity vector; C is the coefficient matrix of all coefficient C_i's in the six equations; and 0 is a vector with all elements equal to zero. The constraints are necessary to enforce the relationship that all individual groups add up to the total (IY1 + IY2 + IY3 ... + IY6 = 1), which is definitely required throughout the regression.

The equation system (V-5) is theoretically acceptable and could be easily solved via a constrained seemingly unrelated regression technique (Zellner, 1962). However, due to the problem of insufficient degrees of freedom, the solution still cannot be attained (Zellner and Huang, 1962). Alternatively, we assume that the building age distribution pattern in 1970, as reported in Table V-4, will continue throughout the projection period. Because there will be no significant deviation of earthquake intensity for any point within the same county boundary, the age distribution pattern and the age intervals reported in Table V-4, will enable us to estimate the county-based potential physical damages due to earthquakes without a detailed survey on housing conditions.

Given the six age intervals stated in (V-5) and assigning index 1 for those buildings which were completed in 1939 or earlier and index 6 for those completed after 1969, the age interval indices are shown in Table V-5.

TABLE V-5

BUILDING AGE INTERVAL INDICES

Index	Building Age Interval
1	1939 and earlier
2	1940 - 1949
3	1950 - 1959
4	1960 - 1964
5	1965 - 1969
6	after 1969

TABLE V-4

BUILDING-AGE DISTRIBUTION BY COUNTY

County/Age Intervals	1 1939 and Earlier	2 1940-1949	3 1950-1959	4 1960-1964	5 1965-1968	6 1969-March 1970
Madison	0.4032	0.1478	0.2235	0.1053	0.0914	0.0288
St. Clair	0.3826	0.1501	0.2556	0.1025	0.0818	0.0274
Franklin	0.4287	0.1028	0.1720	0.1326	0.1161	0.0478
Jefferson	0.2249	0.1070	0.2305	0.2072	0.1697	0.0607
St. Charles	0.1939	0.0740	0.2246	0.2159	0.2156	0.0760
Monroe	0.4784	0.0678	0.1863	0.1297	0.1108	0.0270
St. Louis County	0.2087	0.1276	0.3129	0.1676	0.1446	0.0386
St. Louis City	0.7376	0.1105	0.0871	0.0342	0.0259	0.0047
Clinton	0.5324	0.0792	0.1420	0.1059	0.1061	0.0344
Crittenden	0.2377	0.2043	0.2532	0.1234	0.1142	0.0672
Tipton	0.3745	0.1743	0.1649	0.1327	0.1216	0.0320
Shelby	0.2225	0.1817	0.2954	0.1365	0.1251	0.0388
De Soto	0.2401	0.1119	0.1115	0.2293	0.2010	0.1062
Cape Girardeau	0.4113	0.1272	0.1790	0.1421	0.0884	0.0520
New Madrid	0.4413	0.2257	0.1253	0.0645	0.1020	0.0412

Sources: 1970 Census of Housing, Bureau of the Census, U.S. Department of Commerce.

From the field survey information after the 1971 San Fernando earthquake, we derived the following relationship between damage ratios and housing age groups.[1/]

$$\ln(DR) = 3.89 - 0.67\ IY \qquad R^2 = 0.308 \qquad \text{(V-6)}$$
$$(0.26)^* \quad (0.10)^* \qquad F = 42.78$$

Where DR is the damage ratio of concrete and steel frame buildings with a height of 8 to 13 stories and located in the triangle area of Beverly Hills-Hollywood-West Los Angeles and IY is the index of the building age interval as indicated in Table V-5. The selection of these sample buildings is based on four common characteristics. They are located on the same geologic materials (quaternary-tertiary rocks) (Yerkes et al., 1966); they are located within the isoseismic intensity area (M.M. intensity = VII); they have closely related ductility; and they reflect the height limitation imposed by the City of Los Angeles building code from 1933 until relatively recently (Whitman, Hong, and Reed, 1973). In addition, this information contains the maximum available number of useful data points needed in our estimation.

Nevertheless, the results of equation (V-6) support our inference that recently constructed buildings tend to suffer less damage than older buildings, holding everything else constant. From the results of equation (V-6) we may determine an age adjustment factor, denoted as F1, as follows:[2/]

$$F1 = e^{-0.67i} \qquad \text{(V-7)}$$

Where i = 1 to 6 is for the age interval. Because there are no sufficient samples available for separately estimating the age adjustment factor for the other two types of structures, masonry and wooden frame, equation (V-7) has been applied to all types of structures in this study.

Another factor influencing the potential damage to structures is the susceptibility of ground in the study area to earthquakes. Although earthquake intensity ratings have already implicitly taken into account the various soil conditions that influence the waves along the path from the source of earthquake to the surface, the earthquake intensity itself still is not a sufficient factor in reflecting the diversity of geologic materials within certain isoseismic zones or the susceptibility of the ground on which buildings are erected (Federal Insurance Administration, 1971).

1/ The observations used for our regression tests were selected from the data listing reported in Whitman, et al. (1973). The complete listing of those observations selected are presented in Appendix B.

2/ In an earlier model, this adjustment factor was arbitrarily assumed equal to e^{-i} (Liu and Hsieh, 1979).

The insufficiency of relating damage to earthquake intensity alone as discussed above has long been noticed. Several approaches for improving such insufficiency have been suggested. For example, Freeman (1932) suggested adjusting the average damage ratio by a certain scale in terms of the soil condition under the structures, as indicated in Table V-6.

TABLE V-6

GROUND FACTOR ADJUSTMENT RATE

Type of Construction	Ground Factor	
	Soft	Bedrock or Stable
Wood	2 to 4 times average loss ratio	1/4 to 1/2 average loss ratio
Other	0 to 4 times average loss ratio	0 to 1/2 average loss ratio

Friedman and Roy (1969) on the other hand, set up a system of equations to separately measure the variability of ground conditions with respect to intensity and damages by adding certain values to the magnitude. Their approach has stimulated researchers such as Perkins and Olmstead (1978), Algermissen, Steinbrugge and Lagorio (1978), and Borcherdt, Gibbs, and Fumal (1979) to account for the ground susceptibility of several classes of geologic materials in their studies with an improved method of deriving the intensity increment. But the derived intensity increment varies substantially among models. For example, Perkins and Olmstead calculated a 0.19 intensity increment for Franciscan Assemblage, while that derived by Algermissen, Steinbrugge and Lagorio was -1 for similar geologic materials. The results reported by Perkins and Olmstead are shown in Table V-7 below.

TABLE V-7

INTENSITY INCREMENT BY GROUND FACTOR

Geologic Unit	Intensity Increment
Granitic Rock	-0.29
Franciscan Assemblage	0.19
Most Tertiary and Older Rocks	0.64
Quaternary - Tertiary Rocks	0.82
Alluvium	1.34
Bay Mud	2.43

The intensity increment approach has also been adopted by Mann (1974) in simulating potential earthquake damages. But unlike the results suggested by Perkins and Olmstead, Mann's incorporation of geologic material is in a rather simple format, thus leaving much room for improvement.

In this study, none of the above-mentioned ground adjustment factors will be selected. On the one hand, Freeman's criterion is too simple to be applied to our study area where geologic materials are too divergent to be classified only into two categories: soft and bedrock or stable. In addition to his suggestion that all the structures other than wood be in one category is also too aggregate. On the other hand, the alternative approaches will not be adequate because we believe that there are several factors other than ground conditions, e.g., age of the structure as discussed above, which will influence the vulnerability of the structures. The increment in the intensity adjustment approach will bias the estimation of structure damages if any factors other than ground condition are considered in the model on damage estimation.

Ideally, the relationship between damage and ground conditions could be done by regression of the field survey information on geology on past earthquake damage. However, to date such information is still not available.

In this study, the geologic materials of the study area have been classified into six categories by geologist R. Gentile of the University of Missouri - Kansas City. Each category was then further decomposed into several subclasses as depicted in Figures III-1 to III-4 in Chapter III. However, within each category, the ground susceptibility of the earthquake damage is assumed the same. Moreover, the first and second categories (I and II as represented in Chapter III) bear the same susceptibility as Gentile indicated. Because we are focusing on the countywide potential loss due to earthquakes rather than loss to any single structure, we assumed that all types of structures are scattered evenly over the county by type. Such assumptions might not be very plausible; however, it does enable us to alleviate the difficulty of identifying the geologic material against the functional type (business, industrial, or residential) of each structure. Given the information contained in Figures III-1 to III-4 and our assumptions, we derived the geologic materials distribution pattern by county for the region shown in Table V-8 below.

TABLE V-8

COUNTY GEOLOGIC MATERIALS DISTRIBUTION

	Index of Ground Susceptibility				
	1	2	3	4	5
Madison	--	0.15	0.10	0.75	--
St. Clair	--	--	0.25	0.75	--
Franklin	--	--	0.05	0.90	0.05
Jefferson	--	--	0.33	0.67	--
St. Charles	--	0.40	0.20	0.40	--
Monroe	--	0.40	0.20	0.40	--
St. Louis County	--	--	0.60	0.40	--
St. Louis City	--	0.45	0.55	--	--
Clinton	--	--	0.15	0.85	--
Crittenden	1.0	--	--	--	--
Tipton	--	0.15	0.35	0.50	--
Shelby	0.05	0.15	0.40	0.40	--
De Soto	0.10	0.15	0.25	0.50	--
Cape Girardeau	--	0.80	0.15	0.05	--
New Madrid	1.0	--	--	--	--

The index 1 in Table V-8 corresponds to the category of geologic materials with lowest susceptibility; and the index 5 to the category of geologic materials with highest susceptibility. Because there was no historical information that we could use, we assumed an exponential relationship, as with the age adjustment factor, exists among the structures. The impact of the geologic materials on the damage of the structures, thus, was expressed as follows:

$$F2 = e^{-0.67s} \qquad \text{(V-8)}$$

where s ranges from 1 to 5 and stands for the index of geologic material susceptibility as explained above.

Because geologic materials susceptibility and structure condition, specifically age, are likely to interact in determining the potential damage of a structure, a geometrical average of these two factors was suggested in this study for adjusting the physical damage ratio derived without explicitly considering these two factors. Therefore, for a structure with an unadjusted potential damage ratio, DR^{o}, which is located on the geologic material with sth index and with the age within ith age interval, the adjusted damage ratio, DR*, would look as follows:

$$DR^* = DR^{o} \cdot \left[(1 + e^{-0.67i}) \cdot (1 + e^{-0.67s})\right]^{1/2} \qquad \text{(V-9)}$$

Because of the difficulty in evaluating the potential structural damage in any of the study counties, the adjustment for potential damage of any type of structure will be performed by using the distributed weights of geologic materials and structure age patterns as reported in Tables V-4 and V-8 and the relationships expressed by equation (V-9) above. Thus, for those same types of structures--wooden frame, masonry, or concrete and steel frame--within the ith age interval and sth index of geological materials in any study county, the adjusted damage ratio for these structures would become:

$$DR^*_{is} = DR^o \cdot W_i \cdot W_s \left[(1 + e^{-0.67i})\ (1 + e^{-0.67s})\right]^{1/2} \qquad \text{(V-10)}$$

where W_i is the weight of ith age interval in the structural age distribution pattern and W_s is the weight of geologic material susceptibility with index s in that study county. The aggregated adjusted damage ratio for any type of structure in any county k thus may be expressed as follows:

$$DR^*_k = DR_k \sum_{i=1}^{6} \sum_{s=1}^{5} \cdot W_{ki} \cdot W_{ks} \left[(1 + e^{-.67i})\ (1 + e^{-.67s})\right]^{1/2} \qquad \text{(V-11)}$$

$$= DR_k \cdot ADJ_k$$

where DR_k is the damage ratio derived from equations (V-2) to (V-4) and ADJ_k is the age and ground condition adjustment factor for kth county.[1/] The final form of estimating the potential damage ratios of the three types of structures in kth county, thus, are expressed as follows:

$$DRW_k = 0.004\ (MMI - 5)^{2.46}\ ADJ_k \qquad \text{(V-12)}$$

$$DRM_k = 0.008\ (MMI - 5)^{2.65}\ ADJ_k \qquad \text{(V-13)}$$

$$DRS_k = 0.013\ (MMI - 5)^{2.18}\ ADJ_k \qquad \text{(V-14)}$$

1/ In an earlier model, the age and ground condition adjustment factors are specified as follows:

$$AF1 = \Sigma A_i\ e^{-0.67i}$$
$$AF2 = \Sigma A_s\ e^{-0.67s}$$

Where A_i, A_s = age and ground susceptibility distribution factors of structures and land formations in each county, respectively. The specification of (V-11) above, however, is theoretically more accurate and was finally selected for this study. For the discussion of our earlier model specification, see Liu and Hsieh (1979).

and the damages to each type of structures are derived by:

$$DW_{k,t} = VW_{k,t} \cdot DRW_k \tag{V-15}$$

$$DM_{k,t} = VM_{k,t} \cdot DRM_k \tag{V-16}$$

$$DS_{k,t} = VS_{k,t} \cdot DRS_k \tag{V-17}$$

where $VW_{k,t}$ = market value (1978) of total wooden structures in county k at time t.

$VM_{k,t}$ = market value (1978) of total masonry structures in county k at time t.

$VS_{k,t}$ = market value (1978) of total concrete and steel frame structures in county k at time t.

DRW_k = adjusted potential damage ratio to wooden structures for county k

DRM_k = adjusted potential damage ratio to masonry structures for county k

DRS_k = adjusted potential damage ratio to concrete and steel frame structures for county k.

$DW_{k,t}$ = potential damage value of wooden structures in county k at time t

$DM_{k,t}$ = potential damage value of masonry structures in county k at time t

$DS_{k,t}$ = potential damage value of concrete and steel frame structures in county k at time t.

2. Nonstructural damage estimation: In this section three categories of nonstructural damage functions are estimated, and the damage impact assessment models are established for another two populations at risks. They are human mortality damage functions, personal property damage functions, and human injury relationships. These developments and their interdependent relationships are individually elaborated on in a stepwise manner below.

a. Mortality damage functions: The most critical damage resulting from earthquakes is the loss of life. Bowden and Kates (1974) estimated that the recurrence of an earthquake with the approximate isoseismal distribution of intensity of the 1906 San Francisco earthquake could cause the deaths of from 2,000 to 10,000 people in the entire Bay area, depending upon the time of day such an event would occur. To take a real case as an example, the earthquake which occurred on September 16, 1978, in the northeastern part of Iran took over 10,000 lives despite technological progress and increasing concern about earthquake preparedness (Person, 1979). However, estimation of the potential mortality due to earthquake is far more complicated than estimation of damage to physical structures.

Theoretically, several factors can be linked with potential mortality due to earthquake. The most clear factor is the population density of the area that is hit. A high population density indicates a high percentage of population which would be exposed to earthquake risk and possibly a higher mortality. On the other hand, as historical documents of the damaging earthquakes have revealed, a considerable number of deaths were attributed to the collapse of buildings, which in turn varied with earthquake intensity, building conditions, ground conditions, etc. Also, as indicated by several previous studies, the time of day when earthquakes occur could also be a critical determinant (Mann, 1974; Bowden and Kates, 1974).

Since business and industrial areas generally have a higher density of population in the daytime than in the night, those structures are considered to have a higher potential damage ratio than a residential area where the population density is higher in the night. The influence of the time of day when earthquakes occur thus is clear. Other factors include the degree of preparedness by the earthquake area, availability of hospital facilities, the accessibility of fire engines and ambulances, etc. The potential mortality damage function of earthquake may be expressed as follows:

$$MORT = \theta\ (POPD,\ DR,\ MMI,\ TIME,\ X) \qquad \text{(V-18)}$$

where DR = aggregate damage ratio of all types of structures

POPD = the population density

TIME = the dummy variable to distinguish the day-time earthquake from the night-time earthquake, with "2" for day-time and "1" for evening.

MMI = Modified Mercalli intensity measure.

X = the vector of all other relevant variables not mentioned above.

Empirically, the functional relationship stated in equation (V-18) needs further modifications. First, there is not any information available on the total structure damage ratio of any given earthquake among those that have occurred. However, there is well-recorded information about personal property damage for some past earthquakes. (Blume, 1971; NOAA, 1973). Because personal property is reasonably well-related to the value of structures, personal property damage information may be considered as a proxy for structure damage in the estimation of earthquake impact on mortality.

Before incorporating this personal property damage information into the model, however, two adjustments are essential. First, the recorded personal property damage information is the value of personal property damage when the earthquake occurred. To keep the observations used for our estimation consistent, these values were updated to 1978 values by the growth in the consumer price index.[1/] Second, the total value of personal property may be highly related to the number of population. Hence as the population grows, the total value of personal property will increase and so will the potential amount of personal property damages. However, it is not necessarily true that the potential mortality will increase as does the total amount of personal property (or implicitly, the total amount of the structure damage ratio). Thus, instead of using this adjusted total value of personal property damage as a determinant, the per capita property damage information was used.

Furthermore, there is not sufficient information to trace the actual population distribution pattern over the earthquake-prone area during the time of day when earthquakes occurred. Therefore, it is impossible to determine the variation of population density between diurnal and nocturnal populations for a given geographic area, say, a county or a city. However, such variation exists without any doubt, especially in the case of St. Louis City. To reflect such differences while not distorting the facts, we simply assumed that diurnal population density was about five times that of the nocturnal population in the development of the simulation model utilizing mostly the historical data.

1/ The consumer price index is obtained from "The Basic Economic Statistics" published by the Economic Statistics Bureau of Washington, D. C. The value is convered by the following formula.

$$V_{i,1978} = V_i \cdot \frac{CPI_{1978}}{CPI_i}$$

Where $V_{i,1978}$ is the converted 1978 value of V_i at the ith year's value; CPI_i is the consumer price index at the ith year and CPI_{1978} is the consumer price index in 1978.

Other factors concerning the accessibility to vehicles, hospitals, safety spots, etc., either is impossible to quantify or data do not exist. As a result, in this study they were left to be captured by the interception term included in the model. Furthermore, if no earthquake were to occur, no loss of life should be associated. Therefore, a log linear relationship instead of linear relationship was postulated to estimate the potential mortality of earthquake. The relationship thus was expressed as follows:

$$\ln(MORT) = a_o + a_1 \ln(MMI) + a_2 \ln(POPD) + a_3 \ln(PPD/POP) + a_4 \ln(TIME) \qquad \text{(V-19)}$$

where MORT = number of lives lost due to earthquake

PPD/POP = per capita value of personal property damages

TIME = day - night-time dummy variable with "1" for night-time and "2" for day-time

MMI = Modified Mercalli intensity measure.

The expected impact of each determinant is hypothesized as follows:

$$\frac{\partial MORT}{\partial MMI} > o, \quad \frac{\partial MORT}{\partial POPD} > o, \quad \frac{\partial MORT}{\partial (PD/POP)} > o, \quad \frac{\partial MORT}{\partial TIME} > o$$

Equation (IV-19) was then estimated with over 15 sample observations derived from the 15 past damaging earthquakes with necessary adjustment as stated above.[1/] The estimated results are:

$$\ln(MORT) = \underset{(5.68)}{-5.95} + \underset{(2.51)}{3.48} \cdot \ln(MMI) + \underset{(0.08)^*}{0.41} \ln(POPD) + \underset{(0.24)^*}{0.60} \ln(PPD/POP) - \underset{(0.75)^*}{1.70} \ln(TIME) \qquad \text{(V-20)}$$

$R^2 = 0.885$
D.W. = 2.13
F = 19.20

1/ The complete listing of these underlying data is presented in Appendix B.

where D. W. represents the Durbin-Watson statistics to test the existence of autocorrelation of the equation. All other statistics retain the same definitions as discussed in equations (V-2) to (V-4). All coefficients except that for MMI are statistically significant,[1/] and all but that for TIME have the expected positive impact on mortality. The F value indicates that the equation fits well, and the R^2 value reveals that over 88 percent of the variance in MORT among 15 cases was explained.

While the impact of TIME as estimated contradicts most of the previous related studies, there is no clear indication as to which is the true impact, positive or negative. However, it may be reasonable to accept the hypothesis that day-time mortality determination pattern is different from that of night-time because, at least statistically, the coefficient of TIME is statistically significant. That is to say, the partial impact of the "time" of earthquake occurrence on mortality definitely differs between day-time and evening. Our model indicates that more casualties will be caused by an earthquake occurring in the day-time than in the evening. For this disturbing result, the data on those earthquakes that have occurred during the day were fitted separately from data on earthquakes occurring during night-time to equation (V-19) without the TIME variable. Therefore, instead of having a single equation as reported above, we have two, one for day-time mortality estimation and another for night-time mortality estimation. The results are as follows: [2/]

1/ However, if we consider only the impact of earthquake intensity on potential mortality, we would have:

$$\ln(\text{MORT}) = -19.04 + 9.94 \ln(\text{MMI}) \qquad R^2 = 0.576$$
$$(5.20)^* \quad (2.36)^* \qquad F = 17.69$$

The coefficient of MMI is statistically significant indicating that MMI alone is an important determinant for potential mortality. But with the inclusion of other variables, the standard error of estimate for this variable increased. However, the insignificant results of the coefficient of MMI in equation (V-20) do not necessarily mean that MMI is not relevant in explaining MORT.

2/ Wiggins et al. (1978) related the number of lives lost in the past events to dollar losses for these events and tried to compute life loss due to earthquakes but didn't consider the effects of population diversity on mortality either in day-time or evening.

For diurnal population:

$$\ln(MORTD) = -23.47 + 12.05 \ln(MMI) \qquad R^2 = 0.782 \qquad F = 17.93 \qquad \text{(V-21a)}$$
$$\quad (6.05)^* \quad (2.85)^*$$

$$\ln(MORTD) = -5.23 + 2.51 \ln(MMI) + 0.44 \ln(POPD) \qquad \text{(V-21b)}$$
$$\quad (8.32) \quad (3.90) \qquad (0.11)^*$$
$$+0.63 \ln(PPD/POP) \qquad R^2 = 0.966 \qquad D.W. = 1.70 \qquad F = 28.43$$
$$(0.28)^*$$

For nocturnal population

$$\ln(MORTN) = -14.78 + 8.04 \ln(MMI) \qquad R^2 = 0.313 \qquad F = 2.73 \qquad \text{(V-22a)}$$
$$\quad (11.00) \quad (4.86)^*$$

$$\ln(MORTN) = -5.13 + 3.22 \ln(MMI) + 0.41 \ln(POPD) \qquad \text{(V-22b)}$$
$$\quad (9.47) \quad (4.12) \qquad (0.14)^* \qquad R^2 = 0.789 \qquad D.W. = 2.19 \qquad F = 4.97$$

$$+ 0.91 \ln(PPD/POP)$$
$$(0.83)$$

b. Personal property damage functions: Development of the personal property damage function followed the same procedure as the mortality damage functions discussed above. Conceptually, personal property damage would be closely related to building damages, life loss, earthquake intensity, etc. Again, because the building damage information was incomplete for past damaging earthquakes, the exclusion of this variable as a determinant in explaining the potential personal property damage will bias the estimation. As a substitute, the personal property damage function was estimated with the following relationships:[1/]

$$\ln(PPD/POP) = b_0 + b_1 \cdot \ln(MMI) + b_2 \ln(POPD) + b_3 \ln(MORT) \qquad \text{(V-23)}$$
$$+ b_4 \ln(TIME)$$

The per capita personal property damage is employed as a dependent variable such that the area potential personal property damages can be easily tied to the population growth trend. The dummy variable TIME is included here again to test if any different damaging results exist between day-time and night-time occurrence.

1/ In a preliminary model personal property damage was assumed to be the same as structure damage and was estimated on a lump sum basis instead of per capita value. That is:

$$DPP = VPP \cdot (DW + DM + DS)/(VW + VM + VS)$$

where VPP is the total estimated value of personal property and DPP is the estimated value of personal property damages. All other notations retain the same definitions as appeared in the main text.

Because personal property damage results simultaneously with life loss due to earthquake, in theory equation (V-23) should be estimated simultaneously with equation (V-19). However, because of insufficient samples and data on other exogenous variables, the system regression attempt was abandoned.

Equation (V-23) was also estimated by the ordinary least-squares method using 15 observations as for mortality estimation. The results of the regression are as follows: 1/

$$\ln(PPD/POP) = \underset{(5.76)}{-7.30} + \underset{(2.72)}{2.59}\ \ln(MMI) - \underset{(0.12)^*}{0.32}\ \ln(POPD) + \underset{(0.26)^*}{0.65}\ \ln(MORT) + \underset{(0.80)^*}{1.67}\ \ln(TIME) \qquad (V\text{-}24)$$

$R^2 = 0.749$
$F = 7.46$
$D.W. = 1.89$

Again, it is interesting to note that all coefficients but that of MMI are significant at the 5 percent level. The results indicate that (1) the intensity of earthquake is a positive but not a significant factor in determining personal property damage, at least as far as the 15 samples are concerned; (2) population density is negatively related to personal property damage, which is unexpected. (The reason for this negative relationship may be due to the fact that the residents in the suburban area, where population density is relatively lower, have a higher personal property value than city residents where population rates are relatively higher); (3) mortality has a significant positive impact on potential personal property damage as generally expected; (4) the coefficient of variable TIME is significant, which suggests a separate estimation of day-time personal property damage functions from that of night-time may be warranted. The results of such separate estimations are: 2/

1/ The regression equation with MMI as the sole determinant shows that:

$$\ln(PPD/POP) = \underset{(5.88)}{-6.30} + \underset{(2.67)^*}{7.81}\ \ln(MMI) \qquad R^2 = 0.396,\ F = 8.53$$

MMI alone is a significant determinant of PPD/POP, though its standard error of estimate increased along with the inclusion of other determinants. For the purpose of prediction, it is necessary to retain the variable MMI in equation (V-24) above.

2/ The results of regression with MMI as the determinant alone are:

$$\ln(NPPD/POP) = \underset{(12.13)}{-1.16} + \underset{(5.36)}{5.40}\ \ln(MMI) \qquad R^2 = 0.145,\ F = 1.01$$

$$\ln(DPPD/POP) = \underset{(5.32)}{-16.09} + \underset{(2.50)^*}{12.57}\ \ln(MMI) \qquad R^2 = 0.835,\ F = 25.23$$

The coefficient of MMI in NPPD/POP equation has only marginal explanatory power. However, it is a significant explanatory vehicle in NPPD/POP equation. As a result, the variable is retained in the equation to reflect the possible effect of MMI on NPPD/POP for purposes of prediction.

For night-time personal property damage:

$$\ln(NPPD/POP) = -\underset{(4.78)}{3.97} + \underset{(2.24)}{1.34}\ \ln(MMI) - \underset{(0.11)}{0.14}\ \ln(POPD) \qquad \text{(V-25)}$$

$$+ \underset{(0.23)}{0.25}\ \ln(MORTN) \qquad R^2 = 0.478 \quad F = 1.22$$

For day-time personal property damage:

$$\ln(DPPD/POP) = -\underset{(10.73)}{5.05} + \underset{(5.07)}{2.28}\ \ln(MMI) - \underset{(0.20)*}{0.50}\ \ln(POPD) \qquad \text{(V-26)}$$

$$+ \underset{(0.44)*}{1.00}\ \ln(MORTD) \qquad R^2 = 0.945 \quad F = 17.03$$

While the results of night-time personal property damage did not fit so well as the results for day-time personal property damage, the overall results in these two equations do not seem to have improved much over the previous one. Because all exogenous variables have a higher impact on dependent variables in the day-time estimation equation than in the night-time equation, we would include two separate equations in our model for simulation so that the potential damages can be better understood.

However, since equations (V-21) and (V-25) and (V-22) and (V-26) are to be determined simultaneously when we simulate the entire model, these two pairs of equations have to be solved simultaneously for mortality and personal property damages. The final form of these four equations so generated is as follows:

$$\ln(MORTD) = -22.73 + 10.67\ \ln(MMI) + 0.34\ \ln(POPD) \qquad \text{(V-27)}$$
$$\ln(MORTN) = -11.35 + 5.77\ \ln(MMI) + 0.36\ \ln(POPD) \qquad \text{(V-28)}$$
$$\ln(DPPD/POP) = -27.78 + 12.95\ \ln(MMI) - 0.16\ \ln(POPD) \qquad \text{(V-29)}$$
$$\ln(NPPD/POP) = -6.81 + 2.78\ \ln(MMI) - 0.05\ \ln(POPD) \qquad \text{(V-30)}$$

where DPPD/POP = per capita personal property damage, day-time
NPPD/POP - per capita personal property damage, night-time.

All other notations retain the same definitions as before.

c. Human injury functions: The final population at risk not accounted for so far is the potential number of injuries caused by earthquakes. The data on injuries from past earthquakes are of consideraly poorer quality than those for deaths. Because there is no better way to derive a good relationship to explain the potential injuries of varying earthquake

intensities, most researchers have simply assumed a multiplier and that human injuries are a multiple of the number of deaths due to earthquakes. For example in the NOAA (1973) report a 4-to-1 ratio was established for serious (requiring hospitalization) injuries to deaths, and a 30-to-1 ratio for nonserious injuries. In this study, we used a 100-to-1 ratio to estimate the potential injuries mainly for purposes of illustration. The ratio, though somewhat larger than ratios appearing in previous studies, is probably more appropriate in light of the improved technology and information in the health industry and increased alertness of people and society to earthquakes. As a result, mortality rates could be considerably reduced, but the relative ratio between injuries and fatalities may be correspondingly inflated.

d. Summary of the integrated simulation model: In summary, the complete model of physical and economic damage functions denoted as Model III consists of the following equations:

(1) For structure damages:

$$DW_{k,t} = VW_{k,t} \cdot DRW_f \qquad \text{(V-15)}$$

$$DM_{k,t} = VM_{k,t} \cdot DRM_k \qquad \text{(V-16)}$$

$$DS_{k,t} = VS_{k,t} \cdot DRS_k \qquad \text{(V-17)}$$

where $DRW_k = 0.004\ (MMI-5)^{2.46} \cdot ADJ_k$ (V-12)

$$DRM_k = 0.008\ (MMI-5)^{2.65} \cdot ADJ_k \qquad \text{(V-13)}$$

$$DRS_k = 0.013\ (MMI-5)^{2.18} \cdot ADJ_k \qquad \text{(V-14)}$$

and

$$ADJ_k = \sum_{i=1}^{6} \sum_{s=1}^{5} W_{k,i} \cdot W_{k,s}\ ((1 + e^{-.67i})\ (1 + e^{-.67s}))^{1/2} \qquad \text{(V-11)}$$

(2) For mortality estimation:

$$\ln(MORTD) = -22.73 + 10.67 \ln(MMI) + 0.34 \ln(POPD) \quad (V\text{-}27)$$

$$\ln(MORTN) = -11.35 + 5.77 \ln(MMI) + 0.36 \ln(POPD) \quad (V\text{-}28)$$

(3) For personal property damage:

$$\ln(DDPD/POP) = -27.78 + 12.95 \ln(MMI) - 0.16 \ln(POPD) \quad (V\text{-}29)$$

$$\ln(NPPD/POP) = -6.81 + 2.78 \ln(MMI) - 0.05 \ln(POPD) \quad (V\text{-}30)$$

(4) For injuries estimation:

$$INJD = 100 \cdot MORTD \quad (V\text{-}31)$$

$$INJN = 100 \cdot MORTN \quad (V\text{-}32)$$

where INJD = number of injuries for diurnal population

INJN = number of injuries for noctural population

The complete models developed at an earlier stage of this project, which are denoted as Model I, the first version, and Model II, are also reported in Appendix D in order to shed some light on the development and completion of our final model. The damage estimations based on these three models are reported and compared in the next chapter.

CHAPTER VI

ECONOMIC DAMAGE ESTIMATIONS FOR THE STUDY AREA

In this chapter the physical and economic damage functions model established in Chapter V is applied to the projected information on population, construction, and personal property developed in Chapter IV. The results are then incorporated with the projected earthquake risk data from Chapter II and the ground susceptibility indices developed in Chapter III to simulate the potential damage by earthquake to various populations over the next 50 years.

As stressed in Chapter IV, the projections of population and employment in the study area have already taken into account various factors such as the amount of vacant land available for development, migratory trends from rural to urban areas, projections and plans made by area regional planning agencies, etc. The projected results thus would be useful for a dynamic simulation. Personal property damages are simulated along with the estimation on mortality damage; thus, they are conceptually independent of the projections completed in Chapter IV. Those projections, nevertheless, serve as the upper-bound limit of the estimated damages. Projections on the value of various types of structures were also completed in Chapter IV. However, faced with empirical applications, some additional adjustment procedures were applied to the population estimates to derive more reliable risk population information.

In this chapter, the procedure for data adjustments is discussed first. Because our simulation covers the year 1980 and the five 10-year intervals thereafter, some adjustments to the data base developed in Chapter III are also summarized. The simulation results of this integrated model are presented and discussed in Section B. To gain some insight into the process of model formulation, the results obtained from the present model are compared in Section C with results of previous studies.

A. Data Base Adjustments

1. Structure value adjustment: Although the value of various types of structures projected and reported in Chapter IV have already taken into account the effects of factors such as growth trend of population, employment, the land use patterns, etc., these values also include the costs of both construction and lot. The actual value of any type of structure exposed to the risk of earthquake should exclude the value of the lot. According to Hendershott (1977)

for residential structures, the value of a lot is approximately equal to 20 percent of the total value. For commercial and industrial structures it is estimated to be 10 percent; and for other structures such as railroad, utility facilities, highway construction, etc., 90 percent. The actual value of each type of structure exposed to earthquake risk, denoted by VR, thus may be expressed as follows:

$$VR_{i,t} = V^*_{i,t} \ (1\text{-}SITE_i) \text{ for } i = 1 \text{ to } 4. \qquad \text{(VI-1)}$$

where V* is the value of structures obtained together with the land utilization patterns as described in Chapter IV, and $SITE_1 = 0.2$, $SITE_2 = SITE_3 = 0.1$, and $SITE_4 = 0.9$. The subscript value of 1 to 4 represents residential, commercial, industrial, and other structures.

Another value that is required to be adjusted and yet is difficult to measure is the percentage of a particular type of building material used in the three structure frames. Each type of structure is likely to include all types of building materials. However, unless a detailed field survey is conducted, we cannot determine the percentage mix of building materials in any particular type of structure. It is known that, in general, most residential structures are wooden frame buildings, a good portion of commercial structures are of concrete and steel frame construction, and a considerable share of industrial structures are masonry, concrete, and steel. While it is necessary to conjecture, we have developed the following material mix patterns and feel they are appropriate for estimating the potential damage to structures in the study area.

TABLE VI-1

PERCENTAGE OF BUILDING MATERIAL BY PURPOSE OF STRUCTURES

Building Material	Purposes of Structures			
	Residential	Commercial	Industrial	Other
Wooden frame	80	10	10	10
Masonry	15	30	60	60
Concrete and steel frame	5	60	30	30

The potential damage value to buildings for each county thus would be estimated by the following formula:

(a) for residential structures:

$$DR_t = 0.80 \cdot VR_{1,t} \ DRV + 0.15 \ VR_{1,t} \ DRM + 0.05 \ VR_{1,t} \ DRS \qquad \text{(VI-2)}$$

(b) for commercial structures:

$$DC_t = 0.10\ VR_{2,t}\ DRW + 0.30\ VR_{2,t}\ DRM + 0.60\ VR_{2,t}\ DRS \qquad \text{(VI-3)}$$

(c) for industrial and other structures:

$$DI_t = 0.10\ VR_{3,t}\ DRW + 0.60\ VR_{3,t}\ DRM + 0.30\ VR_{3,t}\ DRS \qquad \text{(VI-4)}$$

$$DO_t = 0.10\ VR_{4,t}\ DRW + 0.60\ VR_{4,t}\ DRM + 0.30\ VR_{4,t}\ DRS \qquad \text{(VI-5)}$$

where $VR_{i,t}$ values are those derived by equation (VI-1), and DRW, DRM, and DRS are the estimated damage ratios to wooden frame, masonry, steel, and concrete structures, respectively. Because we are estimating the potential damage to four major populations for 1980 and the five 10-year intervals from 1980 to 2030, the averages of the populations and values of the four types of structures during each 10-year intervals are used for final estimation.

2. Earthquake prediction: The adjusted data base described above and the physical and economic damage estimation functions incorporated with the earthquake prediction information form the so-called integrated model. To predict the occurrence of earthquakes, Schaefer and Herrman (1977) have developed the following risk functions with respect to intensity and distance from the epicenter.

$$R_n = 1 - (R_a)\ n$$

$$\log_{10} N(I) = a - 0.470\ I$$

$$I(R) = \begin{cases} I_o & R \leq 20 \text{ km} \\ I_o + 3.7 - 0.0011R - 2.7 \log R \text{ if} & R > 20 \text{ km} \end{cases}$$

The intensity risk map of Schaefer and Herrmann, derived from the above risk function and adjusted by distance from the epicenter, provides a probabilistic estimate of earthquake intensity in the central Mississippi valley as illustrated in Figure II-3, (p. 34). The figure gives the maximum intensity distribution which has a 10 percent probability of occurring in a 50-year period.

An alternative approach is to make deterministic estimates of intensity. By this method, as noted by Nuttli (1978), one must know the attenuation of earthquake intensity in the central

Mississippi Valley. Two systems for this approach have been developed. The first one, as illustrated in Figures II-4 and II-5, pp. 39 and 40, assumes two possible earthquakes, one of M.M. intensity VIII and another of M.M. intensity XII occurring at New Madrid, Missouri. The circles on the map represent the outer bounds of a given intensity. The other system, as illustrated in Figures II-6 and II-7 (pp 41 and 42) assumes that the epicenter is located right in Marked Tree, Arkansas, again with M.M. intensity of VIII and XII.

B. Empirical Simulation of Potential Earthquake Damages

1. Probabilistic approach: The final integrated model, (Model III), together with the two models developed earlier and denoted as Model I and Model II, was completely simulated for the year 1980 and the five 10-year intervals from 1980 to 2030. Potential damages to each study county under various intensities, were computed. Partial results of the potential damage to total structures, personal property, and human beings with the probabilistic approach for Model III are reported in Table VI-2. The corresponding results for Models I and II are reported in Tables VI-7 and VI-12, respectively, for purposes of comparison. (Detailed simulation results are contained in Appendix E). Since Model III was considered to be the most comprehensive of the three, we would emphasize this model in the discussion of our results.

The results of the probabilistic approach suggest that if in 1980 the earthquake motion were experienced, which has a 10 percent probability of occurring in the 50-year period, the 15-county region would suffer a $1.2 billion loss in building damage. The heaviest loss by a county would be in Shelby County in the Memphis SMSA, accounting for more than 60 percent of the total $576 million building loss in the entire SMSA. The M.M. intensity in Shelby County would be VIII. For most areas in the St. Louis SMSA, including the City of St. Louis and St. Louis County, the 10 percent, 50-year motion is of M.M. intensity VII. Hence, the result would be relatively lighter damage on a county-by-county basis than in the Memphis SMSA. However, the loss figure in the study region would increase to $1.7 billion should such earthquake motion occur in 2030 or later; about 48 percent ($825 million) of the total loss would be recorded in Shelby County alone.

If the earthquake would occur during the daytime, personal property losses could range from $152 million in 1980 to $271 million in 2030. Loss of life is estimated at 53 to 66 persons, but the human injuries could range from 5,270 to 6,570. If the earthquake occurred during the night, considerable higher damage would result.

The personal property damages could range from $640 million in 1980 to $1.1 billion in 2030, about four times higher than the daytime damage. The potential death toll could be from 140 to 174 persons; and the injuries, from 14,000 to 17,400 persons.

The building damages estimated by Models I and II are ultimately lower than by Model III, mainly due to differences in model structure and the adjustment factor. The results suggest that in 1980 building damages could be from $960 million to about $1.5 billion by Model I, and from $1.1 billion to $1.6 billion by Model II. The day-time damages to human beings estimated by all three models are almost identical, but night-time damage to human beings estimated by Models I and II, which are approximately equal, are only about half the estimation by Model III. The reason is that in Model III mortality rate and personal property damages are determined simultaneously, while in the earlier two models they are determined independently, and personal property damage was assumed to be indifferent to whether the earthquakes occurred during the day-time or night-time. Thus, only one personal property damage function was estimated for the study area in Models I and II. In Model I, it was estimated to be $140 million in 1980 and $300 million for 2030. In Model II, the corresponding figures increased slightly to $200 and $320 million, respectively. The results of these two models in terms of personal property damage estimation are close to those estimated by Model III for daytime earthquakes.

2. The deterministic approach: The deterministic approach, assuming epicenters at New Madrid, Missouri, and Marked Tree, Arkansas, with M.M. intensities of VIII through XII, was also simulated. (Detailed simulation results are contained in Appendix E.) For illustration, the partial results of this approach by Model III with M.M. intensity IX (when damage to all major populations becomes tangible) and M.M. intensity XII (when damage to all major populations becomes monumental) are reported in Tables VI-3 through VI-6. The resulting damages simulated with M.M. intensity IX are selected for discussion so that comparisons with those produced by the probabilistic approach can be made, and the results with M.M. intensity XII are used to project the maximum potential damages that could result from the most severe earthquake striking the study area. The results estimated by both of our earlier models are also reported in Tables VI-8 to VI-11 for Model I and Tables VI-13 to VI-16 for Model II for purposes of comparison and illustration.

If an earthquake with M.M. intensity IX were to occur in New Madrid, both the St. Louis and the Memphis SMSA's would experience M.M. intensity VI, and the major portion of Cape Girardeau County would experience M.M. intensity VII. This is the primary difference between the deterministic approach and probabilistic approach.

TABLE VI-2

POTENTIAL EARTHQUAKE DAMAGES BY COUNTY BY CATEGORY: MODEL III

(Probabilistic Approach, I, max = IX, P = 10.0%)

			Personal Property Damages ($M)				Mortality				Injuries			
	Damages ($M)		Day		Night		Day		Night		Day		Night	
County	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA														
Franklin	3	5	1	2	8	24	0	1	2	3	38	56	215	320
Jefferson	15	27	3	7	20	56	1	2	5	8	135	194	547	804
St. Charles	16	31	1	4	15	46	1	1	4	6	82	123	393	606
St. Louis	272	319	17	23	161	230	3	4	13	15	316	359	1,344	1,540
St. Louis City	142	153	8	8	97	99	6	6	25	25	558	562	2,445	2,474
Clinton	8	12	1	1	6	10	1	1	4	5	95	116	379	464
Madison	74	90	6	8	46	71	2	2	7	9	176	205	724	851
Monroe	3	4	1	1	4	8	1	1	4	5	91	120	361	482
St. Clair	83	100	6	9	52	72	2	2	8	9	189	213	782	887
Total	614	740	43	63	408	615	17	19	72	84	1,680	1,947	7,201	8,429
Cape Girardeau	28	43	8	14	14	27	5	6	9	12	456	573	949	1,209
New Madrid	6	9	6	9	8	11	5	6	9	10	545	629	851	990
Memphis SMSA														
Shelby	521	825	79	151	183	380	10	13	23	30	1,038	1,348	2,267	2,989
Tipton	24	38	5	11	6	13	9	12	12	17	918	1,201	1,250	1,661
Crittenden	24	36	8	14	14	27	4	6	9	12	440	556	914	1,171
De Soto	8	18	2	8	8	32	2	3	6	9	193	317	556	942
Total	576	917	95	184	211	451	26	34	50	68	2,590	3,423	4,987	6,764
15-County Total	1,224	1,709	152	271	641	1,104	53	66	140	174	5,272	6,574	13,987	17,391

PREFACE

Midwest Research Institute (MRI) is pleased to submit this Final Report entitled "Earthquake Risk and Damage Functions: An Integrated Preparedness and Planning Model Applied to New Madrid" to the Division of Problem Focused Research Applications, National Science Foundation (NSF). This study was supported mainly by Grant No. ENV 77-15669 from the Office of Earthquake Hazard Mitigation within the division. In addition, MRI provided a small grant to the principal investigator for earlier investigation and research related to the project.

The primary objective of this study was to provide, in an integrated analytical framework, the methodology and the data needed to guide public and private planning and future decisionmaking for earthquake hazard preparedness and risk mitigation. The focus was on the New Madrid Fault region, especially its effects on the St. Louis and Memphis Standard Metropolitan Statistical Areas. An interdependent planning simulation model was developed to tie together statistically the seismic risk or physical damage functions to economic damage functions for potential earthquake risk assessment and impact evaluation for the next 50 years. It is hoped that the analytical procedures which underlie the entire model, ranging from seismic prediction, geologic analysis, and econometric forecasting and projection to institutional policy evaluation, will serve as a methodological departure for future research studies in the area of risk analysis and hazard mitigation planning.

The Executive Summary provides a synopsis of the entire study. The balance of the report is organized and presented in eight chapters. Chapter I introduces the general background of earthquakes and their damage results. Chapter II describes and predicts various seismological risks in the New Madrid region, and Chapter III documents the surficial materials and classifies ground susceptibility for the region. Populations subject to earthquake risk and the projected populations, 1980 through 2030, are discussed in Chapter IV. The development of the physical and economic damage functions and their applications to damage estimation and impact assessment under the "status quo" scenario are presented respectively in Chapters V and VI. The institutional aspects and policy issues concerning earthquake risk reduction and preparedness are shown in Chapter VII, and the last chapter briefly delineates some important findings, concluding remarks and recommendations.

There are a number of individuals without whose encouragement and assistance this project would not have been completed. Dr. S. C. Liu of the NSF originally brought the earthquake problems of the New Madrid region to our attention and encouraged discussions with other researchers in the field. Drs. Henry Lagorio and William Anderson of NSF provided valuable

comments in the earlier stage of this project, and Dr. Frederick Krimgold served as the project officer and offered insight and guidance to the project throughout the entire period of research. Encouragement from Drs. Charles Theil of the Federal Emergency Management Agency and Gilbert White of the Institute of Behavioral Science, University of Colorado, especially through the National Hazard Research Application Workshops the latter organized for information exchange among professional and practitioners, must be acknowledged.

Our special note of appreciation goes to O. Clarke Mann, William Park, Richard Eisenler, Jeanne Perkins, William Spangle, James and Cynthia Flynn, Ugo Morellis, Howard Kunreuther, Robert Whiteman, and John Wiggins, for either their consulting services or their comments and suggestions which resulted in substantial improvement of this project. Although it is impossible to name all those individuals and agencies who have helped us and cooperated with us during our field trip to study the regional populations at risk, we would like to extend our appreciation to the following agencies: Mississippi-Arkansas-Tennessee Council of Governments/Memphis Delta Development District; East-West Gateway Coordinating Council; St. Louis Regional Commerce and Growth Association; Southeast Missouri Planning Commission; Cape Girardeau Planning Department; courthouses, utility companies, and school districts within the 15 counties. We are particularly indebted to Miss Laura Gagnon who served as a research assistant and conducted the field survey in 1978.

The two most significant contributors to this study were Professor Otto Nuttli of St. Louis University and Professor Richard Gentile of the University of Missouri-Kansas City. Professor Nuttli provided not only the seismological risk assessment and the material contained in Chapter II, but also valuable advice concerning various seismological aspects and statistical interpretation of the results. Professor Gentile completed virtually the entire Chapter III. My coauthors at MRI are: Dr. Chang-Tseh Hsieh, who was responsible for damage model testing and computer simulation, and Mr. Robert Gustafson for institutional aspects and policy issues presented in Chapter VII. We spent many long hours discussing, debating, and finally compromising with each other on research design, methodological development, the conduct of the project, and even on the presentation of this report. Our efforts were directed toward making this study as comprehensive and illustrative as we possible could, within the time and budget. Ms. Rosemary Moran served as a research assistant in data collection, and Ms. Margaret Thomas assisted in the earlier stage of project development. This project was completed under the general administrative supervision of Mr. Bruce W. Macy, Deputy Director, Economics and Management Science Division.

TABLE VI-3

POTENTIAL EARTHQUAKE DAMAGES: MODEL III
(Deterministic Approach: Io = IX at New Madrid)

County	Damages ($M)		Personal Property Damages ($M)				Mortality				Injuries			
			Day		Night		Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA														
Franklin	1	2	0	1	7	21	0	0	2	2	19	27	158	236
Jefferson	3	5	0	1	13	36	0	0	2	3	26	38	225	330
St. Charles	5	10	0	1	12	36	0	0	2	4	27	40	229	353
St. Louis	50	59	2	3	105	150	1	1	6	6	61	69	552	633
St. Louis City	27	29	1	1	63	64	1	1	10	10	108	108	1,009	1,017
Clinton	1	2	0	0	4	6	0	0	2	2	18	22	156	191
Madison	14	17	1	1	30	46	0	0	3	3	34	40	298	350
Monroe	0	1	0	0	2	5	0	0	1	2	18	23	148	198
St. Clair	16	19	1	1	34	47	0	0	3	4	37	41	321	365
Total	117	144	5	9	270	411	2	2	31	36	348	408	3,096	3,673
Cape Girardeau	6	9	1	1	8	15	1	1	3	4	65	82	310	395
New Madrid	10	14	11	19	10	15	12	14	13	16	1,177	1,358	1,350	1,571
Memphis SMSA														
Shelby	36	58	2	4	82	171	0	1	4	6	48	63	431	568
Tipton	1	2	0	0	4	8	0	0	2	2	19	25	160	212
Crittenden	2	2	0	0	6	12	0	0	2	2	20	26	174	223
De Soto	1	2	0	0	5	19	0	0	2	3	21	34	177	300
Total	40	64	2	4	97	210	0	1	10	13	108	148	942	1,303
15-County Total	173	231	19	33	385	651	15	18	57	69	1,698	1,996	5,698	6,942

TABLE VI-4

POTENTIAL EARTHQUAKE DAMAGES: MODEL III
(Deterministic Approach: Io = XII at New Madrid)

County	Damages ($M)		Personal Property Damages ($M)				Mortality				Injuries			
			Day		Night		Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA														
Franklin	39	72	44	111	22	64	14	21	16	24	1,414	2,063	1,639	2,446
Jefferson	81	148	71	174	41	112	20	28	23	34	1,974	2,838	2,334	3,428
St. Charles	146	290	62	171	36	112	20	30	24	37	2,007	3,022	2,375	3,664
St. Louis	1,495	1,750	431	591	323	462	46	52	57	66	4,611	5,241	5,731	6,564
St. Louis City	757	814	216	219	194	198	81	82	105	105	8,144	8,203	10,467	10,548
Clinton	44	66	22	36	11	20	14	17	16	20	1,395	1,689	1,616	1,979
Madison	412	494	150	218	93	142	26	30	31	36	2,571	2,994	3,087	3,628
Monroe	15	24	15	30	8	17	13	18	15	21	1,331	1,751	1,538	2,056
St. Clair	448	539	164	220	104	146	28	31	33	38	2,765	3,114	3,336	3,783
Total	3,437	4,197	1,175	1,770	832	1,273	262	309	320	380	26,212	30,915	32,123	38,096
Cape Girardeau	78	119	50	92	23	43	33	41	27	34	3,269	4,107	2,657	3,383
New Madrid	30	44	11	19	11	19	253	292	71	83	23,000	29,244	7,099	8,262
Memphis SMSA														
Shelby	1,052	1,665	267	576	254	527	36	47	45	59	3,648	4,738	4,473	5,898
Tipton	32	51	6	13	6	13	14	19	17	22	1,430	1,870	1,659	2,205
Crittenden	48	73	36	65	19	37	15	20	18	23	1,548	1,955	1,804	2,311
De Soto	28	69	27	92	14	58	16	26	18	31	1,573	2,592	1,836	3,114
Total	1,160	1,858	336	746	293	635	81	112	98	135	8,199	11,155	9,772	13,528
15-County Total	4,705	6,218	1,572	2,627	1,159	1,970	629	754	516	632	60,680	25,421	51,651	63,269

TABLE VI-5

POTENTIAL EARTHQUAKE DAMAGES: MODEL III
(Deterministic Approach: Io = IX at Marked Tree)

County	Damages ($M)		Personal Property Damages ($M)				Mortality				Injuries			
			Day		Night		Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA														
Franklin	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jefferson	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. Charles	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. Louis	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. Louis City	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clinton	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Madison	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Monroe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. Clair	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cape Girardeau	2	3	0	0	6	12	0	0	2	2	21	27	181	230
New Madrid	0	0	0	0	3	5	0	0	1	2	16	18	130	151
Memphis SMSA														
Shelby	439	696	63	120	169	350	8	11	20	26	841	1,092	1,962	2,588
Tipton	13	21	4	7	6	13	3	4	7	10	330	431	829	967
Crittenden	24	36	8	14	14	27	4	6	9	12	440	556	914	1,171
De Soto	5	13	1	4	7	29	1	2	4	7	108	177	431	730
Total	481	766	76	145	196	419	16	23	40	55	1,719	2,257	4,035	5,456
15-County Total	483	769	76	145	205	436	16	23	43	59	1,756	2,302	4,346	5,837

TABLE VI-6

POTENTIAL EARTHQUAKE DAMAGES: MODEL III
(Deterministic Approach: Io = XII at Marked Tree)

County	Damages ($M)		Personal Property Damages ($M)				Mortality				Injuries			
			Day		Night		Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA														
Franklin	19	35	9	24	16	46	4	6	8	12	402	587	831	1,240
Jefferson	40	72	15	38	29	81	6	8	12	17	562	808	1,183	1,737
St. Charles	71	143	14	37	26	81	6	9	12	19	571	860	1,204	1,857
St. Louis	736	862	94	129	233	333	13	15	29	33	1,312	1,491	2,905	3,327
St. Louis City	377	405	47	48	140	143	23	23	53	53	2,318	2,334	5,305	5,346
Clinton	22	32	5	8	8	14	4	5	8	10	397	481	819	1,003
Madison	202	243	33	47	67	103	7	9	16	18	732	852	1,565	1,839
Monroe	7	11	3	7	6	12	4	5	8	10	379	498	780	1,042
St. Clair	222	267	36	48	75	105	8	9	17	19	787	886	1,690	1,917
Total	1,696	2,070	256	386	600	918	75	89	163	191	7,460	8,797	16,282	19,308
Cape Girardeau	57	87	37	65	20	37	16	20	19	24	1,694	2,014	1,873	2,385
New Madrid	10	14	11	19	10	15	12	14	13	16	1,177	1,358	1,350	1,571
Memphis SMSA														
Shelby	2,518	3,975	267	576	267	576	261	339	127	168	26,090	33,881	12,732	16,790
Tipton	75	121	6	13	6	13	102	134	47	63	10,224	13,375	4,722	6,275
Crittenden	120	182	106	216	34	64	132	166	57	74	13,171	16,639	5,743	7,356
De Soto	49	119	105	362	19	77	48	80	34	57	4,842	7,977	3,371	5,720
Total	2,762	4,397	484	1,167	326	730	543	719	265	362	54,327	71,872	26,568	36,141
15-County Total	4,525	6,568	788	1,637	956	1,700	646	842	460	593	64,568	84,041	46,073	59,405

TABLE VI-7

POTENTIAL EARTHQUAKE DAMAGES: MODEL I
(Probabilistic Approach: I, max = IX, P = 10.0%)

County	Damages ($M)		Personal Property Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	0	0	0	0	0	1	0	0	40	70	30	40
Jefferson	10	20	0	10	2	3	1	2	180	290	140	210
St. Charles	10	40	0	10	1	3	1	2	120	250	80	190
St. Louis	200	240	40	60	6	7	4	5	590	690	430	500
St. Louis City	110	130	20	30	11	12	7	8	1,090	1,160	710	770
Clinton	10	10	10	20	5	7	8	10	510	650	770	960
Madison	60	120	10	30	3	4	3	3	310	410	250	340
Monroe	0	0	0	10	3	4	4	5	310	420	380	500
St. Clair	60	80	10	20	3	4	2	3	310	370	240	280
Total	460	640	90	190	34	45	30	38	3,460	4,310	3,030	3,790
Cape Girardeau	20	50	10	10	3	5	4	6	340	510	370	580
New Madrid	0	10	0	0	2	2	2	2	170	210	160	200
Memphis SMSA												
Shelby	430	710	30	60	5	7	4	6	510	740	380	550
Tipton	20	30	0	0	2	2	1	2	160	220	140	180
Crittenden	20	30	10	20	5	6	7	8	510	640	680	810
De Soto	10	10	0	20	3	5	3	6	300	530	340	570
Total	480	780	40	100	15	20	15	22	1,480	2,130	1,540	2,110
15-County Total	960	1,480	140	300	54	72	51	68	5,450	7,160	5,100	6,680

TABLE VI-8

POTENTIAL EARTHQUAKE DAMAGES: MODEL I
(Deterministic Approach: Io = IX at New Madrid)

County	Damages ($M)		Personal Property Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	1	1	0	1	0	0	0	0	20	33	7	12
Jefferson	1	4	1	2	0	1	0	0	33	59	12	23
St. Charles	2	13	0	3	0	1	0	0	35	92	13	41
St. Louis	27	33	6	9	1	1	0	1	115	136	43	51
St. Louis City	20	23	4	5	2	3	1	1	247	261	89	96
Clinton	1	2	2	4	1	2	1	1	121	154	102	127
Madison	9	21	2	4	1	1	0	0	66	93	28	43
Monroe	0	1	1	2	1	1	1	1	72	99	50	66
St. Clair	11	14	2	3	1	1	0	0	67	81	28	34
Total	72	112	18	33	7	11	3	4	776	1,008	372	493
Cape Girardeau	4	11	1	2	1	1	1	1	78	117	54	82
New Madrid	7	9	2	3	3	3	3	4	267	331	306	378
Memphis SMSA												
Shelby	25	42	1	3	0	1	0	0	41	60	11	16
Tipton	1	1	0	0	0	0	0	0	8	11	2	3
Crittenden	1	1	1	1	0	0	0	0	40	48	19	22
De Soto	1	1	0	2	0	1	0	0	46	79	23	37
Total	28	45	2	6	0	2	0	0	135	198	55	78
15-County Total	111	177	23	44	11	17	7	9	1,256	1,654	787	1,031

TABLE VI-9

POTENTIAL EARTHQUAKE DAMAGES: MODEL I
(Deterministic Approach: Io = XII at New Madrid)

County	Damages ($M)		Personal Property Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	25	47	9	29	5	9	7	12	535	891	737	1,199
Jefferson	49	133	21	70	9	16	13	22	903	1,587	1,258	2,233
St. Charles	80	460	19	121	10	24	13	39	953	2,417	1,344	3,923
St. Louis	1,013	1,233	231	339	31	37	43	50	3,106	3,680	4,268	5,008
St. Louis City	711	828	152	167	65	69	85	92	6,492	6,876	8,487	9,177
Clinton	46	69	82	143	32	40	96	120	3,154	4,016	9,646	12,042
Madison	338	748	82	160	18	25	28	41	1,752	2,459	2,750	4,057
Monroe	15	25	27	56	19	26	47	62	1,889	2,591	4,743	6,242
St. Clair	381	492	82	123	18	21	27	33	1,784	2,150	2,690	3,253
Total	2,658	4,035	705	1,207	207	267	359	471	20,568	26,667	35,923	47,144
Cape Girardeau	48	128	12	30	9	14	15	24	913	1,441	1,453	2,415
New Madrid	16	22	5	7	9	12	17	21	942	1,169	1,678	2,082
Memphis SMSA												
Shelby	899	1,501	53	123	11	16	11	16	1,078	1,582	1,081	1,582
Tipton	26	40	1	2	2	3	2	3	223	298	206	263
Crittenden	35	52	20	34	11	13	19	21	1,659	1,301	1,861	2,146
De Soto	22	51	18	67	12	21	22	36	1,208	2,109	2,226	3,575
Total	982	1,644	92	226	36	53	54	76	3,568	5,290	5,374	7,566
15-County Total	3,704	5,829	814	1,470	261	346	445	592	25,991	34,567	44,428	59,207

TABLE VI-10

POTENTIAL EARTHQUAKE DAMAGES: MODEL I
(Deterministic Approach: Io = IX at Marked Tree)

County	Damages ($M)		Personal Property Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	0	0	0	0	0	0	0	0	0	0	0	0
Jefferson	0	0	0	0	0	0	0	0	0	0	0	0
St. Charles	0	0	0	0	0	0	0	0	0	0	0	0
St. Louis	0	0	0	0	0	0	0	0	0	0	0	0
St. Louis City	0	0	0	0	0	0	0	0	0	0	0	0
Clinton	0	0	0	0	0	0	0	0	0	0	0	0
Madison	0	0	0	0	0	0	0	0	0	0	0	0
Monroe	0	0	0	0	0	0	0	0	0	0	0	0
St. Clair	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0
Cape Girardeau	1	3	0	1	0	0	0	0	25	41	10	17
New Madrid	0	0	0	0	0	0	0	0	10	12	3	4
Memphis SMSA												
Shelby	365	598	21	49	4	6	3	4	428	621	310	447
Tipton	11	17	0	1	1	1	1	1	88	120	59	77
Crittenden	18	27	10	18	5	6	7	8	508	744	676	815
De Soto	4	9	3	12	2	4	2	3	211	376	199	329
Total	398	651	34	80	12	17	13	16	1,235	1,761	1,244	1,668
15-County Total	399	654	34	81	12	17	13	16	1,270	1,814	1,257	1,689

TABLE VI-11

POTENTIAL EARTHQUAKE DAMAGES: MODEL I
(Deterministic Approach: Io = XII at Marked Tree)

County	Damages ($M)		Personal Property Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	14	26	5	16	3	5	3	5	273	453	293	473
Jefferson	27	67	11	35	5	8	5	8	465	769	506	823
St. Charles	46	213	11	56	5	11	6	13	498	1,107	552	1,334
St. Louis	529	638	121	176	15	18	16	19	1,534	1,809	1,616	1,883
St. Louis City	327	383	70	77	30	31	29	31	2,963	3,144	2,867	3,109
Clinton	21	31	37	64	14	18	32	39	1,408	1,793	3,157	3,941
Madison	165	343	40	73	8	11	10	14	829	1,120	979	1,366
Monroe	7	11	12	25	8	12	16	20	843	1,157	1,552	2,043
St. Clair	182	231	39	58	8	10	9	11	832	993	938	1,118
Total	1,318	1,943	346	580	96	124	126	160	9,645	12,345	12,460	16,090
Cape Girardeau	39	105	10	24	7	11	10	16	687	1,090	973	1,628
New Madrid	7	9	2	3	3	3	3	4	267	331	306	378
Memphis SMSA												
Shelby	1,691	2,824	100	231	25	37	35	51	2,529	3,714	3,470	5,082
Tipton	49	76	2	4	5	7	7	8	523	699	663	843
Crittenden	72	104	40	69	27	34	67	78	2,731	3,351	6,738	7,755
De Soto	32	75	26	97	20	35	44	70	1,986	3,474	4,374	7,044
Total	1,844	3,079	168	401	77	113	153	207	7,769	11,238	15,245	20,724
15-County Total	3,208	5,136	526	1,008	183	251	292	387	18,368	25,004	28,984	38,820

TABLE VI-12

POTENTIAL EARTHQUAKE DAMAGES: MODEL II
(Probabilistic Approach: I, max = IX, P = 10.0%)

County	Damages ($M)		Personal Property Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	0	10	0	0	1	1	0	1	50	90	40	60
Jefferson	10	20	10	10	2	3	2	3	220	320	180	250
St. Charles	10	30	0	10	2	2	1	2	150	230	110	160
St. Louis	260	320	60	80	7	8	6	6	700	810	550	630
St. Louis City	120	120	20	30	11	12	7	8	1,100	1,170	720	790
Clinton	10	10	10	20	5	7	8	10	540	690	840	1,040
Madison	70	90	20	30	4	4	3	3	350	410	300	340
Monroe	0	0	0	10	3	4	4	5	310	430	390	520
St. Clair	80	100	20	20	4	4	3	3	350	400	280	320
Total	560	700	140	210	39	45	34	41	3,770	4,550	3,410	4,110
Cape Girardeau	20	30	10	10	4	5	4	6	380	500	440	550
New Madrid	0	10	0	0	2	2	2	2	170	220	170	220
Memphis SMSA												
Shelby	500	780	30	60	6	8	4	6	550	780	430	590
Tipton	20	30	0	0	2	3	2	2	180	250	160	220
Crittenden	20	30	10	20	5	7	7	9	520	710	690	930
De Soto	10	20	10	20	3	6	4	7	340	630	410	720
Total	550	860	50	100	16	24	17	24	1,590	2,370	1,690	2,460
15-County Total	1,130	1,600	200	320	61	76	57	73	5,910	7,640	5,710	7,340

TABLE VI-13

POTENTIAL EARTHQUAKE DAMAGES: MODEL II
(Deterministic Approach: Io = IX at New Madrid)

County	Damages ($M)		Personal Property (Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	1	3	0	1	0	0	0	0	30	49	14	22
Jefferson	3	4	1	3	1	1	0	0	52	74	24	31
St. Charles	5	9	1	3	1	1	0	0	54	85	25	37
St. Louis	48	59	11	16	2	2	1	1	164	191	72	82
St. Louis City	23	23	5	5	3	3	1	1	263	281	97	107
Clinton	1	2	2	4	1	2	1	1	126	160	109	135
Madison	13	16	3	5	1	1	0	0	81	96	38	44
Monroe	0	1	1	2	1	1	1	1	73	100	51	67
St. Clair	15	18	3	4	1	1	0	0	82	95	37	43
Total	108	135	26	43	11	12	4	4	925	1,131	467	568
Cape Girardeau	5	7	1	2	1	1	1	1	90	117	65	81
New Madrid	7	9	2	3	3	4	3	4	279	356	325	420
Memphis SMSA												
Shelby	35	54	2	4	1	1	0	0	50	71	15	21
Tipton	1	2	0	0	0	0	0	0	11	15	3	4
Crittenden	1	2	1	1	0	1	0	0	47	65	25	33
De Soto	1	2	1	3	1	1	0	1	58	108	33	58
Total	38	60	4	8	2	3	0	1	166	259	76	116
15-County Total	158	211	33	56	17	20	8	10	1,460	1,863	933	1,185

TABLE VI-14

POTENTIAL EARTHQUAKE DAMAGES: MODEL II
(Deterministic Approach: Io = XII at New Madrid)

County	Damages ($M)		Personal Property (Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	40	76	15	45	7	12	11	18	714	1,174	1,118	1,784
Jefferson	81	136	34	84	12	18	20	26	1,238	1,782	1,985	2,639
St. Charles	142	265	32	92	13	20	21	31	1,310	2,039	2,130	3,075
St. Louis	1,440	1,749	324	463	38	45	58	67	3,841	4,480	5,799	6,653
St. Louis City	620	657	131	147	59	63	74	82	5,928	6,342	7,444	8,167
Clinton	43	64	76	132	30	38	90	112	3,002	3,821	8,979	11,210
Madison	401	491	95	141	19	23	32	36	1,927	2,271	3,155	3,615
Monroe	14	22	23	49	17	24	42	56	1,742	2,390	4,222	5,556
St. Clair	424	518	90	125	19	22	29	33	1,887	2,179	2,917	3,317
Total	3,205	3,978	820	1,278	214	265	377	461	21,589	26,478	37,749	46,016
Cape Girardeau	66	92	17	31	11	15	20	25	1,140	1,483	2,019	2,535
New Madrid	24	32	7	12	12	16	25	33	1,249	1,593	2,521	3,256
Memphis SMSA												
Shelby	1,010	1,567	59	128	12	16	12	16	1,158	1,628	1,198	1,649
Tipton	29	45	1	3	2	3	2	3	239	339	228	317
Crittenden	36	52	21	42	11	15	19	26	1,080	1,481	1,914	2,586
De Soto	25	59	20	84	13	24	25	44	1,314	2,436	2,514	4,403
Total	1,100	1,723	101	257	38	58	58	89	3,791	5,884	5,854	8,955
15-County Total	4,395	5,825	945	1,578	275	354	480	608	27,769	35,438	48,143	60,762

TABLE VI-15

POTENTIAL EARTHQUAKE DAMAGES: MODEL II
(Deterministic Approach: Io = IX at Marked Tree)

County	Damages ($M)		Personal Property (Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	0	0	0	0	0	0	0	0	0	0	0	0
Jefferson	0	0	0	0	0	0	0	0	0	0	0	0
St. Charles	0	0	0	0	0	0	0	0	0	0	0	0
St. Louis	0	0	0	0	0	0	0	0	0	0	0	0
St. Louis City	0	0	0	0	0	0	0	0	0	0	0	0
Clinton	0	0	0	0	0	0	0	0	0	0	0	0
Madison	0	0	0	0	0	0	0	0	0	0	0	0
Monroe	0	0	0	0	0	0	0	0	0	0	0	0
St. Clair	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0
Cape Girardeau	2	2	0	1	0	0	0	0	34	44	15	19
New Madrid	0	0	0	0	0	0	0	0	12	15	4	5
Memphis SMSA												
Shelby	421	654	25	54	5	7	4	5	467	658	353	485
Tipton	12	19	1	1	1	1	1	1	97	138	68	94
Crittenden	18	26	10	21	5	7	7	9	516	708	692	934
De Soto	5	11	4	16	2	5	2	4	244	452	244	427
Total	456	710	40	92	13	20	14	19	1,324	1,956	1,357	1,940
15-County Total	458	712	40	93	13	20	14	19	1,370	2,015	1,376	1,964

TABLE VI-16

POTENTIAL EARTHQUAKE DAMAGES: MODEL II

(Deterministic Approach: Io = XII at Marked Tree)

County	Damages ($M)		Personal Property (Damages ($M)		Mortality				Injuries			
					Day		Night		Day		Night	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA												
Franklin	19	37	7	22	3	6	4	6	339	557	400	638
Jefferson	40	66	17	41	6	8	7	9	587	844	708	941
St. Charles	69	129	16	45	6	10	8	11	621	966	760	1,097
St. Louis	708	861	159	228	18	21	21	24	1,828	2,132	2,081	2,388
St. Louis City	308	327	65	73	28	20	27	30	2,841	3,039	2,698	2,960
Clinton	21	31	37	65	14	18	32	40	1,422	1,811	2,202	3,997
Madison	196	240	47	69	9	11	11	13	915	1,078	1,128	1,292
Monroe	7	11	11	24	8	11	15	20	826	1,132	1,505	1,981
St. Clair	210	257	44	62	9	10	11	12	902	1,041	1,053	1,198
Total	1,578	1,959	403	629	101	125	136	165	10,281	12,600	13,535	16,492
Cape Girardeau	48	67	12	23	8	10	12	15	802	1,043	1,216	1,527
New Madrid	7	9	2	3	3	4	3	4	279	356	325	420
Memphis SMSA												
Shelby	2,447	3,798	144	311	32	45	49	67	3,190	4,487	4,862	6,690
Tipton	69	108	3	7	7	9	9	13	655	931	920	1,278
Crittenden	97	141	56	113	33	46	90	122	3,344	4,585	9,030	12,197
De Soto	43	101	35	145	24	45	58	101	2,411	4,468	5,787	10,131
Total	2,656	4,148	238	576	96	145	206	303	9,600	14,471	20,599	30,296
15-County Total	4,289	6,183	655	1,231	208	284	357	487	20,962	28,470	35,675	48,735

For the deterministic approach, the seismic impact area, or the contour lines representing the earthquake, would be circles around the epicenter, whereas the shape of the entire fault encompassing all possible epicenters determines the damage area for the probabilistic approach. With the deterministic approach, building damage in the region was estimated at $173 million in 1980 and $231 million after 2030, as compared to $1.2 and $1.7 billion by the probabilistic approach. Although St Louis and Shelby counties and the City of St. Louis would account for over 60 percent of the total building loss in the study area, New Madrid County would suffer the most proportionally. About 20 percent of the total value of structures in New Madrid County would be damaged in contrast to less than 1 percent of the total value of structures in St. Louis and Shelby counties and the City of St. Louis. If the earthquake occurred during the day-time, personal property damages are estimated at $19 million in 1980 and up to $33 million after 2030. About 60 percent of this personal property damage would be in New Madrid County alone. The potential casualties would be 15 to 18 deaths during the projection period. These deaths would primarily be in New Madrid County (about 80 percent); the potential injuries would number 1,700 persons in 1980 and 2,000 persons in 2030.

If the earthquake were to occur during the night-time, personal property damage would reach $385 million in 1980 and $650 million after 2030. These figures are about 20 times the day-time loss. In addition to the differences in model structure and modification, another explanation for this loss difference may be the unpreparedness of people in a dark environment. The death toll is estimated at 57 to 69 persons during the projection period, and the corresponding injuries would be 5,700 to 6,940 persons. The day-time and evening losses in New Madrid are very close. However, considerably higher human damage would be expected for a night-time earthquake than a day-time earthquake in the two urban SMSA's due to changes in diurnal and nocturnal populations among counties within each SMSA and the associated risk of population density.

The building damages estimated by Models I and II are not too far from those estimated by Model III, and the personal property damages estimated by these two models are similar to the day-time personal property damages produced by Model III; the same is true for day-time mortality and injuries estimations. However, casualties caused by night-time earthquakes in Models I and II are significantly smaller than those resulting from Model III. If one believes that some correlation does exist between mortality and personal property damage, which was used as a proxy for building destruction in our model, the results of Model III would be more plausible for reflecting the potential risk to human beings.

If an earthquake with M.M. intensity XII were to strike New Madrid, the major portion of Cape Girardeau would experience ground motion with an M.M. intensity of X; and both SMSA's, and intensity of IX. Of course, very severe damage could result. Building damage is estimated at $4.7 billion in 1980 and $6.2 billion in 2030, with about 50 percent of the damage in the central area of the two SMSA's, the City of St. Louis in St. Louis SMSA and Shelby County in Memphis SMSA. New Madrid, as the hypothetical epicenter with MMI XII, would suffer $30 million building damage in 1980, or about 42 percent of the total market value if all structures in the county would be destroyed.

If such an earthquake occurred during the day-time in 1980, it could claim about $1.6 billion in personal property damage, 630 lives, and about 60,000 injuries. Should this earthquake occur 50 years later, the damaging impact would be much more serious, with personal property damages estimated at $2.6 billion, human death amounting to 754, and injuries exceeding 75,000.

Those counties with high population densities, especially St. Louis County, City of St. Louis, and Shelby County, would expect higher mortality and injuries for a night-time earthquake than a day-time earthquake. In the St. Louis SMSA, the total mortality for a night-time earthquake of this intensity in 1980 was estimated at 320 persons as compared to 262 persons for day-time; and in the year 2030 it was estimated at 380 persons for night-time earthquake occurrence and 309 persons for day-time. In New Madrid, the epicenter death toll in the evening would number 71 persons in 1980, less than one-third of that estimated for day-time earthquakes. Again, the difference in casualties between day-time and evening occurrences is largely attributed to different model specifications and population density estimates. However, most of the personal property in New Madrid County would still be lost regardless of the time the earthquake occurred.

Building damages estimated from earlier models for an earthquake of this intensity are lighter than those estimated by Model III for the reasons explained above. But, mortality estimations for night-time earthquakes do not differ significantly. Similarly property damage estimates by Models I and II are close to that estimated for night-time earthquakes from Model III. Only in the estimation of day-time earthquake mortality does considerable difference exist. Estimates by Models I and II are less than one half those estimated by Model III, again for the reasons explained above.

If the epicenter were moved to Marked Tree, Arkansas, the most severely damaged area would shift from New Madrid County to the Memphis SMSA as revealed by the partial results reported in Tables VI-5 and VI-6. An earthquake with an epicenter of M.M. intensity IX means that the Memphis SMSA would experience ground motion of M.M. intensity VII to VIII. Two rural counties, New Madrid and Cape Girardeau, would experience an intensity of M.M. VI; and the St. Louis SMSA area, an intensity of V. Virtually no damages would be expected for the St. Louis SMSA. For the entire study region, such an earthquake would result in about $483 million in building damages in 1980 and about $766 million 50 years later. As expected, all losses would be concentrated within the Memphis SMSA, with over 90 percent of the damage recorded in Shelby County.

Loss of life would range from 16 persons in 1980 to 23 persons in 2030 if the earthquake occurred during the day-time. The associated personal property damage would be from $76 million in 1980 to $145 million in the last decade of the projection period; and the injuries would rise from 1,750 to 2,300 persons. The damages would be considerably heavier if the earthquake occurred during the night. In 1980, 43 persons would lose their lives and 59 deaths might be expected in 2030. Personal property damage would be three times higher than that resulting from a day-time earthquake of the same intensity. The damage would be approximately $205 million in 1980 and about $436 million during the last decade of the simulation. The corresponding figures for injuries would be 4,350 persons in 1980 and 5,800 persons in 2030. Again, most damages would occur in the Memphis SMSA, particularly in Shelby County.

Because the epicenter of Marked Tree is closer to a highly populated urban area than the epicenter of New Madrid, heavier damages would be expected for an earthquake of the same intensity. As just delineated, building damages would be about tripled, and personal property damages about quadrupled.

The results of the three models with earthquake epicenter located at Marked Tree can be compared in the same manner as discussed above, with New Madrid being considered as the epicenter. Such comparisons thus are omitted from this duscussion, and the corresponding results estimated by Models I and II are reported in Tables VI-10, VI-11, VI-15, and VI-16 for further reference.

If an earthquake with M.M. intensity XII were to hit Marked Tree, Arkansas, Memphis SMSA and Cape Girardeau would experience the earthquake at an M.M. intensity of IX; and the St. Louis SMSA, VIII. It could be a disaster to the study area, especially to the Memphis SMSA. Building damages alone could reach $4.5 billion in 1980 and about $6.5 billion in 2030. More than 60 percent of these damages would be in the Memphis SMSA.

If this severe earthquake occurred during the day-time in 1980, personal property damages could amount to $800 million; about 630 persons would be killed; and more than 60,000 persons would be injured. While the probability of occurrence may be cumulative as time elapses, and continuous urban growth may still follow the historical patterns without any improved preparedness for earthquake, we estimated that personal property damages in 2030 could reach $1.6 billion. A total of 840 persons might be the victims of this quake, and over 80,000 persons are likely to be injured if no new mitigation plans are contemplated and risk reduction programs implemented during the next five decades.

If the earthquake occurred during night-time, the personal property damages would be about the same, but the human damage might be reduced slightly, 460 deaths and 46,000 injuries in 1980 and 600 deaths and 60,000 injuries in 2030.

Although the building damages under this earthquake simulation are about the same as those estimated using New Madrid as the epicenter, the day-time earthquake mortality in the region was estimated to be higher, and the night-time earthquake mortality lower than if the quake were located at New Madrid. These contrasting results may be attributed to the three factors that are summarized below.

First, the mortality rate is a nonlinear function of earthquake intensity and other determinants. The slope of the function for diurnal population was considerably different from that estimated for nocturnal population. Moreover, the day-time earthquake mortality would be lower than that of night-time earthquake for an earthquake of intensity IX or below; and vise versa for an earthquake of intensity X and above. In other words, a turning point was also estimated from the historical records.

Second, the population growth rate and population density for each county is independently determined. Therefore, for a certain county the earthquake mortality could very well be lower than other counties in earlier years of the projection period, but higher in the later years.

Third, the earthquake intensity of one county can be altered with different approaches and assumptions. For example, Shelby County would experience M.M. intensity X if Marked Tree, Arkansas, is assumed to be the epicenter with an intensity of XII; but if the epicenter was seismologically shifted to New Madrid and had the same intensity, Shelby County would experience M.M. intensity IX. Therefore, the estimated results would be different.

3. Building damages projection with alternative data base: As discussed in Chapter IV, alternative data of all structures were provided by estimating the values of the structures in the region by the replacement cost method of new construction. These estimated values are considerably higher than our evaluation in terms of market values generated by the information provided by county assessors. Undoubtedly, the potential building damage estimated with replacement costs of new construction would be higher than estimated with our data base. Since Park's data were for 1978, 1990, 2000, and 2025, his data were extrapolated to correspond to our data base year, 1980, and the five 10-year intervals from 1980 to 2030. These values were then incorporated into Model III to simulate the potential building damages in terms of replacement cost of new construction. The results of this simulation with the probabilistic approach as well as with the deterministic approach are shown in Table VI-17.

The results indicate that, with the probabilistic approach, building damages could reach $3.8 billion in 1980 and about $5.0 billion in 2030, as against $1.2 billion and $1.7 billion, respectively, for 1980 and 2030 by the market value approach.

The difference in building damage estimations is even greater if we employ the deterministic approach for seismic risk assessment. With New Madrid as the epicenter and the maximum earthquake intensity as predicted from the probabilistic approach (M.M. intensity IX), the damages would surge to $647 million in 1980 and to over $800 million in 2030. If the epicentral intensity were registered at M.M. intensity XII, the building damages could skyrocket to $16 billion in 1980 and to over $20 billion in 2030. In this case, more than 75 percent of these damages would be in the St. Louis SMSA, particularly in the City of St. Louis and St. Louis County.

If the epicenter were shifted to Marked Tree, the Memphis SMSA would be a major disaster area, especially Shelby County. At this epicenter, with M.M. intensity of IX, $1 billion damage could be caused in 1980 and in 2030, $1.7 billion. Most of this damage (about 90 percent) would occur in Shelby County. With an epicentral intensity of XII, the corresponding damages were estimated at $13 billion in 1980 and $18 billion in 2030.

The simulation results of potential building damage by replacement cost of new construction are about three to four times higher than those simulated previously on the basis of market values. Even if we consider only the cost of the superstructure, which ranges from 50 to 75 percent of the total building cost and is the primary portion of the building needing replacement after earthquake damage, the figure for potential damages is still considerably higher than those derived by market value. In the light of the recent Santa Barbara earthquake and its associated intangible impact, it might be preferable to use conservative estimates or to use those results derived from the market values for decision-making.

TABLE VI-17

POTENTIAL EARTHQUAKE BUILDING DAMAGES
By Alternative Approaches [a]

County	Probabilistic Approach		Deterministic Approach: Io = New Madrid, MMI = IX		Deterministic Approach: Io = New Madrid, MMI = XII		Deterministic Approach: Io = Marked Tree, MMI = IX		Deterministic Approach: Io = Marked Tree, MMI = XII	
	1980	2030	1980	2030	1980	2030	1980	2030	1980	2030
St. Louis SMSA										
Franklin	10	50	6	10	226	346	0	0	110	168
Jefferson	50	140	15	24	397	696	0	0	196	338
St. Charles	60	100	16	32	453	928	0	0	220	458
St. Louis	730	860	135	159	4,037	4,725	0	0	1,987	2,327
St. Louis City	600	600	116	116	3,255	3,256	0	0	1,621	1,620
Clinton	10	10	1	3	62	86	0	0	31	42
Madison	320	410	64	78	1,895	2,272	0	0	929	1,118
Monroe	0	0	1	4	41	84	0	0	19	39
St. Clair	430	550	86	105	2,419	2,965	0	0	1,199	1,469
Total	2,210	2,720	440	531	12,785	15,358	0	0	6,312	7,579
Cape Girardeau	110	140	22	34	289	452	7	11	211	331
New Madrid	70	70	96	98	288	308	0	0	96	98
Memphis SMSA										
Shelby	1,140	1,830	79	128	2,314	3,663	966	1,531	5,540	8,745
Tipton	50	80	3	4	83	97	34	40	195	230
Crittenden	60	110	5	5	149	197	74	97	372	491
De Soto	20	30	2	3	137	131	24	25	240	226
Total	1,270	2,050	89	140	2,683	4,088	1,098	1,693	6,347	9,692
15-County Total	3,760	4,980	647	803	16,045	20,206	1,105	1,704	12,966	17,700

a/ Estimated by Model III, using data base provided by William R. Park.

C. Comparison with Mann's Study

As stated previously, no attempt has ever been made to quantitatively assess the potential earthquake damages in the New Madrid region, and almost all studies concerning earthquake damages estimation in other areas are following the spirit of a deterministic approach; that is, the earthquake intensity of the study area being given.

Similarly, the damage estimation reported by Mann (1974) used the same assumption (Business Insurance, 1978). However, since Mann's study is the only one found with quantitative estimates for the Memphis SMSA, which is a portion of our study area, his damage estimations will be compared to those derived from our Model III. Since only those damages under M.M. intensities VII, VIII, and IX were reported in Mann's study, the comparison will be made only with reference to these three intensities. Furthermore, since the structures values in Mann's report were estimated with constant 1970 values, the damage values reported in Mann's report are adjusted upward by an annual rate of inflation of 6 percent to represent the 1978 values.

The estimated building damages by Mann adjusted by 6 percent rate of inflation for Memphis SMSA with M.M. intensities of VII to IX are plotted in Figures VI-1 to VI-3. If the SMSA were hit by an earthquake of M.M. intensity VII, the building damages of $210 million estimated by Model III coincides with Mann's estimation for those buildings with Zone 3 earthquake loading. His estimated damages for those buildings without earthquake loading strategy would be about $270 million, and for the case that buildings are enforced with earthquake loading, $210 million; both are in 1978 dollars. In 2020, the corresponding figures would be $310 million from our model and $650 and $320 million, respectively, from Mann's projections.

Our estimates are considerably lower than Mann's results with earthquake intensity equal to VIII. For example, we estimated the potential building damages to be about $600 million in 1980 and growing to over $830 million in 2020, while Mann pointed out that the potential damages would range from $640 million to $780 million in 1980 for buildings with and without earthquake loading strategy, respectively, and the corresponding figures in 2020 are $970 million and $2.1 billion, respectively. The difference becomes greater when the earthquake intensity is higher than IX. For example, in 2020 we predicted building damage of $1.7 billion for Memphis SMSA caused by an earthquake of MMI-IX, but damages are $2.2 billion and $3.4 billion in Mann's report for buildings with and without the assumption of earthquake loading.

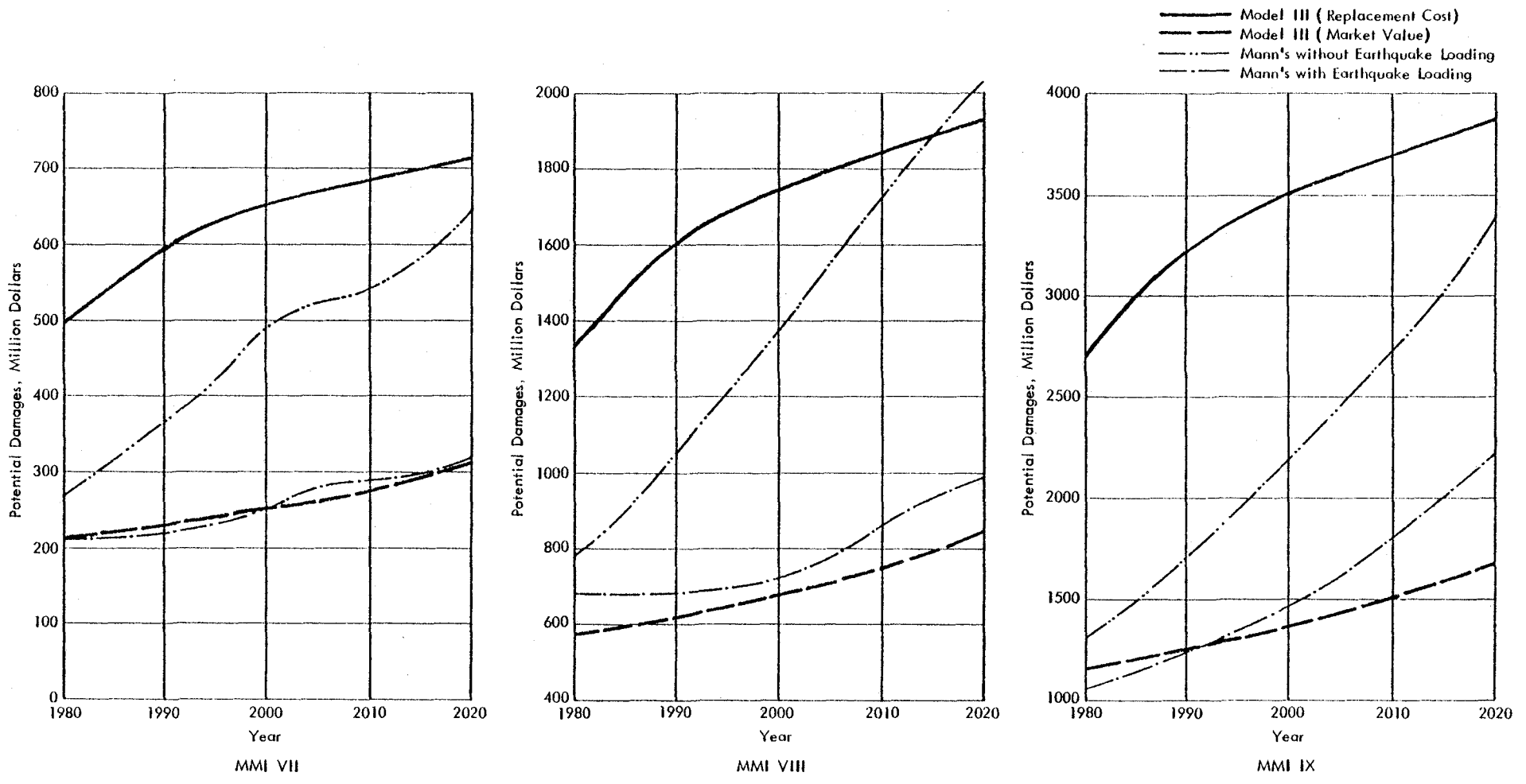


Figure VI-1. The Comparisons of Building Damage Estimations

If the replacement cost approach of structure damage is selected for simulation, however, overall results are higher than Mann's, no matter whether or not the earthquake loading requirements are enforced. For reference purposes, the results simulated from Model III based on replacement costs are also plotted in Figure VI-1.

The difference in mortality estimations is more significant than in building damages estimations. If the Memphis SMSA suffered earthquake motion with M.M. intensity VII in 1980, we estimated the life loss to range from 6 to 23 persons, respectively, for day-time and night-time populations. The corresponding figures in 2020 would be from 7 to 32 persons. In contrast, Mann's estimations are far higher than ours, no matter if the earthquake loading strategy is implemented or not. For 1980, his death estimations were from 100 to 270 persons, and for 2020, from 270 to 770 persons with the same earthquake intensity.

If the area were hit in 1980 by an earthquake motion of M.M. intensity IX, our estimations are 82 persons and 98 persons, respectively, for day-time and night-time populations. The corresponding figures for 2020 would be 105 and 127 persons, depending upon the time of the day when the earthquake occurs. In Mann's report, figures range from 550 to 2,250 persons in 1980 and from 1,150 to 5,150 persons in 2020 depending on whether or not the strategy of earthquake loading for buildings is enforced.

In summary, our estimations are considerably lower than Mann's projections. However, in view of the fact that people in this country have increasingly concerned themselves with preparedness for and mitigation of earthquakes on the one hand, and government has increasingly stressed the requirement and policies of earthquake hazard reduction on the other, our conservative estimation may be more realistic and appropriate in reflecting the potential damages to the study area in the future.

CHAPTER VII

HAZARD MITIGATION AND RISK REDUCTION MANAGEMENT

At the present time, the ability to detect and locate an impending earthquake is limited, and neither the present state of the art nor the present distribution of instrumentation permits socially useful predictions on a routine basis. Therefore, an expression such as "area of intensive study" might reflect more accurately the confidence level of interpretations of the observed phenomena in some areas than would an actual prediction. Thus, in terms of a high degree of confidence, there is insufficient scientific basis for issuing an authoritative prediction that will affect large urban areas (National Academy of Sciences, 1976).

However, scientists recently have been able to forecast some large earthquakes with limited reliability. The Alaska earthquake on February 28, 1979, as well as the November 1978, earthquake in Oaxaca, Mexico, were both anticipated on the basis of careful reading of historical records of earthquakes and a basic understanding of crustal plat motions. While they were not true predictions (a prediction being the relatively precise time, location, and magnitude of a future event), the forecasting of the locations of large (magnitude greater than 7 on the Richter scale) earthquakes is seen as a significant step in the right direction (Kerr, 1979).

The greatest weakness in the present U.S. program of earthquake prediction is the inadequacy of field projects aimed specifically at detecting and understanding earthquake precursors. The U.S. effort is limited both in the kinds of observations and experiments performed and in a real coverage. Field observation is disproportionately concentrated in California and New England, leaving relatively less attention to other seismically active parts of the country. The study region New Madrid is a typical example.

Prediction capabilities will depend, for a long time to come, on relatively dense instrumentation of highly seismic areas. At present, amply instrumented regions in the United States have been chosen more on the basis of seismic activity than of social importance. Consequently, early successful predictions are likely to be for areas of relatively low population density. Eventually, a decision will have to be made about when and where to install instrumentation intended primarily to provide socially useful warnings rather than research data.

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On the basis of present experience and understanding, it is reasonable to say that reliable prediction of smaller earthquakes will precede that of larger earthquakes. Small earthquakes occur frequently, their precursors occur over a short period of time, and their sources can be defined with regional networks.

An earthquake prediction includes several elements, probability, intensity, location, advance notice and time window (the period during which the earthquake is expected to occur). The types of information needed to provide the necessary data to make the earthquake prediction model work include statistical methods and geophysical methods. The first uses the catalogued history of earthquakes in a region as a key to estimating when and where such future events may occur. The second involves the observation and interpretation of certain changes in the physical environment in earthquake-prone regions as indicators of an impending event. Based on the first approach toward earthquake prediction, the preceding chapters have produced an earthquake risk and damage impact assessment for the New Madrid region in general and the 15 counties in the region in particular. Sizable potential damages in both structure distinction and human injuries were predicted on a county-by-county basis for the period from 1980 through 2030.

The primary responsibility for planning and responding to earthquake predictors is assigned to federal, state, local, and private agencies who have a broad concern for community and economic planning and for disaster preparedness and response. Response agencies are mostly under local control and are organized in a manner that respects political boundaries. We will address in the following sections varying issues and aspects essential to earthquake preparedness, risk reduction, and mitigation as well as emergency assistance planning, programming, and management in the region.

A. Existing Institutions and Policies for Disaster Mitigation and Response

Federal policies for disaster assistance and earthquake hazards assistance are contained in legislation which has provided a uniform and continuing means of disaster assistance to state and local governments affected by national disasters. In 1950 Congress passed Public Law 81-875 which authorized the President, upon request of a governor, to provide supplementary federal assistance to disaster-affected portions of the state following a presidential declaration of major disaster. Subsequent legislation, including the Disaster Relief Act of 1966, Public Law 89-769; the Disaster Relief Act of 1969, Public Law 91-79; and the Disaster Relief Act of 1970,

Public Law 91-606 broadened the scope of aid available to states, communities, and individuals without altering the concept that such aid is supplemental to the efforts and resources of state and local governments.[1/]

Most of these provisions in the public law were repealed by the Disaster Relief Act of 1974, Public Law 93-288,[2/] which added a new category of emergency assistance to protect lives and property or to avert or lessen the threat of a disaster. It also expanded the range of federal assistance available to state and local government, certain private nonprofit institutions, and individual disaster victims. Public Law 93-288 is applicable to all emergencies or major disasters declared since April 1, 1974.

In 1977 Congress passed Public Law 95-124 which deals specifically with earthquake hazards reduction.[3/] The purpose of the Act is to reduce the risks to life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program. Among the objectives of the earthquake hazards reduction program are the implementation, in all areas of high or moderate seismic risk, of a system (including personnel, technology, and procedures) for predicting damaging earthquakes and for identifying, evaluating, and accurately characterizing seismic hazards.

According to the Working Group on Earthquake Hazards Reduction (1978) in the Office of Science and Technology Policy, "Federal and State earthquake contingency planning is inadequate to respond effectively to a large-magnitude earthquake in or near a heavily populated region." Major reasons for the failure to provide sufficient predisaster planning include a lack of interest by some states; and the Federal Disaster Assistance Administration (FDAA) and the Office of Management and Budget feel that this type of planning is a state and local responsibility and should not be funded by the federal government. Comprehensive predisaster planning was established in Title II of Public Law 93-288, Disaster Relief Act Amendments of 1974, which provides for the establishment of federal and state disaster preparedness programs including:

1/ Public Law 91-606, 91st Congress, S.3619, December 31, 1970, An Act to revise and expand Federal programs for relief from the effects of major disasters, and for other purposes; may be cited as the Disaster Relief Act of 1970.

2/ Public Law 93-288, 93rd Congress, S.3062, May 22, 1974, An Act entitled the "Disaster Relief Act Amendments of 1974;" may be cited as the Disaster Relief Act of 1974.

3/ Public Law 95-124, 95th Congress, S.126, October 7, 1977, An Act to reduce the hazards of earthquakes and for other purposes; may be cited as the Earthquake Hazards Reduction Act of 1977.

1. Preparation of disaster preparedness plans for mitigation, warning, emergency operation, rehabilitation and recovery;

2. Training and exercises;

3. Postdisaster critiques and evaluation;

4. Annual review of programs;

5. Coordination of federal, state and local preparedness programs;

6. Application of science and technology; and

7. Research.

This program is administered by the Federal Disaster Assistance Administration in the Department of Housing and Urban Devleopment. In April 1979 a new agency, the Federal Emergency Management Agency (FEMA), was established to formally reorganize and consolidate the planning, mitigation and assistance functions and responsibilities that were previously under several separate federal agencies, including the FDAA and Federal Insurance and Hazard Mitigation (FIHM). It is hoped that through the central agency that public decisions regarding natural hazard mitigation and emergency assistance can be made more efficient and effective.

Predisaster planning in the New Madrid study region has been somewhat typical from the conditions found by the Working Group in other parts of the nation. The states of Missouri (1977), Tennessee (1978), Arkansas (1977), Mississippi (1977) and Illinois (1978) have all completed statewide disaster plans which include earthquake damages. These plans list the individual state departments, divisions, and offices having an emergency response function along with their assigned responsibilities; explain the implementation of Public Law 93-288; and describe responsibilities of the state, local and federal governments in managing disasters.

In Arkansas the Emergency Service Act No. 511 was passed in 1973. The Mississippi Code Annotated Section 33-15-1 and Tennessee Code Annotated Chapter 6 authorize a Civil Defense Council. The enabling acts are directed toward relieving suffering from natural disaster through planned emergency programs. All state agencies are directed to cooperate to the fullest extent possible with each other and with the federal and local governments, relief agencies, and the Red Cross.

On the local level, emergency disaster relief is handled primarily by Civil Defense Councils or Emergency Services. Memphis and Shelby County, Tennessee, have a joint unit, the Memphis and Shelby County Civil Defense Council. In Crittenden County, Arkansas, the unit is called the Emergency

Services of Crittenden County; in De Soto Mississippi, the unit is the Hernando-De Soto County Civil Defense Council. Each of these organizations is staffed and has a master plan for disaster response. Their basic plan includes plans for all groups such as police, fire, health, and hospitals.

Similarly, the City of St. Louis, Missouri, Revised its Disaster Operation Plan in June 1975. The definition of a natural emergency in the plan includes earthquake phenomena, and the plan states briefly the plans and procedures designed to coordinate the activities of these agencies should it become necessary to mobilize the community's resources to combat the effects of a major disaster. Each participating agency is responsible for its own plan of operation and for its efficient execution during the emergency. Each county in the St. Louis metropolitan area has a plan of operation for disasters, and each community within the metropolitan area has a Director of Civil Defense who handles disaster operations.

In the nonmetropolitan areas of the study region (Cape Girardeau County and New Madrid County) disaster planning is more limited. In Cape Girardeau County, a disaster plan has been developed which includes both a notification and an action plan. The Cape Girardeau County Office of Disaster Planning and Operations is a part-time office only with no full-time coordinator. The county has no planning or zoning; thus, little is being done in preparation for a major natural disaster. New Madrid County has no office for disaster planning, and no disaster plan has been developed. The only coordination for natural disaster is with representatives of federal offices located in the county, and representatives of these agencies meet only rarely.

Charitable or nonprofit groups, notably the Red Cross, can contribute substantially to disaster relief. The American Red Cross and its chapters are authorized by congressional charter to undertake relief activities for the purpose of mitigating the suffering caused by disasters. Damaging earthquakes are included among the extreme acts of nature as a result of which families or individuals need the basic necessities of life as well as personal humanitarian services.

B. Predisaster Planning (Disaster Mitigation)

1. Seismic protective requirements in building codes for new construction: In the United States and much of the world, 90 percent of the loss of life in earthquakes and a major part of the economic loss have been due to the failure of weak structures. Past history shows that properly designed and constructed facilities can withstand major earthquakes. The best way to reduce the loss of life and property from earthquake is to restrict the use of land in high-risk

sites and to impose appropriate engineering and materials standards upon new and existing structures.

Almost every existing structure, even those constructed only a few years ago under then-current seismic building codes, is technically deficient in some way in the light of modern knowledge. For some structures, little or no attention was given to earthquake resistance, and these present the greatest danger. Building codes in many active seismic areas do not require a seismic design; therefore, almost all buildings are deficient in some way in terms of earthquake resistance. The cost of correcting all such construction is almost incalculable. Thus, the wide use of earthquake-resistant design construction practices is essential, and a balanced program of improving the resistance of existing structures should be pursued.

No specific seismic requirements are included in the existing building codes in the four major study areas (St. Louis and Memphis metropolitan areas, and Cape Girardeau and New Madrid counties). Despite the absence of a seismic element in the codes, buildings of quality construction built in strict conformance with the existing building codes, except for certain historically weak types of construction, would have a great measure of seismic resistance.

Two implementations which appear to be important for upgrading future building codes are:

. Revise building codes to provide specific measures aimed at greater seismic protection in buildings. Such effective measures would include not using materials vulnerable to quakes, requirements for structural design consistent with expected quakes, and requirements for special engineering and geological studies for potentially hazardous sites.

. Provide more rigid enforcement of the existing building regulations and the prohibition of weak construction in vital and high occupancy facilities.

In the study area, building codes should be amended to include requirements for stronger buildings to withstand seismic events and should reflect the seismic risk unique to each specific area and the nature of the occupancy. Thus, the adoption of existing codes designed for other geographic areas, e.g. California, is not necessarily appropriate for this study region.

2. Seismic element in land use policy, planning, zoning, and subdivision regulations: Seismic safety is a minor factor in

land-use planning and is primarily concerned with location of areas prone to landslides and liquefaction, ground settlement, severe lurching, and other hazardous phenomena occurring during earthquakes. However, land-use planning that takes these earthquake-prone areas into account can be among the most effective measures for saving lives and property and minimizing disruption in the case of earthquake. Land-use planning is even more important as population density increases. Implementation measures in land-use planning directly related to earthquake mitigation include local risk mapping and establishment of zoning and subdivision regulation.

Fundamental to all efforts to regulate construction practices in an area is the preparation of maps which indicate the relative levels of risk of earthquake and earthquake-related losses. Local risk mapping can help control the increase of risk in unsuitable areas and direct the use of land to its most appropriate use (Office of Science and Technology, 1978). The potential earthquake risks both in terms of physical and economic risk, were mapped and presented in the preceding chapters. For example, seismic risk was discussed in Chapter II, and the vulnerability of ground conditions was studied in Chapter III.

The regulations concerned with subdivision and zoning of land in an urban development is a very critical action in urban development. Once land has been subdivided, the chain of development events created by zoning and subdivision makes it nearly impossible to correct any mistakes made other than through redevelopment. It is therefore very important that the use of land planning for development be carefully analyzed with regard to seismic and other hazards (MATCOG/MDDD, 1974).

To date, according to the Working Group on Earthquake Hazards Reduction, the federal, state and local governmental units generally have little understanding of earthquake hazards and do not apply earthquake hazards information to their land-use planning and development decisions.

Governmental concern at all levels for seismic safety is often limited, and there has been general unwillingness to take effective action because of the cost or the political unpopularity of regulatory action. However, governmental policies and programs to reduce earthquake hazards through land-use planning can be effective if programs and policies are carefully formed and firmly implemented.

The federal government has the responsibility of making wise land-use and development decisions concerning the location and construction of federal buildings and facilities to reduce earthquake hazards. State governments have the power through various financial and technical resources to require local units of government to limit hazards and mitigate damage in earthquake-prone areas. Similarly, local government should be provided adequate power and financial incentives to promote seismic safety.

A number of measures have been identified by the National Academy of Science (1975) Panel on the Public Policy Implications of Earthquake Prediction to mitigate earthquake damage in local areas. Among the most pertinent steps for the New Madrid study area are:

. Earthquake-risk maps should be developed and a record of land use should be kept in relation to risk, identifying areas and facilities that might merit critical attention in case of an earthquake warning.

. A community plan should be modified or developed which identifies the earthquake-related land-use problems that merit priority attention.

. Existing zoning and subdivision regulations should be reviewed and the necessary revisions made to ensure reduction of seismic hazards in the planning areas.

The land-use maps developed in Chapter IV, however primitive they may look, could be studied in the future jointly with those risks and vulnerability maps in Chapters II and III to achieve better land utilization planning and policies so that the earthquake risk can be reduced.

3. Review of seismic hazards in vital public systems:

(a) Critical facilities: Critical facilities are the public and private facilities or utilities which help a community stay alive and functioning, i.e., health care facilities, fire and police facilities, etc. These facilities are sometimes termed "urban lifelines." The failure of one or more of these lifelines to function can bring human suffering to an urban area.

Previous earthquakes point to three kinds of associated disasters: direct financial loss; unemployment; and the inability to cope with secondary disasters (fire, famine, epidemics and human casualties).

Health care facilities are vital in a time of disaster, but existing facilities in the New Madrid study region will not be sufficient to handle the expanded requirements for medical services during a major earthquake disaster. Since area hospitals have not been built to withstand earthquake stresses, they may become unusable at a time they are needed most. As hospital facilities are built or existing structures remodeled or expanded, new standards to increase their resistance to earthquake should be considered part of the building plans. Although in the Memphis area, some recently built hospitals have incorporated designs to withstand some levels of earthquake forces, this consideration has not been observed in newly built hospitals in other areas.

Buildings which house vital facilities needed in time of community disaster (highway patrol, police and fire departments, city and county administration, public health, communication facilities, and the National Guard) also require earthquake-resistant structures. Unfortunately, at the present time, practically none of these facilities in the New Madrid study area are designed for earthquake resistance. As these existing structures are replaced or remodeled, it is recommended that they be designed to withstand some earthquake forces. A major earthquake could render these facilities unusable if the buildings were severly damages or if they collapsed. Likewise, the failure of communication systems because of overloading or power failure would restrict operations.

Children in school form a large segment of the population which would be directly affected by an earthquake during school hours. Thus, school facilities should be earthquake resistant. Because school buildings are usually designated as relief shelters and emergency health care facilities during a disaster, the requirement for schools to be earthquake resistant takes on even greater importance.

None of the existing school structures in the Memphis SMSA have been designed for earthquake resistance. Many of the older school buildings were built of masonry bearing wall, type C construction, which is the most susceptible to earthquake motion. Similar conditions exist in the St. Louis SMSA and in Cape Girardeau and New Madrid counties. These buildings would present a serious hazard to the school population during school hours and could not be used as emergency medical and relief shelters during a major earthquake.

Most critical urban lifeline facilities in the New Madrid study area could not withstand major earthquake forces. The probability of future damage to these facilities and the economic and social impacts on the total urban structure warrant a complete assessment of the vulnerability of facilities in the area so adequate public policies can be developed.

(b) Vital public facilities: Another category of systems includes the vital public facilities needed to keep an urban population functioning, e.g., transportation, communications, energy, and water. Each system is composed of many facilities which are all vulnerable to earthquake forces. With few exceptions, no vital public facilities in the New Madrid study area have been designed specifically to resist earthquake forces.

(c) Earthquake insurance: Earthquake insurance is an effective means of mitigating the economic losses from an earthquake disaster for individuals, institutions, and businesses. It should be looked upon as an instrument to soften the financial losses resulting from property damage in the event of an earthquake. An effective earthquake insurance program should encourage good design and construction by means of lower rates and should not reward a building owner for having a weakly constructed building (National Academy of Sciences, 1978).

While earthquake insurance is available in the New Madrid study area, either as separate coverage or as part of an umbrella type coverage including other hazards, it is not widely used. Insurance agents indicate that there is little public demand for earthquake coverage because local residents and businesses refuse to pay attention to the events whose probability of occurrence may be below some threshold level. As a result, individuals and business establishments in the region are not likely to be insured more as a result of lack of information on the potential hazard and available insurance than because a thorough benefit/cost study associated with such a disaster and insurance premiums has been made. This present study, however aggregate it may appear, may still provide some information with which to gain insight into individual risk benefit/cost trade-offs.

Before earthquake insurance becomes a vital force in the mitigation program against earthquake damage, however, the following should take place:

. Local populace should be made aware of the potential for earthquake damage in the area.

. Insurance companies should provide information on costs and depth of coverage of earthquake insurance available in the area.

. Loans made by federally insured and sponsored loaning institutions should be protected by earthquake and flood insurance.

C. Seismic Risk Prediction, Impact Assessment and Implications

Within the past 10 years, many seismologists have become convinced that the prediction of earthquakes can be made within fairly close limits (where the place, time, and magnitude of the quake are specified). This observation is in contrast to the generally accepted view that earthquakes occur suddenly without advance warnings and only can be predicted in a most undefined manner and nonspecific as to time and place of occurrence. Established methods for identifying high-risk areas depend on the past incidence of quakes and the mapping of fault structures. New methods rely on the established methods in addition to the consideration of premonitory signs that occur in advance of quakes (changing physical properties of rocks under stress and surface tilting).

The successful development of measures for predicting earthquakes, particularly high intensity earthquakes, will provide the possibilities for hazard reduction activity. There is also the potential for community disruption in response to an earthquake warning much greater than the public is accustomed to in the case of floods, hurricane, and tornado warnings. Because the precursors for larger earthquakes are believed to develop over a period of years, the long-term warnings can affect the growth potential of regions and can have significant implications in relation to evacuation and social and economic stability.

The opportunity to conduct a hazard reduction program before the quake occurs is an important contribution of earthquake prediction. A program of this type can save lives and property and avert large-scale community disruption. An important part of this program will include the evacuation of selected high risk areas. Extensive evacuation does not appear to be necessary because apart from the danger of landslides, the earth movements produced by a quake are generally not directly fatal to individuals in the affected area. Death and injury come principally from the collapse of buildings and other vulnerable structures, and from fire. Individuals at a safe distance from buildings and away from a course of flood waters occasioned by a collapsed dam can usually experience a quake in relative safety. Accordingly, general evacuation of a large area need seldom be considered. But selective evacuation of specific locations made vulnerable by the placement of dams, by the proximity of structures that are not resistant to seismic disturbance such as a nuclear power plant, and by the risk of fire and release of toxic materials may be desirable (National Academy of Sciences, 1975).

The response of business operations to a prediction of earthquake will vary. Some firms will respond with active attempts to mitigate expected damage from earthquakes or economic disruption resulting from prediction. Other firms may choose to ignore entirely the threat of earthquake. Whether responses are active or passive usually rests on a complex set of forces.

The location of a business primary market influences in large part the way it will adjust. For example, a business whose market is confined generally to the immediate area has most of its capital value tied up in the local population and will most likely stay in the area. On the other hand, national chains are much less affected by local reputation and hence are more flexible.

A prediction of earthquake in an area may also affect the market and market value for such businesses as real estate and housing, where the price of land and housing may plummet significantly below what a realistic assessment of damages would warrant.

Employment may decline from disaster-induced dislocation and may be reduced as buyers postpone buying durable goods until after the quake has occurred. Such a recession would probably be short-lived and could be followed by a boom fueled by abnormally high levels of savings and a high demand for durables in the post-quake period.

A prediction could also influence the market for capital. A prediction of an imminent earthquake would reduce the availability of external financing for firms because banks and other leading institutions would be hesitant to make long-term capital commitments when price changes cannot be anticipated. Such a shortage would choke off investments for those firms that depend on borrowing for investment purposes (National Academy of Sciences, 1978).

The extent to which these impacts will be felt will depend upon a number of variables including the reliability of earthquake risk information, potential damage assessment, general attitudes towards earthquake hazard mitigation, social and private benefit/cost calculation, regulation policy, and effectiveness of public mitigation program implementation.

D. Participating Agencies in Regional Disaster Planning and Mitigation

The response to natural disasters includes a vast array of services and resources which are available from federal, state, and local governments. The availability of these services and resources depends upon the size of the area and the degree of damage sustained. If the damage is beyond the capabilities available at the local level and all local resources have been committed, state assistance can be requested. Similarly, the governor of each state, after reviewing the damage to private, public, and agricultural resources, can request the President to declare a major disaster or emergency. Following a presidential declaration of a major disaster or an emergency, the President's Disaster Relief Program can provide supplemental federal assistance to states, communities, and individuals.

1. Federal: The Federal Disaster Assistance Programs (1976) are intended to supplement the efforts and available resources of states, local governments, and disaster relief organizations. Although the primary responsibility for disaster relief rests with state and local agencies, there are many federal programs available.

The greatest single source of federal disaster assistance is provided under the authority of the Disaster Relief Act of 1974, Public Law 93-288, which is implemented by the Federal Disaster Assistance Administration (FDAA) following a presidential declaration of a major disaster.

The President may also make a determination that an emergency exists requiring assistance to supplement state and local efforts to save lives and protect property, public health and safety, or to avert or lessen the threat of a disaster. This program of emergency relief makes available assistance which because of the pressures of time or the unique capabilities of a federal agency can be rendered more readily by the federal government.

2. State: Under the auspices of the Federal Disaster Assistance Administration, state plans (Mississippi, Arkansas, Tennessee, Missouri and Illinois) have been developed which identify and assign responsibilities for actions required of the state and local government to respond to the threat or occurrence of any disaster prior to and independent of a presidential declaration. Each state department, commission, office, and agency assigned emergency functions within the plan have prepared an appendix to the state plan outlining emergency functions and standard operating procedures. While earthquakes are designated in the definition of disasters, no specific plans at the state level have been developed to deal with this phenomenon specifically.

It is the responsibility of local governments to take immediate steps to alleviate suffering, protect life and property, and commit available resources before requesting assistance from the state government.

3. Local: Local governments (city and county) within the study areas have developed emergency preparedness and disaster relief plans and work with state and federal agencies in comprehensive planning. The Memphis SMSA has dealt most closely with the problem of earthquakes and is more aware of the earthquake risk than other local communities in the New Madrid study area. The Regional Earthquake Risk Study prepared by M & H Engineering and Memphis State University for MATCOG/MDDD in 1974 is by far the most comprehensive document completed in the New Madrid study area. The report describes the seismic risk in the Memphis metropolitan area and was prepared to aid in the establishment of a public policy regarding earthquake protection. The St. Louis SMSA and Cape Girardeau and New Madrid counties have developed plans for responding to various disasters both on a county and community level. The active participation of disaster operation offices at the local level varies from the daily operation of an office in the City of St. Louis to a part-time office operation in Cape Girardeau and no formal office in New Madrid.

An attempt to identify the participation of various local lifeline and critical facilities offices (fire, police, water, health, hospitals, transportation, civil defense, etc.) in major disaster mitigation and planning was made by means of a questionnaire sent to these agencies and through field visits in each of the study areas. Response to the questionnaires and interviews during the field survey indicated that very few local departments have prepared a natural disaster relief plan of developed general procedures or guidelines to follow should a major disaster occur in their area. Likewise, very few agencies have had contact with other groups (local government, state agencies, federal agencies or private groups) concerning disaster planning. The following positve responses to the questions concerning disaster planning were obtained.

St. Louis: All agencies responding from the City of St. Louis indicated that they are a part of the Disaster Plan coordinated and supervised by the St. Louis Disaster Operations Office (1975). None of the agencies indicated that they have developed their own plans for disasters including earthquakes. Major planning groups interested in disaster planning in St. Louis and providing information concerning building age and construction and population projections include the East-West Gateway Coordinating Council and the Regional Commerce and Growth Association.

Cape Girardeau and New Madrid Counties: All agencies responding to the questionnaire indicated that they have not participated in disaster relief planning or developed procedures or guidelines to follow should a major natural disaster occur in the area. In Cape Girardeau County, mention was made of the part-time Cape Girardeau County Office of Disaster Planning and Operation as the only local agency engaged in disaster relief planning. The Cape Girardeau County Planning Commission although interested in disaster planning has not prepared a master plan of this type. However, hospitals in the county have their own disaster plan and emergency radio system.

Contacts with the New Madrid County Agricultural Extension Service indicated that the only disaster coordination and planning efforts are conducted by various local offices of the federal government and that these agencies meet very irregularly.

Memphis: A number of agencies have actively participated in disaster relief planning, including:

* Mississippi-Arkansas-Tennessee Council of Governments/Memphis Delta Development District (MATGO/MDDD): This agency has prepared a natural disaster relief plan and has developed general procedures and guidelines to follow should a natural disaster occur. The agency has prepared an earthquake mitigation plan and has developed general procedures concerning actions to be taken should a major earthquake occur. These are contained in the report, "Earthquake Risk in the Memphis Area," issued in 1976. The

Agency also instigated the "Regional Earthquake Risk Study" prepared in 1974 that was discussed earlier in this chapter. This agency has presented the 1976 earthquake report to local groups and to the local civil defense agency.

* Memphis-Shelby County Civil Defense: This agency has included earthquake planning within their general plan encompassing all potential disasters for the Memphis area. The plan for the civil defense agency and the plans for more than 20 agencies included within the comprehensive plan list specific facilities, personnel, and equipment as well as procedures to be used in any emergency. Because all emergencies require the mobilization of the same vital facilities, hospitals, communications, police, firefighting, emergency agencies and temporary relief shelters, one basic plan is used.

The Memphis-Shelby County Civil Defense Office has a combined Emergency Medical/Civil Defense Communications Center which operates 24 hours a day. The center allows constant contact with all local emergency services agencies. This communication network and special coordinating efforts with radio amateurs, damage assessment experts, organized volunteers and others help bring the community closer to being prepared. According to the Director of Civil Defense, "Experience and study have illustrated to those emergency services, periodic exercises, combined with constantly evolving plans make it possible to state that we of Memphis-Shelby County Civil Defense feel that we provide the level of preparedness required by our local government."

* Memphis Area Transit Authority: The Authority has developed plans and procedures should a major natural disaster occur. These actions are part of the Civil Defense Emergency Operations Plan.

* Memphis and Shelby County Office of Planning and Development: This agency has participated in several efforts associated with disaster mitigation and earthquake risks. A Civil Defense Shelter Plan was prepared for the Civil Defense Office during the late 1960's, and the Office participated in the MATCOG/MDDD "Earthquake Risk Study" prepared for the Memphis area in the early 1970's.

* Memphis Division of Fire Services: Emergency procedures for the Fire Department are incorporated in the Shelby County Civil Defense Plan.

* City of Memphis Hospital: The hospital has developed general procedures and guidelines to follow should a major natural disaster occur. This plan is coordinated with other hospitals in the area, and the Memphis-Shelby County Civil Defense Agency is cognizant of the plan.

* Memphis Division of Public Works: The agency has developed an Emergency Operation Plan to maximize the preservation of life and property through the effective use of capabilities and resources of the Division of Public Works should a disaster strike the City of Memphis-Shelby County.

* Memphis and Shelby County Health Department: A formal plan of action should a nuclear or natural disaster occur has been developed by the Memphis-Shelby County Health Department. This plan, adopted in 1977, is coordinated through the Memphis-Shelby County Defense Emergency Operating Procedure.

E. Concluding Remarks

The review of existing institutions and policies for disaster mitigation and response and seismic risk planning and prediction in the 15-county New Madrid study area indicated a substantial need for: (1) greater community awareness, concern and cooperation by all levels of community infrastructure in terms of earthquake preparedness; and (2) the development of special strategies and planning for mitigating the social and economic losses which may be sustained in the study area when a major earthquake occurs. While some of the local disaster preparedness organizations have included the earthquake phenomena in their list of disasters for which they are responsible to provide assistance when they occur, in most cases these organizations have not fully studied the unique characteristics and problems which earthquakes generate, or have not provided specific solutions to these problems in their policies and plans for disaster relief.

CHAPTER VIII

SUMMARY AND RECOMMENDATIONS

A. Conclusions and Summary

The potential physical and economic risks of earthquake hazard and the resulting damages for the New Madrid earthquake zone have been studied and evaluated. An integrated model was developed for analyzing the potential damages of earthquakes with a variety of data on seismic hazard, predicted earthquake recurrence possibilities, regional ground conditions, and the inventory of the major populations--structure, personal property, and human beings--that are subject to the estimated earthquake risks in the next 50 years in the study region covering two metropolitan areas (St. Louis and Memphis) and two rural counties (Cape Girardeau and New Madrid). The model and information collected in this study were then used to predict the potential damages of earthquakes from 1980 to 2030 under the scenario of no new mitigation programs being implemented for the region. Physical and economic damages were simulated under three different seismological risk concepts; namely, the probabilistic approach, the deterministic approach with New Madrid, Missouri, as an epicenter, and the deterministic approach with Marked Tree, Arkansas, as another epicenter of energy source.

The model developed in this study differs in several aspects from other models that have appeared in previous studies of the same nature:

. Conceptually, the model systematically analyzes the work produced by seismologists, geologists, structural engineers, economists, and social scientists to quantitatively estimate the potential risk of earthquakes in a given region for a future period with a reasonable planning horizon--the next 50 years.

. Methodologically, the integrated physical and economic damage functions of varying types of structures were established on the basis of the historical data and the results developed by other earthquake researchers. The model specification developed in this study would allow the damage ratios to be correlated to earthquake intensity on a continuous basis. This would relax the restrictions of damage functions being determined discretely.

. The interrelationships of building age and ground susceptibility and their joint effect on earthquake resistance have been incorporated into the model for building damage estimation. Thus, a more integrated approach for earthquake risk estimation has been quantitatively established.

. Furthermore, attempts have been made to account for the interdependent relationships among building damage, mortality, and personal property damage with varying econometric estimation techniques. The mortality damage model in log-linear form includes population density and computed economic damage estimation in a recursive manner. This seems to be another advancement in integrated damage modeling and empirical damage estimations; i.e., the flexibility and adaptability of the models for natural hazard risk estimation have been tested and strengthened empirically.

The data bases developed for damage estimations and predictions for the study area are also different, at least in the following dimensions:

. Seismological risks in the study region were estimated with data supplied by both the probabilistic approach and the deterministic approach. And the surficial materials and ground conditions of the region were classified and the indexes of earthquake susceptibility developed for the first time in the region.

. The population projections took into account factors such as migration patterns; new household formation; present and expected socioeconomic structure changes; and industrial and community development characteristics, including development and construction trends and land utilization patterns. Zoning and regulations for natural hazard protection and emergency preparedness in general and for earthquake damage investigation in particular have been investigated, and the populations at risk thus set up would be more realistic for making better and more efficient policy decisions.

. The structures have been projected by incorporating the present inventory information, the growth trend of population and employment and the changing patterns of zonations in each county and their impact on the growth and distribution of each type of structure. The values of structures calculated from county assessor's records were compared to the reconstruction costs of new structures to provide a range of estimates of the structure values.

. The data collected from various published sources were further checked with site visits and personal interviews to assure their high quality and reliability.

The simulation of earthquake damages has been performed with two earthquake predictions--the probabilistic approach and the deterministic approach. The earthquake risk predicted by each approach is based on different assumptions on the earthquake recurrence rate, the intensity and attenuation, and other relevant seismic information. It is estimated that the central portion of the study region has a 10.0 percent probability of experiencing a maximum Modified Mercalli intensity (MMI) of IX in the next

50 years. The deterministic approach also was used to generate isoseismic contour maps for two specific epicenters--New Madrid and Marked Tree for MMI-VIII through MMI-XII.

The results from our damage simulation models indicate that considerable damage would result in the study area if it were hit by an earthquake with an intensity of MMI-IX or above. A summary of one of the simulated results in terms of potential damages is presented in Table VIII-1 below for purposes of illustration. Detailed simulation results are shown in Appendix D-1. The results of our damage simulations, including several interesting points which are different from other related works, are briefly delineated as follows:

. If an earthquake of M.M. intensity IX should hit the region, say in 1980, our model shows that the structural damages, primarily the buildings in terms of constant 1978 market value, would range from $173 million to $1.2 billion depending on the estimated probability of occurrence of such an earthquake--or the approach for earthquake risk estimation used--and its epicentral location. As expected, the damage would be higher the later the quake hits the region. For instance, the model estimated the structure damage would be from $231 million to $1.7 billion if the same event would occur 50 years later. It should be noted that the actual damage in the region would be much greater since geographically we have included in our study only a portion (15 counties together) of the total area within each isoseismal region.

. According to Gupta and Nuttli (1976), the first of the three major New Madrid earthquakes that occurred in 1811-1812 might have had an M.M. intensity equivalent to XI. Its return period is estimated to be from 500 to 1,000 years. Should such an earthquake hit the region again in 1980 rather than in the remote future, our model has estimated that damage to structures in these 15 counties may range from $2.3 to $2.5 billion, depending again on whether the epicenter is located in New Madrid or Marked Tree. The potential damage is apparently a function of its distance from the epicenter, and date of occurrence.

. In a like manner, Table VIII-1 shows that personal property damage caused by those earthquakes will also be substantial. For an earthquake of M.M. intensity of IX occurring in the night-time, the property loss value would be from $205 to $641 million in 1980, and from $436 million to $1.1 billion in 2030. Should an earthquake similar to those of 1811 to 1812 return in the year 2000, the 15 counties being studied would suffer a personal property loss of about $945 million to $1.05 billion.

TABLE VIII-1

SUMMARY OF POTENTIAL EARTHQUAKE DAMAGES: MODEL III

	Building Damage ($M)			Personal Property Damages ($M)-Night			Mortality (persons)						Injuries (persons)					
							Day			Night			Day			Night		
	1980	2000	2030	1980	2000	2030	1980	2000	2030	1980	2000	2030	1980	2000	2030	1980	2000	2030
(A) Probabilisitc Approach: $I_{,max}$ = IX (P = 10.0%)																		
St. Louis SMSA	614	662	740	408	490	615	17	18	19	72	77	84	1,680	1,794	1,947	7,201	7,718	8,429
Cape Girardeau	28	33	43	14	19	27	5	5	6	9	11	12	456	509	573	949	1,065	1,209
New Madrid	6	7	9	8	8	11	5	6	6	9	9	10	545	560	629	851	875	990
Memphis SMSA	576	682	917	211	281	451	26	29	34	50	56	68	2,590	2,886	3,423	4,987	5,616	6,764
Total	1,224	1,385	1,709	641	798	1,104	53	57	66	140	153	174	5,272	5,748	6,574	13,987	15,275	17,391
(B) Deterministic Approach: I_o = IX at New Madrid, Missouri																		
St. Louis SMSA	117	127	144	270	326	411	2	2	2	31	33	36	348	373	408	3,096	3,341	3,673
Cape Girardeau	6	7	7	8	11	15	1	1	1	3	3	4	65	73	82	310	348	395
New Madrid	10	11	14	10	10	15	12	12	14	13	14	16	1,177	1,209	1,358	1,350	1,389	1,571
Memphis SMSA	40	48	64	97	130	210	0	1	1	10	11	13	108	122	148	942	1,072	1,303
Total	173	193	231	385	477	651	15	16	18	57	61	69	1,698	1,777	1,996	5,698	6,150	6,942
(C) Deterministic Approach: I_o = IX at Marked Tree, Arkansas																		
St. Louis SMSA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cape Girardeau	2	2	3	6	9	12	0	0	0	2	2	2	21	24	27	181	203	230
New Madrid	0	0	0	3	3	5	0	0	0	1	1	2	16	16	18	130	134	151
Memphis SMSA	481	570	651	196	261	419	16	19	23	40	45	55	1,719	1,908	2,257	4,035	4,537	5,456
Total	483	572	654	205	273	436	16	19	23	43	48	59	1,756	1,948	2,302	4,346	4,874	5,837
(D) Deterministic Approach: I_o = XI at New Madrid, Missouri																		
St. Louis SMSA	1,695	1,838	2,071	600	725	917	75	80	88	163	176	193	7,459	8,036	8,798	16,281	17,570	19,307
Cape Girardeau	43	50	65	17	23	32	10	11	13	14	16	18	1,030	1,148	1,294	1,411	1,584	1,797
New Madrid	25	28	36	11	14	19	100	103	116	43	44	50	10,014	10,285	11,557	4,297	4,420	5,001
Memphis SMSA	574	682	921	213	285	461	23	26	32	50	56	69	2,333	2,637	3,175	4,952	5,636	6,856
Total	2,337	2,598	3,093	841	1,047	1,429	208	220	248	270	292	330	20,836	22,106	24,824	26,941	29,210	32,961
(E) Deterministic Approach: I_o = XI at Marked Tree, Arkansas																		
St. Louis SMSA	629	683	770	414	500	633	18	19	21	75	81	89	1,794	1,933	2,116	7,535	8,131	8,935
Cape Girardeau	28	33	43	14	19	27	5	5	6	9	11	12	456	509	573	949	1,065	1,209
New Madrid	5	6	7	7	8	10	3	3	4	7	7	8	335	344	386	684	704	796
Memphis SMSA	1,789	2,119	2,847	310	418	684	193	215	255	151	170	205	19,328	21,511	25,515	15,129	17,046	20,546
Total	2,451	2,841	3,667	745	945	1,354	219	242	286	242	269	314	21,913	24,297	28,590	24,297	26,946	31,486

. While casualties in terms of human deaths have been estimated to be small--ranging from several to several hundred persons in the 15-county region, depending on the time of a day the quake hits the area--the human injuries estimated would be considerable. The number of injuries may range from 1,700 to 30,000, depending again on when, where, and what type of earthquake occurs. While the casualty losses were estimated with U.S. historical data and found to be lower than normally expected, a higher than conventionally assumed rate of injury to fatality was employed in this study not only to balance the potential earthquake damages on human beings but also to take into account the improved medical sciences and technology for saving lives as well as the increased awareness and preparedness for natural hazards.

. The damage results shown in Table VIII-1 are much smaller relative to the estimates made by Mann (1974) for the Memphis SMSA, and our estimates may be considered conservative. However, conservative estimates are also useful for decisionmakers in making mitigation policies and preparing for future earthquakes since the minimum damages are basically the baseline estimations required for many policy issues, e.g., zero base budgeting. Another justification for using relatively conservative estimates is that continuous scientific and technological improvement increased public awareness and public policies toward natural hazard prevention and mitigation in the past decades which has jointly, to a certain extent, reduced the potential earthquake risk. The recent example of a reduced earthquake risk might be illustrated by the August earthquake, in which Gilroy, California, registered at 5.8 or 5.9 on the Richter scale, but which resulted in no human life loss and little structural damage. However, it did cause considerable architectural damage and some injuries.

. Because of the nature of our physical damage model and the uneven distribution of diurnal and nocturnal populations as well as the seismological risk by county in the region, the potential life loss in each county resulting from a day-time earthquake would be lower than from a night-time earthquake if the earthquake is of M.M. intensity IX or below. And for the earthquake of M.M. intensity X and above, the results would generally be reversed. These results, although clearly shown in Appendix D-1, are not easily recognized in such an aggregate table as Table VIII-1 except for New Madrid County in Section (D) and Memphis SMSA in Section (E).

These results are different from almost all similar damage studies, where mortality for diurnal population is either higher (in most of the related studies) than for nocturnal population or vice versa (in only a few of the similar studies) for any given intensity. Because our estimation is to extrapolate the historical relationship between mortality and earthquake intensity and to account for the simultaneity of our model in explaining the interactive relationships among mortality, building damages, and personal property damages, our log-linear model may represent a certain type of non-linear, long S-shaped ($\int$) dose-response relationship and thus may provide

a more convincing measurement for the potential damage of various types of earthquake risks for different types of populations. Because of the diversity of our damage estimates, which are a function of not only the time of earthquake occurrence but also the intensity, distance, and other risk considerations or determinants, our estimation results have to be interpreted carefully. It should be noted again that the estimations are for only 15 counties within the New Madrid earthquake zone, whose area of potential damage embraces many times that number.

B. Recommendations

1. Naturally there are areas in this model that could be further improved whenever the research opportunity materializes.

First, the damage ratio in this study has been constructed only for three types of structures--wooden frame, masonry, and concrete and steel frame--mainly due to the restriction of available historical data. The damage ratio of concrete structures is logically different from that of the steel frame structures. Hence, it would be desirable to separately develop one physical damage function and one damage ratio for each of these types of structures when data become available.

Second, even within each type of structure, say masonry, the earthquake resistance of each building may vary because of difference in architectural design, building purpose, the degree of maintenance, etc., in addition to the age of the building and the surficial material on which it was built. Therefore, for each type of structure it would be desirable to develop several additional series of damage functions to account for the diversity of structure risk characteristics.

Third, the impact of age on building damages was estimated from the historical records of concrete structures and then applied to the wooden frame and masonry structures due to the paucity of data for these two types of structures. Such treatment may lead to a biased estimation for potential damages to wooden frame and masonry buildings. If resources are available, we would recommend further research work be done toward a more complete model of damage estimation.

Fourth, the partial impact of varying geologic material conditions on the building was assumed to be the same as that of the age factor. This definitely is not a good assumption. However, presently there is no such study on this subject, despite the fact that the impact of geologic material on potential earthquake damages has been frequently recognized. An in-depth study of this partial impact and its interactive influence with the deteriorating condition of the structures (or age factor as used in this study), the type and use of the building, its architectural design, etc., would be a significant contribution to earthquake damage modeling.

Finally, the human injury rate was estimated to be proportionally related to the mortality rate. This functional relationship needs to be further tested and modified when additional data become available. And simultaneous-equations models may be developed for the interdependent relationships.

2. In addition to the improvements over the physical and economic damage model development, more research on risk population estimation is by all means warranted. It would seem desirable to conduct a more detailed field survey or inventory on the number and the characteristics of various risk populations in this earthquake-prone area. A refined investigation such as this would undoubtedly provide more reliable input for damage model simulation in general and for government quake hazard reduction policy planning in particular.

3. According to the interviews conducted during our study period, we found virtually no earthquake preparedness plans included in the industrial development and land utilization plans for St. Louis SMSA and the two rural counties, let alone mitigation and emergency or disaster relief programs specifically designed for coping with earthquake hazard. No continuous or permanent educational policies for the improvement of public awareness of the potential damages of the quake were found; and consequently, no significant risk reduction plans were observed in the study region. The specific building and zoning codes for earthquake hazard reduction were nonexistent in almost all counties. One explanation for the lack of concern is that people in this region are not aware of the potential for damage caused by earthquakes. It is hoped that the results reported in this study would provide the public and private agencies concerned with earthquake damage mitigation in the New Madrid region the kind of information needed for making future policy decisions. Thus, it is desirable that we disseminate the estimated damage results and other pertinent information derived from this study to the people in this 15-county region (and also to adjacent counties) and subsequently to study their awareness of and responsiveness to earthquake damage in general and their specific actions toward damage mitigation in particular.

4. This study attempts to combine the efforts of an interdisciplinary team consisting of a seismologist, geologist, construction engineer, economist, and systems analyst. It was derived from an integrated model of physical and economic damage functions for damage estimates by earthquake receptors or populations at risk. The methodology presented in this study has demonstrated its feasibility in estimating the potential risk of the New Madrid earthquake area in the future and its flexibility for application to study the potential earthquake damage in other areas. Thus, the methodological procedure may be replicated and tested again for other earthquake-prone regions in this country. Consequently, the damage results can be compared to those of earlier studies so that range estimates (not just point

estimate) regarding potential earthquake hazards may be presented for making better and more efficient public policies in mitigation and emergency management.

5. For those urban land utilization and industrial development plans drawn previously for the study region, especially those in the City of St. Louis and in Shelby County, we highly recommend that they be reexamined against the data and information produced in this study. New buildings and other developments along the river front must be planned carefully to take into account the least ground susceptibility indexes constructed for the area if potential earthquake risk is to be mitigated and physical and economic damages to be minimized. It would also be appropriate to suggest that a reexamination of land use planning, especially long-range planning, be considered jointly by all regional planning agencies. Since most of the commercial and industrial plans have evolved with little or no consideration of earthquake risk in general and ground susceptibility in particular, this reexamination and, consequently, redesigning of future land use patterns will be likely to reduce considerably the earthquake risk potential. In light of the potential damages simulated in this study for the region, the social benefit of the risk reduction and hazard mitigation work would seem to be enormous and the rate of returns to the public investment in these areas highly competitive.

REFERENCES

Algermissen, S. T. "Seismic Risk Studies in the U.S." Proc. Fourth World Conference on Earthquake Engineering, 1:14-27. Association Chilena de Sismologia y Interieria Antisimica, Santiago, Chili. January 14, 1969.

Algermissen, S. T., and D. M. Perkins. "A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous U.S." U.S. Department Interior, U.S. Geolog. Surv. Open-File Rep. No. 76-416. 1976.

Algermissen, S. T., and K. V. Steinbrugge. "Earthquake Losses to Buildings in the San Francisco Bay Area." Pages 61-72 in E. E. Brable (ed.), Progress of Seismic Zonation in the San Francisco Bay Region. U.S. Department Interior, U.S. Geolog. Survey 1979.

Algermissen, S. T., K. V. Steinbrugge, and H. J. Lagorio. "Estimation of Earthquake Losses to Buildings (Except Single Family Dwellings)." U.S. Dept. Interior, U.S. Geolog. Surv. Open-File Rep. No. 78-441. 1978.

State of Arkansas, Office of Emergency Services. "Arkansas Emergency Operations Plan." April 1977.

Baker, L. N. Geology of the New Madrid S. E. and Hubbard Lake Quadrangle in Kentucky. U.S. Dept. Interior, U.S. Geolog. Surv. GQ-292. 1963.

Balsman, B. J., K. M. Bratton, T. G. Tucker, and K. M. Krone. "The Master Plan for Cape Girardeau County, Missouri." Southeast Missouri Regional Planning and Economic Development Commission. May 1977.

Blume, J. A. "Civil Structures and Earthquake Safety." Proc. Conf. Earthquake Risk: 109-115. Joint Committee on Seismic Safety to the California Legislature. September 22-24, 1971.

Blythe, E. W. "Geology of Reelfoot Lake and Vicinity." Field Trip No. 3 in Field Trips of West Tennessee. Tennessee Division of Geology, Rep. of Invest. No. 36, pp. 64-76. April 1975.

Borcherdt, D., J. F. Gibbs, and T. E. Fumal. "Progress on Ground Motion Predictions for the San Francisco Bay Region, California." Pages 13-25 in E. E. Brable (ed.), Progress of Seismic Zonation in the San Francisco Bay Region. U.S. Dept. Interior, U.S. Geolog. Surv. 1979.

Bowden, M. J., and R. W. Kates. "The Coming San Francisco Earthquake: After the Disaster." Pages 62-81 in H. C. Cochrane, J. E. Haas, M. J. Bowden, and R. W. Kates (eds.), Social Science Perspective on the Coming San Francisco Earthquake--Economic Impact, Prediction, and Reconstruction. Natural Hazard Research Working Paper No. 25. Institute of Behavioral Science, University of Colorado. 1974.

Brable, E. E. (ed.). Progress on Seismic Zonation in the San Francisco Bay Region. U.S. Dept. Interior, U.S. Geolog. Surv. 1979.

Burke, K., and J. F. Dewey. "Plume-Generated Triple Junctions: Kay Inductors in Applying Plate Tectonics to Old Rocks." J. Geol. 81:406-433. 1973.

Business Insurance. "Natural Hazard Losses to Skyrocket: Study." Page 52. November 13, 1978.

Caplan, W. M. "Subsurface Geology and Related Oil and Gas Possibilities of Northeastern Arkansas." Arkansas Resources and Development Commission, Division of Geology, Bull. No. 20. 1954.

Carder, D. S. Earthquake Investigations in Western U.S., 1931-1964. U.S. Dept. Commerce, Coastal and Geodetic Survey Pub. No. 41-2. 1965.

Cochrane, H. C., J. E. Haas, M. J. Bowden, and R. W. Kates (eds.). Social Science Perspective on the Coming San Francisco Earthquake--Economic Impact, Prediction, and Reconstruction. Natural Hazard Research Working Paper No. 25. Institute of Behavioral Science, University of Colorado. 1974.

Collins, W. E. "Physical Constraints to Urban Development in Nineteen Selected Areas in Missouri." Missouri Geological Survey and Water Resources, Misc. Pub. No. 26. Missouri Department of Community Affairs. March 1974.

Cornell, C. A. "Engineering Seismic Risk Analysis." Bull. Seismolog. Soc. Amer. 58:1583-1606. 1968.

Cornell, C. A. "Probabilistic Estimate of Damage to Structures Under Seismic Load." Pages 473-488 in D. A. Howell, I. P. Haigh, and C. Taylor (eds.) Dynamic Waves in Civil Engineering. London: Interscience. 1971.

Cornell, C. A. "Seismic Risk Analysis Support Documents." Cambridge: M.I.T. Press. 1974.

Cornell, C. A., and H. A. Merz. "Seismic Risk Analysis of Boston." Proc. Amer. Soc. Civ. Eng. 101:2027-2043. 1974.

The Council of State Governments with the Natural Hazards Research and Applications Information Center, Institute of Behavioral Science, University of Colorado. National Conference on Earthquakes and Related Hazards (an invitational conference). Boulder, Colorado, November 16-18, 1977.

Culver, C. G., H. S. Lew, G. C. Hart, and C. W. Pinkhams. National Hazards Evaluation of Existing Buildings. U.S. Dept. Commerce, Natl. Bur. Standards. January 1975.

Cushing, E. M., et al. "General Geology of the Mississippi Embayment." U.S. Dept. Interior, U.S. Geolog. Surv. Prof. Pap. No. 488-B. 1964.

Dapples, E. C. Basic Geology for Science and Engineering. New York: John Wiley. 1959.

Davison, C. Great Earthquakes. London: Thomas Murby. 1936.

East-West Gateway Coordinating Council. Year 2000 Land Use Plan, St. Louis Metropolitan Region. October 1977.

Ervin, P. C., and L. D. McGinnis. "Reelfoot Rift: Reactivated Precursor to the Mississippi Embayment." Geolog. Soc. Amer. Bull. 86:1287-1295. 1975.

Evernden, J. F. "Magnitude Determinations at Regional and Near-Regional Distances in the United States." Bull. Seismolog. Soc. Amer. 57:591-639 1967.

Ewing, R. D., A. W. Johnson, and J. C. Kariotis. "Methodology for Mitigation of Seismic Hazards in Existing Unreinforced Masonry Buildings." Quarterly Report for the National Science Foundation. January 1979.

Federal Disaster Assistance Administration. Authorities and Regulations for the Federal Disaster Assistance Program. Department of Housing and Urban Development. May 1976.

"Federal Emergency Management," Federal Register, Vol. 44. July 24, 1979.

Federal Insurance Administration. Report on Earthquake Insurance. U.S. Dept. Housing and Urban Development. 1971.

Fisk, H. "Geological Investigation of the Alluvial Valley of the Lower Mississippi Delta." Mississippi River Commission. U.S. Army Corps of Engineers, War Department. 1944.

Flint, R. F. Glacial and Quaternary Geology. New York: John Wiley. 1971

Freeman, J. R. Earthquake Damage and Earthquake Insurance. McGraw-Hill 1932.

Friedman, D. G. "Computer Simulation in Natural Hazard Assessment." Institute of Behavioral Science, University of Colorado. 1975.

Friedman, D. G., and T. S. Roy. Computer Simulation of the Earthquake Hazard, The Travelers Insurance Company. May 27, 1969.

Friesema, H. P., J. Caporaso, G. Goldstein, R. Lineberry, and R. McCleary. Aftermath. Beverly Hills: Sage Publications. 1979.

Fuller, M. L. "New Madrid Earthquake." U.S. Geolog. Surv. Bull. No. 494. Washington: U.S. GPO. 1912.

Glossary of Geology. American Geological Institute, Washington, D.C. 1972.

Grohskopf, J. G. "Subsurface Geology of the Mississippi Embayment of Southeast Missouri." Missouri Geological Survey and Water Resources, 2nd Ser., Vol. 37. 1955.

Gupta, I. N., and O. W. Nuttli. "Spatial Attenuation of Intensities for Central U.S. Earthquakes." Bull. Seismolog. Soc. Amer. 66:743-751. June 1976.

Gutenberg, B., and C. F. Richter. Seismicity of the Earth. Princeton, N.J.: Princeton University Press. 1954.

Haas, J. E., R. W. Kates, and M. J. Bowden (eds.). Reconstruction Following Disaster. Cambridge: M.I.T. Press. 1977.

Harrison, D. G. "Memorandum for Local Civil Defense Directors/Coordinators." Defense Civil Preparedness Agency, Region Six. June 30, 1978.

Heck, N. H. Earthquakes. New York: Hafner Publishing Co. 1965.

Heck, N. H. Earthquake History of the United States, Part I - Continental United States (rev.). U.S. Dept. Commerce, Coastal and Geodetic Survey Ser. No. 609. 1974.

Heigold, P. C. "Notes on the Earthquake of November 9, 1968, in Southern Illinois." Illinois State Geological Survey, Environ. Geolog. Notes No. 24. December 1968.

Hendershott, P. H., Understanding Capital Markets, Volume I: A Flow of Funds Financial Model. Lexington, Mass.: Lexington Books. 1977.

Hirschberg, J. G., P. Gordon, and W. J. Petak. "Natural Hazards: Socio-economic Impact Assessment Model." Report by J. H. Wiggins Company. 1978.

Hodgson, J. H. Earthquakes and Earth Structures. Englewood Cliffs, N. J.: Prentice-Hall. 1964.

Hunt, C. D., K. M. Bratton, and T. G. Tucker. "Comprehensive Plan for Cape Girardeau, Missouri." Southeast Missouri Regional Planning Commission. June 1975.

State of Illinois, Emergency Services and Disaster Agency. "Illinois Comprehensive Disaster Response Plan." December 1978.

State of Kansas, Geological Survey. J. Kansas Geol. Surv. 1(3):6. 1979.

Keller, E. A. Environmental Geology. Columbus, Ohio: Charles E. Merrill. 1976.

Kerr, R. A. "Another Successful Quake Forecast." Science 16 March: 1091. 1979.

Krinitzsky, E. L. "State of the Art for Assessing Earthquake Hazards in the United States: Fault Assessment in Earthquake Engineering." U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. May 1974.

Laird, R. T., J. B. Perkins, D. A. Bainbridge, J. B. Baker, R. T. Boyd, D. Huntsman, P. E. Staub, and M. B. Tucker. Quantitative Land-Capability Analysis. U.S. Dept. Interior, U.S. Geolog. Surv. 1979.

Leighton, M. M., and H. B. Willman. "Loess Formations of the Mississippi Valley." Illinois Geological Survey, Rep. Invest. No. 149. 1950.

Liu, B.-C. "Physical and Economic Damage Functions for Earthquakes in New Madrid." Proc. Amer. Stat. Assoc. August 1979.

Liu, B.-C. and C.-T. Hsieh. "Earthquake Risk and Damage Estimates for New Madrid." Proc. Natl. Conf. Earthquake Eng. Stanford University. 1979.

Liu, B.-C., and E. S. Yu, Air Pollution Damage Functions and Regional Damage Estimates (Westport, Connecticut: Technomic Publishing Company, 1977).

Liu, S. C., and L. W. Fagel. "Environment for Physical Design: A Statistical Analysis." Bell System Tech. J. Vol. 51. November 1972.

Lutzen, E. E., and J. O. Rockaway. "Engineering Geology of St. Louis County, Missouri." Missouri Geological Survey and Water Resources, Eng. Geol. Ser. No. 4. 1974.

MacCabe, M. P. "Earthquake Hazards Reduction Program Project Summaries--Field Year 1978." U.S. Dept. of Interior. U.S.G.S. Open-File Rep. No. 79-387. 1979.

Mann, O. C. "Regional Earthquake Risk Study, Appendix D." M & H Engineering and Memphis State University. September 30, 1974.

Marcuson, W. F., and P. A. Gilbert. "Earthquake Liquefaction Potential at Patoka Dam, Indiana." U.S. Army Engineer Waterways Experiment Station, Soils and Pavement Laboratory, Vicksburg, Mississippi, Misc. Pap. No. S-72-42. December 1972.

Martel, R. R. "Earthquake Damage to Type III Buildings in Long Beach, 1933" in D. S. Carder (ed.), Earthquake Investigation in the Western United States 1931-1964. U.S. Department of Commerce, Coastal and Geodetic Survey Pub. No. 41-2. 1965.

Mateker, Emil J. "Earthquakes in Missouri." Washington Univ. Mag. 39:49-50. 1968.

McCracken, M. H. "Structural Features of Missouri." Missouri Geological Survey and Water Resources, Rep. Invest. No. 49. 1971.

MATCOG/MDDD, Mississippi-Arkansas-Tennessee Council of Governments--Memphis Delta Development District. "Regional Earthquake Risk Study." M & H Engineering and Memphis State University, Tech. Rep. September 30, 1974.

McGinnis, L. D. "Earthquakes and Crustal Movements as Related to Water Load in the Mississippi Valley Region." Illinois Geological Survey, Cir. No. 344. 1963.

McGuire, R. K. "Fortran Computer Program for Seismic Risk Analysis." U.S. Dept. Interior, U.S. Geolog. Surv. Open-File Rep. 1976.

Memphis and Shelby County Planning Commission. Frayser Planning District Study. March 1977.

Memphis and Shelby County Planning Commission. Raleigh Bartlett Planning District Study. June 1974.

Memphis and Shelby County Planning Commission. Whitehaven Levi Planning District Study. February 1976.

Miller, D. E., et al. "Water Resources - St. Louis Area, Missouri." Missouri Geological Survey and Water Resources. Water Resources Rep. No. 30. 1974.

State of Mississippi, Civil Defense Agency. "Mississippi Natural Disaster Plan." October 1977.

State of Missouri, Department of Natural Resources, Geology Division. "The Resources of St. Charles County, Missouri--Land, Water and Minerals." 1975.

State of Missouri, Disaster Preparedness Program. "Missouri Comprehensive Emergency Preparedness and Disaster Relief Plan." Federal Disaster Assistance Administration. 1977.

Missouri Geological Survey. "Alaskan Earthquakes Affect Missouri Water Wells." Vol. 4, No. 4, p. 3. 1964a.

Missouri Geological Survey. "Alaskan Earthquakes: Summary of Wells Affected." Vol. 4, No. 5, p. 3. 1964b.

Mitchell, B. J. "Radiation and Attenuation of Rayleigh Waves from the Southeastern Missouri Earthquake of October 21, 1965." J. Geophys. Res. 78: 886-899. 1973.

Moneymaker, B. C. "Some Early Earthquakes in Tennessee and Adjacent States (1699-1850)." Tennessee Acad. Sci. J. 29:224-233. July 1954.

National Academy of Sciences. Seismology: Responsibilities and Requirements of a Growing Science. Washington, D.C. 1969.

National Academy of Sciences. Earthquake Prediction and Public Policy, Commission on Sociotechnical Systems, Panel on the Public Policy Implications of Earthquake Prediction of the Advisory Committee on Emergency Planning. Washington, D.C. 1975.

National Academy of Sciences. Predicting Earthquakes, A Scientific and Technical Evaluation--With Implications for Society, Assembly of Mathematical and Physical Sciences, Panel on Earthquake Prediction of the Committee on Seismology. Washington, D.C. 1976.

National Academy of Sciences. A Program of Studies on the Socioeconomic Effects of Earthquake Predictions, Committee on Socioeconomic Effects of Earthquake Predictions, Commission on Sociotechnical Systems. Washington, D.C. 1978.

NOAA, National Oceanic and Atmospheric Administration. "San Fernando, California, Earthquake of February 9, 1971, "U.S. Dept. of Commerce. 1973.

New Columbia Encyclopedia. New York: Columbia University Press. 1975.

Norton, D. M., and R. Streitz. "Mass Movement." Pages 61-70 in G. D. McKenzie and R. O. Utgard (eds.), Man and His Physical Environment. Minneapolis: Burgess Publishers. 1975.

Nuttli, O. W. "Magnitude, Intensity and Ground Motion Relations for Earthquakes in the Central United States." Proc. Internat. Conf. Microzonation for Safer Construction. 1:307-318. 1972.

Nuttli, O. W. "The Mississippi Valley Earthquakes of 1811-1812: Intensities, Ground Motion and Magnitudes." Bull. Seismolog. Soc. Amer. 63(1). February 1973a.

Nuttli, O. W. "Seismic Wave Attenuation and Magnitude Relations for Eastern North America." J. Geophys. Res. 78:876-885. 1973b.

Nuttli, O. W. "State of the Art for Assessing Earthquake Hazards in the United States--Design Earthquakes for Central United States." Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. January 1973c.

Nuttli, O. W. "Magnitude-Recurrence Relation for Central Mississippi Valley Earthquakes." Bull. Seismolog. Soc. Amer. 64:1189-1207. 1974.

Nuttli, O. W. "Seismicity of the Mississippi Embayment." Proc. ACRS Seismic Activity Subcommittee of the Nuclear Regulatory Commission Meeting in Los Angeles, March 22-23, 1976. 1977.

Nuttli, O. W. "Deterministic Estimate of Intensity Distribution." Communication Note. 1978.

OBERS Projections. States, Vol. 5. U.S. Water Resources Council, Washington, D.C. September 1972. 211 pp.

Office of Emergency Preparedness. Disaster Preparedness, "Earthquakes," p. 73-86; "Landslides," p. 87-90. Report to Congress. January 1972.

Office of Science and Technology. Earthquake Hazards Reduction Issues for an Implementation Plan. Policy Working Group on Earthquake Hazards Reduction, Exec. Off. President. 1978.

Page, R. A., J. A. Blune, and W. B. Joyner. "Earthquake Shaking and Damage to Buildings." Science pp. 601-608. August 1975.

Parks, W. S., and R. W. Lounsburg. "Environmental Geology of Memphis, Tennessee, Field Trip." Pages 35-63 in Field Trips of West Tennessee. Tennessee Division of Geology. 1975.

Paté, M. E. "Public Policy in Earthquake Effects Mitigation: Earthquake Engineering and Earthquake Prediction." Ph.D. Dissertation, Stanford University. May 1978.

Penick, James, Jr. The New Madrid Earthquake of 1811-1812. Columbia: University of Missouri Press. 1976.

Perkins, J., and D. Olmstead. "Earthquake Intensity and Related Costs in the San Francisco Bay Area." Association of Bay Area Governments, February 1978.

Person, W. J. "Earthquake, September-October 1978." Earthquake Information Bulletin, pp. 71-73. March-April 1979.

Pettijohn, F. J. Sedimentary Rocks. New York: Harper and Row. 1975.

Piskin, K., and R. E. Bergstrom. "Glacial Drift in Illinois: Thickness and Character." Illinois Geolog. Circ. No. 490. 1975.

Richter, C. F. Elementary Seismology. San Francisco: W. F. Freeman, p. 768. 1958.

Rinehart, W., S. T. Algermissen, and M. Gibbons. Estimation of Earthquake Losses to Single Family Dwellings. U.S. Dept. of Interior, U.S. Geolo. Surv. January 1976.

City of St. Louis, Disaster Operations Office. "The St. Louis Disaster Operations Plan for Disasters and Nuclear Attack." June 1975.

Saucier, R. T. Page 5 in "Effects of the New Madrid Earthquake Series in the Mississippi Alluvial Valley." U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, p. 5. 1977.

Schaefer, S. F., and R. B. Herrmann. "Seismic Risk Analysis Applied to the Central U.S." Earthquake Notes 48(4):35-43. 1977.

Seed, B. H. "Soil Problems and Soil Behavior." Pages 227-251 in R. L. Wiegel (ed.), Earthquake Engineering. Englewood Cliffs, N. J.: Prentice Hall. 1970.

Schaeffer and Roland, Inc. "Evaluation of the Economics, Social and Environmental Effects of Floodplain Regulations." Report prepared for the Department of Housing and Urban Development. February 1979.

Schrader, E. E., H. C. Biggleston, and C. A. Weers. "San Francisco Earthquake February 9, 1971." Pacific Fire Rating Bureau, San Francisco. 1972.

Stauder, W., M. T. Kramer, G. W. Fischer, S. F. Schaefer, and S. T. Morrissey. "Seismic Characteristics of Southeast Missouri as Indicated by a Regional Telemetered Microearthquake Array." Bull. Seismolog. Soc. Amer. 66:1953-1964. 1976.

Stearns, R. G. "Geologic Considerations Related to the Earthquake Problems in the Lower Mississippi Valley." Housing and Urban Development and Dept. of Commerce, National Oceanic and Atmospheric Adm., Meeting. March 16, 1972.

Stearns, R. G. "Field Trips in West Tennessee." Tennessee Division of Geology, Report of Investigation No. 36. 1975.

Stearns, R. G., and R. A. Miller. "Earthquake Hazards in Tennessee." Environmental Geological Ser. No. 4. State of Tennessee, Department of Conservation, Division of Geology. 1977.

Stearns, R. G., and J. T. Wilson. "Relationships of Earthquakes and Geology in West Tennessee and Adjacent Areas." Tennessee Valley Authority. 1972.

Stearns, R. G., and Ann Zurawski. "Post-Cretaceous Faulting in the Head of the Mississippi Embayment." Southeastern Geology 17(4):207-227. 1976.

Steinbrugge, K. V. "Earthquake Hazard in the San Francisco Bay Area: A Continuing Problem in Public Policy." Institute of Governmental Studies, University of California, Berkeley. 1968.

Steinbrugge, K. V. "Studies in Seismicity and Earthquake Damage Statistics, 1969, Appendix A." U.S. Dept. Commerce, Environmental Science Service Admin., Coastal and Geodetic Survey, Rockville, Maryland. 1969.

Steinbrugge, K. V. "The Santa Rosa Earthquakes of 10/1/69." U.S. Dept. Commerce, Environmental Science Service Admin., Coastal and Geodetic Survey. 1970.

Steinbrugge, K. V., and D. F. Moran. "An Engineer's Study of the Southern California Earthquake of July 21, 1952 and Its Aftershocks." Bull. Seismolog. Soc. Amer., Vol. 44. April 1954.

Steinbrugge, K. V., and E. E. Schrader. "Earthquake Damage and Related Statistics." Pages 691-723 in San Fernando, California, Earthquake of February 9, 1971. National Oceanic and Atmospheric Admin. 1973.

Stout, L. N., and D. Hoffman. "An Introduction to Missouri's Geologic Environment." Missouri Geological Survey and Water Resources, Ed. Ser: No. 3. 1973.

State of Tennessee, Office of Civil Defense and Emergency Preparedness. "Tennessee Disaster Assistance Plan." February 1978.

Tubbesing, S. K. (ed.). Natural Hazards Data Resources: Uses and Needs. Monograph No. 27. Program on Technology, Environment, and Man, Institute of Behavioral Science, University of Colorado. 1979.

U.S. Army Corps of Engineers. "Geological Investigation of Faulting in the Lower Mississippi Valley." U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi. Tech. Mem. No. 3-311. 1950.

U.S. Census of Population: 1970, General Social and Economic Characteristics (Illinois, PC(1)-C15). U.S. Department of Commerce, Bureau of the Census. Washington: U.S. GPO. April 1972(a).

U.S. Census of Population: 1970, General Social and Economic Characteristics (Mississippi, PC(1)-C26). U.S. Department of Commerce, Bureau of the Census. Washington: U.S. GPO, February 1972(b).

U.S. Census of Population: 1970, General Social and Economic Characteristics (Tennessee, PC(1)-C44). U.S. Department of Commerce, Bureau of the Census. Washington: U.S. GPO. March 1972(c).

U.S. Census of Population and Housing: 1970, Census Tracts (Memphis, Tenn.-Ark. SMSA, PHC(1)-127. U.S. Department of Commerce, Bureau of the Census. Washington: U.S. GPO. May 1972(a).

U.S. Census of Population and Housing: 1970, Census Tracts (St. Louis, Mo.-Ill. SMSA, PHC(1)-181). U.S. Department of Commerce, Bureau of the Census. Washington: U.S. GPO. April 1972(b).

U.S. Department of the Interior, Geological Survey. News Release, July 19, 1976.

Van Nostrand's Scientific Encyclopedia, Van Nostrand Reinhold Company. 1976.

Wailes, C. D. Jr., and A. C. Honer. "Earthquake Damage Analyzed by Long Beach Officials." Eng. News Rec. May 25, 1933.

Wascher, H. L., R. P. Humbert, and J. G. Cody. "Loess in the Southern Mississippi Valley; Identification and Distribution of the Loess Sheets." Soil Sci. Soc. Amer. Proc. 12:389-399. 1948.

Wells, F. G. "Ground-Water Resources of Western Tennessee." U.S. Geological Survey, Water-Supply Pap. No. 656. 1933.

Whitman, R. V., S. T. Hong, and J. W. Reed. "Optimum Seismic Protection and Building Damage Statistics." M.I.T. Dept. Civil Eng. Res. Rep. No. R73-24. 1973.

Whitman, R. V., J. M. Biggs, J. Brennan III, C. A. Cornell, R. de Neufuille and E. H. Vanmarke. "Seismic Design Decision Analysis--Methodology and Pilot Application." Report No. 10. M.I.T. Dept. Civ. Eng., Res. Rep. No. R74-15. 1974.

Wiegel, R. L. (ed.). Earthquake Engineering. Englewood Cliffs, N.J.: Prentice-Hall. 1970.

Wiggins, J. H., J. E. Slosson, and J. P. Krohn. "Natural Hazards: Earthquake, Landslide, Expansive Soil." Report for National Science Foundation by J. H. Wiggins Company. October 1978.

Willman, H. B., and J. C. Frye. "Pleistocene Stratigraphy of Illinois." Illinois Geolog. Surv. Bull., Vol. 94. 1970.

The World Almanac and Book of Facts. New York: Newspaper Enterprise Assoc., Inc. 1978.

Yerkes, R. F., T. H. McCulloh, J. E. Schoellhamer, and J. G. Vedder. "Geology of the Los Angeles Basin California - An Introduction," U.S. Dept. of Interior, U.S. Geolog. Surv. 1966.

Yersak, R. C. "New Madrid County: A Comprehensive Plan for Development." Bootheel Regional Planning Commission. November 1976.

Youd, L. T. "Liquefaction, Flow and Associated Ground Failure." U.S. Geolog. Surv. Circ. No. 688. 1973.

Zellner, A. "An Efficient Method of Estimating Seemingly Unreleated Regressions and Tests of Aggregation Bias." J. Amer. Stat. Assoc. 57:348-368. June 1962.

Zellner, A., and D. S. Huang. "Further Properties of Efficient Estimators for Seemingly Unrelated Regression Equations." Internat. Econ. Rev. Oct.: 300-313. 1962.

APPENDIX A

GLOSSARY

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GLOSSARY

Alluvium - Loose material transported and deposited by streams; generally consists of clay, silt, sand, or gravel, or a mixture of these materials. Includes sediments deposited in river beds, floodplains, and lakes.

Bedrock - The solid rock exposed at the surface or underlying surface materials such as clay, gravel, or silt.

Chert - A compact, siliceous rock composed predominantly of quartz; occurs as beds, nodules, lenses, or fragments within various types of bedrock. Also referred to as flint.

Clay - A composition of particles of very fine grain size, usually very plastic.

Claystone - An indurated clay having the texture and composition but lacking the fine lamination or fissility of shale. A massive mudstone in which clay predominates over silt.

Colluvium - Loose material accumulated at the base of slopes and cliffs as a result of slope wash and gravity; generally consists of a mixture of the materials occurring higher on the slope or cliff.

Conglomerate - Consolidated gravel.

Cyclic Sedimentary Bedrock - Sequences of strata that show a consistent repetition of two or more kinds of rock that alternate usually through a considerable thickness. An individual cycle commonly consists of thin beds of shale, limestone, sandstone, claystone, and coal.

Dolomite - A rock composed principally of the mineral dolomite $CaMg(CO_3)_2$ or calcium-magnesium carbonate. Dolomites are basically similar to limestones with the exception of their magnesium content.

Fault - A fracture or fracture zone in bedrock along which movement has occurred, offsetting the rocks or one side in relation to the other. The seismic earth waves that produce earthquakes are generated by slippage of adjacent rock masses along faults.

Floodplain - A strip of relatively smooth land bordering a river or stream that is subject to flooding. It is built of alluvium or sediments (such as sand, silt, clay, and gravel) carried by flood waters and deposited in sluggish water away from swift currents.

Flow - Mass movement of unconsolidated materials that exhibits a continuity of motion and a plastic or semifluid behavior resembling that of a viscous fluid (e.g., earthflow).

Fold - A curve or bend in rock strata.

Formation - A geologic unit consisting of a succession of strata useful for mapping.

Glacial Drift - A general term applied to all rock material (clay, sand, gravel, boulders, etc.) transported by a glacier and deposited directly by or from ice, or by running water emanating from a glacier. Drift includes unstratified materials (till) and stratified deposits such as outwash. A thoroughly mixed cross-section of all the soil and rock materials which the ice overrode.

Gravel - An unconsolidated deposit of rounded particles larger than sand.

Groundwater - Water, which at a particular time, is either passing through or standing in the soil and the underlying strata and is free to move under the influence of gravity.

Karst - A type of terrain characterized by solutional features such as sinkholes, caves and gullies, enlarged joints, and pinnacled bedrock surfaces. Much of the drainage in a karst area is through underground channels.

Landslide - Rapid downslope movement of rock and/or soil. Also used as a general term for all types of downslope movement.

Limestone - A rock composed of calcium carbonate ($CaCO_3$) and formed by either organic or inorganic sedimentary processes.

Liquefaction - The temporary transformation of a loosely packed sediment into a fluid mass caused by the collapse of the structure by shock or strain.

Lithology - The physical character of a rock includes rock and mineral content, grain size, color, etc.

Loess - A soil material, relatively uniform in texture and appearance, that is transported and deposited by wind. It consists predominantly of silt with some sand and clay. Often standing in stable vertical bluffs.

Permeability - The ability of a soil or rock to transmit fluids or gases.

Physiographic Features - Individual features of the earth's surface that combine to produce the landscape in a given area. Examples of such features include slopes, hills, valleys, scarps, and ridges.

Porosity - The property of a rock or soil containing voids.

Relief - The difference in elevation between the high and low points in a given area.

Residual Soil - Soil formed in place by the disintegration and decomposition of bedrock.

Residuum - Surficial materials (soil) derived from the weathering or decomposition of bedrock in place.

Rotational Landslide - Type of landslide that develops in homogeneous material.The The movement is likely to be rotational along a slide plane.

Sandstone - A detrital sedimentary rock formed by the cementation of individual grains of sand size.

Sediment - Loose unconsolidated rock and mineral grains that is being or has been transported by any of the earth's external processes.

Shale - A thinly layered sedimentary rock made up of silt and clay-sized particles.

Sinkhole - A funnel-shaped depression in the land surface, generally circular or subcircular in outline. Sinkholes originate in a number of ways, all related to underground solution of bedrock, particularly limestone.

Slope - A land surface deviation from the level horizontal plane, measured in percentage (units vertical drop per 100 horizontal units). Thus a slope of 15 percent has 15 feet of vertical drop for each 100 feet of horizontal distance. A 1 percent slope has a gradient drop of 1 foot in elevation for 100 feet of horizontal distance. Slopes of 1 percent or less are considered flat slopes; a gentle slope is greater than 1 percent and not more than 10 percent; steep slopes are greater than 10 percent.

Soil - Unconsolidated material several feet thick formed by environmental factors acting on geologic material over time and conditioned by relief to produce a sequence of layers or horizons which occupy predictable and mappable parts of the landscape; includes all loose or unconsolidated material overlying bedrock, regardless of the origin or thickness of the material.

Surficial Materials - Unconsolidated and residual, alluvial, glacial, or wind blown deposits overlying bedrock or occurring on or near the earth's surface; corresponds with the engineering use of the term "soil."

Till or Glacial Till - Unsorted and unstratified glacial material, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by water from the glacier and consisting of a heterogeneous mixture of clay, sand, gravel, and boulders varying widely in size and shape.

Topography - The shape of the earth, including the size and shape of hills, valleys, and other physical features.

Translational (slab) Landslide - Type of landslide in which the movement takes place along a definite fracture plane such as a weak clay layer or bedding plane.

Water Table - The upper surface of groundwater or that level below which the soil is saturated with water. Apparent water table is the level to which the water level rises when holes are dug in soils.

APPENDIX B

SELECTED INPUT STATISTICS FOR PHYSICAL AND ECONOMIC DAMAGE FUNCTION DEVELOPMENT

TABLE B-1

SELECTED HISTORICAL DAMAGING EARTHQUAKES
AND DAMAGE STATISTIC IN U.S.A.

Date and Time of Occurance	Earthquake Center			Intensity	No. of Deaths	Personal Property Damage	
	Center	Area Sq. Mi.	Population			Record Value ($M)	1978 Value ($M)
August 31, 1886 (9:51 PM)	Charleston, South Carolina	945	52,500	X	110	6	42
April 18, 1906 (5:12 AM,PST)	San Francisco, California	45	456,000	XI	800	80	558
June 29, 1925 (6:42 AM)	Santa Barbara, California	2,737	65,000	VIII	14	6.5	24
March 10, 1933 (5:54 PM, PST)	Long Beach, California	4,069	2,382,000	IX	102	50	252
October 18, 1935 (9:48 PM,MST)	Helena, Montana	3,477	20,200	VIII	2	2	10
October 31, 1935 (11:38 AM,MST)	Helena, Montana	3,477	20,200	VIII	2	2	10
May 18, 1940 (8:37 PM,PST)	Imperial Valley, California	4,284	59,740	X	9	6	28
April 13, 1949 (11:56 AM,PST)	Olympia, Washington	714	44,800	VIII	8	25	68
July 21, 1952 (4:52 AM,PDT)	Kern County, California	8,152	230,000	XI	12	60	147

TABLE B-1 (Concluded)

August 22, 1952 (3:41 PM,PDT)	Bakersfield, California	8,152	230,000	VIII	2	11	27
December 21, 1954 (11:56 AM,PST)	Eureka, California	3,586	69,000	VII	1	1	2
August 17, 1959 (11:37 PM,MST)	Hebgen Lake, Montana	2,517	27,000	X	28	4	9
March 27, 1964 (5:36 PM, AST)	Prince William Sound, Alaska	927	125,000	XI	125	311	654
April 29, 1965 (8:29 AM,PDT)	Puget Sound, Washington	2,128	1,046,000	VIII	6	12.5	26
February 2, 1971 (6:10 AM,PDT)	San Fernando California	4,069	7,032,000	IX	65	700	1,128

Sources: K. V. Steinbrugge, "Earthquake Damage and Structural Performance in the U.S.," in R. L. Wiegel, ed., Earthquake Engineering, (Englewood, Cliff, N. J.: Prentice-Hall, 1970, pp. 172-173.
The figures of population and area are derived from the information reported in previous "Population Census" by U.S. Department of Commerce.

TABLE B-2

SAMPLE OBSERVATIONS FOR STRUCTURES DAMAGE ESTIMATIONS

(A) Wooden Frame Structures:

Sources	Intensity	Damge Ratios
Steinbrugge	6	0.005
Steinbrugge	6.5	0.0125
Steinbrugge	7	0.0267
Steinbrugge	7.5	0.05
Steinbrugge	8	0.085
Steinbrugge	8.5	0.105
Steinbrugge	9	0.12
1933 Long Beach	8	0.04
1925 Santa Barbara	7	0.025
1971 San Fernando	9	0.066
Paté	7	0.015
Paté	8	0.065
Paté	9	0.135
Paté	10	0.25
Paté	11	0.375
Page, Blume, Joyner	6	0.002
Page, Blume, Joyner	7	0.02
Page, Blume, Joyner	8	0.05
Page, Blume, Joyner	9	0.08
Page, Blume, Joyner	10	0.12

TABLE B-2 (Continued)

(B) Masonry structures:

Sources	Intensity (MMI)	Damage Ratios
1933 Long Beach	8.5	0.24
1925 Santa Barbara	8	0.15
1952 Kern County	8	0.24
1969 Santa Rosa	7.5	0.10
1971 San Fernando	9	0.18
Insurance Underwriter	7	0.05*
Insurance Underwriter	8	0.15*
Insurance Underwriter	9	0.30*
Insurance Underwriter	10	0.50*
Paté	7	0.02
Paté	8	0.125
Paté	9	0.35
Paté	10	0.50
Paté	11	0.65
Page, Blume, Joyner	6	0.01
Page, Blume, Joyner	7	0.05
Page, Blume, Joyner	8	0.15
Page, Blume, Joyner	9	0.35
Page, Blume, Joyner	10	0.50

TABLE B-2 (Concluded)

(C) Concrete and Steel Frame Structures:

Sources	Intensity (MMI)	Damage Ratios
1906 San Francisco	9	0.35*
1906 San Francisco	10	0.60*
1952 Kern County	6	0.025*
1952 Kern County	7	0.08*
1952 Kern County	8	0.11*
1964 Alaska	8	0.258*
1969 Santa Rosa	7.5	0.055*
1971 San Fernando	7	0.082*
Paté	7	0.019*
Paté	8	0.11*
Paté	9	0.21*
Paté	10	0.37*
Paté	11	0.50*
Page, Blume, Joyner	6	0.01
Page, Blume, Joyner	7	0.05
Page, Blume, Joyner	8	0.15
Page, Blume, Joyner	9	0.35
Page, Blume, Joyner	10	0.50

Note: * indicates the value is the average of all recorded damage ratios with the same MMI.

Sources: R. A. Page, J. A. Blume, and W. B. Joyner, "Earthquake Shaking and damage to Buildings," Science, August 1975, pp. 601-608; M. E. Paté, Public Policy in Earthquake Effects Mitigation, Earthquake Engineering and Earthquake Prediction, Ph.D. dissertation, Stanford University, May 1978; and the summary of all earthquakes damage records in O. C. Mann, "Building and Contents Damage Parameters," in Regional Earthquake Risk Study, M&H Engineering and Memphis State University, September 30, 1974, Appendix D.

TABLE B-3

SELECTED BUILDING DAMAGE RATIOS: LOS ANGELES
CONCRETE AND STEEL FRAME STRUCTURES

Building Number	Height (Floor)	Year Completed	Site Location	Damage Ratio
(A) Concrete Structures				
74	12	1923	44	.02020
187	11	1923	44	.02255
259	10	1923	44	.02667
395	12	1929	44	.00036
458	12	1966	44	.00050
486	10	1907	44	.04916
492	12	1926	44	.04046
504	13	1927	44	.00583
523	10	1924	44	.09122
527	12	1921	44	.10906
585	9	1913	44	.01673
677	10	1930	44	.00400
680	12	1926	44	.21225
693	12	1956	44	.00148
701	12	1913	44	.07097
846	12	1914	44	.03814
900	8	1964	44	.00551
956	12	1913	44	.04081
960	12	1913	44	.04435
970	12	1961	44	.00078
1082	11	1924	44	.08053
1134	10	1921	44	.02794
1153	8	1923	44	.00480
1181	12	1927	44	.04059
1300	12	1927	44	.00570
1316	12	1927	44	.14508
1403	9	1924	44	.04022
1472	8	1926	44	.00366
1476	9	1918	44	.00183
1543	12	1970	44	.00004
1572	10	1920	44	.00235
1578	8	1906	44	.01047
1694	10	1925	44	.00806

TABLE B-3 (Continued)

1716	13	1929	44	.00434
1720	11	1927	44	.00500
1730	11	1915	44	.00114
1751	9	1909	44	.00006
1788	12	1913	44	.05570
1824	13	1913	44	.00400
50	12	1968	43	.00665
114	13	1929	43	.01333
183	12	1971	43	.00069
202	9	1963	43	.00327
301	11	1966	43	.00129
328	11	1965	43	.00786
1371	9	1963	43	.01056
1534	12	1955	43	.00032
1647	12	1929	43	.00034
1837	12	1967	43	.00092
555	11	1952	42	.00316
785	8	1962	42	.00372
796	8	1965	42	.00066
855	12	1964	42	.00050
1375	8	1966	42	.00130
1616	12	1964	42	.00039
304	9	1964	34	.00738
1062	11	1966	34	.00239
1083	12	1960	34	.02055
1170	12	1927	34	.00146
1235	11	1964	34	.00390
1332	11	1968	34	.00057

(B) Steel Frame Structures

49	11	1926	44	.11000
53	12	1916	44	.00287
55	12	1912	44	.00642
154	13	1928	44	.01200
218	11	1929	44	.00546
275	13	1928	44	.00309
277	12	1930	44	.00800
293	10	1923	44	.02087
314	11	1923	44	.28612
356	8	1934	44	.01467
466	11	1925	44	.08800
471	10	1924	44	.00592
526	10	1924	44	.01341
556	12	1967	44	.00167

TABLE B-3 (Concluded)

572	13	1949	44	.00054
602	12	1924	44	.00667
604	13	1930	44	.00052
766	12	1912	44	.01703
835	11	1908	44	.08309
841	10	1912	44	.01044
881	13	1926	44	.00200
1029	11	1932	44	.03000
1040	11	1927	44	.00400
1141	12	1948	44	.02033
1158	11	1911	44	.00115
1336	11	1928	44	.01045
1341	10	1965	44	.00035
1361	12	1958	44	.00113
1405	13	1912	44	.01170
1657	11	1928	44	.01001
1717	13	1929	44	.00571
1749	11	1928	44	.01150
1778	11	1927	44	.00357
330	13	1929	43	.00900
375	12	1949	43	.00081
698	12	1955	43	.00207
1089	13	1957	43	.01512
570	8	1963	42	.00042
738	8	1960	42	.00030
826	11	1948	42	.01329
1169	12	1956	42	.00258
1250	13	1964	42	.00046
1799	8	1955	42	.00049
173	12	1959	34	.00059
378	8	1967	34	.00108
828	13	1956	34	.00392
1260	12	1965	34	.00063
1488	12	1959	34	.00069

Source: R. V. Whitman, S. T. Hong, and J. W. Reed, "Optimum Seismic Protection and Building Damage Statistics", Department of Civil Engineering Research Report, R 73-24, M. I. T. April, 1973.

APPENDIX C

STRUCTURAL PRESENTATION OF THE PHYSICAL AND ECONOMIC DAMAGE FUNCTIONS IN MODELS I AND II

(1) MODEL 1

$$DRW = 0.008\ (MMI-5)^{2.46}\ [(1 + AF1)\ (1 + AF2)]^{\frac{1}{2}} \leq 1.0 \qquad (1)$$

$$DRW = 0.013\ (MMI-5)^{2.18}\ [(1 + AF1)\ (1 + AF2)]^{\frac{1}{2}} \leq 1.0 \qquad (2)$$

$$DW = VW \cdot DRW \cdot p \quad \left\{ p = 1.0 \text{ for deterministic approach} \right. \qquad (3)$$

$$DB = VB \cdot DRB \cdot p \quad \left\{ p = 1/N(I) \text{ for probabilistic approach} \right. \qquad (4)$$

$$AF1 = \sum_{i=1}^{n} a_i\ EXP^{-i} \qquad (5)$$

$$AF2 = \sum_{s=1}^{n} a_s\ EXP^{-s} \qquad (6)$$

$$DPP = VPP \cdot (DW + DB)/(VW + VB) \qquad (7)$$

$$\ln(MORTN) = \underset{(9.47)}{-5.13} + \underset{(4.12)}{3.22} \cdot \ln(MMI) + \underset{(0.14)}{0.41} \ln(POPD) + \underset{(0.83)}{0.91} \ln(DPP/POP) \qquad (8)$$

$R^2 = 0.789$ DW = 2.19 F = 4.97

$$\ln(MORTD) = \underset{(8.32)}{-5.23} + \underset{(3.90)}{2.51} \cdot \ln(MMI) + \underset{(0.11)}{0.44} \ln(POPD) + \underset{(0.28)}{0.63} \ln(DPP/POP) \qquad (9)$$

$R^2 = 0.966$ DW = 1.70 F = 28.43

$$INJN = 100 \cdot MORTN \qquad (10)$$

$$INJD = 100 \cdot MORTD \qquad (11)$$

where DRW = Physical damage rate of wooden structures.
DRB = Physical damage rate of other structures.
MMI = Modified Mercalli intensity or predicted earthquake intensity.
AF1 = Age adjustment factor for all structures by year interval of construction, i.

AF2 = Ground susceptibility adjustment factor by soil and geological condition scale, s.

DW = Computed damage for wooden structure.

DB = Computed damage for other structures.

VW = Replacement value of wooden structure.

VB = Replacement value of other structures.

P = Probability of earthquake recurrence of a given intensity (I) during the study period.

a_i, a_s = Age and ground susceptibility distribution factors of structures and land formation in each county, respectively.

DPP = Computed economic damage of personal preperty.

VPP = Replacement value of personal property.

MORTN = Mortality - night time.

MORTD = Mortality - day time.

POPD = Population density.

(DPP/POP) = Per capita personal property damage value, 0.978 dollars.

INJN = Human injuries - night time.

INJD = Human injuried - day time.

(2) MODEL II

$$DRW = .004\ (MMI - 5)^{2.46}\ [(1 + AF1)(1 + AF2)]^{\frac{1}{2}} \leq 1.0 \qquad (2)$$

$$DRM = .008\ (MMI - 5)^{2.65}\ [(1 + AF1)(1 + AF2)]^{\frac{1}{2}} \leq 1.0 \qquad (3)$$

$$DRS = .013\ (MMI - 5)^{2.18}\ [(1 + AF1)(1 + AF2)]^{\frac{1}{2}} \leq 1.0 \qquad (4)$$

$$DW = VW \cdot DRW \qquad (5)$$

$$DM = VM \cdot DRM \qquad (6)$$

$$DS = VS \cdot DRS \qquad (7)$$

$$AF1 = \sum_{i=1}^{N} a_i \cdot e^{-.67_i} \qquad (8)$$

$$AF2 = \sum_{s=1}^{M} a_s \cdot e^{-.67_s} \qquad (9)$$

$$DPP = VPP \cdot (DW + DM + DS)/(VW + VM + VS) \qquad (10)$$

$$\ln(MORTN) = \underset{(9.47)}{-5.13} + \underset{(4.12)}{3.22} \cdot \ln(MMI) + \underset{(0.14)}{0.41}\ \ln(POPD) + \underset{(0.83)}{0.91}\ \ln\ (DPP/POP) \qquad (11)$$

$R^2 = 0.789$ DW = 2.19 F = 4.97

$$\ln(MORTD) = \underset{(8.32)}{-5.23} + \underset{(3.90)}{2.51} \cdot \ln(MMI) + \underset{(0.11)}{0.44}\ \ln(POPD) + \underset{(0.28)}{0.63}\ \ln(DPP/POP) \qquad (12)$$

$R^2 = 0.966$ DW = 1.70 F = 28.43

$$INJN = 100 \cdot MORTN \qquad (13)$$

$$INJD = 100 \cdot MORTD \qquad (14)$$

where DRW = Physical damage rate to wooden structures.

DRM = Physical damage rate to masonry structures.

DRS = Physical damage rate to concrete and steel framed structures.

MMI = Modified Mercalli intensity or predicted earthquake intensity.

AF1 = Age adjustment factor for all structures by year interval of construction, i.

AF2 = Ground susceptibility adjustment factor by soil and geological condition scale, s.

DW = Computed damage for wooden structures.

DM = Computed damage for masonry structures.

DS = Computed damages for concrete and steel framed structures.

VW = Replacement value of wooden structures.

VM = Replacement value of masonry structures.

VS = Replacement value of concrete and steel framed structures.

a_i, a_s = Age and ground susceptibility distribution factors of structures and land formation in each county, respectively.

DPP = Computed economic damage of personal property.

VPP = Replacement value of personal property.

MORTN = Mortality--nighttime.

MORTD = Mortality--daytime.

POPD = Population density.

(DPP/POP) = Per capita personal property damage value, 1978 dollars.

INJN = Human injuries--nighttime.

INJD = Human injuries--daytime.

APPENDIX D

SIMULATION RESULTS OF EARTHQUAKE DAMAGES ESTIMATIONS BY COUNTY, MMI, AND SELECTED EARTHQUAKE RISK RECEPTOR, 1980-2030

TABLE D-1

BUILDING DAMAGES (IN MILLION DOLLARS)
PROBABILISTIC APPROACH (PROB. = 0.1)

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	3	3	4	4	4	5
JEFFERSON	15	17	19	21	24	27
ST CHARLES	16	19	22	25	27	31
ST LOUISCO	272	283	291	300	309	319
ST LOUISCY	142	143	145	147	150	153
CLINTON	8	9	9	10	11	12
MADISON	74	76	79	82	86	90
MONROE	3	3	3	4	4	4
ST CLAIR	83	87	90	93	96	100
TOTAL ST LOUIS SMSA	614	639	662	686	711	740
CAPE GIRAR	28	31	33	36	39	43
NEW MADRID	6	7	7	8	8	9
SHELBY	521	562	615	677	747	825
TIPTON	24	26	28	31	34	38
CRITTENDEN	24	26	28	30	33	36
DESOTO	8	9	11	13	15	18
TOTAL MEMPHIS SMSA	576	623	682	751	829	917
15-COUNTY TOTAL	1224	1299	1385	1481	1588	1709

TABLE D-2

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
PROBABILISTIC APPROACH (PROB. = 0.1)

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	1	1	1	1	1	2
JEFFERSON	3	4	5	5	6	7
ST CHARLES	1	2	2	3	3	4
ST LOUISCO	17	18	19	20	22	23
ST LOUISCY	8	8	8	8	8	8
CLINTON	1	1	1	1	1	1
MADISON	6	7	7	7	8	8
MONROE	1	1	1	1	1	1
ST CLAIR	6	7	7	8	8	9
TOTAL ST LOUIS SMSA	43	47	51	55	58	63
CAPE GIRAR	8	9	10	11	13	14
NEW MADRID	6	6	7	8	9	9
SHELBY	79	90	101	115	132	151
TIPTON	5	6	7	8	10	11
CRITTENDEN	8	9	10	11	12	14
DESOTO	2	3	4	5	6	8
TOTAL MEMPHIS SMSA	95	108	122	139	160	184
15-COUNTY TOTAL	152	171	191	213	240	271

TABLE D-3

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
PROBABILISTIC APPROACH (PROB. = 0.1)

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	8	10	13	16	19	24
JEFFERSON	20	29	37	42	49	56
ST CHARLES	15	21	28	35	40	46
ST LOUISCO	161	176	192	202	215	230
ST LOUISCY	97	89	90	92	94	99
CLINTON	6	6	7	8	9	10
MADISON	46	53	55	59	65	71
MONROE	4	5	6	7	7	8
ST CLAIR	52	57	61	65	69	72
TOTAL ST LOUIS SMSA	408	446	490	525	567	615
CAPE GIRAR	14	17	19	21	24	27
NEW MADRID	8	8	8	9	10	11
SHELBY	183	212	240	279	325	380
TIPTON	6	7	8	10	11	13
CRITTENDEN	14	15	18	20	23	27
DESOTO	8	11	15	20	25	32
TOTAL MEMPHIS SMSA	211	245	281	328	385	451
15-COUNTY TOTAL	641	716	798	883	985	1104

TABLE D-4

MORTALITY - DAY (PERSONS)
PROBABILISTIC APPROACH (PROB. = 0.1)

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	1	1
JEFFERSON	1	2	2	2	2	2
ST CHARLES	1	1	1	1	1	1
ST LOUISCO	3	3	3	3	4	4
ST LOUISCY	6	5	5	5	6	6
CLINTON	1	1	1	1	1	1
MADISON	2	2	2	2	2	2
MONROE	1	1	1	1	1	1
ST CLAIR	2	2	2	2	2	2
TOTAL ST LOUIS SMSA	17	17	18	18	19	19
CAPE GIRAR	5	5	5	5	5	6
NEW MADRID	5	5	6	6	6	6
SHELBY	10	11	11	12	13	13
TIPTON	9	10	10	11	11	12
CRITTENDEN	4	5	5	5	5	6
DESOTO	2	2	2	3	3	3
TOTAL MEMPHIS SMSA	26	27	29	30	32	34
15-COUNTY TOTAL	53	55	57	60	63	66

TABLE D-5

MORTALITY - NIGHT (PERSONS)
PROBABILISTIC APPROACH (PROB. = 0.1)

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	2	2	3	3	3	3
JEFFERSON	5	6	7	7	8	8
ST CHARLES	4	5	5	5	6	6
ST LOUISCO	13	14	14	15	15	15
ST LOUISCY	25	24	24	24	24	25
CLINTON	4	4	4	4	4	5
MADISON	7	8	8	8	8	9
MONROE	4	4	4	4	5	5
ST CLAIR	8	8	8	9	9	9
TOTAL ST LOUIS SMSA	72	74	77	79	82	84
CAPE GIRAR	9	10	11	11	12	12
NEW MADRID	9	8	9	9	9	10
SHELBY	23	24	25	27	28	30
TIPTON	12	13	14	15	16	17
CRITTENDEN	9	10	10	11	11	12
DESOTO	6	6	7	8	9	9
TOTAL MEMPHIS SMSA	50	53	56	60	64	68
15-COUNTY TOTAL	140	146	153	159	166	174

TABLE D-6

INJURIES - DAY (PERSONS)
PROBABILISTIC APPROACH (PROB. = 0.1)

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	38	41	45	49	52	56
JEFFERSON	135	154	168	176	185	194
ST CHARLES	82	93	103	112	118	123
ST LOUISCO	316	326	337	342	350	359
ST LOUISCY	558	541	544	547	552	562
CLINTON	95	100	103	107	111	116
MADISON	176	185	187	192	198	205
MONROE	91	98	105	110	115	120
ST CLAIR	189	195	201	205	209	213
TOTAL ST LOUIS SMSA	1680	1734	1794	1840	1891	1947
CAPE GIRAR	456	486	509	528	550	573
NEW MADRID	545	545	560	580	604	629
SHELBY	1038	1094	1145	1207	1276	1348
TIPTON	918	968	1020	1074	1136	1201
CRITTENDEN	440	458	479	502	529	556
DESOTO	193	217	242	266	293	317
TOTAL MEMPHIS SMSA	2590	2737	2886	3050	3232	3423
15-COUNTY TOTAL	5272	5502	5748	5998	6277	6574

TABLE D-7

INJURIES - NIGHT (PERSONS)
PROBABILISTIC APPROACH (PROB. = 0.1)

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	215	231	257	277	298	320
JEFFERSON	547	628	690	726	764	804
ST CHARLES	393	451	502	545	576	606
ST LOUISCO	1344	1392	1439	1465	1501	1540
ST LOUISCY	2455	2379	2394	2408	2430	2474
CLINTON	379	396	412	426	446	464
MADISON	724	763	773	794	822	851
MONROE	361	391	419	441	461	482
ST CLAIR	782	809	832	851	870	887
TOTAL ST LOUIS SMSA	7201	7440	7718	7934	8168	8429
CAPE GIRAR	949	1015	1065	1107	1156	1209
NEW MADRID	851	850	875	908	948	990
SHELBY	2267	2396	2514	2659	2819	2989
TIPTON	1250	1322	1396	1475	1565	1661
CRITTENDEN	914	954	1000	1051	1109	1171
DESOTO	556	629	706	783	864	942
TOTAL MEMPHIS SMSA	4987	5300	5616	5968	6358	6764
15-COUNTY TOTAL	13987	14605	15275	15917	16629	17391

TABLE D-8

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	1	1	1	1	1	1
NEW MADRID	5	5	6	6	7	7
SHELBY	0	0	0	0	0	0
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	0	0	0	0	0	0
15-COUNTY TOTAL	6	6	7	7	8	9

TABLE D-9

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	1	1	2	2	2	2
JEFFERSON	3	3	3	4	4	5
ST CHARLES	5	6	7	8	9	10
ST LOUISCO	50	52	54	55	57	59
ST LOUISCY	27	27	28	28	29	29
CLINTON	1	2	2	2	2	2
MADISON	14	14	14	15	16	17
MONROE	0	1	1	1	1	1
ST CLAIR	16	16	17	18	18	19
TOTAL ST LOUIS SMSA	117	123	127	132	138	144
CAPE GIRAR	6	7	7	8	9	9
NEW MADRID	10	11	11	12	13	14
SHELBY	36	39	43	48	53	58
TIPTON	1	1	1	1	2	2
CRITTENDEN	2	2	2	2	2	2
DESOTO	1	1	1	2	2	2
TOTAL MEMPHIS SMSA	40	44	48	53	59	65
15-COUNTY TOTAL	174	184	194	206	218	233

TABLE D-10

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	7	8	9	10	12	13
JEFFERSON	15	17	19	21	24	27
ST CHARLES	26	31	37	41	46	53
ST LOUISCO	272	283	291	300	309	319
ST LOUISCY	142	143	145	147	150	153
CLINTON	8	9	9	10	11	12
MADISON	74	76	79	82	86	90
MONROE	3	3	3	4	4	4
ST CLAIR	83	87	90	93	96	100
TOTAL ST LOUIS SMSA	629	657	683	709	737	770
CAPE GIRAR	19	21	23	25	27	29
NEW MADRID	18	19	20	22	23	25
SHELBY	194	210	230	253	279	309
TIPTON	6	6	7	8	9	9
CRITTENDEN	9	10	10	11	12	13
DESOTO	5	6	8	9	11	13
TOTAL MEMPHIS SMSA	214	232	255	281	310	344
15-COUNTY TOTAL	880	929	980	1036	1098	1169

TABLE D-11

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	19	22	25	28	31	35
JEFFERSON	40	47	52	58	64	72
ST CHARLES	71	85	99	112	125	143
ST LOUISCO	736	765	787	811	835	862
ST LOUISCY	377	381	385	391	399	405
CLINTON	22	24	26	28	30	32
MADISON	202	206	213	222	232	243
MONROE	7	8	9	10	11	11
ST CLAIR	222	232	241	250	258	267
TOTAL ST LOUIS SMSA	1695	1770	1838	1908	1984	2071
CAPE GIRAR	43	47	50	55	59	65
NEW MADRID	25	26	28	31	33	36
SHELBY	521	562	615	677	747	825
TIPTON	16	17	19	21	23	25
CRITTENDEN	24	26	28	30	33	36
DESOTO	14	17	20	24	28	34
TOTAL MEMPHIS SMSA	574	622	682	752	831	921
15-COUNTY TOTAL	2337	2465	2599	2746	2908	3093

TABLE D-12

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	39	45	51	57	64	72
JEFFERSON	81	95	107	118	131	148
ST CHARLES	146	174	202	228	254	290
ST LOUISCO	1495	1555	1600	1647	1696	1750
ST LOUISCY	757	766	774	785	801	814
CLINTON	44	49	53	57	61	66
MADISON	412	420	434	451	472	494
MONROE	15	17	18	20	22	24
ST CLAIR	448	468	487	504	519	539
TOTAL ST LOUIS SMSA	3436	3588	3725	3867	4020	4195
CAPE GIRAR	78	85	92	100	109	119
NEW MADRID	30	32	35	38	41	44
SHELBY	1052	1136	1243	1367	1507	1665
TIPTON	32	35	38	42	46	51
CRITTENDEN	48	52	56	61	66	73
DESOTO	28	34	41	49	57	69
TOTAL MEMPHIS SMSA	1161	1257	1378	1518	1677	1858
15-COUNTY TOTAL	4706	4963	5230	5523	5847	6216

TABLE D-13

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	4	4	5	5	6	6
SHELBY	0	0	0	0	0	0
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	0	0	0	0	0	0
15-COUNTY TOTAL	4	4	5	5	6	6

TABLE D-14

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	1
JEFFERSON	0	1	1	1	1	1
ST CHARLES	0	0	1	1	1	1
ST LOUISCO	2	2	3	3	3	3
ST LOUISCY	1	1	1	1	1	1
CLINTON	0	0	0	0	0	0
MADISON	1	1	1	1	1	1
MONROE	0	0	0	0	0	0
ST CLAIR	1	1	1	1	1	1
TOTAL ST LOUIS SMSA	6	7	7	8	9	9
CAPE GIRAR	1	1	1	1	1	1
NEW MADRID	11	12	14	15	17	19
SHELBY	2	2	2	3	3	4
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	2	3	3	4	4	5
15-COUNTY TOTAL	21	23	25	28	31	34

TABLE D-15

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	2	2	3	3	4	4
JEFFERSON	3	4	5	5	6	7
ST CHARLES	2	3	4	5	6	7
ST LOUISCO	17	18	19	20	22	23
ST LOUISCY	8	8	8	8	8	8
CLINTON	1	1	1	1	1	1
MADISON	6	7	7	7	8	8
MONROE	1	1	1	1	1	1
ST CLAIR	6	7	7	8	8	9
TOTAL ST LOUIS SMSA	45	50	55	59	63	68
CAPE GIRAR	5	6	6	7	7	8
NEW MADRID	11	12	14	15	17	19
SHELBY	14	16	18	20	23	27
TIPTON	1	1	1	1	1	2
CRITTENDEN	1	2	2	2	2	3
DESOTO	1	1	2	2	3	4
TOTAL MEMPHIS SMSA	17	20	23	26	30	35
15-COUNTY TOTAL	79	88	97	107	118	130

TABLE D-16

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	9	11	14	17	20	24
JEFFERSON	15	21	27	30	34	38
ST CHARLES	14	19	24	29	33	37
ST LOUISCO	94	102	110	115	121	129
ST LOUISCY	47	44	44	45	46	48
CLINTON	5	5	6	6	7	8
MADISON	33	37	38	40	44	47
MONROE	3	4	5	5	6	7
ST CLAIR	36	39	41	43	46	48
TOTAL ST LOUIS SMSA	256	281	309	331	356	385
CAPE GIRAR	22	26	29	32	35	39
NEW MADRID	11	12	14	15	17	19
SHELBY	79	90	101	115	132	151
TIPTON	5	5	6	7	8	9
CRITTENDEN	8	9	10	11	12	14
DESOTO	6	8	10	13	16	20
TOTAL MEMPHIS SMSA	98	112	127	146	169	195
15-COUNTY TOTAL	387	432	479	524	578	638

TABLE D-17

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	44	52	66	79	94	111
JEFFERSON	71	98	122	137	155	174
ST CHARLES	62	86	110	134	152	171
ST LOUISCO	431	467	505	526	557	591
ST LOUISCY	216	200	203	206	210	219
CLINTON	22	25	27	30	33	36
MADISON	150	169	174	185	201	218
MONROE	15	18	22	25	27	30
ST CLAIR	164	177	189	200	210	220
TOTAL ST LOUIS SMSA	1174	1293	1419	1521	1639	1771
CAPE GIRAR	50	58	65	72	81	92
NEW MADRID	11	12	14	15	17	19
SHELBY	267	305	357	420	494	576
TIPTON	6	7	8	10	11	13
CRITTENDEN	36	40	45	50	57	65
DESOTO	27	36	47	60	76	92
TOTAL MEMPHIS SMSA	336	388	457	540	638	747
15-COUNTY TOTAL	1573	1752	1954	2149	2375	2628

TABLE D-18

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	3	4	4	5	5	6
NEW MADRID	7	7	8	8	9	10
SHELBY	0	0	0	0	0	0
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	0	0	0	0	0	0
15-COUNTY TOTAL	10	11	12	13	15	16

TABLE D-19

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	7	9	12	14	17	21
JEFFERSON	13	19	24	28	32	36
ST CHARLES	12	17	22	27	32	36
ST LOUISCO	105	115	125	131	140	150
ST LOUISCY	63	58	59	60	61	64
CLINTON	4	4	5	5	6	6
MADISON	30	35	36	38	42	46
MONROE	2	3	4	4	5	5
ST CLAIR	34	37	40	42	45	47
TOTAL ST LOUIS SMSA	270	296	326	350	379	412
CAPE GIRAR	8	10	11	12	14	15
NEW MADRID	10	10	10	12	13	15
SHELBY	82	95	108	125	146	171
TIPTON	4	4	5	6	7	8
CRITTENDEN	6	7	8	9	10	12
DESOTO	5	6	9	11	15	19
TOTAL MEMPHIS SMSA	97	113	130	151	178	209
15-COUNTY TOTAL	384	428	477	525	584	651

TABLE D-20

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	11	14	18	22	26	32
JEFFERSON	20	29	37	42	49	56
ST CHARLES	18	25	34	42	49	56
ST LOUISCO	161	176	192	202	215	230
ST LOUISCY	97	89	90	92	94	99
CLINTON	6	6	7	8	9	10
MADISON	46	53	55	59	65	71
MONROE	4	5	6	7	7	8
ST CLAIR	52	57	61	65	69	72
TOTAL ST LOUIS SMSA	414	454	500	538	582	633
CAPE GIRAR	12	14	16	18	20	23
NEW MADRID	11	12	14	15	17	19
SHELBY	126	146	166	192	224	262
TIPTON	6	7	8	9	10	12
CRITTENDEN	10	11	12	14	16	18
DESOTO	7	10	13	18	23	29
TOTAL MEMPHIS SMSA	149	173	199	232	273	321
15-COUNTY TOTAL	586	654	729	803	892	995

TABLE D-21

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	16	20	26	32	38	46
JEFFERSON	29	42	54	62	71	81
ST CHARLES	26	37	49	61	70	81
ST LOUISCO	233	255	279	292	312	333
ST LOUISCY	140	129	131	133	136	143
CLINTON	8	9	10	11	13	14
MADISON	67	77	80	85	94	103
MONROE	6	7	8	9	11	12
ST CLAIR	75	82	89	94	100	105
TOTAL ST LOUIS SMSA	600	658	725	780	843	917
CAPE GIRAR	17	20	23	25	28	32
NEW MADRID	11	12	14	15	17	19
SHELBY	183	212	240	279	325	380
TIPTON	6	7	8	10	11	13
CRITTENDEN	14	15	18	20	23	27
DESOTO	10	14	19	25	33	42
TOTAL MEMPHIS SMSA	213	248	285	334	393	461
15-COUNTY TOTAL	841	939	1047	1154	1282	1429

TABLE D-22

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	22	27	36	44	53	64
JEFFERSON	41	58	75	85	98	112
ST CHARLES	36	51	68	85	98	112
ST LOUISCO	323	354	387	406	432	462
ST LOUISCY	194	179	182	185	189	198
CLINTON	11	13	14	16	18	20
MADISON	93	107	111	118	130	142
MONROE	8	9	11	13	15	17
ST CLAIR	104	114	123	130	138	146
TOTAL ST LOUIS SMSA	833	913	1006	1082	1170	1272
CAPE GIRAR	23	27	31	34	39	43
NEW MADRID	11	12	14	15	17	19
SHELBY	254	294	334	387	451	527
TIPTON	6	7	8	10	11	13
CRITTENDEN	19	21	24	28	32	37
DESOTO	14	20	27	35	46	58
TOTAL MEMPHIS SMSA	293	342	393	459	540	635
15-COUNTY TOTAL	1160	1295	1444	1590	1766	1969

TABLE D-23

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	3	3	3	4	4	4
SHELBY	0	0	0	0	0	0
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	0	0	0	0	0	0
15-COUNTY TOTAL	3	3	4	4	4	4

TABLE D-24

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	1	1	1	1	1	1
ST LOUISCY	1	1	1	1	1	1
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	3	4	4	4	4	4
CAPE GIRAR	1	1	1	1	1	1
NEW MADRID	12	12	12	13	13	14
SHELBY	0	1	1	1	1	1
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	1	1	1	1	1	1
15-COUNTY TOTAL	17	17	18	18	19	20

TABLE D-25

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	1	1	1	1	1	1
JEFFERSON	1	2	2	2	2	2
ST CHARLES	1	2	2	2	2	2
ST LOUISCO	3	3	3	3	4	4
ST LOUISCY	6	5	5	5	6	6
CLINTON	1	1	1	1	1	1
MADISON	2	2	2	2	2	2
MONROE	1	1	1	1	1	1
ST CLAIR	2	2	2	2	2	2
TOTAL ST LOUIS SMSA	18	19	19	20	21	21
CAPE GIRAR	3	3	3	3	3	4
NEW MADRID	36	36	37	39	40	42
SHELBY	2	3	3	3	3	3
TIPTON	1	1	1	1	1	1
CRITTENDEN	1	1	1	1	1	1
DESOTO	1	1	1	1	2	2
TOTAL MEMPHIS SMSA	6	6	6	7	7	8
15-COUNTY TOTAL	63	64	66	68	71	74

TABLE D-26

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	4	4	5	5	5	6
JEFFERSON	6	6	7	7	8	8
ST CHARLES	6	7	7	8	8	9
ST LOUISCO	13	14	14	14	15	15
ST LOUISCY	23	22	23	23	23	23
CLINTON	4	4	4	4	5	5
MADISON	7	8	8	8	8	9
MONROE	4	4	4	5	5	5
ST CLAIR	8	8	8	9	9	9
TOTAL ST LOUIS SMSA	75	77	80	83	85	88
CAPE GIRAR	10	11	11	12	12	13
NEW MADRID	100	100	103	107	111	116
SHELBY	10	11	11	12	13	13
TIPTON	4	4	5	5	5	5
CRITTENDEN	4	5	5	5	5	6
DESOTO	4	5	6	6	7	7
TOTAL MEMPHIS SMSA	23	25	26	28	30	32
15-COUNTY TOTAL	208	213	221	229	238	248

TABLE D-27

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	14	15	17	18	19	21
JEFFERSON	20	22	25	26	27	28
ST CHARLES	20	23	25	27	29	30
ST LOUISCO	46	48	49	50	51	52
ST LOUISCY	81	79	80	80	81	82
CLINTON	14	15	15	16	16	17
MADISON	26	27	27	28	29	30
MONROE	13	14	15	16	17	18
ST CLAIR	28	29	29	30	31	31
TOTAL ST LOUIS SMSA	262	272	282	291	299	309
CAPE GIRAR	33	35	36	38	39	41
NEW MADRID	253	253	260	270	281	292
SHELBY	36	38	40	42	45	47
TIPTON	14	15	16	17	18	19
CRITTENDEN	15	16	17	18	19	20
DESOTO	16	18	20	22	24	26
TOTAL MEMPHIS SMSA	82	87	93	99	105	112
15-COUNTY TOTAL	630	647	672	697	725	754

TABLE D-28

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	1	1	1	1	1	1
NEW MADRID	7	7	7	7	8	8
SHELBY	0	0	0	0	0	0
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	0	0	0	0	0	0
15-COUNTY TOTAL	8	8	8	8	9	9

TABLE D-29

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	2	2	2	2	2	2
JEFFERSON	2	3	3	3	3	3
ST CHARLES	2	3	3	3	3	4
ST LOUISCO	6	6	6	6	6	6
ST LOUISCY	10	10	10	10	10	10
CLINTON	2	2	2	2	2	2
MADISON	3	3	3	3	3	3
MONROE	1	2	2	2	2	2
ST CLAIR	3	3	3	3	4	4
TOTAL ST LOUIS SMSA	31	32	33	34	36	37
CAPE GIRAR	3	3	3	4	4	4
NEW MADRID	13	13	14	14	15	16
SHELBY	4	5	5	5	5	6
TIPTON	2	2	2	2	2	2
CRITTENDEN	2	2	2	2	2	2
DESOTO	2	2	2	2	3	3
TOTAL MEMPHIS SMSA	9	10	11	11	12	13
15-COUNTY TOTAL	57	59	61	64	67	69

TABLE D-30

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	4	4	5	5	5	6
JEFFERSON	5	6	7	7	8	8
ST CHARLES	6	6	7	8	8	9
ST LOUISCO	13	14	14	15	15	15
ST LOUISCY	25	24	24	24	24	25
CLINTON	4	4	4	4	4	5
MADISON	7	8	8	8	8	9
MONROE	4	4	4	4	5	5
ST CLAIR	8	8	8	9	9	9
TOTAL ST LOUIS SMSA	75	78	81	84	86	89
CAPE GIRAR	7	7	8	8	8	9
NEW MADRID	25	25	26	26	28	29
SHELBY	10	11	12	12	13	14
TIPTON	4	4	4	5	5	5
CRITTENDEN	4	4	5	5	5	5
DESOTO	4	5	5	6	7	7
TOTAL MEMPHIS SMSA	23	24	26	28	30	32
15-COUNTY TOTAL	130	135	141	146	152	159

TABLE D-31

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	8	9	10	11	12	12
JEFFERSON	12	14	15	16	17	17
ST CHARLES	12	14	15	17	18	19
ST LOUISCO	29	30	31	32	32	33
ST LOUISCY	53	51	52	52	53	53
CLINTON	8	9	9	9	10	10
MADISON	16	16	17	17	18	18
MONROE	8	8	9	10	10	10
ST CLAIR	17	17	18	18	19	19
TOTAL ST LOUIS SMSA	163	169	176	181	187	193
CAPE GIRAR	14	15	16	16	17	18
NEW MADRID	43	43	44	46	48	50
SHELBY	23	24	25	27	28	30
TIPTON	8	9	9	10	11	11
CRITTENDEN	9	10	10	11	11	12
DESOTO	9	11	12	13	14	16
TOTAL MEMPHIS SMSA	50	53	56	60	64	69
15-COUNTY TOTAL	269	280	292	304	316	330

TABLE D-32

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	16	18	20	21	23	24
JEFFERSON	23	27	29	31	33	34
ST CHARLES	24	27	30	33	35	37
ST LOUISCO	57	59	61	62	64	66
ST LOUISCY	105	101	102	103	104	105
CLINTON	16	17	18	18	19	20
MADISON	31	33	33	34	35	36
MONROE	15	17	18	19	20	21
ST CLAIR	33	34	35	36	37	38
TOTAL ST LOUIS SMSA	321	333	347	357	369	381
CAPE GIRAR	27	28	30	31	32	34
NEW MADRID	71	71	73	76	79	83
SHELBY	45	47	50	52	56	59
TIPTON	17	18	19	20	21	22
CRITTENDEN	18	19	20	21	22	23
DESOTO	18	21	23	26	29	31
TOTAL MEMPHIS SMSA	98	104	111	119	127	135
15-COUNTY TOTAL	517	537	561	583	607	633

TABLE D-33

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	11	11	12	12	13	13
NEW MADRID	335	335	344	356	371	386
SHELBY	0	0	0	0	0	0
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	0	0	0	0	0	0
15-COUNTY TOTAL	346	346	356	369	384	400

TABLE D-34

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	19	20	22	24	25	27
JEFFERSON	26	30	32	34	36	38
ST CHARLES	27	30	33	36	38	40
ST LOUISCO	61	63	65	66	68	69
ST LOUISCY	108	104	105	106	107	108
CLINTON	18	19	20	21	21	22
MADISON	34	36	36	37	38	40
MONROE	18	19	20	21	22	23
ST CLAIR	37	38	39	40	40	41
TOTAL ST LOUIS SMSA	346	359	373	384	396	409
CAPE GIRAR	65	70	73	76	79	82
NEW MADRID	1177	1175	1209	1252	1303	1358
SHELBY	48	51	53	56	59	63
TIPTON	19	20	21	22	23	25
CRITTENDEN	20	21	22	23	25	26
DESOTO	21	23	26	29	32	34
TOTAL MEMPHIS SMSA	108	115	122	130	139	147
15-COUNTY TOTAL	1697	1720	1777	1842	1917	1996

TABLE D-35

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	97	104	115	123	132	141
JEFFERSON	135	154	168	176	185	194
ST CHARLES	137	156	173	187	197	207
ST LOUISCO	316	326	337	342	350	359
ST LOUISCY	558	541	544	547	552	562
CLINTON	95	100	103	107	111	116
MADISON	176	185	187	192	198	205
MONROE	91	98	105	110	115	120
ST CLAIR	189	195	201	205	209	213
TOTAL ST LOUIS SMSA	1794	1860	1933	1990	2050	2116
CAPE GIRAR	283	302	316	327	341	356
NEW MADRID	3622	3618	3720	3854	4012	4180
SHELBY	250	263	275	290	307	324
TIPTON	98	103	109	114	121	128
CRITTENDEN	106	110	115	121	127	134
DESOTO	108	121	135	149	164	177
TOTAL MEMPHIS SMSA	561	598	634	675	719	764
15-COUNTY TOTAL	6261	6377	6603	6846	7121	7416

TABLE D-36

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	402	432	477	512	548	587
JEFFERSON	562	640	699	733	770	808
ST CHARLES	571	650	720	778	819	860
ST LOUISCO	1312	1356	1399	1423	1456	1491
ST LOUISCY	2318	2250	2263	2275	2295	2334
CLINTON	397	414	429	444	463	481
MADISON	732	769	778	798	824	852
MONROE	379	409	436	458	478	498
ST CLAIR	787	812	834	852	870	886
TOTAL ST LOUIS SMSA	7459	7731	8036	8274	8523	8798
CAPE GIRAR	1030	1098	1148	1191	1241	1294
NEW MADRID	10014	10002	10285	10656	11091	11557
SHELBY	1038	1094	1145	1207	1276	1348
TIPTON	407	429	452	476	503	532
CRITTENDEN	440	458	479	502	529	556
DESOTO	448	503	561	619	680	738
TOTAL MEMPHIS SMSA	2333	2485	2637	2804	2987	3175
15-COUNTY TOTAL	20836	21315	22107	22925	23842	24823

TABLE D-37

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	1414	1518	1675	1801	1927	2063
JEFFERSON	1974	2248	2457	2577	2706	2838
ST CHARLES	2007	2284	2531	2735	2877	3022
ST LOUISCO	4611	4765	4917	5001	5117	5241
ST LOUIS CITY	8144	7905	7952	7995	8066	8203
CLINTON	1395	1454	1508	1559	1626	1689
MADISON	2571	2702	2735	2804	2897	2994
MONROE	1331	1436	1533	1611	1678	1751
ST CLAIR	2765	2853	2930	2992	3056	3114
TOTAL ST LOUIS SMSA	26211	27165	28238	29075	29950	30915
CAPE GIRAR	3269	3484	3645	3780	3938	4107
NEW MADRID	23083	25081	26027	26964	28066	29244
SHELBY	3648	3844	4023	4241	4482	4738
TIPTON	1430	1507	1588	1672	1768	1870
CRITTENDEN	1548	1610	1685	1765	1858	1955
DESOTO	1573	1769	1972	2175	2389	2592
TOTAL MEMPHIS SMSA	8199	8730	9267	9854	10497	11155
15-COUNTY TOTAL	63020	64690	67178	69672	72450	75422

TABLE D-38

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	90	97	101	105	110	115
NEW MADRID	684	683	704	731	762	796
SHELBY	0	0	0	0	0	0
TIPTON	0	0	0	0	0	0
CRITTENDEN	0	0	0	0	0	0
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	0	0	0	0	0	0
15-COUNTY TOTAL	774	780	805	836	872	911

TABLE D-39

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	158	170	189	204	219	236
JEFFERSON	225	258	284	298	314	330
ST CHARLES	229	263	293	318	335	353
ST LOUISCO	552	572	591	602	617	633
ST LOUISCY	1009	977	984	989	999	1017
CLINTON	156	163	169	175	183	191
MADISON	298	314	318	326	338	350
MONROE	148	161	172	181	189	198
ST CLAIR	321	332	342	349	357	365
TOTAL ST LOUIS SMSA	3096	3210	3341	3444	3552	3671
CAPE GIRAR	310	332	348	361	377	395
NEW MADRID	1350	1348	1389	1442	1504	1571
SHELBY	431	456	478	506	536	568
TIPTON	160	169	179	189	200	212
CRITTENDEN	174	181	190	200	211	223
DESOTO	177	200	225	249	275	300
TOTAL MEMPHIS SMSA	942	1006	1072	1143	1222	1304
15-COUNTY TOTAL	5697	5896	6149	6390	6656	6941

TABLE D-40

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	384	415	460	497	534	574
JEFFERSON	547	628	690	726	764	804
ST CHARLES	557	639	712	773	816	859
ST LOUISCO	1344	1392	1439	1465	1501	1540
ST LOUISCY	2455	2379	2394	2408	2430	2474
CLINTON	379	396	412	426	446	464
MADISON	724	763	773	794	822	851
MONROE	361	391	419	441	461	482
ST CLAIR	782	809	832	851	870	887
TOTAL ST LOUIS SMSA	7535	7812	8131	8381	8644	8935
CAPE GIRAR	694	743	779	810	846	884
NEW MADRID	2479	2476	2550	2648	2762	2885
SHELBY	1049	1109	1164	1230	1305	1383
TIPTON	389	411	435	459	487	517
CRITTENDEN	423	441	463	486	513	542
DESOTO	431	487	547	607	670	730
TOTAL MEMPHIS SMSA	2292	2449	2608	2783	2975	3173
15-COUNTY TOTAL	13000	13480	14069	14621	15227	15878

TABLE D-41

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	831	896	994	1073	1153	1240
JEFFERSON	1183	1358	1492	1569	1652	1737
ST CHARLES	1204	1381	1539	1671	1763	1857
ST LOUISCO	2905	3008	3109	3166	3243	3327
ST LOUISCY	5305	5140	5173	5202	5251	5346
CLINTON	819	856	890	922	963	1003
MADISON	1565	1649	1671	1715	1776	1839
MONROE	780	845	905	954	996	1042
ST CLAIR	1690	1747	1798	1838	1879	1917
TOTAL ST LOUIS SMSA	16281	16880	17570	18110	18677	19307
CAPE GIRAR	1411	1510	1584	1646	1719	1797
NEW MADRID	4297	4292	4420	4589	4788	5001
SHELBY	2267	2396	2514	2659	2819	2989
TIPTON	841	889	939	993	1053	1117
CRITTENDEN	914	954	1000	1051	1109	1171
DESOTO	930	1053	1182	1311	1448	1578
TOTAL MEMPHIS SMSA	4952	5292	5636	6013	6429	6856
15-COUNTY TOTAL	26941	27972	29209	30357	31612	32961

TABLE D-42

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = NEW MADRID
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	1639	1768	1961	2118	2275	2445
JEFFERSON	2334	2679	2943	3095	3259	3423
ST CHARLES	2375	2724	3037	3296	3479	3664
ST LOUISCO	5731	5934	6134	6246	6399	6564
ST LOUISCY	10467	10142	10206	10265	10361	10543
CLINTON	1616	1689	1756	1818	1901	1979
MADISON	3087	3254	3297	3385	3504	3623
MONROE	1538	1667	1785	1882	1966	2059
ST CLAIR	3336	3448	3547	3626	3708	3783
TOTAL ST LOUIS SMSA	32124	33305	34667	35732	36852	38055
CAPE GIRAR	2657	2842	2981	3098	3235	3353
NEW MADRID	7099	7090	7303	7582	7910	8262
SHELBY	4473	4727	4961	5246	5562	5898
TIPTON	1659	1754	1854	1958	2077	2205
CRITTENDEN	1804	1881	1973	2074	2189	2311
DESOTO	1836	2078	2332	2586	2857	3114
TOTAL MEMPHIS SMSA	9772	10441	11119	11864	12685	13528
15-COUNTY TOTAL	51651	53678	56071	58276	60682	63268

TABLE D-43

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	155	167	183	202	222	246
TIPTON	5	5	6	6	7	8
CRITTENDEN	9	10	10	11	12	13
DESOTO	1	1	1	2	2	2
TOTAL MEMPHIS SMSA	169	183	200	221	244	269
15-COUNTY TOTAL	169	183	200	221	244	269

TABLE D-44

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	2	2	2	2	3	3
NEW MADRID	0	0	0	0	0	0
SHELBY	439	474	519	571	630	696
TIPTON	13	14	16	17	19	21
CRITTENDEN	24	26	28	30	33	36
DESOTO	5	6	8	9	11	13
TOTAL MEMPHIS SMSA	481	521	570	628	693	766
15-COUNTY TOTAL	484	523	573	630	696	769

TABLE D-45

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	1	1	2	2	2	2
JEFFERSON	3	3	3	4	4	5
ST CHARLES	5	6	7	8	9	10
ST LOUISCO	50	52	54	55	57	59
ST LOUISCY	27	27	28	28	29	29
CLINTON	1	2	2	2	2	2
MADISON	14	14	14	15	16	17
MONROE	0	1	1	1	1	1
ST CLAIR	16	16	17	18	18	19
TOTAL ST LOUIS SMSA	117	123	127	132	138	144
CAPE GIRAR	10	11	12	13	14	16
NEW MADRID	2	2	2	2	2	3
SHELBY	919	993	1086	1195	1317	1455
TIPTON	28	30	33	36	40	44
CRITTENDEN	48	52	56	61	66	73
DESOTO	14	17	20	24	28	34
TOTAL MEMPHIS SMSA	1009	1092	1196	1316	1452	1606
15-COUNTY TOTAL	1139	1228	1337	1464	1607	1769

TABLE D-46

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	7	8	9	10	12	13
JEFFERSON	15	17	19	21	24	27
ST CHARLES	26	31	37	41	46	53
ST LOUISCO	272	283	291	300	309	319
ST LOUISCY	142	143	145	147	150	153
CLINTON	8	9	9	10	11	12
MADISON	74	76	79	82	86	90
MONROE	3	3	3	4	4	4
ST CLAIR	83	87	90	93	96	100
TOTAL ST LOUIS SMSA	629	657	683	709	737	770
CAPE GIRAR	28	31	33	36	39	43
NEW MADRID	5	5	6	6	7	7
SHELBY	1629	1758	1923	2114	2331	2574
TIPTON	49	53	58	64	71	78
CRITTENDEN	83	90	97	105	115	126
DESOTO	28	34	41	49	57	69
TOTAL MEMPHIS SMSA	1789	1935	2119	2333	2574	2847
15-COUNTY TOTAL	2451	2628	2841	3084	3357	3667

TABLE D-47

BUILDING DAMAGES (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	19	22	25	28	31	35
JEFFERSON	40	47	52	58	64	72
ST CHARLES	71	85	99	112	125	143
ST LOUISCO	736	765	787	811	835	862
ST LOUISCY	377	381	385	391	399	405
CLINTON	22	24	26	28	30	32
MADISON	202	206	213	222	232	243
MONROE	7	8	9	10	11	11
ST CLAIR	222	232	241	250	258	267
TOTAL ST LOUIS SMSA	1695	1770	1838	1908	1984	2071
CAPE GIRAR	57	62	68	73	80	87
NEW MADRID	10	11	11	12	13	14
SHELBY	2518	2718	2972	3267	3600	3975
TIPTON	75	82	90	99	109	121
CRITTENDEN	120	129	140	152	167	182
DESOTO	49	59	70	84	99	119
TOTAL MEMPHIS SMSA	2763	2988	3273	3602	3975	4397
15-COUNTY TOTAL	4525	4832	5190	5597	6052	6570

TABLE D-48

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	11	13	14	16	18	21
TIPTON	1	1	1	1	1	1
CRITTENDEN	1	2	2	2	2	3
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	13	15	17	19	22	25
15-COUNTY TOTAL	13	15	17	19	22	25

TABLE D-49

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	63	72	80	91	105	120
TIPTON	4	4	5	6	6	7
CRITTENDEN	8	9	10	11	12	14
DESOTO	1	1	2	2	3	4
TOTAL MEMPHIS SMSA	76	86	97	110	127	145
15-COUNTY TOTAL	76	87	97	111	127	146

TABLE D-50

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	1
JEFFERSON	0	1	1	1	1	1
ST CHARLES	0	0	1	1	1	1
ST LOUISCO	2	2	3	3	3	3
ST LOUISCY	1	1	1	1	1	1
CLINTON	0	0	0	0	0	0
MADISON	1	1	1	1	1	1
MONROE	0	0	0	0	0	0
ST CLAIR	1	1	1	1	1	1
TOTAL ST LOUIS SMSA	6	7	7	8	9	9
CAPE GIRAR	1	2	2	2	2	2
NEW MADRID	1	1	1	1	1	1
SHELBY	220	252	293	344	404	470
TIPTON	6	7	8	9	10	12
CRITTENDEN	36	40	45	50	57	65
DESOTO	6	8	10	13	16	20
TOTAL MEMPHIS SMSA	268	306	355	416	488	567
15-COUNTY TOTAL	276	315	366	427	499	580

TABLE D-51

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	2	2	3	3	4	4
JEFFERSON	3	4	5	5	6	7
ST CHARLES	2	3	4	5	6	7
ST LOUISCO	17	18	19	20	22	23
ST LOUISCY	8	8	8	8	8	8
CLINTON	1	1	1	1	1	1
MADISON	6	7	7	7	8	8
MONROE	1	1	1	1	1	1
ST CLAIR	6	7	7	8	8	9
TOTAL ST LOUIS SMSA	45	50	55	59	63	68
CAPE GIRAR	8	9	10	11	13	14
NEW MADRID	4	4	5	5	6	6
SHELBY	267	305	357	420	494	576
TIPTON	6	7	8	10	11	13
CRITTENDEN	106	121	139	162	188	216
DESOTO	27	36	47	60	76	92
TOTAL MEMPHIS SMSA	406	469	551	651	769	897
15-COUNTY TOTAL	464	533	621	726	850	986

TABLE D-52

PERSONAL PROPERTY DAMAGES - DAY (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	9	11	14	17	20	24
JEFFERSON	15	21	27	30	34	38
ST CHARLES	14	19	24	29	33	37
ST LOUISCO	94	102	110	115	121	129
ST LOUISCY	47	44	44	45	46	48
CLINTON	5	5	6	6	7	8
MADISON	33	37	38	40	44	47
MONROE	3	4	5	5	6	7
ST CLAIR	36	39	41	43	46	48
TOTAL ST LOUIS SMSA	256	281	309	331	356	385
CAPE GIRAR	37	43	48	53	58	65
NEW MADRID	11	12	14	15	17	19
SHELBY	267	305	357	420	494	576
TIPTON	6	7	8	10	11	13
CRITTENDEN	106	121	139	162	188	216
DESOTO	105	141	184	235	296	362
TOTAL MEMPHIS SMSA	485	574	688	825	989	1167
15-COUNTY TOTAL	788	911	1058	1224	1421	1635

TABLE D-53

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	115	133	151	175	205	239
TIPTON	5	6	7	8	9	11
CRITTENDEN	10	11	12	14	16	18
DESOTO	5	6	9	11	15	19
TOTAL MEMPHIS SMSA	135	156	179	209	245	287
15-COUNTY TOTAL	135	156	179	209	245	287

TABLE D-54

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	6	8	9	10	11	12
NEW MADRID	3	3	3	4	4	5
SHELBY	169	195	222	257	300	350
TIPTON	6	7	8	9	11	13
CRITTENDEN	14	15	18	20	23	27
DESOTO	7	10	13	18	23	29
TOTAL MEMPHIS SMSA	196	227	261	304	357	418
15-COUNTY TOTAL	205	238	273	317	372	435

TABLE D-55

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	7	9	12	14	17	21
JEFFERSON	13	19	24	28	32	36
ST CHARLES	12	17	22	27	32	36
ST LOUISCO	105	115	125	131	140	150
ST LOUISCY	63	58	59	60	61	64
CLINTON	4	4	5	5	6	6
MADISON	30	35	36	38	42	46
MONROE	2	3	4	4	5	5
ST CLAIR	34	37	40	42	45	47
TOTAL ST LOUIS SMSA	270	296	326	350	379	412
CAPE GIRAR	10	12	13	15	16	18
NEW MADRID	5	5	5	6	6	7
SHELBY	236	273	310	360	420	490
TIPTON	6	7	8	10	11	13
CRITTENDEN	19	21	24	28	32	37
DESOTO	10	14	19	25	33	42
TOTAL MEMPHIS SMSA	272	316	362	422	496	582
15-COUNTY TOTAL	556	628	707	793	898	1020

TABLE D-56

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	11	14	18	22	26	32
JEFFERSON	20	29	37	42	49	56
ST CHARLES	18	25	34	42	49	56
ST LOUISCO	161	176	192	202	215	230
ST LOUISCY	97	89	90	92	94	99
CLINTON	6	6	7	8	9	10
MADISON	46	53	55	59	65	71
MONROE	4	5	6	7	7	8
ST CLAIR	52	57	61	65	69	72
TOTAL ST LOUIS SMSA	414	454	500	538	582	633
CAPE GIRAR	14	17	19	21	24	27
NEW MADRID	7	7	8	8	9	10
SHELBY	264	302	351	411	483	564
TIPTON	6	7	8	10	11	13
CRITTENDEN	26	29	33	37	43	49
DESOTO	14	20	27	35	46	58
TOTAL MEMPHIS SMSA	310	358	418	493	583	684
15-COUNTY TOTAL	745	836	945	1061	1198	1354

TABLE D-57

PERSONAL PROPERTY DAMAGES - NIGHT (IN MILLION DOLLARS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	16	20	26	32	38	46
JEFFERSON	29	42	54	62	71	81
ST CHARLES	26	37	49	61	70	81
ST LOUISCO	233	255	279	292	312	333
ST LOUISCY	140	129	131	133	136	143
CLINTON	8	9	10	11	13	14
MADISON	67	77	80	85	94	103
MONROE	6	7	8	9	11	12
ST CLAIR	75	82	89	94	100	105
TOTAL ST LOUIS SMSA	600	658	725	780	843	917
CAPE GIRAR	20	23	27	29	33	37
NEW MADRID	10	10	10	12	13	15
SHELBY	267	305	357	420	494	576
TIPTON	6	7	8	10	11	13
CRITTENDEN	34	37	42	48	56	64
DESOTO	19	27	36	47	61	77
TOTAL MEMPHIS SMSA	326	376	443	525	622	731
15-COUNTY TOTAL	955	1068	1206	1345	1512	1700

TABLE D-58

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	2	2	2	2	2	3
TIPTON	1	1	1	1	1	1
CRITTENDEN	1	1	1	1	1	1
DESOTO	0	0	0	0	0	0
TOTAL MEMPHIS SMSA	4	4	4	5	5	5
15-COUNTY TOTAL	4	4	4	5	5	5

TABLE D-59

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	8	9	9	10	10	11
TIPTON	3	3	4	4	4	4
CRITTENDEN	4	5	5	5	5	6
DESOTO	1	1	1	1	2	2
TOTAL MEMPHIS SMSA	17	18	19	20	21	23
15-COUNTY TOTAL	18	19	19	21	22	23

TABLE D-60

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	1	1	1	1	1	1
ST LOUISCY	1	1	1	1	1	1
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	3	4	4	4	4	4
CAPE GIRAR	1	1	1	1	1	1
NEW MADRID	1	1	1	1	1	1
SHELBY	30	32	33	35	37	39
TIPTON	12	12	13	14	15	15
CRITTENDEN	15	16	17	18	19	20
DESOTO	4	5	6	6	7	7
TOTAL MEMPHIS SMSA	62	65	69	72	77	81
15-COUNTY TOTAL	67	71	74	78	83	88

TABLE D-61

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	1	1	1	1	1	1
JEFFERSON	1	2	2	2	2	2
ST CHARLES	1	2	2	2	2	2
ST LOUISCO	3	3	3	3	4	4
ST LOUISCY	6	5	5	5	6	6
CLINTON	1	1	1	1	1	1
MADISON	2	2	2	2	2	2
MONROE	1	1	1	1	1	1
ST CLAIR	2	2	2	2	2	2
TOTAL ST LOUIS SMSA	18	19	19	20	21	21
CAPE GIRAR	5	5	5	5	5	6
NEW MADRID	3	3	3	4	4	4
SHELBY	93	98	103	108	115	121
TIPTON	37	39	41	43	45	48
CRITTENDEN	48	50	52	54	57	60
DESOTO	16	18	20	22	24	26
TOTAL MEMPHIS SMSA	193	204	215	227	241	255
15-COUNTY TOTAL	219	231	243	256	271	286

TABLE D-62

MORTALITY - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	4	4	5	5	5	6
JEFFERSON	6	6	7	7	8	8
ST CHARLES	6	7	7	8	8	9
ST LOUISCO	13	14	14	14	15	15
ST LOUISCY	23	22	23	23	23	23
CLINTON	4	4	4	4	5	5
MADISON	7	8	8	8	8	9
MONROE	4	4	4	5	5	5
ST CLAIR	8	8	8	9	9	9
TOTAL ST LOUIS SMSA	75	77	80	83	85	88
CAPE GIRAR	16	17	18	19	19	20
NEW MADRID	12	12	12	13	13	14
SHELBY	261	275	288	303	321	339
TIPTON	102	108	114	120	126	134
CRITTENDEN	132	137	143	150	158	166
DESOTO	48	54	61	67	74	80
TOTAL MEMPHIS SMSA	543	574	605	640	679	719
15-COUNTY TOTAL	646	680	716	754	796	840

TABLE D-63

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	9	9	10	10	11	12
TIPTON	3	4	4	4	4	4
CRITTENDEN	4	4	5	5	5	5
DESOTO	2	2	2	2	3	3
TOTAL MEMPHIS SMSA	18	19	21	22	23	25
15-COUNTY TOTAL	18	19	21	22	23	25

TABLE D-64

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	2	2	2	2	2	2
NEW MADRID	1	1	1	1	1	2
SHELBY	20	21	22	23	24	26
TIPTON	7	8	8	9	9	10
CRITTENDEN	9	10	10	11	11	12
DESOTO	4	5	5	6	7	7
TOTAL MEMPHIS SMSA	40	43	45	48	51	55
15-COUNTY TOTAL	43	46	49	52	55	58

TABLE D-65

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	2	2	2	2	2	2
JEFFERSON	2	3	3	3	3	3
ST CHARLES	2	3	3	3	3	4
ST LOUISCO	6	6	6	6	6	6
ST LOUISCY	10	10	10	10	10	10
CLINTON	2	2	2	2	2	2
MADISON	3	3	3	3	3	3
MONROE	1	2	2	2	2	2
ST CLAIR	3	3	3	3	4	4
TOTAL ST LOUIS SMSA	31	32	33	34	36	37
CAPE GIRAR	4	5	5	5	5	6
NEW MADRID	3	3	3	3	4	4
SHELBY	39	41	43	46	49	52
TIPTON	15	15	16	17	18	19
CRITTENDEN	18	19	20	21	22	23
DESOTO	9	11	12	13	14	16
TOTAL MEMPHIS SMSA	81	86	91	97	103	110
15-COUNTY TOTAL	120	126	133	140	148	156

TABLE D-66

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	4	4	5	5	5	6
JEFFERSON	5	6	7	7	8	8
ST CHARLES	6	6	7	8	8	9
ST LOUISCO	13	14	14	15	15	15
ST LOUISCY	25	24	24	24	24	25
CLINTON	4	4	4	4	4	5
MADISON	7	8	8	8	8	9
MONROE	4	4	4	4	5	5
ST CLAIR	8	8	8	9	9	9
TOTAL ST LOUIS SMSA	75	78	81	84	86	89
CAPE GIRAR	9	10	11	11	12	12
NEW MADRID	7	7	7	7	8	8
SHELBY	73	77	81	85	91	96
TIPTON	27	29	30	32	34	36
CRITTENDEN	33	35	36	38	40	42
DESOTO	18	21	23	26	29	31
TOTAL MEMPHIS SMSA	151	161	170	181	193	205
15-COUNTY TOTAL	243	256	269	283	299	315

TABLE D-67

MORTALITY - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	8	9	10	11	12	12
JEFFERSON	12	14	15	16	17	17
ST CHARLES	12	14	15	17	18	19
ST LOUISCO	29	30	31	32	32	33
ST LOUISCY	53	51	52	52	53	53
CLINTON	8	9	9	9	10	10
MADISON	16	16	17	17	18	18
MONROE	8	8	9	10	10	10
ST CLAIR	17	17	18	18	19	19
TOTAL ST LOUIS SMSA	163	169	176	181	187	193
CAPE GIRAR	19	20	21	22	23	24
NEW MADRID	13	13	14	14	15	16
SHELBY	127	135	141	149	158	168
TIPTON	47	50	53	56	59	63
CRITTENDEN	57	60	63	66	70	74
DESOTO	34	38	43	48	52	57
TOTAL MEMPHIS SMSA	266	283	300	319	340	361
15-COUNTY TOTAL	461	485	510	536	564	594

TABLE D-68

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	199	210	220	232	245	259
TIPTON	78	82	87	91	97	102
CRITTENDEN	106	110	115	121	127	134
DESOTO	21	23	26	29	32	34
TOTAL MEMPHIS SMSA	404	426	448	473	500	529
15-COUNTY TOTAL	404	426	448	473	500	529

TABLE D-69

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	21	23	24	25	26	27
NEW MADRID	16	16	16	17	17	18
SHELBY	841	886	927	978	1033	1092
TIPTON	330	347	366	386	408	431
CRITTENDEN	440	458	479	502	529	556
DESOTO	108	121	135	149	164	177
TOTAL MEMPHIS SMSA	1719	1813	1908	2015	2133	2257
15-COUNTY TOTAL	1756	1851	1948	2056	2176	2302

TABLE D-70

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	19	20	22	24	25	27
JEFFERSON	26	30	32	34	36	38
ST CHARLES	27	30	33	36	38	40
ST LOUISCO	61	63	65	66	68	69
ST LOUISCY	108	104	105	106	107	108
CLINTON	18	19	20	21	21	22
MADISON	34	36	36	37	38	40
MONROE	18	19	20	21	22	23
ST CLAIR	37	38	39	40	40	41
TOTAL ST LOUIS SMSA	346	359	373	384	396	409
CAPE GIRAR	110	117	122	127	132	138
NEW MADRID	81	80	83	86	89	93
SHELBY	2996	3156	3303	3482	3681	3890
TIPTON	1174	1238	1304	1373	1452	1536
CRITTENDEN	1548	1610	1685	1765	1858	1955
DESOTO	448	503	561	619	680	738
TOTAL MEMPHIS SMSA	6165	6508	6853	7240	7670	8119
15-COUNTY TOTAL	6702	7064	7431	7837	8287	8759

TABLE D-71

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	97	104	115	123	132	141
JEFFERSON	135	154	168	176	185	194
ST CHARLES	137	156	173	187	197	207
ST LOUISCO	316	326	337	342	350	359
ST LOUISCY	558	541	544	547	552	562
CLINTON	95	100	103	107	111	116
MADISON	176	185	187	192	198	205
MONROE	91	98	105	110	115	120
ST CLAIR	189	195	201	205	209	213
TOTAL ST LOUIS SMSA	1794	1860	1933	1990	2050	2116
CAPE GIRAR	456	486	509	528	550	573
NEW MADRID	335	335	344	356	371	386
SHELBY	9333	9834	10292	10849	11467	12121
TIPTON	3658	3856	4062	4278	4523	4785
CRITTENDEN	4764	4956	5185	5434	5717	6018
DESOTO	1573	1769	1972	2175	2389	2592
TOTAL MEMPHIS SMSA	19328	20415	21511	22736	24096	25515
15-COUNTY TOTAL	21914	23096	24296	25611	27067	28591

TABLE D-72

INJURIES - DAY (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	402	432	477	512	548	587
JEFFERSON	562	640	699	733	770	808
ST CHARLES	571	650	720	778	819	860
ST LOUISCO	1312	1356	1399	1423	1456	1491
ST LOUISCY	2318	2250	2263	2275	2295	2334
CLINTON	397	414	429	444	463	481
MADISON	732	769	778	798	824	852
MONROE	379	409	436	458	478	498
ST CLAIR	787	812	834	852	870	886
TOTAL ST LOUIS SMSA	7459	7731	8036	8274	8523	8798
CAPE GIRAR	1604	1709	1788	1854	1932	2014
NEW MADRID	1177	1175	1209	1252	1303	1358
SHELBY	26090	27490	28770	30328	32055	33881
TIPTON	10224	10779	11354	11959	12644	13375
CRITTENDEN	13171	13702	14334	15023	15806	16639
DESOTO	4842	5444	6069	6694	7352	7977
TOTAL MEMPHIS SMSA	54327	57415	60528	64004	67857	71872
15-COUNTY TOTAL	64567	68030	71561	75384	79615	84042

TABLE D-73

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = VIII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	0	0	0	0	0	0
NEW MADRID	0	0	0	0	0	0
SHELBY	895	945	992	1049	1112	1180
TIPTON	332	351	371	392	415	441
CRITTENDEN	423	441	463	486	513	542
DESOTO	177	200	225	249	275	300
TOTAL MEMPHIS SMSA	1826	1938	2050	2177	2317	2463
15-COUNTY TOTAL	1826	1938	2050	2177	2317	2463

TABLE D-74

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = IX

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	0	0	0	0	0	0
JEFFERSON	0	0	0	0	0	0
ST CHARLES	0	0	0	0	0	0
ST LOUISCO	0	0	0	0	0	0
ST LOUISCY	0	0	0	0	0	0
CLINTON	0	0	0	0	0	0
MADISON	0	0	0	0	0	0
MONROE	0	0	0	0	0	0
ST CLAIR	0	0	0	0	0	0
TOTAL ST LOUIS SMSA	0	0	0	0	0	0
CAPE GIRAR	181	193	203	211	220	230
NEW MADRID	130	130	134	139	145	151
SHELBY	1962	2074	2176	2301	2440	2588
TIPTON	728	770	813	859	911	967
CRITTENDEN	914	954	1000	1051	1109	1171
DESOTO	431	487	547	607	670	730
TOTAL MEMPHIS SMSA	4035	4285	4537	4818	5131	5457
15-COUNTY TOTAL	4346	4608	4873	5168	5496	5838

TABLE D-75

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = X

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	158	170	189	204	219	236
JEFFERSON	225	258	284	298	314	330
ST CHARLES	229	263	293	318	335	353
ST LOUISCO	552	572	591	602	617	633
ST LOUISCY	1009	977	984	989	999	1017
CLINTON	156	163	169	175	183	191
MADISON	298	314	318	326	338	350
MONROE	148	161	172	181	189	198
ST CLAIR	321	332	342	349	357	365
TOTAL ST LOUIS SMSA	3096	3210	3341	3444	3552	3671
CAPE GIRAR	439	470	493	512	535	559
NEW MADRID	317	316	326	338	353	368
SHELBY	3921	4144	4349	4599	4877	5171
TIPTON	1454	1538	1625	1717	1821	1933
CRITTENDEN	1804	1881	1973	2074	2189	2311
DESOTO	930	1053	1182	1311	1448	1578
TOTAL MEMPHIS SMSA	8110	8617	9129	9701	10334	10993
15-COUNTY TOTAL	11962	12613	13289	13995	14773	15592

TABLE D-76

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XI

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	384	415	460	497	534	574
JEFFERSON	547	628	690	726	764	804
ST CHARLES	557	639	712	773	816	859
ST LOUISCO	1344	1392	1439	1465	1501	1540
ST LOUISCY	2455	2379	2394	2408	2430	2474
CLINTON	379	396	412	426	446	464
MADISON	724	763	773	794	822	851
MONROE	361	391	419	441	461	482
ST CLAIR	782	809	832	851	870	887
TOTAL ST LOUIS SMSA	7535	7812	8131	8381	8644	8935
CAPE GIRAR	949	1015	1065	1107	1156	1209
NEW MADRID	684	683	704	731	762	796
SHELBY	7279	7693	8073	8537	9053	9600
TIPTON	2700	2855	3017	3187	3381	3588
CRITTENDEN	3314	3456	3625	3809	4020	4244
DESOTO	1836	2078	2332	2586	2857	3114
TOTAL MEMPHIS SMSA	15129	16082	17046	18120	19309	20546
15-COUNTY TOTAL	24297	25593	26947	28338	29871	31486

TABLE D-77

INJURIES - NIGHT (PERSONS)
DETERMINISTIC APPROACH EPICENTER = MARKED TREE
INTENSITY = XII

COUNTY	1980	1981-1990	1991-2000	2001-2010	2011-2020	2021-2030
FRANKLIN	831	896	994	1073	1153	1240
JEFFERSON	1183	1358	1492	1569	1652	1737
ST CHARLES	1204	1381	1539	1671	1763	1857
ST LOUISCO	2905	3008	3109	3166	3243	3327
ST LOUISCY	5305	5140	5173	5202	5251	5346
CLINTON	819	856	890	922	963	1003
MADISON	1565	1649	1671	1715	1776	1839
MONROE	780	845	905	954	996	1042
ST CLAIR	1690	1747	1798	1838	1879	1917
TOTAL ST LOUIS SMSA	16281	16880	17570	18110	18677	19307
CAPE GIRAR	1873	2004	2102	2184	2281	2385
NEW MADRID	1350	1348	1389	1442	1504	1571
SHELBY	12732	13456	14121	14931	15833	16790
TIPTON	4722	4993	5276	5574	5913	6275
CRITTENDEN	5743	5989	6282	6602	6967	7356
DESOTO	3371	3817	4282	4750	5246	5720
TOTAL MEMPHIS SMSA	26569	28256	29961	31858	33959	36141
15-COUNTY TOTAL	46072	48487	51022	53594	56422	59404