5. Estimates of Direct Damage

5.1 Introduction

The analysis of seismic vulnerability of lifeline systems and the economic impact of disruption is based on an assessment of three factors:

- Seismic hazard,
- Lifeline inventory, and
- Vulnerability functions.

In this investigation these factors are used to quantify vulnerability and impact of disruption in terms of (1) direct damage and (2) economic losses resulting from direct damage and loss of function of damaged facilities. Estimates of direct damage to lifelines, expressed in terms of percent replacement value and dollar loss, are discussed in this chapter. Indirect economic losses are discussed in Chapter 6.

Direct damage is defined as damage resulting directly from ground shaking or other collateral loss causes such as liquefaction. For each facility, it is expressed in terms of cost of repair divided by replacement cost and varies from 0 to 1.0 (0% to 100%). In this project it is estimated using (1) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), (2) inventory data specifying the location and type of facilities affected (from Chapter 2), and (3) vulnerability functions that relate seismic intensity and site conditions to expected damage (from Appendix B).

5.2 General Analytical Approach for Estimating Direct Damage

The earthquake survival of lifelines depends on their seismic performance characteristics. As described in Chapter 3 and summarized in Appendix B, the seismic performance of lifeline components has been characterized in this study using data developed from the database of expert opinion elicited in the ATC-13 project (ATC, 1985). This expert opinion was based in part on observations of lifeline components performance in previous earthquakes as well as estimates of expected performance based on knowledge of seismic design procedures and criteria. Thus, component vulnerability data for this study is essentially empirically based, rather than resulting from detailed analyses of each lifeline component.

The analysis approach to estimate direct damage considers both damage resulting from ground shaking as well as damage resulting from liquefaction. Damage due to other collateral loss causes, such as landslide and fire following earthquake, are not included because of the unavailability of inventory information and the lack of available models for estimating these losses nationwide.

The analysis approach for computing direct damage due to ground shaking proceeded as follows. For each earthquake scenario, MMI levels were assigned to each 25-km grid cell in the affected region, using the Everden MMI model, assigned magnitude, and assigned fault rupture location (from Chapter 4). Damage states were then estimated for each affected lifeline component (node or link) in each grid cell, using the motion-damage curves provided in Appendix B. As described in the following sections, the procedure for utilizing the motion-damage curves varied slightly by facility type, depending on whether the lifeline was a site specific facility, or a regional transmission (extended) network.

Damage due to liquefaction was estimated using a two-step method, also taken from ATC-13 (ATC, 1985). First, the probability of ground failure in each grid cell was calculated on the basis of the soil condition and associated liquefaction probability assessments provided in Table 8.4 of the ATC-13 report (p. 230). Only one soil unit (as defined by Everden) was assumed to be liquefiable: Unit A, which was assumed to be alluvium with water table less than 3-meters deep. Direct damage due to liquefaction in each Unit A grid cell was then estimated as follows:

$$DMG(PG) = DMG(S) \, x \, p(GFI) \, x \, 5 \quad \text{(for surface facilities)} \qquad (5.1)$$

and

$$DMG(PG) = DMG(S) \times p(GFI) \times 10 \quad \text{(for buried facilities)} \qquad (5.2)$$

where:

DMG(S)	= Mean damage caused by shaking
DMG(PG)	= Mean damage caused by poor ground
p(GFI)	= Probability of a given ground failure intensity, taken directly, noncumulatively, from Table 8.4 (ATC-13) for a given shaking intensity

After damages due to ground shaking and liquefaction were established for each facility in each affected grid cell, the total direct damage for each facility was calculated. As suggested in ATC-13, the total direct damage, DMG(T), was simply the sum of damage due to shaking plus damage due to liquefaction, with the sum always equal to or less than 1.0 (100 %):

$$DMG(T) = DMG(S) + DMG(PG) \qquad (5.3)$$

Cautionary Note Regarding Analysis Approach. In the scenario earthquakes it is assumed that the damage factor is uniquely related to the MMI zone in the manner prescribed in ATC-13 (ATC, 1985). There may be one or more MMI zones within each 25 km grid cell, depending on spatial attenuation. In either case, lifeline damage is assumed to be uniform within each MMI zone. Experts who supplied data to the ATC-13 project may question application of their opinions to cases where lifeline damage does not occur uniformly within a grid cell or MMI zone. In the ATC-13 Questionnaire, on which the damage factors and loss of function statistics are based, the damage factor is defined as damage due to ground shaking only (see ATC-13, p. 175). This approach probably led ATC-13 experts to provide an adequate picture of lifeline damage in many cases. For example, damage to pipelines in southern San Fernando Valley as a result of the 1971 earthquake was primarily due to ground shaking, and was geographically distributed in a way that it is reasonable to speak of average damage within a given MMI zone. Damage to pipelines in northern San Fernando Valley was more closely spaced and more severe due to ground rupture and to other significant ground distortions associated with nearby fault movement; at least some experts who provided opinions probably considered the fact that higher MMI is associated with such effects and incorporated it in their response despite instructions to consider only ground shaking. In this case, also, it is reasonable to speak of average damage. Thus, damage due to ground distortion can, at least in some cases, also be presented as uniform or average throughout a given MMI zone. Damage statistics prepared in this way are best applied in situations where not only the hazard (ground shaking and ground distortions) but also the structures of interest (pipelines, highway bridges, electrical substations) are distributed somewhat uniformly. It is significant that most of the pipeline damage statistics from San Fernando and from other earthquakes are derived from distribution and transmission networks, which are relatively dense within the MMI zones considered. The conditions that shaped ATC-13 expert opinion are most nearly approximated in such cases (for example, a dense network of transmission and distribution pipelines); it is reasonable to use ATC-13 damage factors for these situations.

However, to the extent that structures occur sparsely in a grid cell or MMI zone, conditions differ from those on which many expert opinions are based. This is because fewer lifeline components will be damaged at all if there are fewer components to coincide with damaging ground conditions. In the extreme case of a single lifeline structure in a 25-km grid cell, it may be misleading to apply statistics derived from regions with a dense array of structures. In at least some regions of the scenario earthquakes, there appear to be only a few lifeline components passing through the MMI zones or 25-km grid cells. In instances where trunk and transmission lines are sparse in a MMI zone or grid cell, application of ATC-13 statistics may be misleading because structure and hazard coincide much less frequently than is assumed. This possibility introduces an additional type of uncertainty that affects the average damage factors used in this study.

The foregoing discussion is based on intuition, not on rigorous analytical modeling. However, if this discussion is valid, the effect of applying

ATC-13 statistics in this study may result in overestimates of damage.

5.3 Direct Damage Estimates for Site-Specific Lifelines

Direct damage to site-specific lifelines, i.e., lifelines that consist of individual sited or point facilities (e.g., hospitals), were estimated using the methodology specified above. For airports, ports and harbors, medical care facilities (hospitals), and broadcast stations, the inventory data summarized in Chapter 2 were used to define the number and distribution of facilities. For fire and police stations, locations were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas, and number of facilities affected were estimated by proxy, assuming the previously established relationships between population and number of facilities.

For summary and comparative purposes, four damage states are considered in this study:

- Light damage (1-10% replacement value);
- Moderate damage (10-30% replacement value);
- Heavy damage (30-60% replacement value); and
- Major to destroyed (60-100% replacement value).

The total number of affected facilities and the percentage of facilities in each damage state are summarized for each scenario earthquake in Tables 5-1 through 5-6. Following is a discussion of the direct damage impact on each site-specific lifeline considered.

5.3.1 Airports

Direct damage summaries for civil and general aviation airports for the various scenario earthquakes (Tables 5-1a and 5-1b) indicate that damage to terminals is expected to be particularly high in the magnitude-8.0 New Madrid and Puget Sound earthquake scenarios. For example, for the New Madrid magnitude-8.0 event, 13% of the airports in Arkansas (23 in total), 6% of the airports in Missouri (25 in total), and 2% in Tennessee (4 in total) would sustain major to destructive damage (60 to 100%) (Table 5-1a). The Puget Sound magnitude-7.5 scenario event would seriously affect an even larger number of airport terminals, with 12% or approximately 43 airports expected to sustain damage in this same range (60 to 100%). In the case of the Cape Ann and Charleston events, direct damage to terminals is also significant. Direct damage to runways (Table 5-1b), on the other hand, is relatively low for most scenario events; if damage does occur, it is usually less than 30%.

The reason for the relatively high impact on airports in the Puget Sound event is assumed to be due to the high concentration of airports near the source zone and poor ground, i.e., liquefiable sites. For the New Madrid event, the cause appears to be due to a combination of poor ground, low ground-motion attenuation with distance, and lack of seismically resistant design construction features.

5.3.2 Ports and Harbors

Since ports and harbors are located in the coastal regions, only those scenario earthquakes affecting these regions will negatively impact this facility type. As indicated in Table 5-2, the most severe damages to ports and harbors are expected for the Charleston and Puget Sound events. For example, one hundred percent, or 20 ports and harbors, in South Carolina can be expected to sustain heavy damage (30 to 60%), and 73%, or approximately 22 such facilities would be similarly affected in Georgia. In Washington, 14% of the ports (approximately 11) would be similarly affected. Numerous ports and harbors in these states would also sustain moderate damage (10 to 30%), as would approximately 22 such facilities in California for the Hayward magnitude-7.5 event. The primary cause of such damage, of course, is poor ground.

5.3.3 Medical Care Facilities

Direct damage summaries for medical care facilities (hospitals) for the various scenario earthquakes (Table 5-3) suggest that damage to this facility type will be relatively high for the Puget Sound, Charleston, New Madrid, Fort Tejon, and Hayward scenario events. For example, damage data for the Puget Sound and Charleston events indicate that 15% of the hospitals in Washington (15 in total) and 13% of

Table 5-1a Damage Percent for Air Transportation Terminals for Each Scenario Earthquake (Percent of Airports in State)

NEW MADRID (M=8.0)						
Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	11%	5%	17%	18%	26%	64%
Moderate 10-30 %	< 1%	0%	21%	13%	3%	19%
Heavy 30-60 %	0%	0%	5%	0%	0%	0%
Major to Destructive 60-100 %	0%	6%	13%	2%	0%	0%

CHARLESTON (M=7.5)			
Total Number	South Carolina 147	North Carolina 309	Georgia 343
Light Damage 1-10 %	33%	24%	28%
Moderate 10-30 %	20%	1%	1%
Heavy 30-60 %	0%	0%	0%
Major to Destructive 60-100 %	4%	0%	2%

CAPE ANN (M=7.0)					
Total Number	Massachusetts 149	Connecticut 115	Delaware 37	Rhode Island 55	New Hampshire 63
Light Damage 1-10 %	77%	57%	65%	55%	56%
Moderate 10-30 %	< 1%	0%	0%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	4%	0%	0%	0%	0%

WASATCH FRONT (M=7.5)	
Total Number	Utah 107
Light Damage 1-10 %	15%
Moderate 10-30 %	23%
Heavy 30-60 %	0%
Major to Destructive 60-100 %	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 869	California 869	Washington 364
Light Damage 1-10 %	9%	12%	15%
Moderate 10-30 %	2%	14%	6%
Heavy 30-60 %	0%	< 1%	6%
Major to Destructive 60-100 %	0%	0%	12%

NEW MADRID (M=7.0)						
Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	< 1%	< 1%	31%	19%	7%	32%
Moderate 10-30 %	0%	2%	12%	< 1%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	3%	1%	2%	0%	0%

Table 5-1b Damage Percent for Air Transportation Runways for Each Scenario Earthquake (Percent of Airports in State)

	NEW MADRID (M=8.0)					
Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	< 1%	< 1%	20%	3%	< 1%	17%
Moderate 10-30 %	0%	5%	15%	< 1%	0%	0%
Heavy 30-60 %	0%	1%	0%	2%	0%	0%
Major to Destructive 60-100 %	0%	6%	0%	0%	0%	0%

	CHARLESTON (M=7.5)		
Total Number	South Carolina 147	North Carolina 309	Georgia 343
Light Damage 1-10 %	2%	1%	1%
Moderate 10-30 %	3%	0%	2%
Heavy 30-60 %	1%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 149	Connecticut 115	Delaware 37	Rhode Island 55	New Hampshire 63	Utah 107
Light Damage 1-10 %	< 1%	0%	0%	0%	0%	5%
Moderate 10-30 %	4%	0%	0%	0%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 869	California 869	Washington 364	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	4%	7%	6%	0%	2%	12%	< 1%	0%	2%
Moderate 10-30 %	2%	14%	16%	0%	3%	1%	< 2%	0%	0%
Heavy 30-60 %	0%	< 1%	0%	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 5-2 Damage Percent for Ports for Selected Scenario Earthquakes (Percent of Ports in State)

	CHARLESTON (M=7.5)			CAPE ANN (M=7.0)				
Total Number	South Carolina 20	North Carolina 16	Georgia 30	Massachusetts 34	Connecticut 22	Delaware 10	Rhode Island 22	New Hampshire 9
Light Damage 1-10 %	0%	0%	10%	100%	0%	0%	86%	0%
Moderate 10-30 %	0%	0%	0%	0%	0%	0%	0%	0%
Heavy 30-60 %	100%	0%	73%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 125	California 125	Washington 77
Light Damage 1-10 %	4%	0%	25%
Moderate 10-30 %	22%	34%	26%
Heavy 30-60 %	0%	0%	14%
Major to Destructive 60-100 %	0%	0%	0%

Table 5-3 Damage Percent for Medical Care Facilities for Each Scenario Earthquake (Percent of Facilities in State)

	NEW MADRID (M=8.0)							*CHARLESTON (M=7.5)*		
Total Number	*Illinois* 249	*Missouri* 171	*Arkansas* 99	*Tennessee* 167	*Kentucky* 125	*Indiana* 102	*Mississippi* 127	*South Carolina* 91	*North Carolina* 161	*Georgia* 207
Light Damage 1-10 %	22%	6%	16%	18%	20%	7%	62%	30%	15%	32%
Moderate 10-30 %	0%	0%	29%	14%	< 1%	0%	17%	7%	2%	1%
Heavy 30-60 %	0%	0%	3%	0%	0%	0%	0%	10%	0%	0%
Major to Destructive 60-100 %	0%	3%	7%	< 1%	0%	0%	0%	3%	0%	1%

	CAPE ANN (M=7.0)					*WASATCH FRONT (M=7.5)*
Total Number	*Massachusetts* 167	*Connecticut* 66	*Delaware* 13	*Rhode Island* 22	*New Hampshire* 40	*Utah* 53
Light Damage 1-10 %	90%	50%	46%	82%	48%	17%
Moderate 10-30 %	0%	0%	0%	0%	0%	51%
Heavy 30-60 %	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	2%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	*FORT TEJON (M=8.0)*	*PUGET SOUND (M=7.5)*
Total Number	*California* 478	*California* 478	*Washington* 102
Light Damage 1-10%	12%	16%	7%
Moderate 10-30%	16%	20%	18%
Heavy 30-60 %	9%	10%	5%
Major to Destructive 60-100 %	0%	0%	10%

the hospitals in South Carolina (12 in total) would sustain heavy or major-to-destructive damage (30 to 100%). In the New Madrid magnitude-8.0 event, 10% of the hospitals in Arkansas (10 in total) and 3% of the hospitals in Missouri (5 in total) would sustain similar damage. In California, 10% and 9%, or 48 and 43 hospitals, respectively, would sustain heavy damage (30-to-60%) in the Fort Tejon and Hayward scenarios. It is worth noting that results from a separate study by Applied Technology Council (ATC, 1991) appear to be comparable for the magnitude-7.5 Hayward fault scenario.

As in the case of airports, the reason for severe damage to hospital facilities in the Puget Sound, New Madrid, and Charleston events is assumed to be strongly correlated with poor ground conditions and construction practices.

5.3.4 Police and Fire Stations

As in the case of medical care facilities, direct damage data for police and fire stations (Tables 5-4 and 5-5) suggest that damage to this facility type will be more severe for the New Madrid, Charleston, and Puget Sound events than for the California, Wasatch Front, and Cape Ann events. For example, data for the New Madrid magnitude-8.0 event indicate that 9% of the fire stations and 8% of the police stations in Arkansas would sustain heavy or major-to-destructive damage (30 to 100%). Thirteen and twelve percent, respectively, of fire and police stations in South Carolina would be similarly damaged in the Charleston scenario event, and 15% and 8%, respectively, would be similarly affected by the Puget Sound magnitude-7.5 scenario event.

The reason for severe damage to fire and police stations in the Puget Sound, New Madrid, and Charleston events is assumed to be strongly correlated with poor ground conditions and construction practices.

5.3.5 Broadcast Stations

Direct damage to broadcast stations for the eight scenario earthquakes follows a slightly different pattern than for the other site-specific lifelines. As indicated in Table 5-6, direct damage is relatively high for the magnitude-8 New Madrid, Charleston, and Puget Sound events and slightly less for the Wasatch Front and Fort Tejon events. Data for the New Madrid magnitude-8.0 earthquake scenario indicate that 17% of the broadcast stations in Arkansas (approximately 78 in total) would sustain heavy damage or major-to-destructive damage (30 to 100%). For the Charleston event, 23% or 87 broadcast stations would be similarly affected, and for the Puget Sound event, 14% (122 in total) would be similarly affected. Percentages for the Wasatch Front and Fort Tejon equal approximately 5%, representing 54 damaged broadcast stations in Utah and 77 or fewer in California.

5.4 Direct Damage Estimates for Extended Lifeline Networks

This section presents direct damage estimates for extended network lifelines, such as highways, railroads and other networks at the bulk and/or regional level. The inventory data provided in Chapter 2 were used to define the location of all nodes and links. For all systems except pipelines, direct damage is estimated using the methodology specified above. Results are presented in terms of (1) the same four damage states used for site-specific lifelines, and (2) maps indicating the damaged portions of each extended network for the various scenario earthquakes.

For pipelines, direct damage is estimated (1) using the damage curves specified in Appendix B (in terms of breaks per kilometer), (2) a model that estimates the probability of breaks occurring within given lengths of pipe subjected to given earthquake shaking intensities (Khater, M., et al., 1989), and (3) a special procedure for estimating damage due to liquefaction. Breaks are assumed to occur according to a nonhomogeneous Poisson process. The probability P_f of having at least one break in a line with length L is given by

$$P_f(L, MMI(x)) = 1 - \prod_{k=1}^{N} P_s(l_k, MMI_k) \qquad (5.4)$$

where

$$P_s(l_k, MMI_k) = \exp(-\lambda_k x\, l_k) \quad k=1,...,N \qquad (5.5)$$

in which Π is the multiplier operator; N is the number of grid cells through which the pipeline

Table 5-4 Damage Percent for Fire Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)						*CHARLESTON (M=7.5)*		
Total Number	*Illinois 923*	*Missouri 41*	*Arkansas 185*	*Tennessee 378*	*Kentucky 285*	*Mississippi 200*	*South Carolina 275*	*North Carolina 570*	*Georgia 490*
Light Damage 1-10 %	4%	2%	15%	18%	6%	14%	18%	2%	14%
Moderate 10-30 %	2%	1%	15%	5%	0%	10%	1%	0%	1%
Heavy 30-60 %	0%	2%	9%	0%	0%	0%	13%	0%	1%
Major to Destructive 60-100 %	0%	< 1%	0%	< 1%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	*FORT TEJON (M=8.0)*	*PUGET SOUND (M=7.5)*	*NEW MADRID (M=7.0)*				
Total Number	*California 2230*	*California 2230*	*Washington 361*	*Missouri 410*	*Arkansas 185*	*Tennessee 378*	*Kentucky 285*	*Mississippi 200*
Light Damage 1-10 %	7%	15%	3%	0%	15%	10%	< 1%	5%
Moderate 10-30 %	3%	27%	18%	1%	8%	0%	0%	0%
Heavy 30-60 %	0%	0%	15%	1%	0%	< 1%	0%	0%
Major to Destructive 60-100 %	0%	< 1%	0%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)		*WASATCH FRONT (M=7.5)*
Total Number	*Massachusetts 459*	*Rhode Island 69*	*Utah 140*
Light Damage 1-10%	57%	5%	51%
Moderate 10-30%	0%	0%	11%
Heavy 30-60 %	2%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%

Table 5-5 Damage Percent for Police Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)						CHARLESTON (M=7.5)		
Total Number	Illinois 232	Missouri 102	Arkansas 48	Tennessee 98	Kentucky 74	Mississippi 52	South Carolina 70	North Carolina 132	Georgia 126
Light Damage 1-10 %	4%	2%	14%	10%	5%	13%	16%	2%	13%
Moderate 10-30 %	2%	1%	10%	5%	0%	9%	1%	0%	1%
Heavy 30-60 %	0%	2%	8%	0%	0%	0%	12%	0%	1%
Major to Destructive 60-100 %	0%	<1%	0%	<1%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)		WASATCH FRONT (M=7.5)	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)				
Total Number	Massachusetts 118	Rhode Island 18	Utah 34	California 580	California 580	Washington 94	Missouri 102	Arkansas 48	Tennessee 98	Kentucky 74	Mississippi 52
Light Damage 1-10 %	26%	5%	22%	6%	14%	3%	0%	14%	9%	<1%	5%
Moderate 10-30 %	0%	0%	10%	3%	8%	16%	1%	7%	0%	0%	0%
Heavy 30-60 %	2%	0%	0%	0%	0%	8%	1%	0%	<1%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	<1%	0%	0%	0%	0%	0%	0%

Table 5-6 Damage Percent for Broadcast Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 600	Missouri 524	Arkansas 456	Tennessee 587	Kentucky 474	Indiana 407	Mississippi 416	South Carolina 377	North Carolina 697	Georgia 604
Light Damage 1-10 %	8%	6%	16%	6%	16%	4%	51%	15%	17%	23%
Moderate 10-30 %	< 1%	0%	14%	20%	7%	0%	16%	24%	4%	16%
Heavy 30-60 %	0%	0%	12%	4%	< 1%	0%	12%	5%	1%	1%
Major to Destructive 60-100 %	0%	4%	5%	1%	1%	0%	0%	18%	0%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT M=7.5)
Total Number	Massachusetts 274	Connecticut 155	Delaware 42	Rhode Island 53	New Hampshire 112	Utah 900
Light Damage 1-10 %	38%	50%	74%	70%	40%	10%
Moderate 10-30 %	35%	0%	0%	26%	0%	27%
Heavy 30-60 %	0%	0%	0%	0%	0%	5%
Major to Destructive 60-100 %	1%	0%	0%	0%	0%	0%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 1,538	California 1,538	Washington 872	Illinois 600	Missouri 524	Arkansas 456	Tennessee 587	Kentucky 474	Mississippi 416
Light Damage 1-10 %	4%	16%	2%	0%	1%	12%	13%	6%	15%
Moderate 10-30 %	8%	4%	8%	< 1%	0%	15%	11%	2%	3%
Heavy 30-60 %	1%	4%	5%	0%	1%	4%	< 1%	1%	0%
Major to Destructive 60-100 %	0%	< 1%	9%	0%	2%	0%	1%	0%	0%

Table 5-7 Damage to Railroad System (Length of Roadbed, Km)

Events	Light Damage 1-10%	Moderate 10-30%	Heavy 30-60%	Major to Destructive 60-100%
Cape Ann	0	0	63	0
Charleston	890	85	980	0
Fort Tejon	640	340	825	47
Hayward	988	47	445	140
New Madrid (M=8.0)	3,000	670	1,780	485
New Madrid (M=7.0)	1,198	0	640	0
Puget Sound	340	0	650	0
Wasatch Front	770	300	0	0
Total System Length = 270,611 km				

passes; l_k and MMI_k are the length of the lifeline element and the Modified Mercalli Intensity, respectively, within grid cell k; and λ_k is the mean break rate (taken from Appendix B).

Maps are provided showing sections of pipeline for which the probability of failure exceeds 60% for the various scenario earthquakes. For soil conditions where liquefaction is possible, a break is assumed at each location where the pipeline crosses into a liquefiable zone.

5.4.1 Railroad System

The railroad system is a highly redundant system, and damage to the system due to the selected events was found to be relatively localized to the epicentral area. Direct damage to the railroad system for each scenario event is summarized in Table 5-7, which lists the length (km) of damaged railroad right-of-way within each damage state. The damage estimates are based on damage curves for track/roadbed and exclude damage to related facility types not included in the project inventory--railway terminals, railway bridges and tunnels.

The direct damage data suggest that the magnitude-8 New Madrid, Fort Tejon, and Hayward events would cause the most extensive damage, with 2,265 km, 872 km, and 585 km of roadbed, respectively, sustaining damage in the 30 to 100% range. Damage in the Charleston, Puget Sound, and magnitude-7.0 New Madrid events would also be severe, with 980, 650, and 640 km of roadbed, respectively, sustaining heavy damage (30-to-60 %). Maps showing the distribution of damage to the railroad system for each of the 8 events are provided in Figures 5-1 to 5-8.

5.4.2 Highway System

The highway system is also a highly redundant system, consisting of freeways/highways and bridges. As is in the case of the railroad system, damage to the highway system for each scenario event was found to be localized to the epicentral area. Direct damage to freeways/highways, expressed in terms of km of roadway in the various damage states, are summarized in Table 5-8 and plotted on Figures 5-9 to 5-16 for the eight scenario earthquakes. Bridge damage, expressed in terms of the percent of bridges in each damage state, is summarized in Table 5-9. The roadway and bridge damage data are based, respectively, on damage curves for freeways/highways and for conventional bridges; the estimates exclude damage to tunnels, which are not included in the project inventory. We note also that all bridges are assumed to be conventional bridges because of (1) lack of capacity/size information in the project inventory and (2) the very small percentage of major bridges in the overall national database.

Tables 5-8 and 5-9 indicate that direct damage is not expected to be as severe for freeways/highways as it is for bridges. For

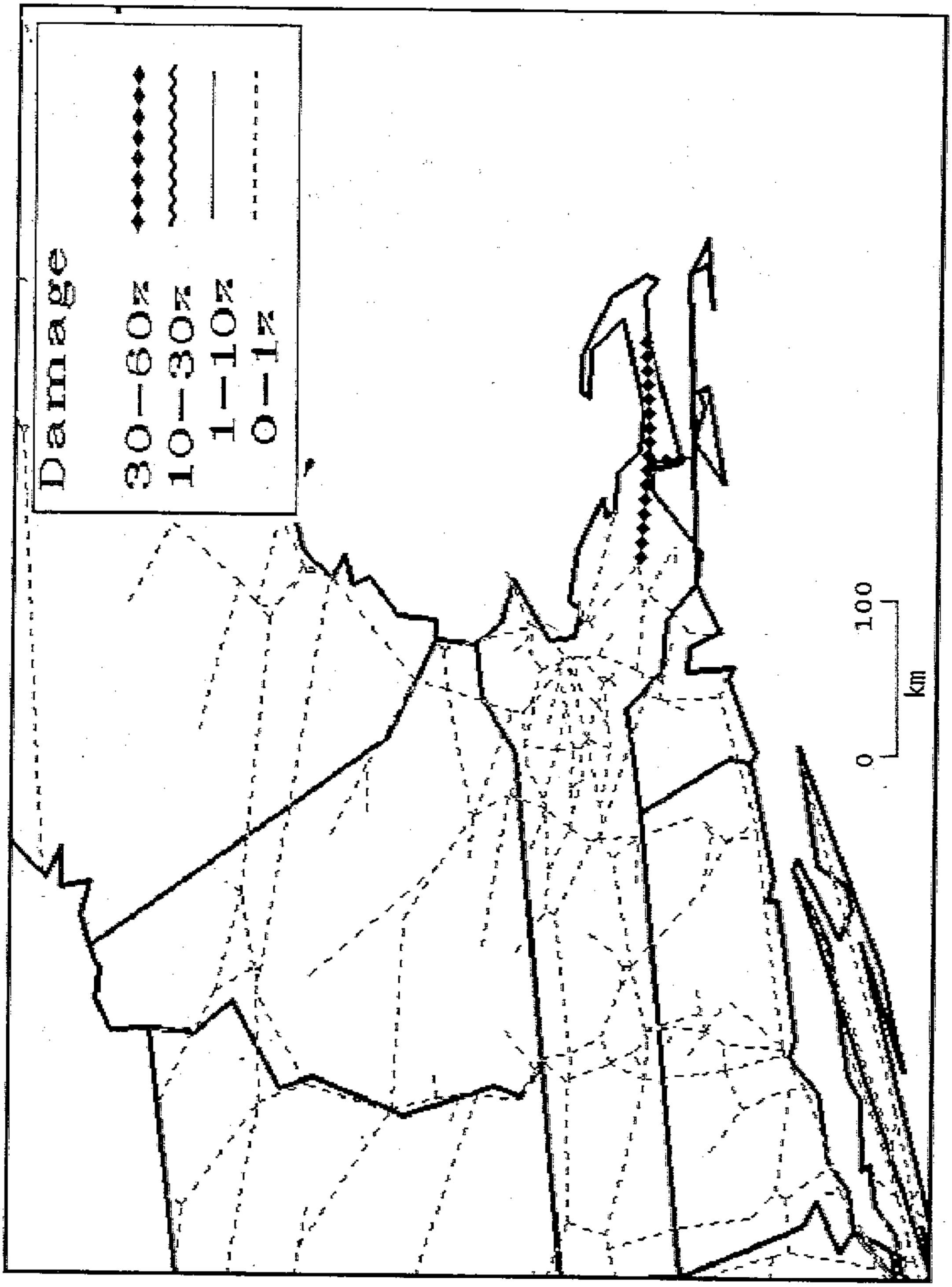


Figure 5-1 *Damage to railroad system following Cape Ann event (M=7.0).*

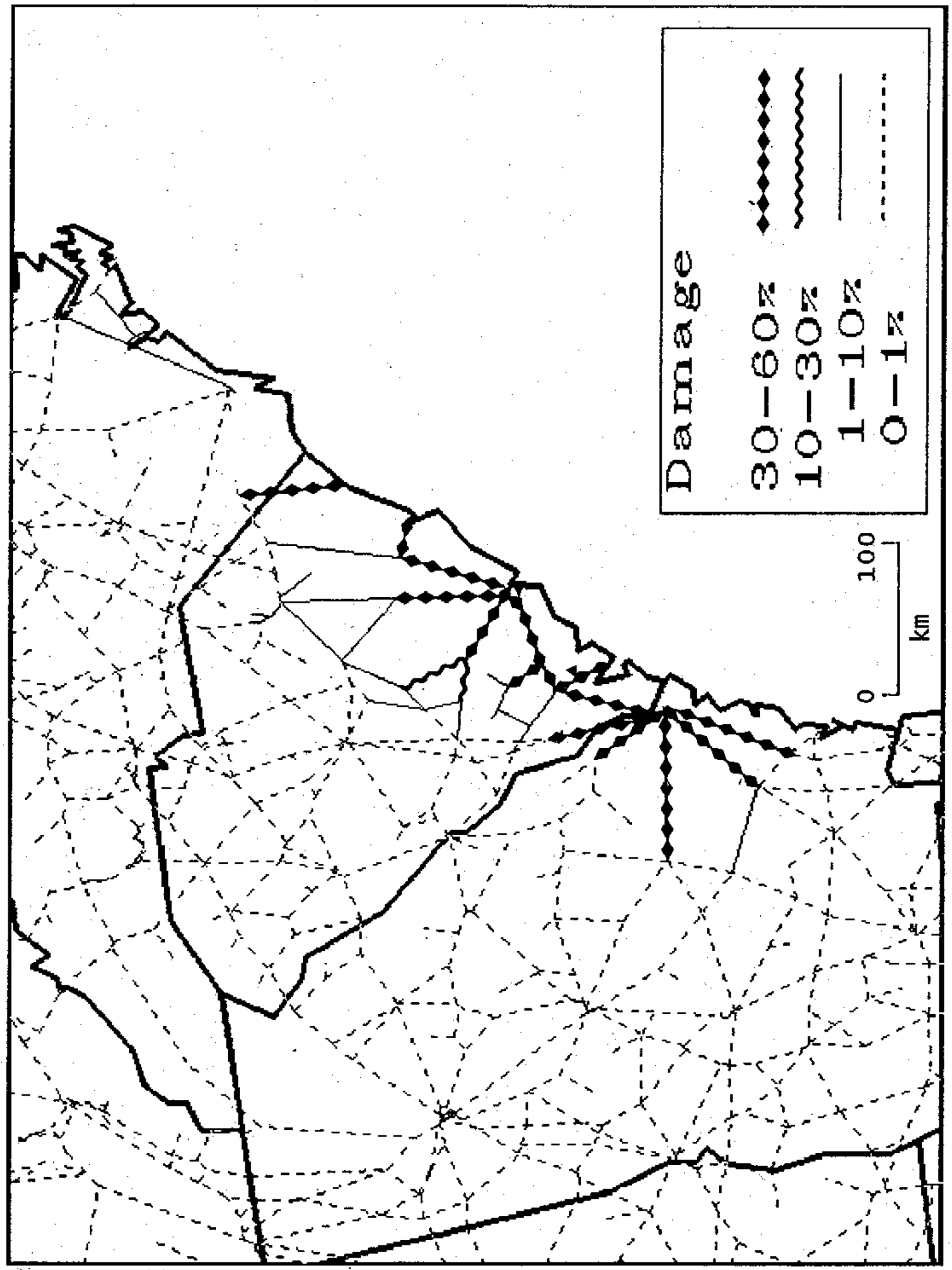


Figure 5-2. *Damage to railroad system following Charleston event (M=7.5).*

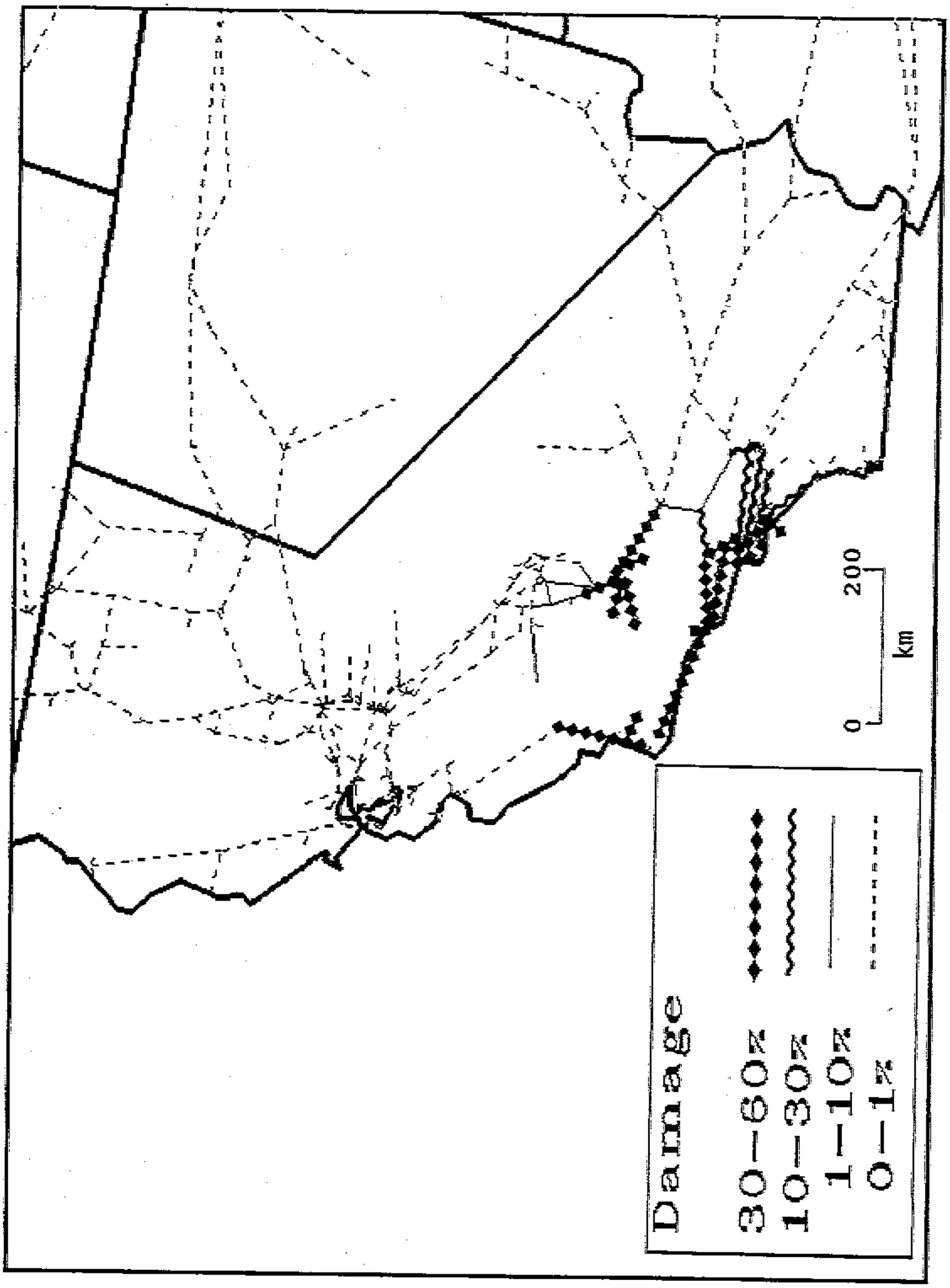


Figure 5-3 *Damage to railroad system following Fort Tejon event (M=8.0).*

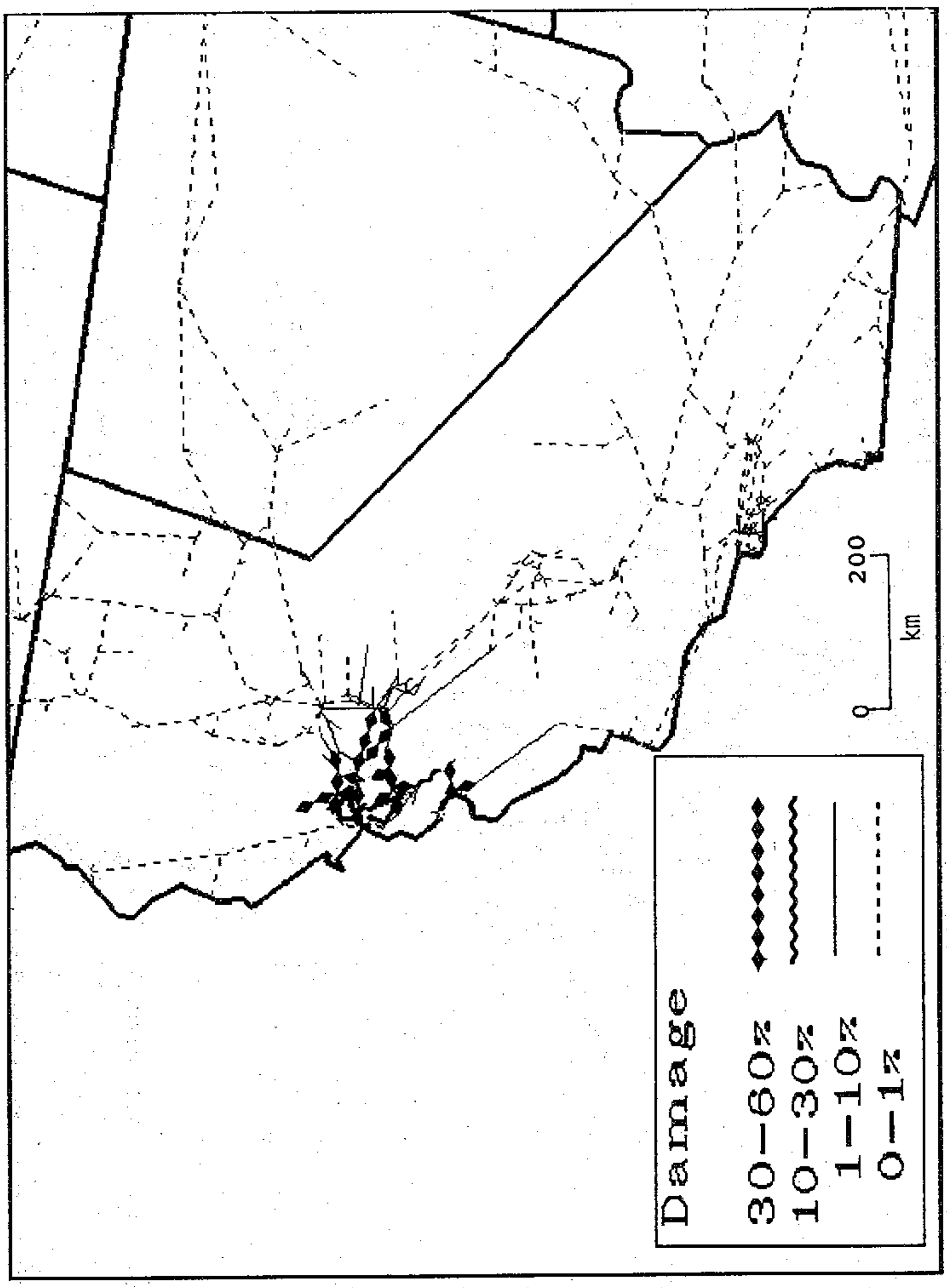


Figure 5-4 *Damage to railroad system following Hayward event (M=7.5).*

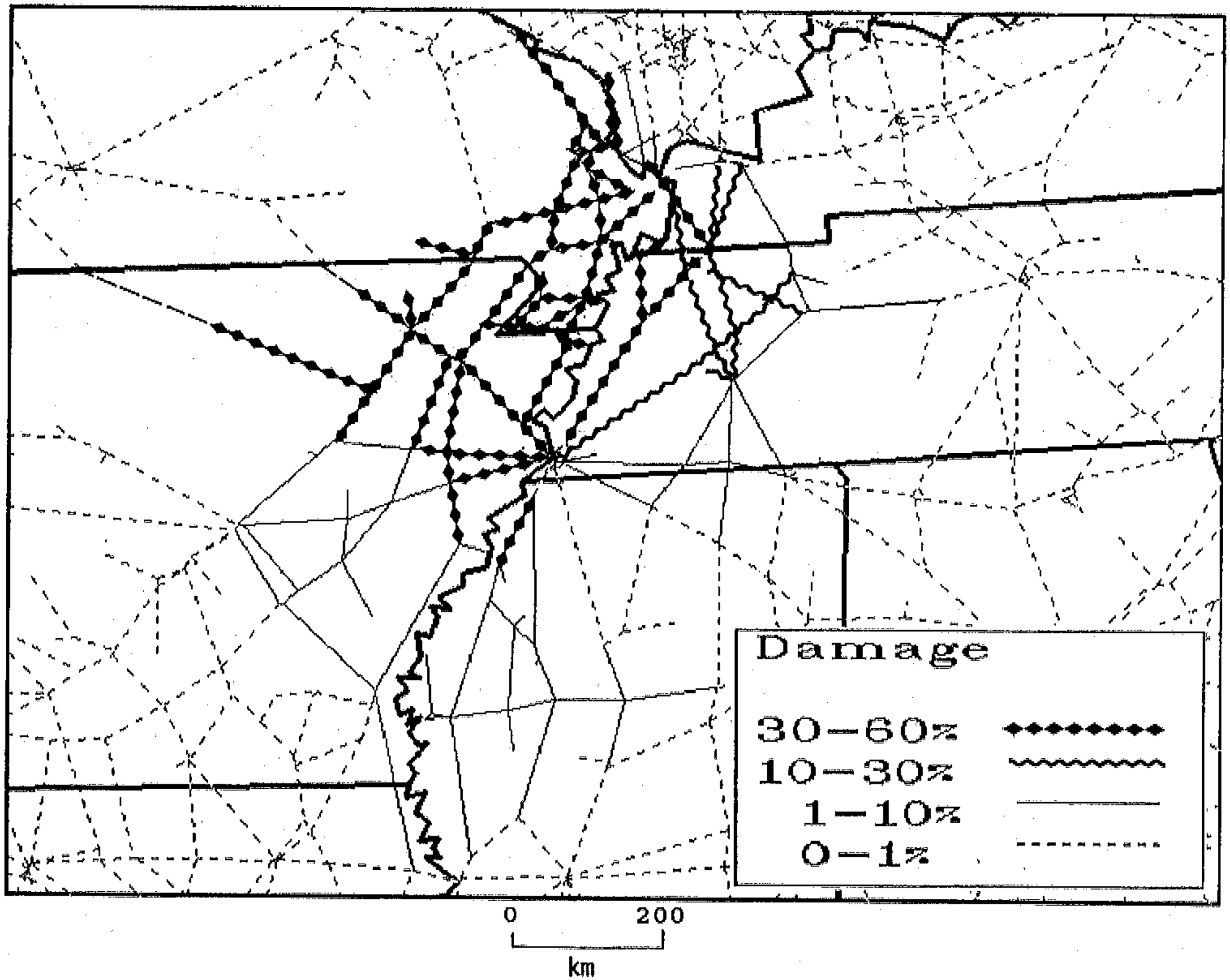


Figure 5-5 *Damage to railroad system following New Madrid event (M=8.0).*

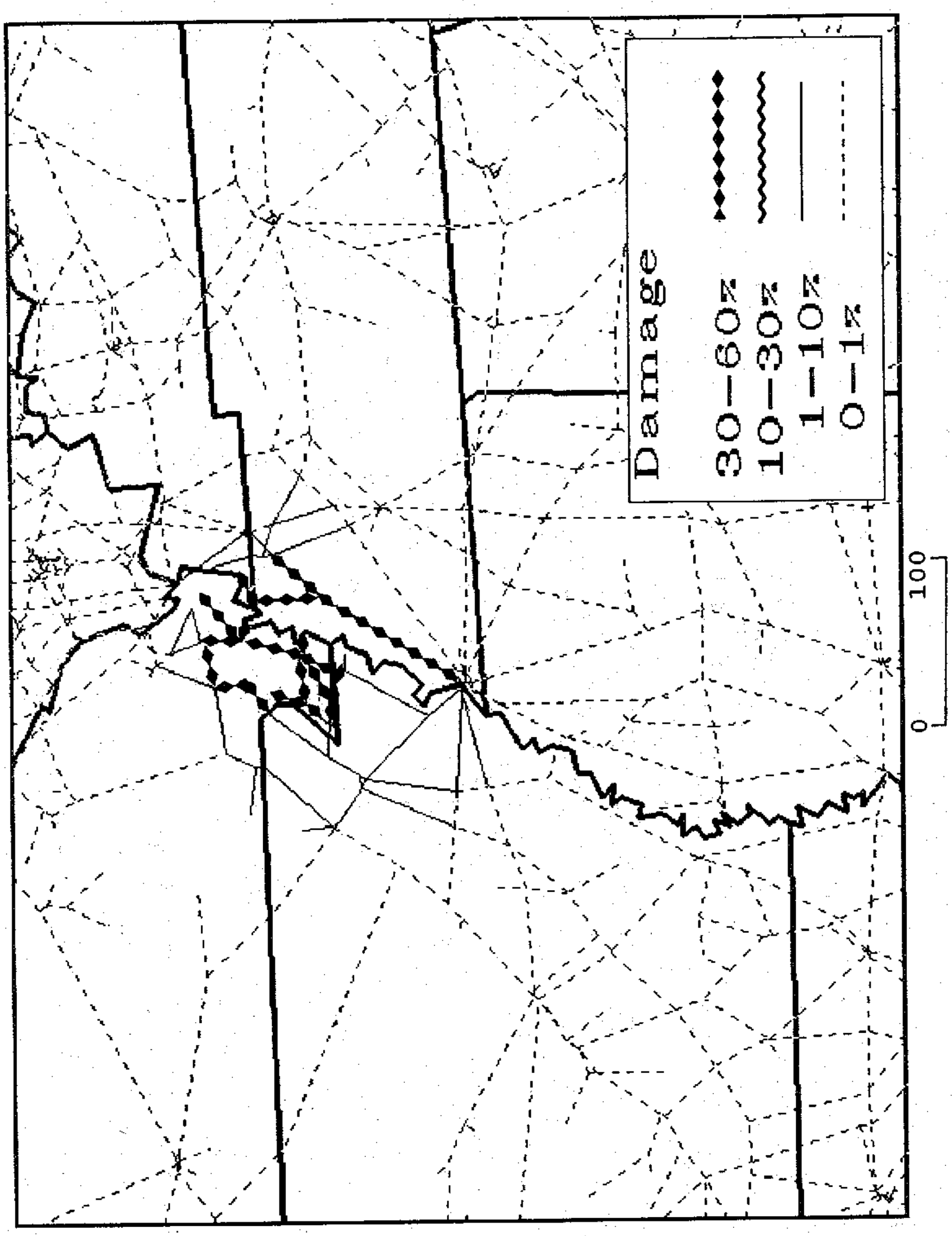


Figure 5-6 *Damage to railroad system following New Madrid event (M=7.0).*

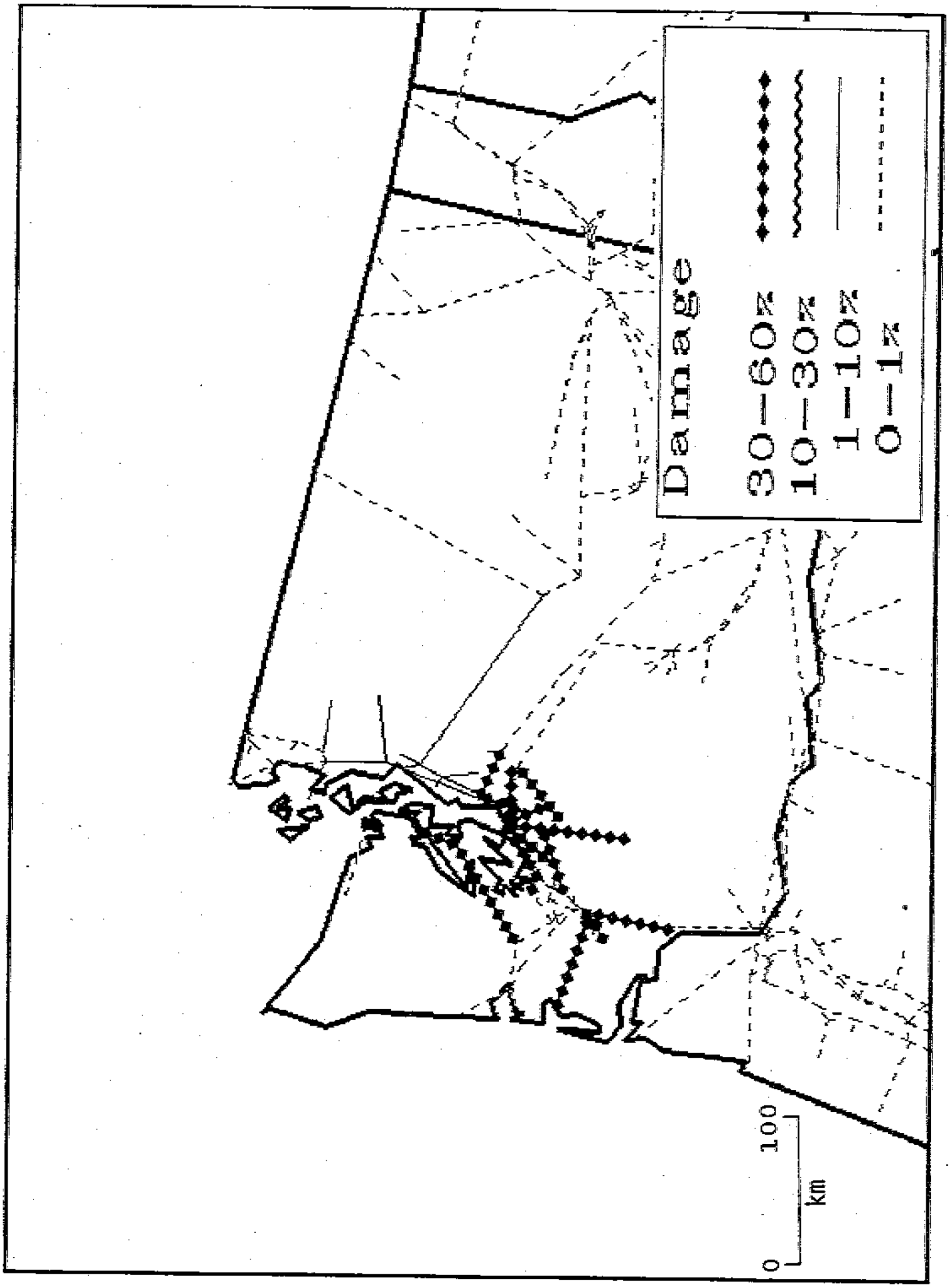


Figure 5-7 *Damage to railroad system following Puget Sound event (M=7.5).*

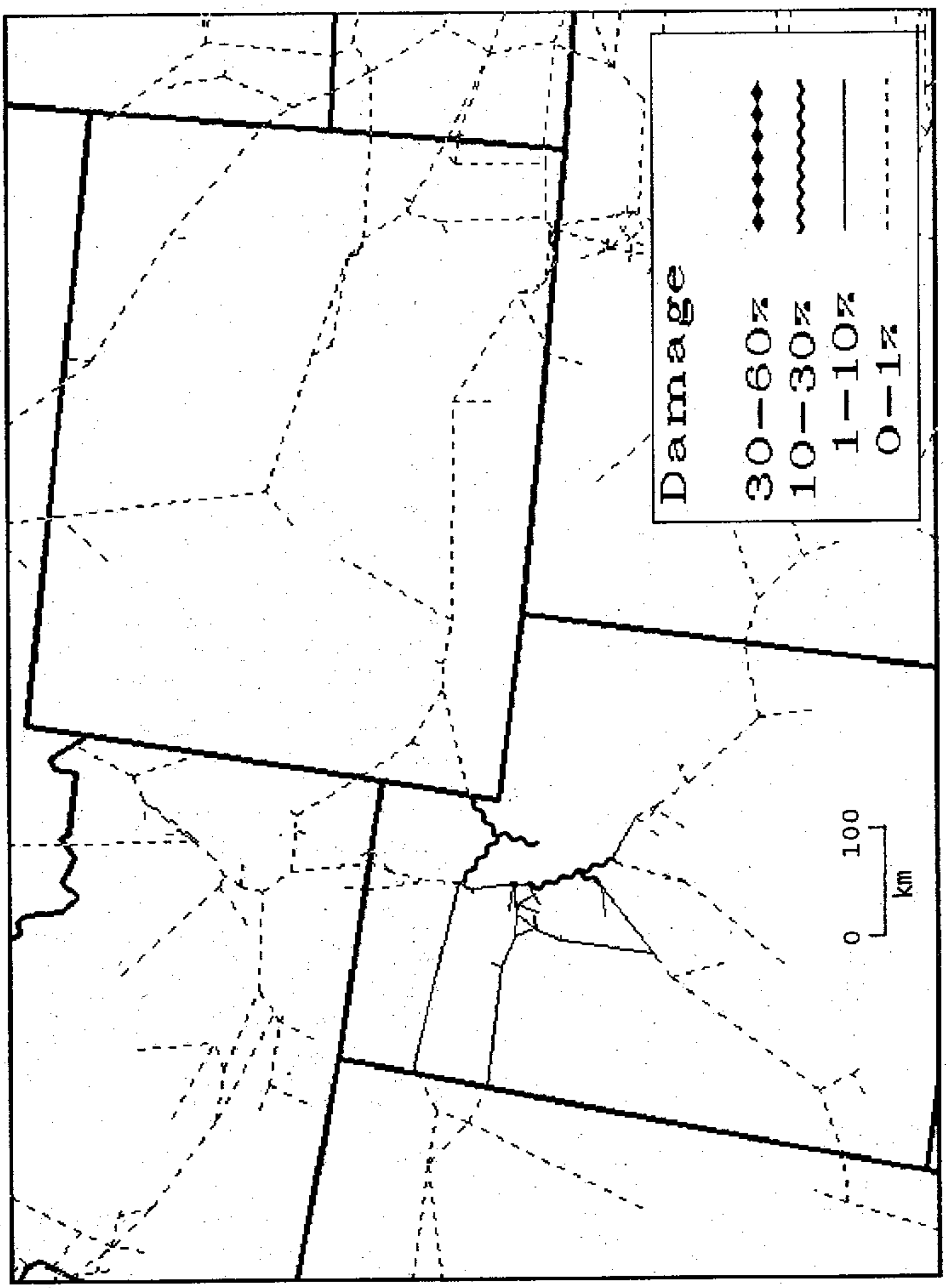


Figure 5-8 *Damage to railroad system following Wasatch Front event (M=7.5).*

Table 5-8 Damage to Freeway/Highway System (Length of Highway, Km)

Event	Light Damage 1-10%	Moderate 10-30%	Heavy 30-60%	Major to Destructive 60-100%
Cape Ann	74	182	0	0
Charleston	2,182	999	0	0
Fort Tejon	2,174	1,557	0	0
Hayward	1,567	476	0	0
New Madrid (M=8.0)	4,967	2,753	0	0
New Madrid (M=7.0)	1,800	720	0	0
Puget Sound	665	769	0	0
Wasatch Front	1,392	0	0	0

Total System Length = 489,892 km

example, direct damage to freeways/highways is not expected to exceed 30% at any location for any scenario earthquake. Data for bridges (Table 5-9), however, suggest that direct damage will range from 30-to-100 % for various locations affected by the Charleston, New Madrid (magnitude-8.0), Puget Sound, and Wasatch Front events. Bridges in Utah appear to be at the greatest risk, with 25 percent of the bridges (approximately 287 bridges) expected to sustain damage in the 30-to-100 % range. Eighteen percent of the bridges in Arkansas (approximately 423), 16 % in Washington (approximately 305), and eleven percent in Tennessee (approximately 407) would sustain similar levels of damage. The difference in expected performance between highways and bridges results from the difference in damage curves for these two structure types.

5.4.3 Electric System

Direct damage estimates for the electric system are based on curves for transmission lines and transmission substations and exclude damage to related facility types not included in the project inventory--nuclear and fossil-fuel power plants, and hydroelectric power plants (dams). Damage data for each scenario earthquake are summarized in Tables 5-10 and 5-11, which provide the length of transmissions lines and percent of substations, respectively, in each damage state. Maps provided in Figures 5-17 through 5-24 show plots of damage to transmission lines for the eight scenario earthquakes.

Damage data for transmission lines (Table 5-10 and Figures 5-17 through 5-24) indicate that damage to this facility type is expected to be greatest for the New Madrid (magnitude 8.0) and Fort Tejon events, in which 800 km and 1370 km, respectively, would sustain damage ranging from 10-to-30 %.

Direct damage data for transmission substations, summarized in Table 5-11, indicate that this facility type would be severely impacted in all scenario events. The impacts are most severe in the Puget Sound, magnitude-8.0 New Madrid, Wasatch Front, Charleston, and Hayward events. For these scenario earthquakes, 46 % of the transmission substations in Washington, 39 % in Arkansas, 30 % in South Carolina, 30 % in Utah and 27 % in California would sustain damage in the 30-to-100 % range.

5.4.4 Water System

Direct damage to those water transmission systems for which inventory data are available are summarized in Tables 5-12 and 5-13. These estimates are based on damage curves for aqueducts and exclude damage to pumping stations and dams, which are not included in the project inventory. The data indicate that 38 and 20 km of the aqueduct system (Table 5-12), respectively, would sustain moderate to heavy damage (10-to-60 %) in the Fort Tejon and

Table 5-9 Damage Percent for Highway Bridges for Each Scenario Earthquake (Percent of Bridges in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 4,674	Missouri 4,496	Arkansas 2,353	Tennessee 3,698	Kentucky 2,797	Indiana 3,326	Mississippi 3,096	South Carolina 2,134	North Carolina 3,120	Georgia 4,193
Light Damage 1-10 %	10%	6%	16%	8%	16%	2%	56%	15%	9%	17%
Moderate 10-30 %	1%	0%	12%	9%	3%	0%	16%	15%	1%	17%
Heavy 30-60 %	0%	0%	5%	4%	0%	0%	0%	6%	< 1%	< 1%
Major to Destructive 60-100 %	< 1%	0%	13%	7%	3%	0%	8%	1%	< 1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 2,013	Connecticut 1,878	Delaware 297	Rhode Island 283	New Hampshire 1,020	Utah 1,149
Light Damage 1-10 %	46%	45%	21%	76%	53%	7%
Moderate 10-30 %	37%	0%	0%	15%	1%	11%
Heavy 30-60 %	0%	0%	0%	0%	0%	10%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	15%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 7,948	California 7,948	Washington 1,908
Light Damage 1-10 %	4%	22%	8%
Moderate 10-30 %	2%	< 1%	12%
Heavy 30-60 %	0%	0%	3%
Major to Destructive 60-100 %	0%	0%	13%

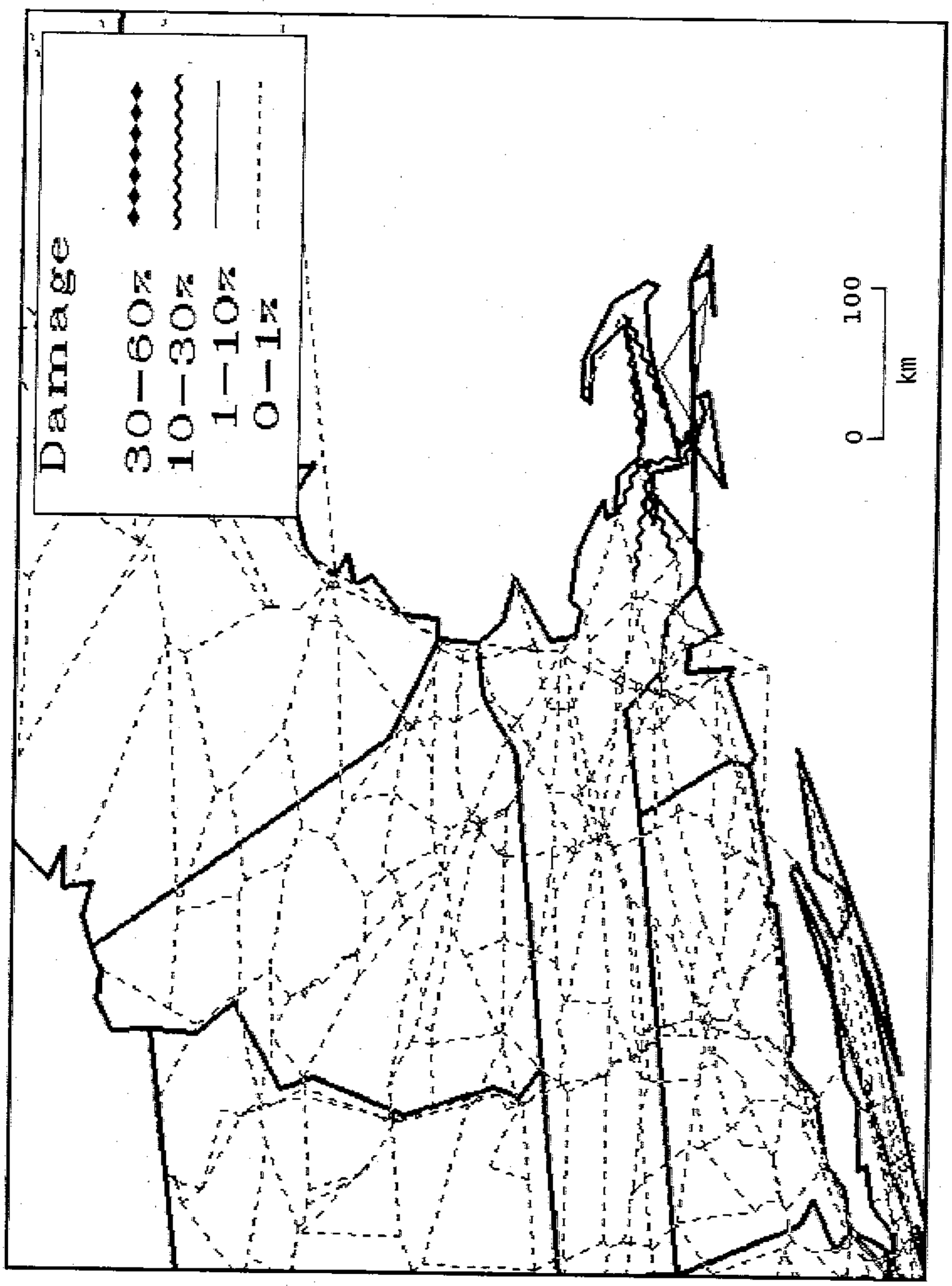


Figure 5-9 *Damage to highways following Cape Ann event (M=7.0).*

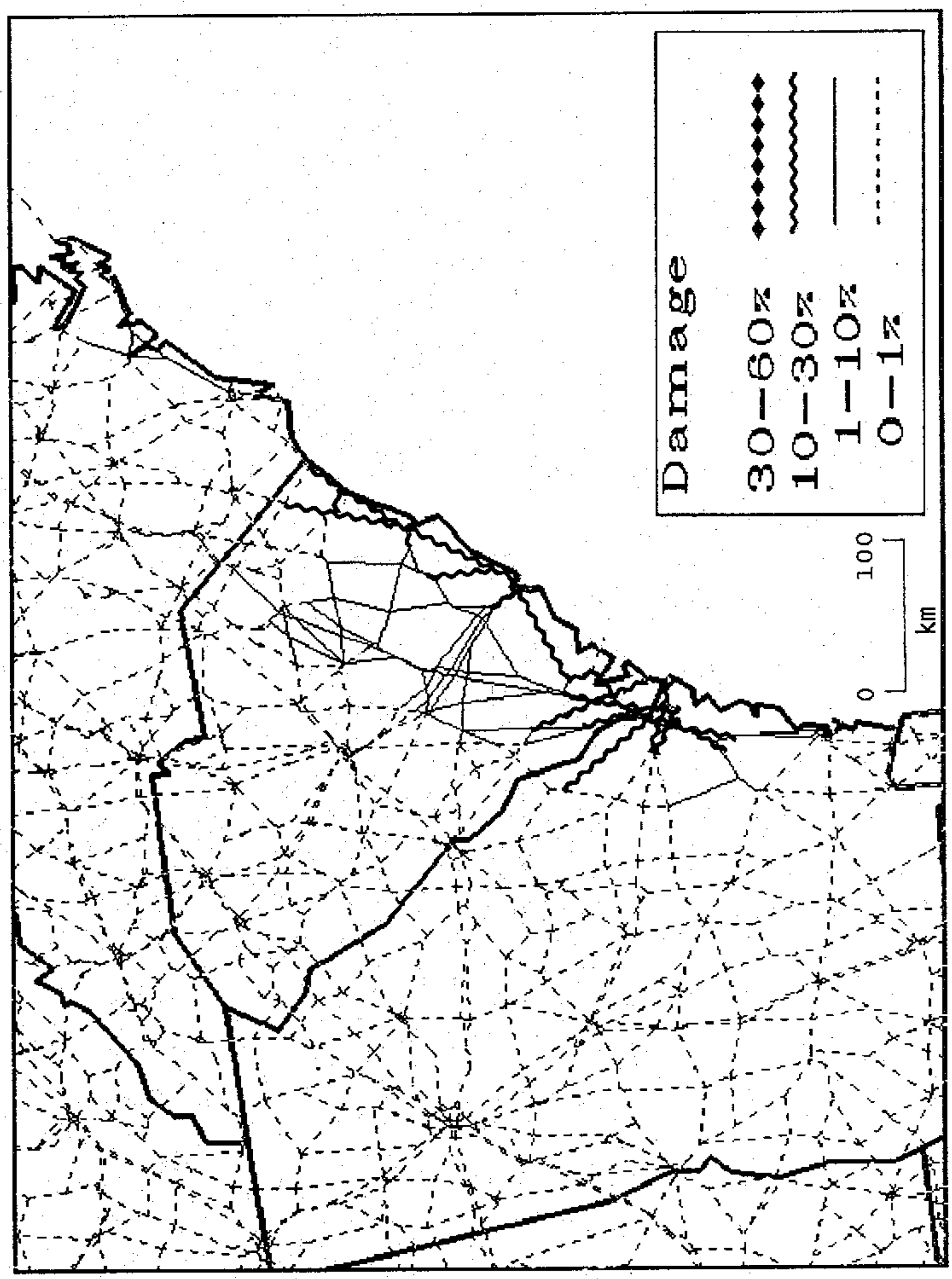


Figure 5-10 *Damage to highways following Charleston event (M=7.5).*

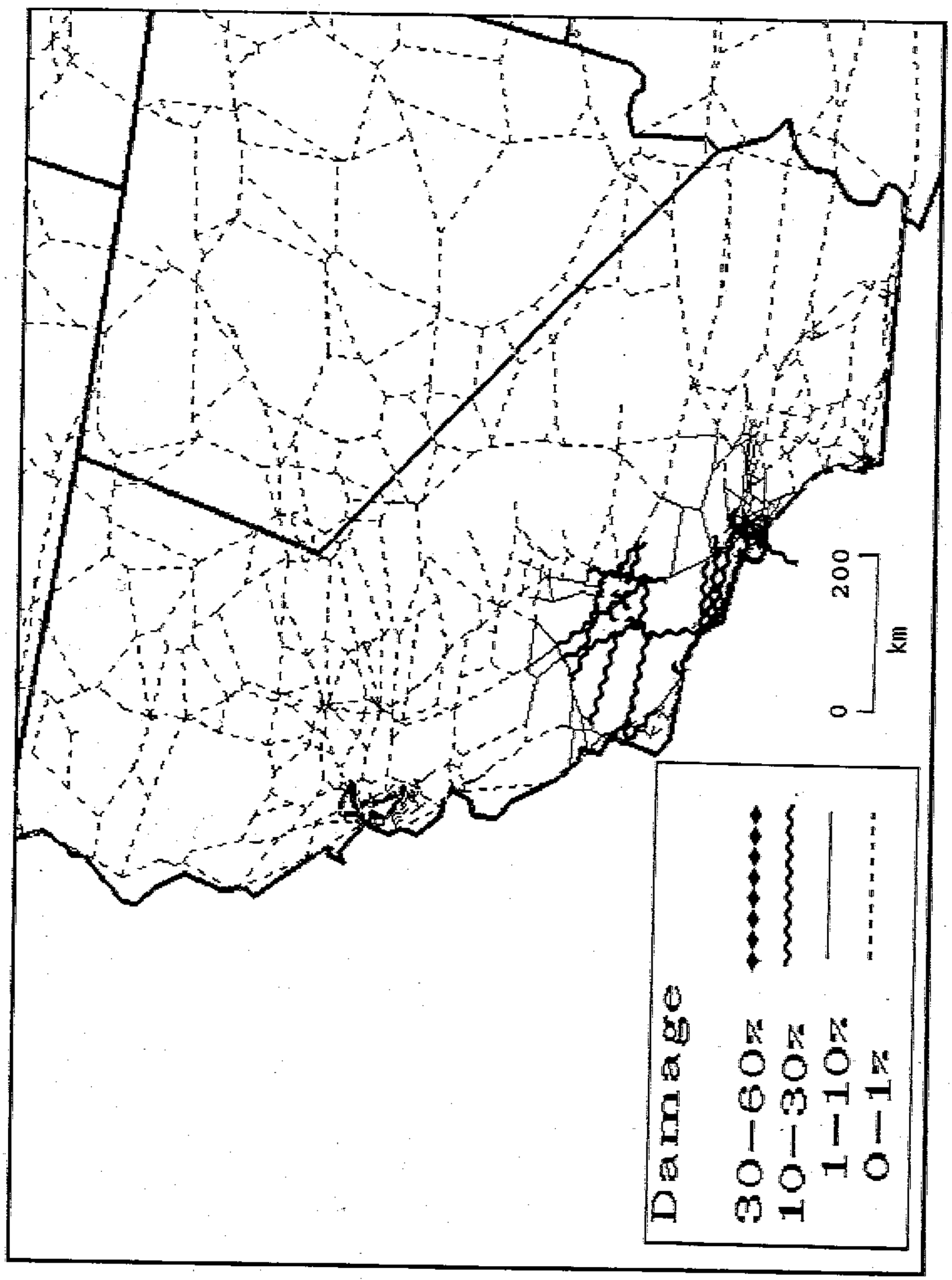


Figure 5-11 *Damage to highways following Fort Tejon event (M=8.0).*

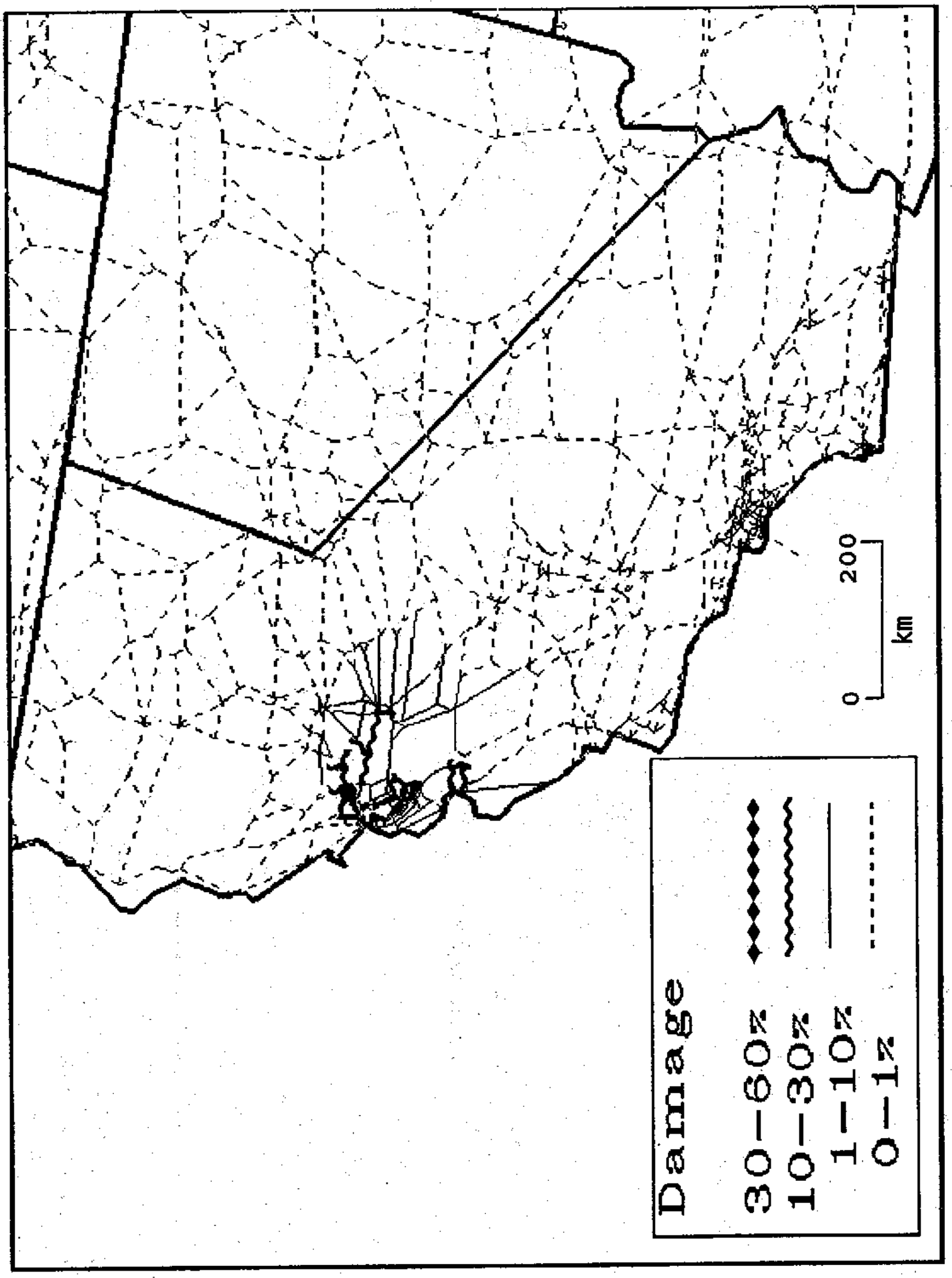


Figure 5-12 *Damage to highways following Hayward event (M=7.5).*

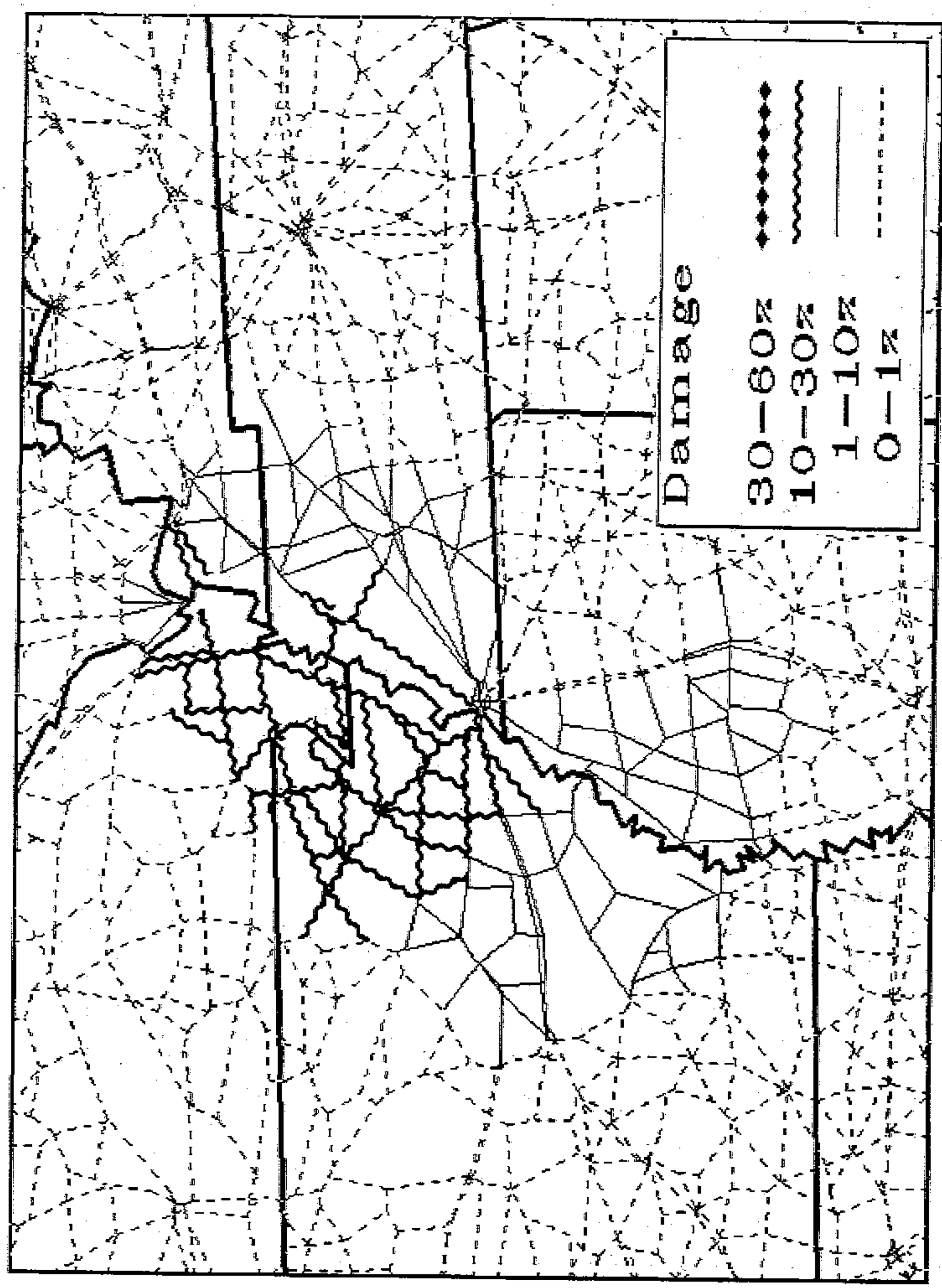


Figure 5-13 *Damage to highways following New Madrid event (M=8.0).*

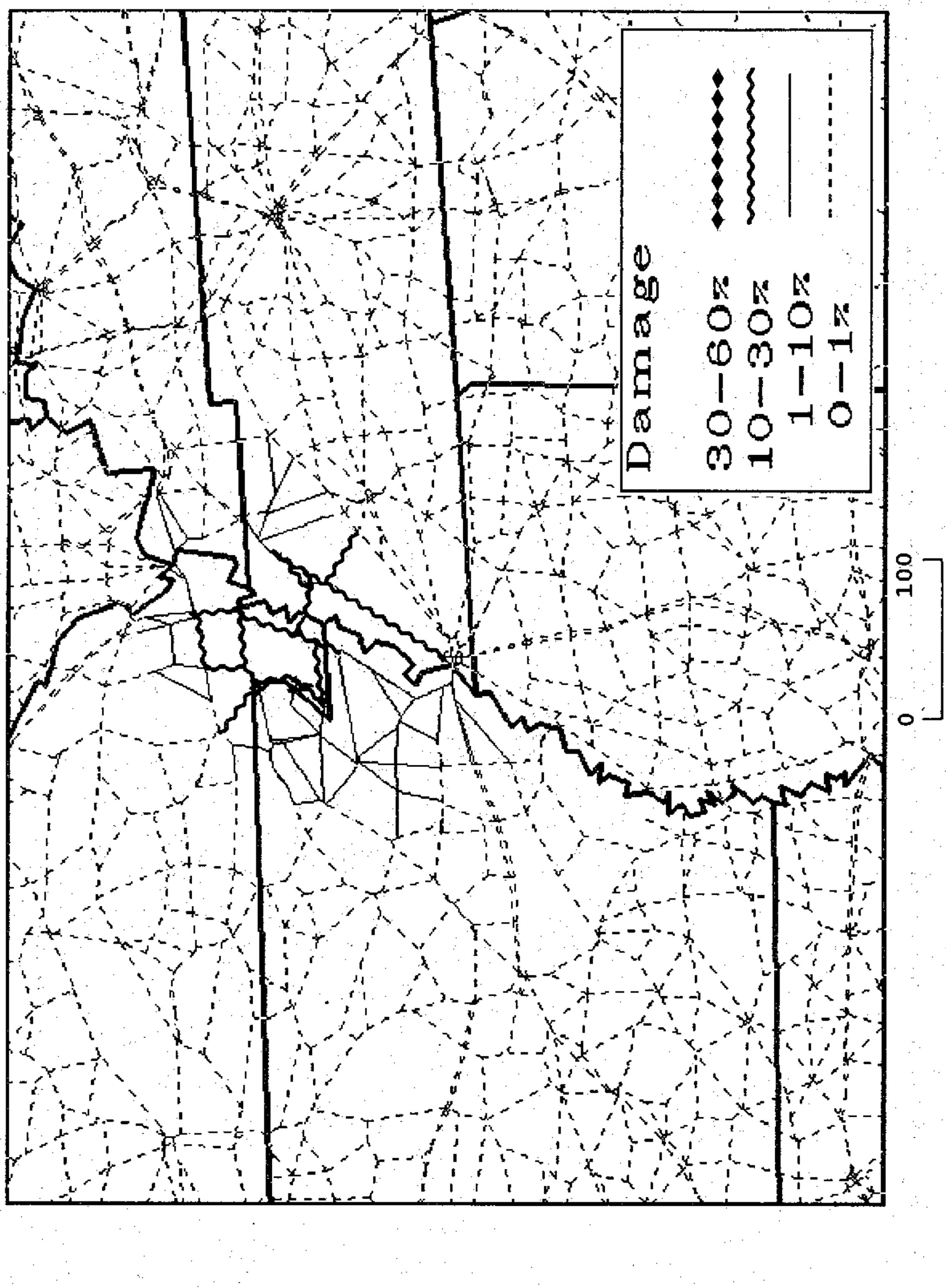


Figure 5-14 *Damage to highways following New Madrid event (M=7.0).*

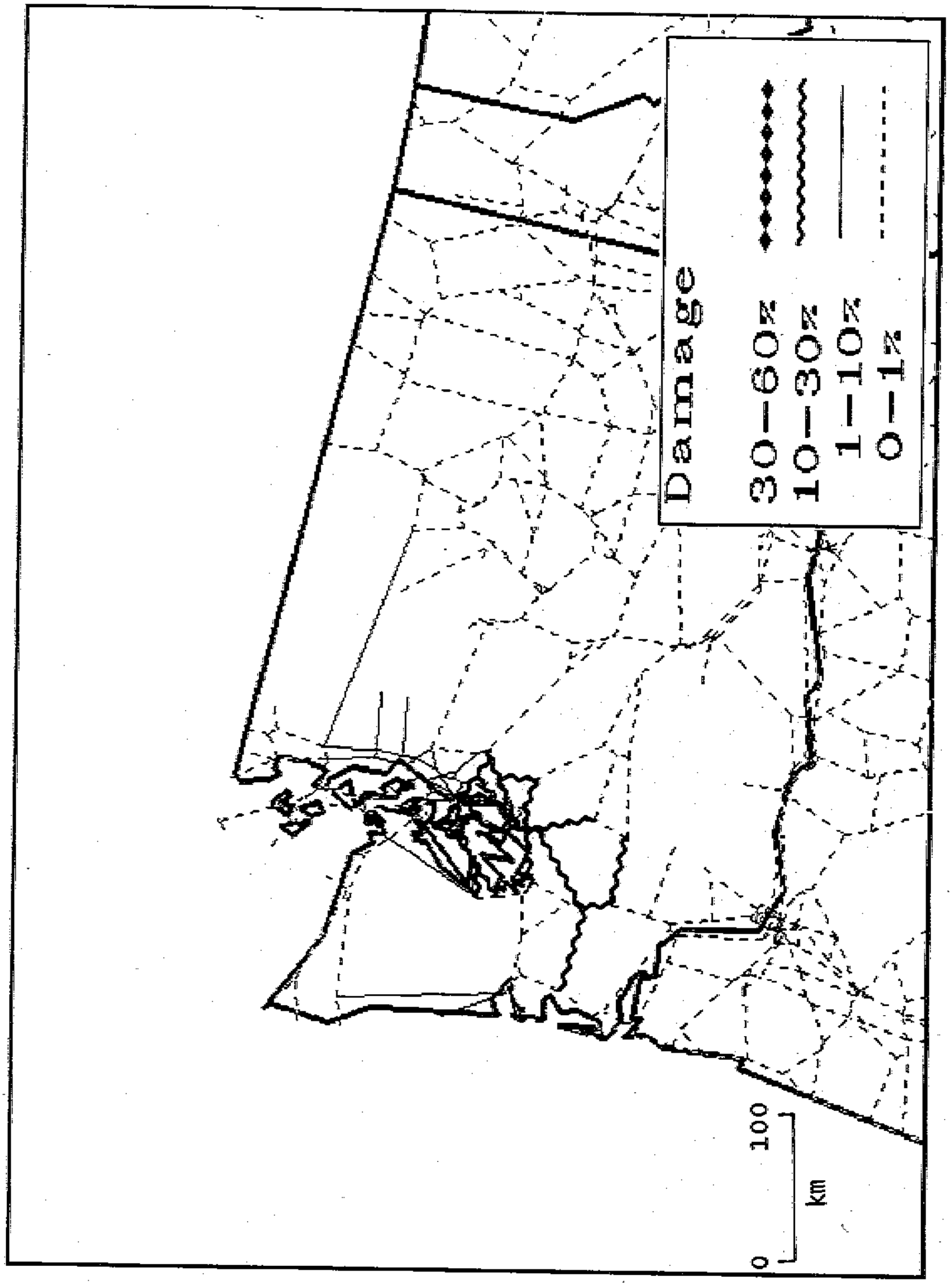


Figure 5-15 *Damage to highways following Puget Sound event (M=7.5).*

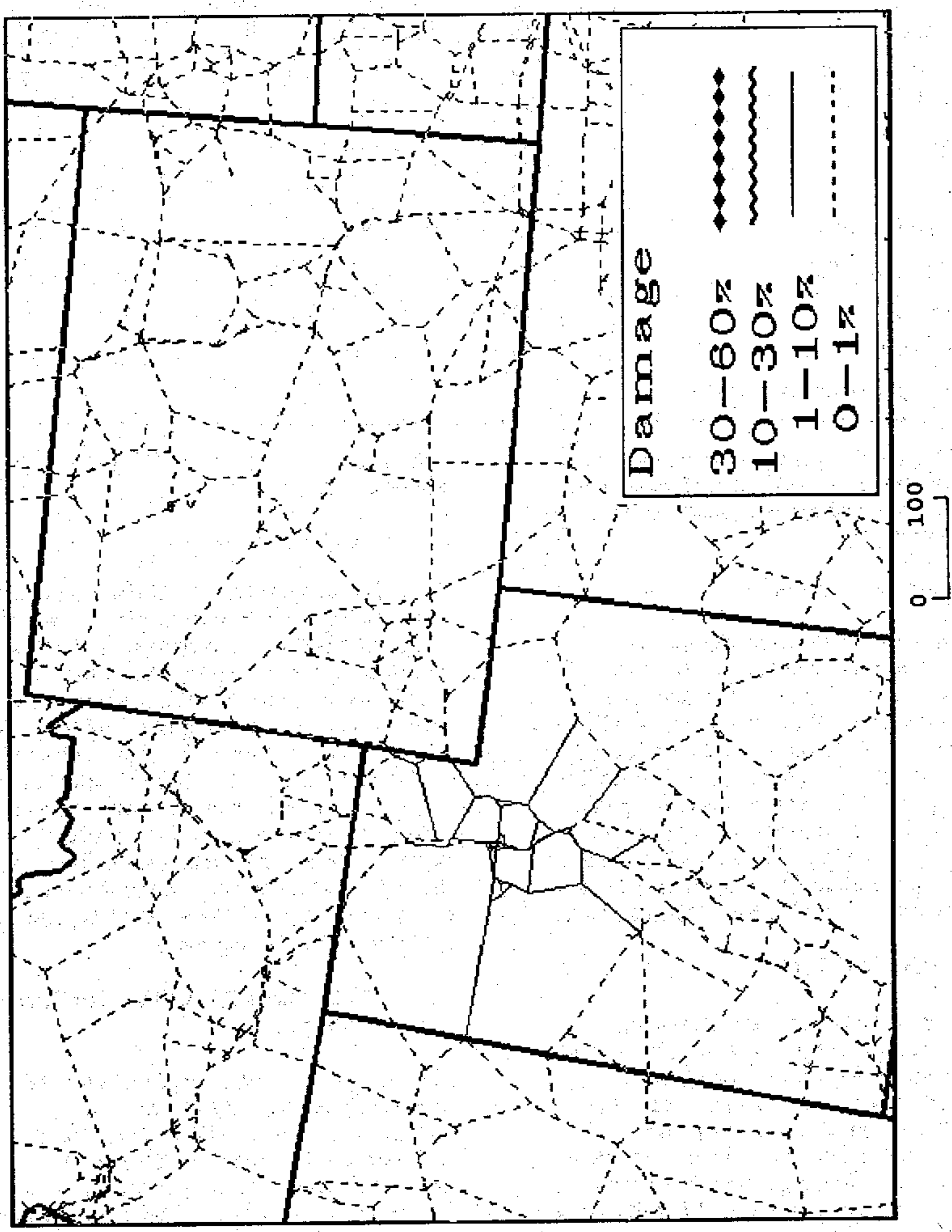


Figure 5-16 *Damage to highways following Wasatch Front event (M=7.5).*

Table 5-10 Damage to Electric Transmission Lines (Length of Line, Km)

Event	Light Damage 1-10%	Moderate 10-30%	Heavy 30-60%	Major to Destructive 60-100%
Cape Ann	275	0	0	0
Charleston	4,840	27	0	0
Fort Tejon	6,645	1,370	0	0
Hayward	6,320	0	0	0
New Madrid (M=8.0)	6,840	800	0	0
New Madrid (M=7.0)	2,610	0	0	0
Puget Sound	3,860	0	0	0
Wasatch Front	1,370	0	0	0

Total System Length = 441,981 km

Hayward scenario events, respectively. Maps provided in Figures 5-25 and 5-26 show plots of damage to water aqueduct systems for these two California events.

5.4.5 Crude Oil System

Direct damage to the crude oil system, estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines described above, are plotted in Figures 5-27 through 5-29. Data are included for only those events for which damage to this facility type is expected: the two New Madrid events and the Fort Tejon earthquake. Figures 5-27 through 5-29 show pipeline section(s) damaged due to the magnitude-8.0 New Madrid, Fort Tejon, and magnitude-7.0 New Madrid events.

5.4.6 Refined Oil System

Direct damage to the refined oil system, estimated using damage curves for transmission pipelines and refineries and the special probabilistic model for pipelines described above, are plotted in Figures 5-30 and 5-31. These plots indicate that one major section of pipeline would be damaged, with probability of 60% or greater, due to the New Madrid events. We note also that a major refinery (capacity 150,000 barrel/day) would sustain light damage (1-to-10 %) due the Hayward event, and two major refineries with capacities of 420,000 and 100,000 barrels/day, respectively, would sustain light damage due to the Fort Tejon and Puget Sound events.

5.4.7 Natural Gas System

As in the case of crude and refined oil pipelines, direct damage to the natural gas system was estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines described above. Damage to this facility type, plotted in Figures 5-32 through 5-37, is expected for six of the eight scenario earthquakes; excluded are the Charleston and Cape Ann scenario events for which direct damage to natural gas pipelines is estimated to be zero. Broken pipelines shown (Figures 5-32 through 5-37) are node-to-node sections having one or more links estimated as damaged with a probability of 60% or greater.

5.5 Dollar Loss Resulting from Direct Damage

The total direct damage dollar loss for the various lifeline systems and scenario earthquakes were calculated on the basis of the damage statistics summarized above and assumed replacement costs for the lifeline facility types considered (Table 5-13). Assumed replacement cost values are based on data collected for various facility sizes and regions, which were then weighted to account for the estimated distribution of facility sizes in the national database.

Table 5-11 Damage Percent for Electric Transmission Substations for Each Scenario Earthquake (Percent of Substations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Indiana 89	Mississippi 93	South Carolina 100	North Carolina 76	Georgia 86
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	14%	8%	22%	16%	24%	2%	63%	43%	20%	33%
Heavy 30-60 %	0%	0%	10%	9%	7%	0%	8%	14%	0%	3%
Major to Destructive 60-100 %	0%	8%	29%	6%	1%	0%	10%	16%	1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 153	Connecticut 69	Delaware 3	Rhode Island 22	New Hampshire 22	Utah 10
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	82%	42%	33%	100%	45%	30%
Heavy 30-60 %	0%	0%	0%	0%	0%	20%
Major to Destructive 60-100 %	5%	0%	0%	0%	0%	10%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 205	California 205	Washington 155	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Mississippi 93
Light Damage 1-10 %	8%	11%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	13%	6%	12%	0%	2%	21%	16%	16%	14%
Heavy 30-60 %	14%	< 1%	3%	0%	0%	16%	0%	0%	2%
Major to Destructive 60-100 %	13%	12%	43%	0%	6%	6%	3%	0%	0%

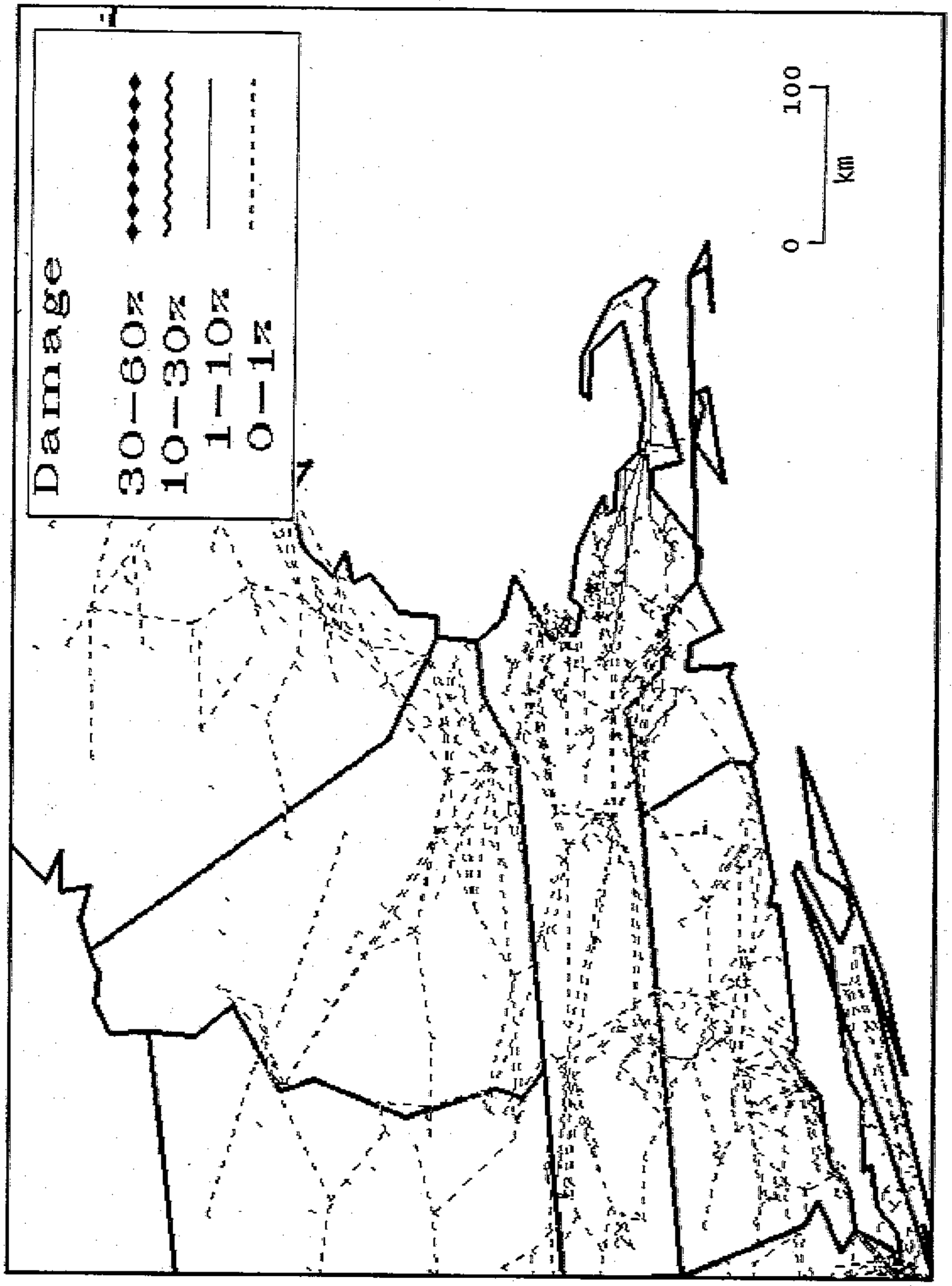


Figure 5-17 *Damage to electric power transmission lines following Cape Ann event (M=7.0).*

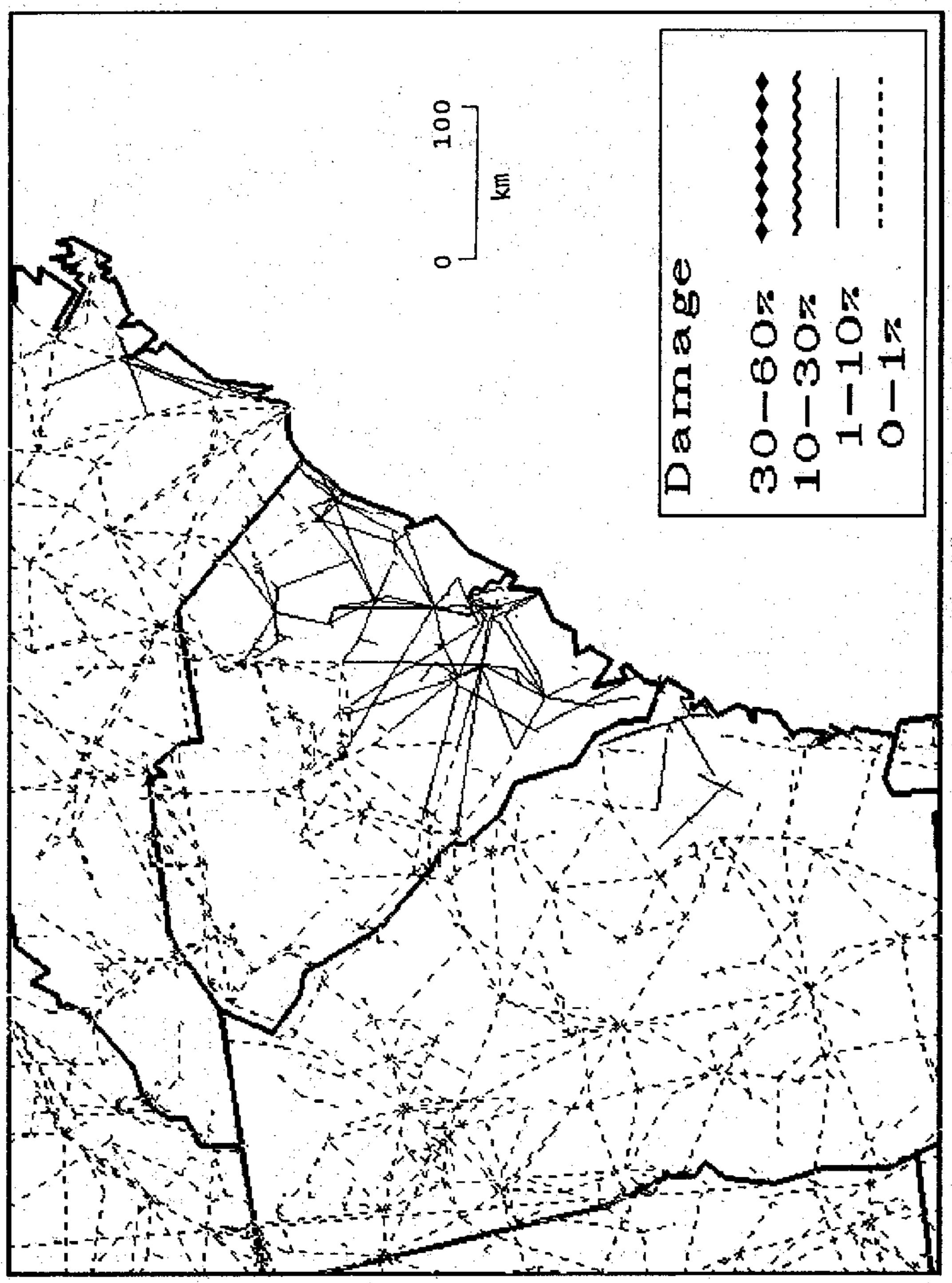


Figure 5-18 *Damage to electric power transmission lines following Charleston event (M=7.5).*

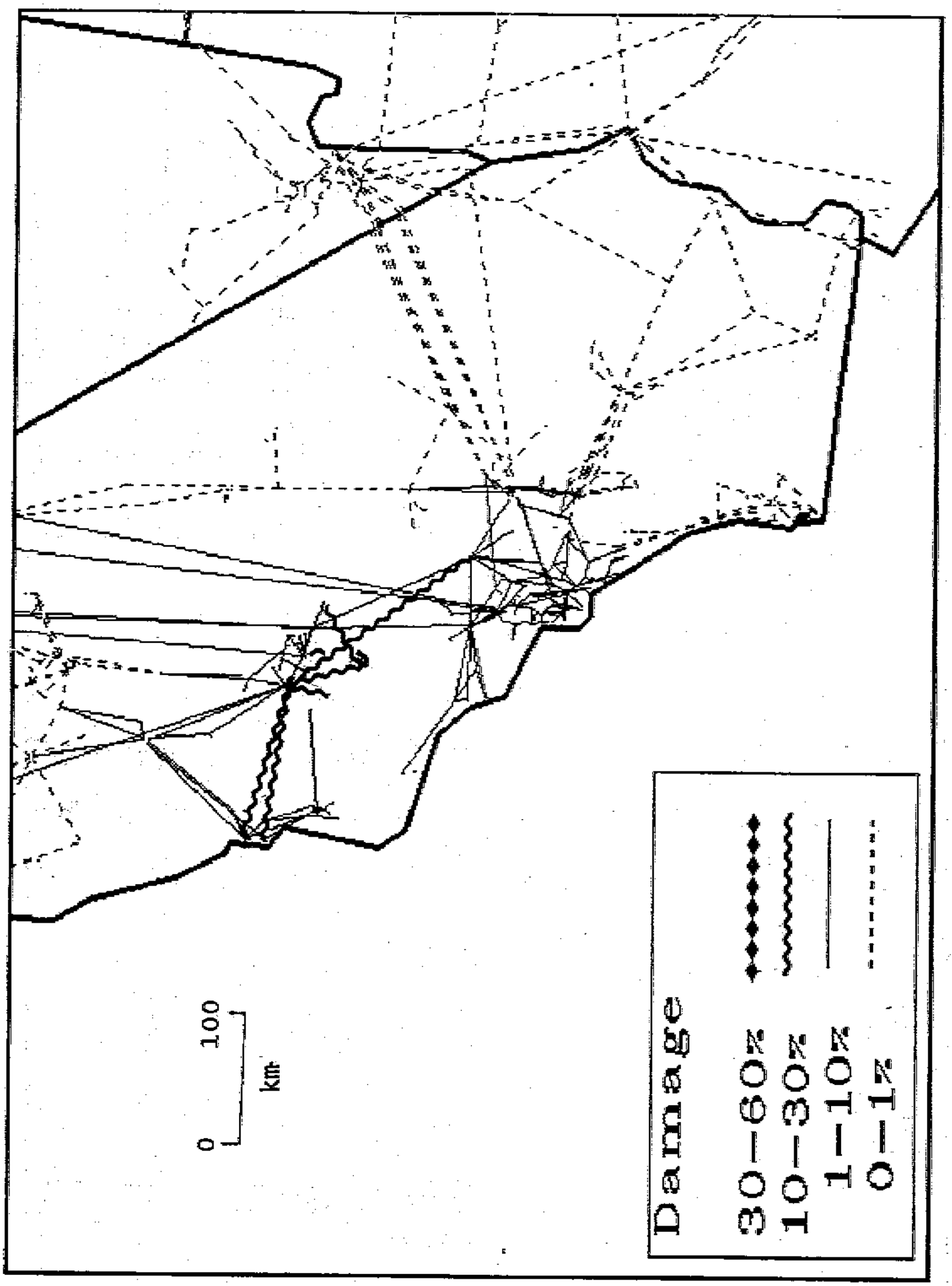


Figure 5-19 *Damage to electric power transmission lines following Fort Tejon event (M=8.0).*

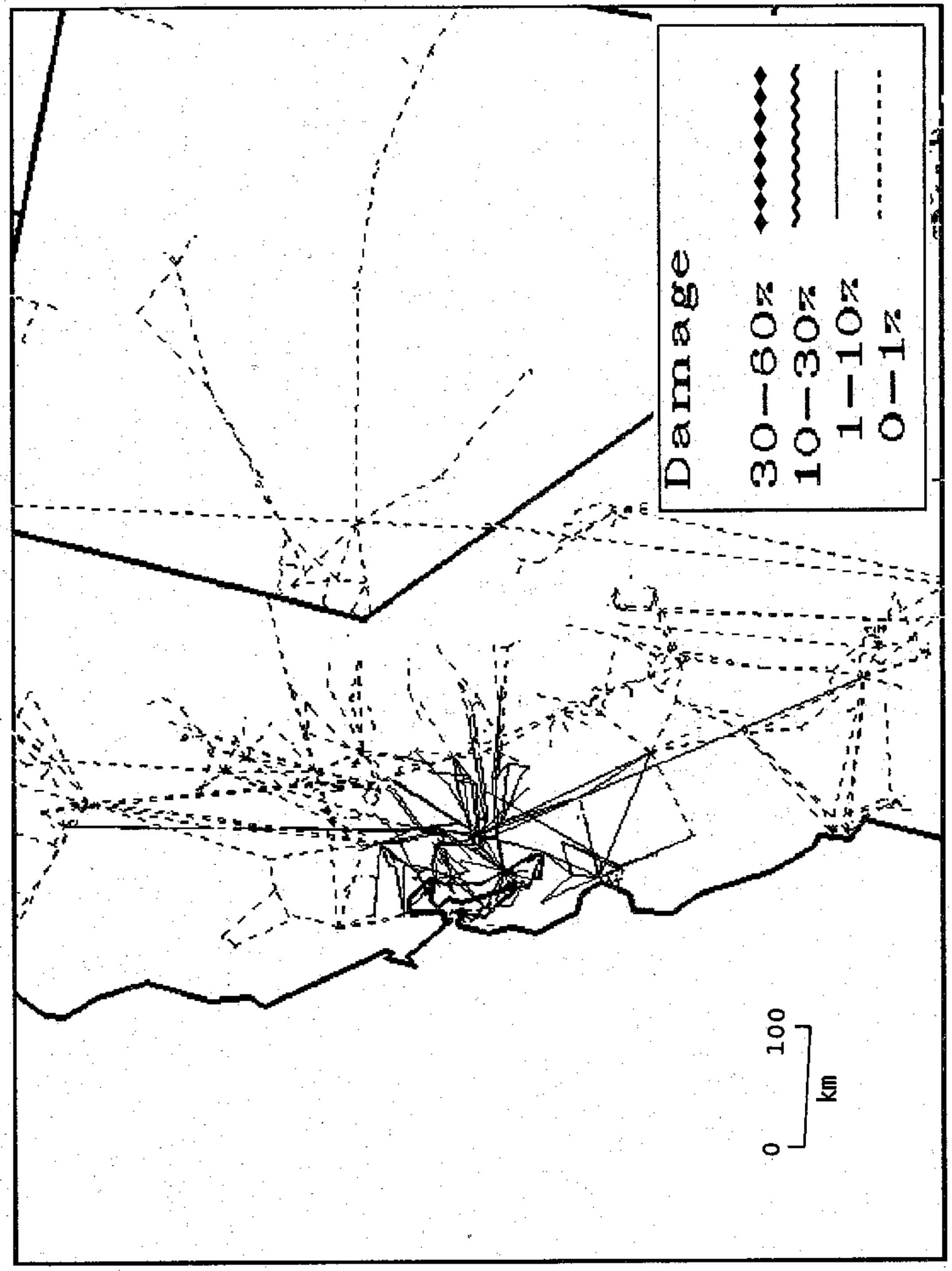


Figure 5-20 Damage to electric power transmission lines following Hayward event (M=7.5).

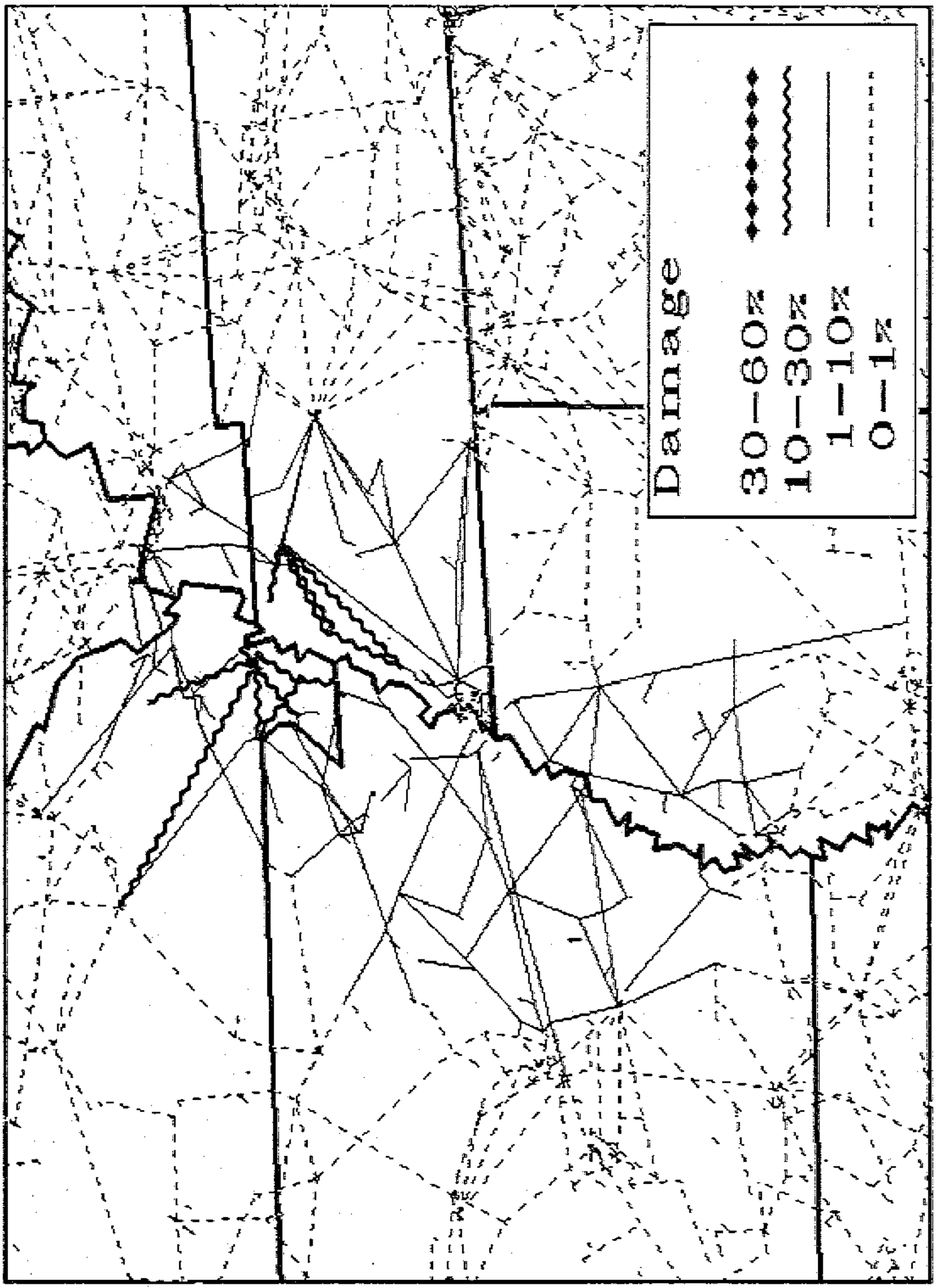


Figure 5-21 Damage to electric power transmission lines following New Madrid event (M=8.0).

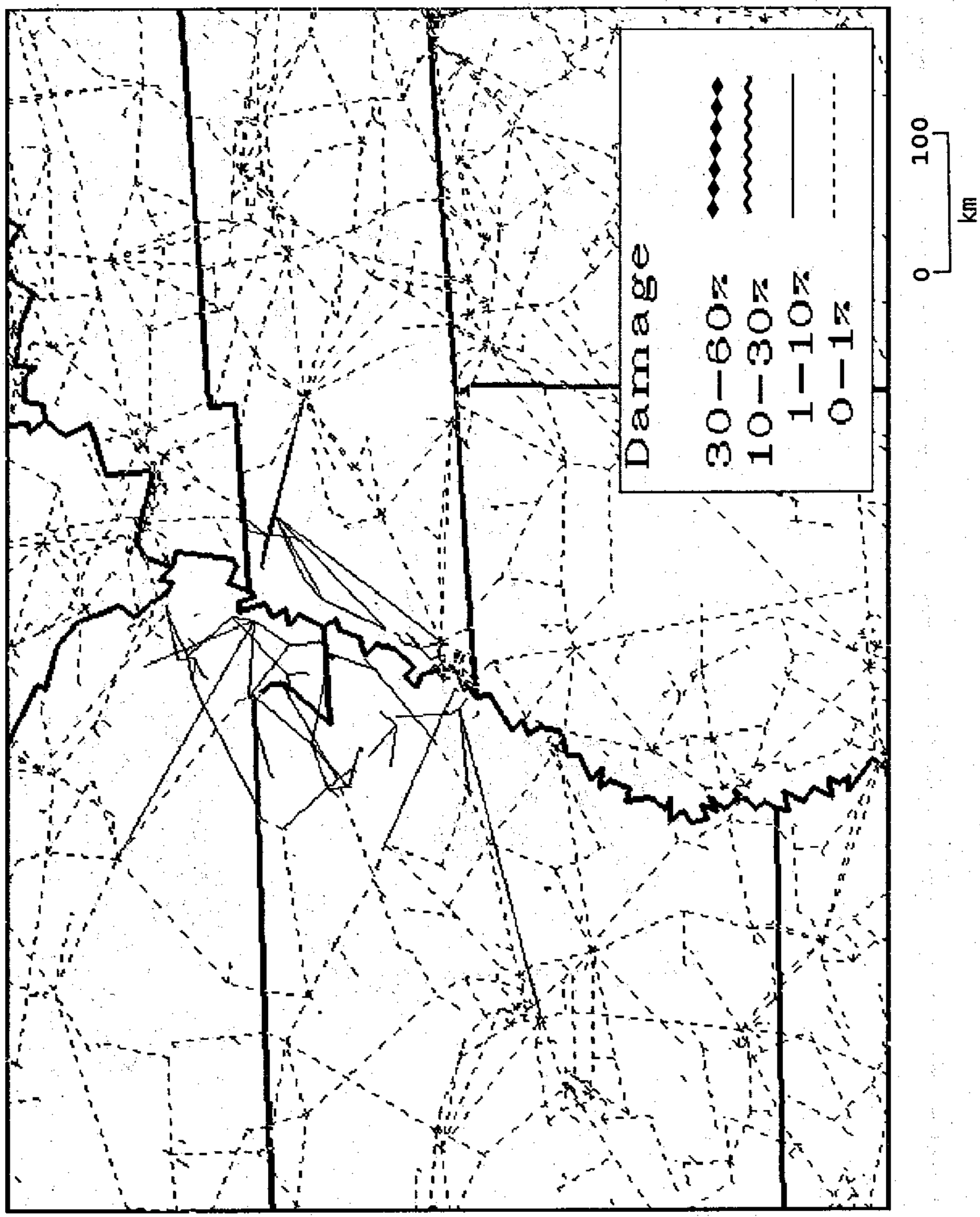


Figure 5-22 *Damage to electric power transmission lines following New Madrid event (M=7.0).*

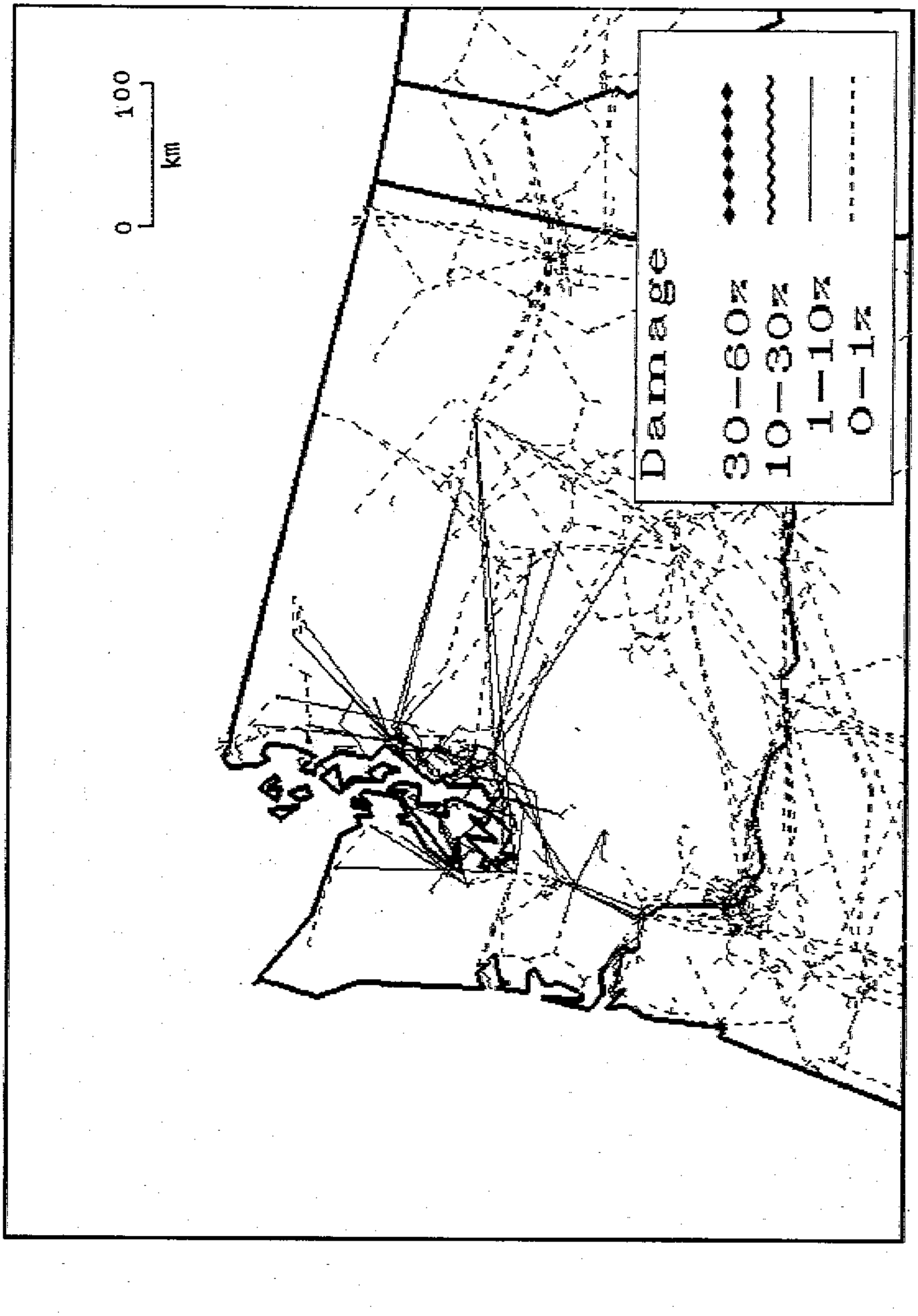


Figure 5-23 *Damage to electric power transmission lines following Puget Sound event (M=7.5).*

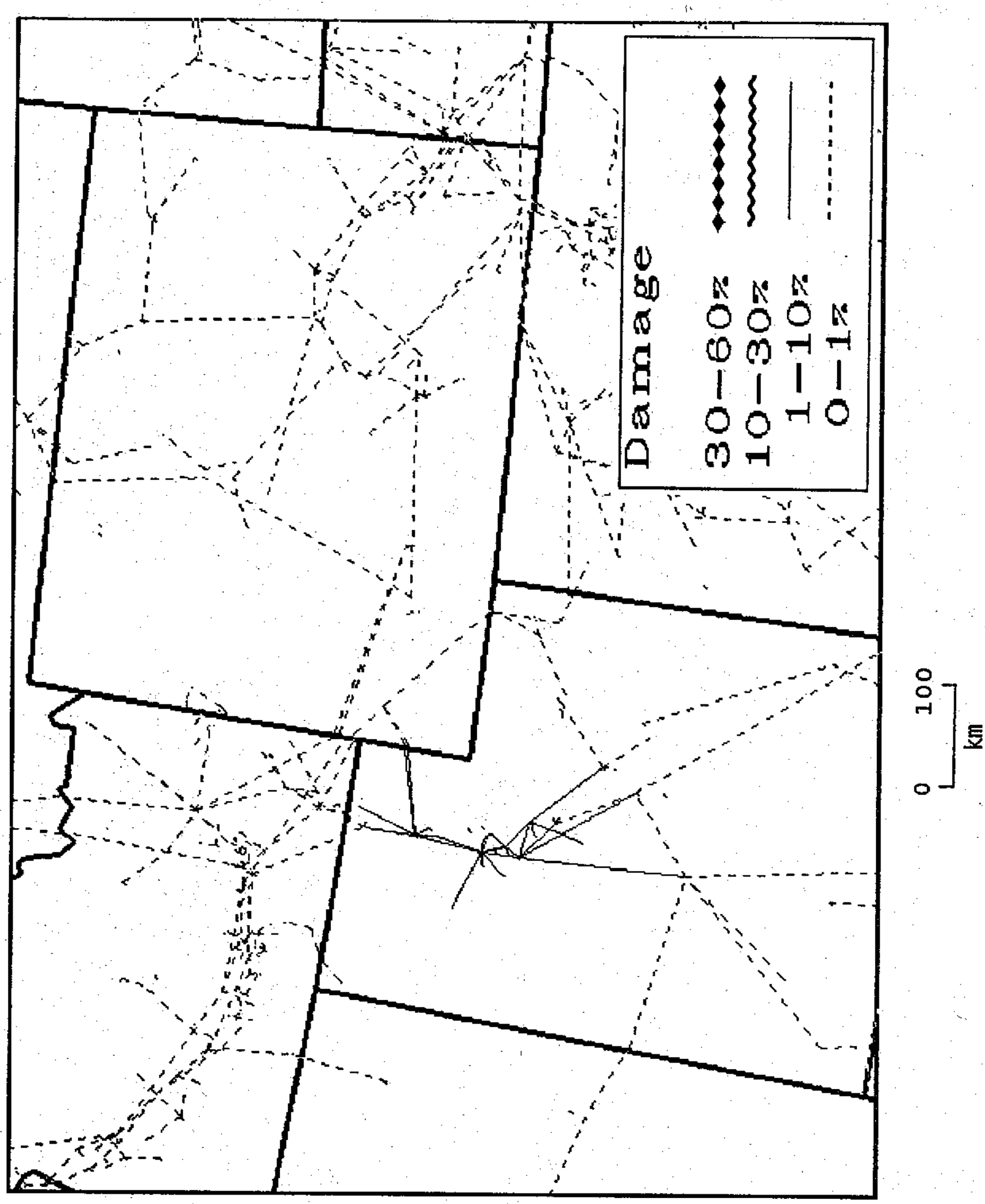


Figure 5-24 Damage to electric power transmission lines following Wasatch Front event (M=7.5).

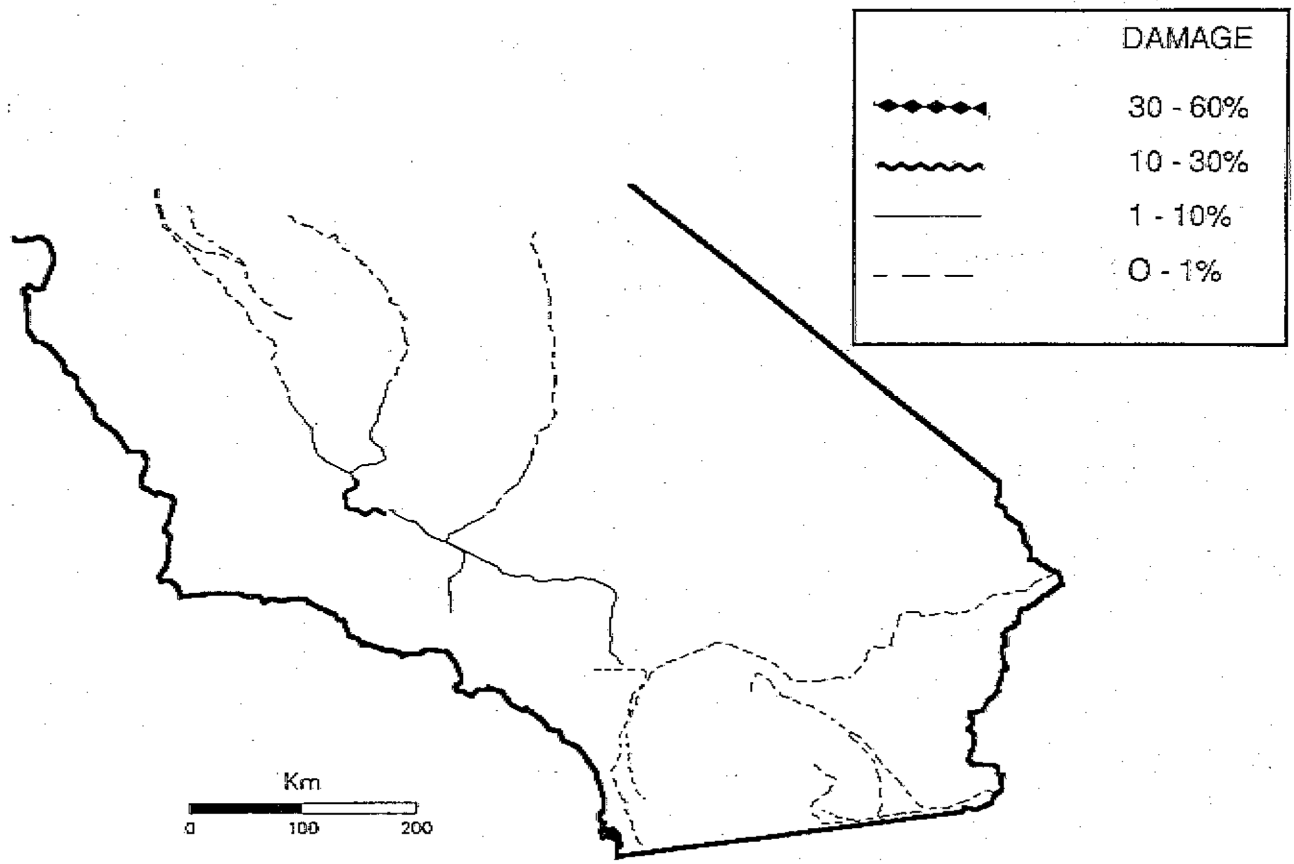


Figure 5-25 *Damage to water aqueduct system following Fort Tejon event (M=8.0).*

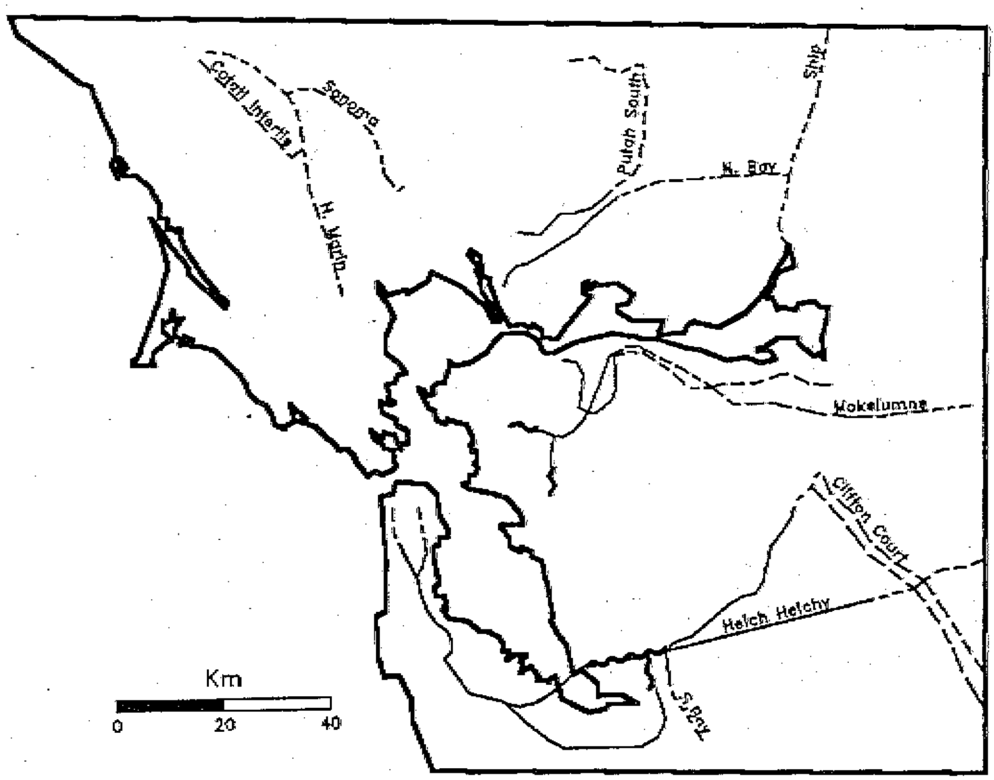


Figure 5-26 *Damage to water aqueduct system following Hayward event (M=7.5).*

Table 5-12 Damage to Water Aqueduct System (Length of Aqueduct, Km)

Event	*Light Damage 1-10%*	*Moderate 10-30%*	*Heavy 30-60%*	*Major to Destructive 60-100%*
Fort Tejon	350	36	2	0
Hayward	240	20	1	0
Puget Sound	60	0	0	0

Table 5-13 Cost Estimates for Lifeline Components

System	*Component*	*Cost Estimate**
Railway	Tracks/Roadbeds	$500,000/mile**
Highway	Conventional highway bridge	$1,200,000
	Freeway/Highway	$1,400,000/mile**
	Local Roads	$300,000/mile**
Air Transportation	Terminals	$4,000,000
	Runways/Taxiways	$1,000,000/runway
Sea/Water Transportation	Ports/Cargo Handling Equipment	$20,000,000
Electric	Distribution Lines	$150,000/mile**
	Transmission Lines	$500,000/mile**
	Transmission Substations	$400/person***
Water Supply	Transmission Aqueducts	$5,000,000/mile**
Natural Gas	Transmission Aqueducts	$300,000/mile**
Petroleum Fuels	Transmission Pipelines	$300,000/mile**
Emergency Service	Medical Care Facilities (assumes 85,000 square foot average size)	$35,000,000
	Fire Stations (assumes 5,000 square foot average size)	$400,000
	Police Stations (assumes 11,000 square foot average size)	$1,000,000

*1991 Dollars
**1 mile = 1.609 km.
***in service area

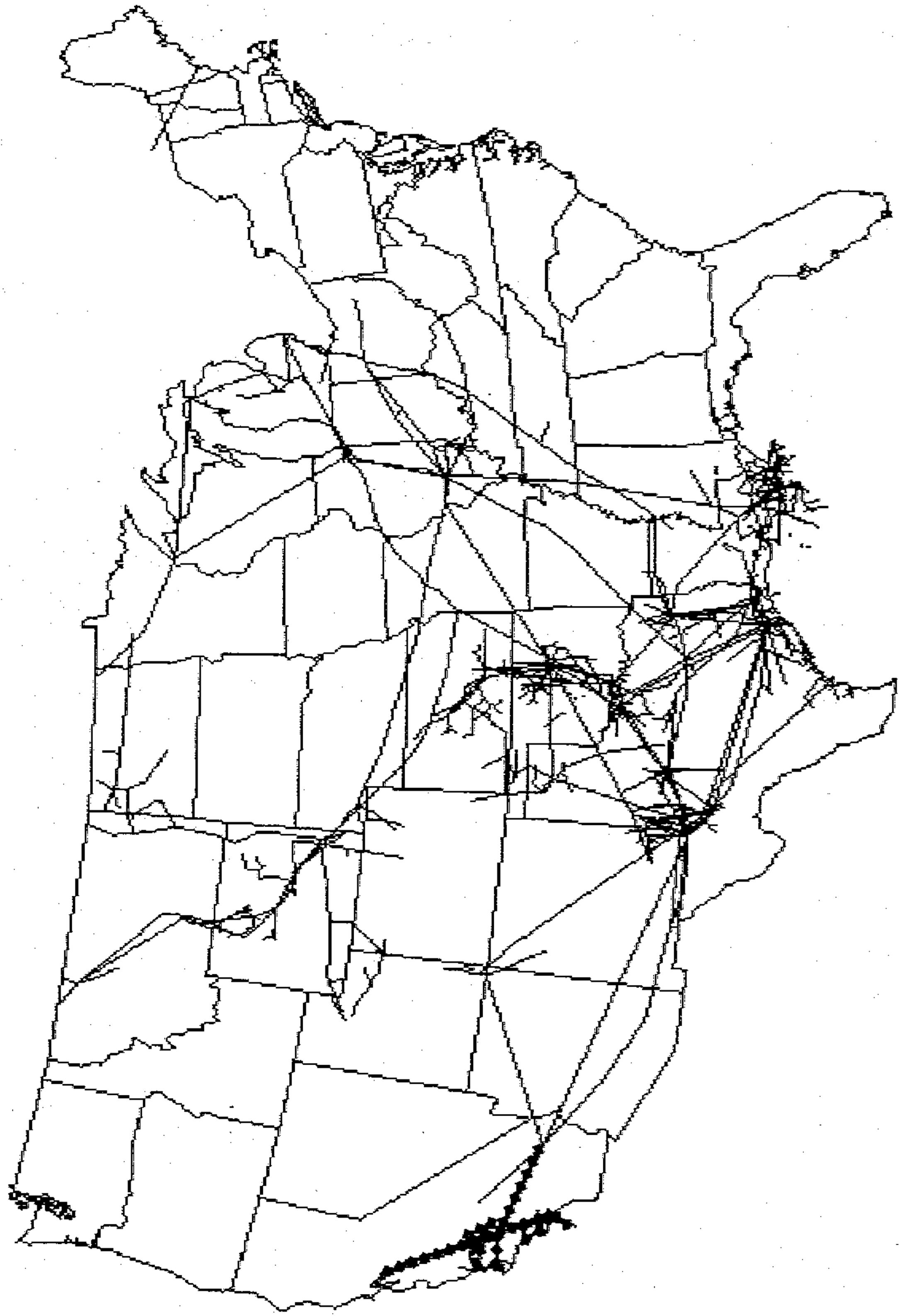


Figure 5-27 Damage to crude oil system following Fort Tejon event (M=8.0). Broken pipelines are shown with solid diamonds.

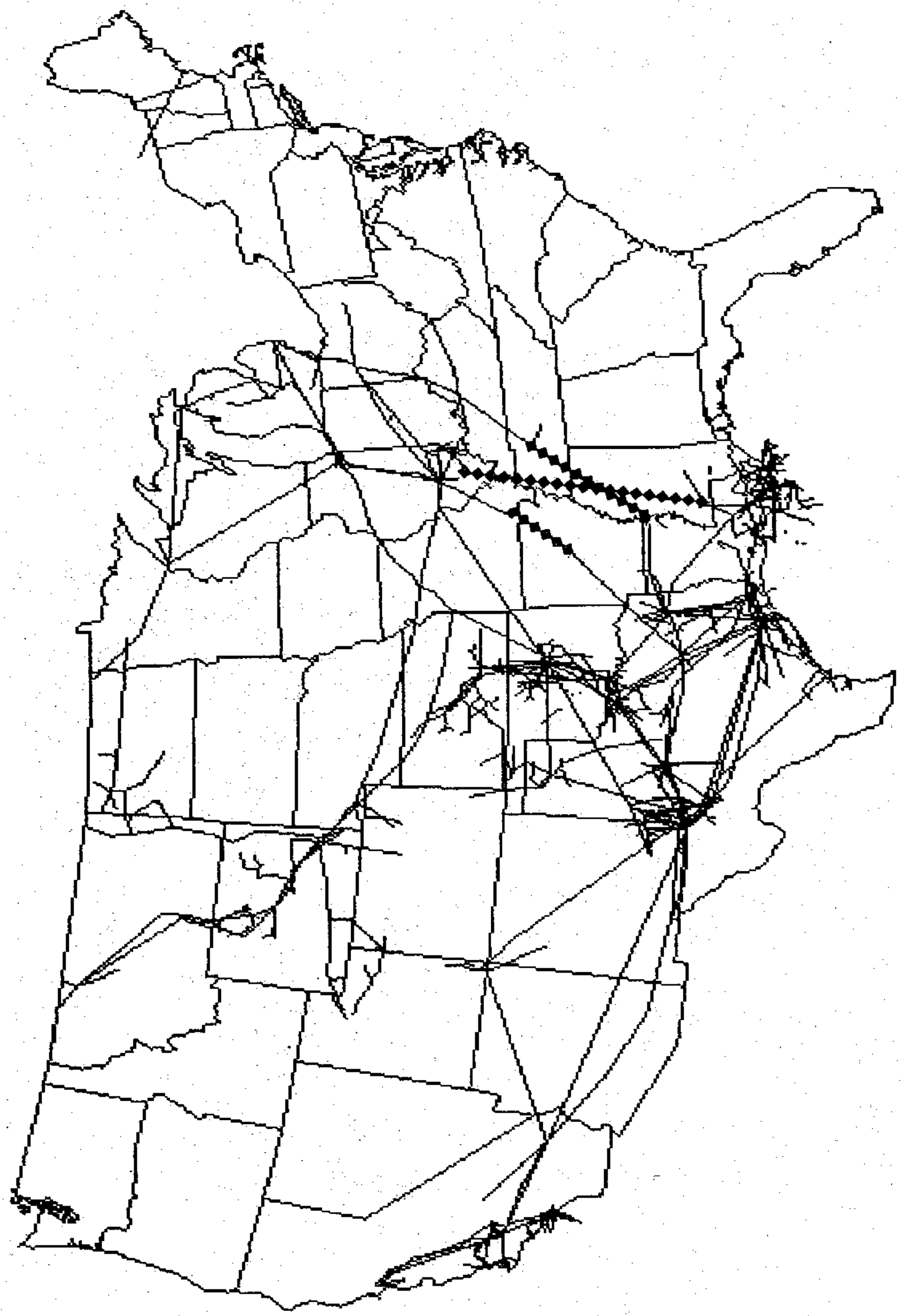


Figure 5-28 *Damage to crude oil system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

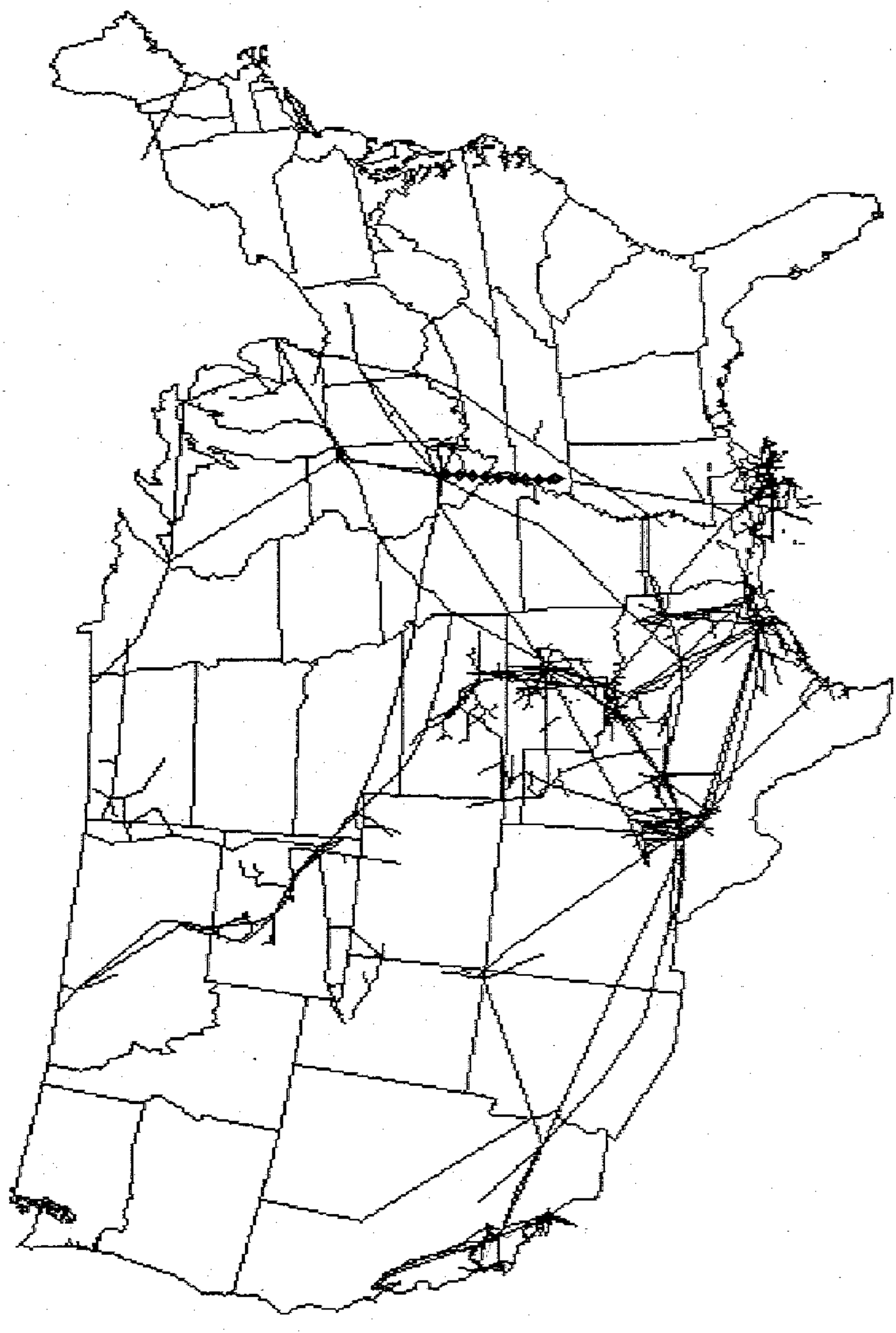


Figure 5-29 *Damage to crude oil system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

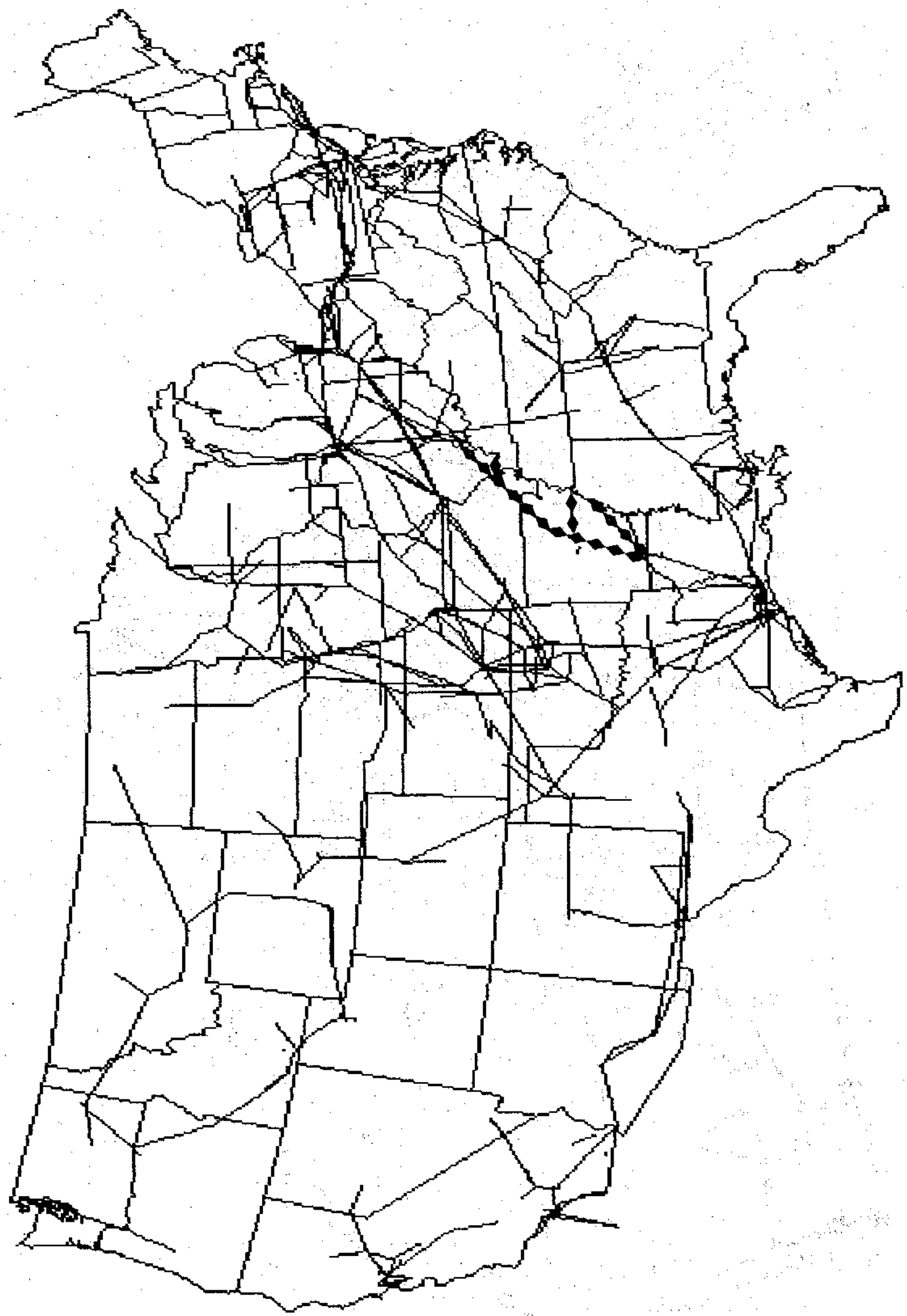


Figure 5-30 *Damage to refined oil system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

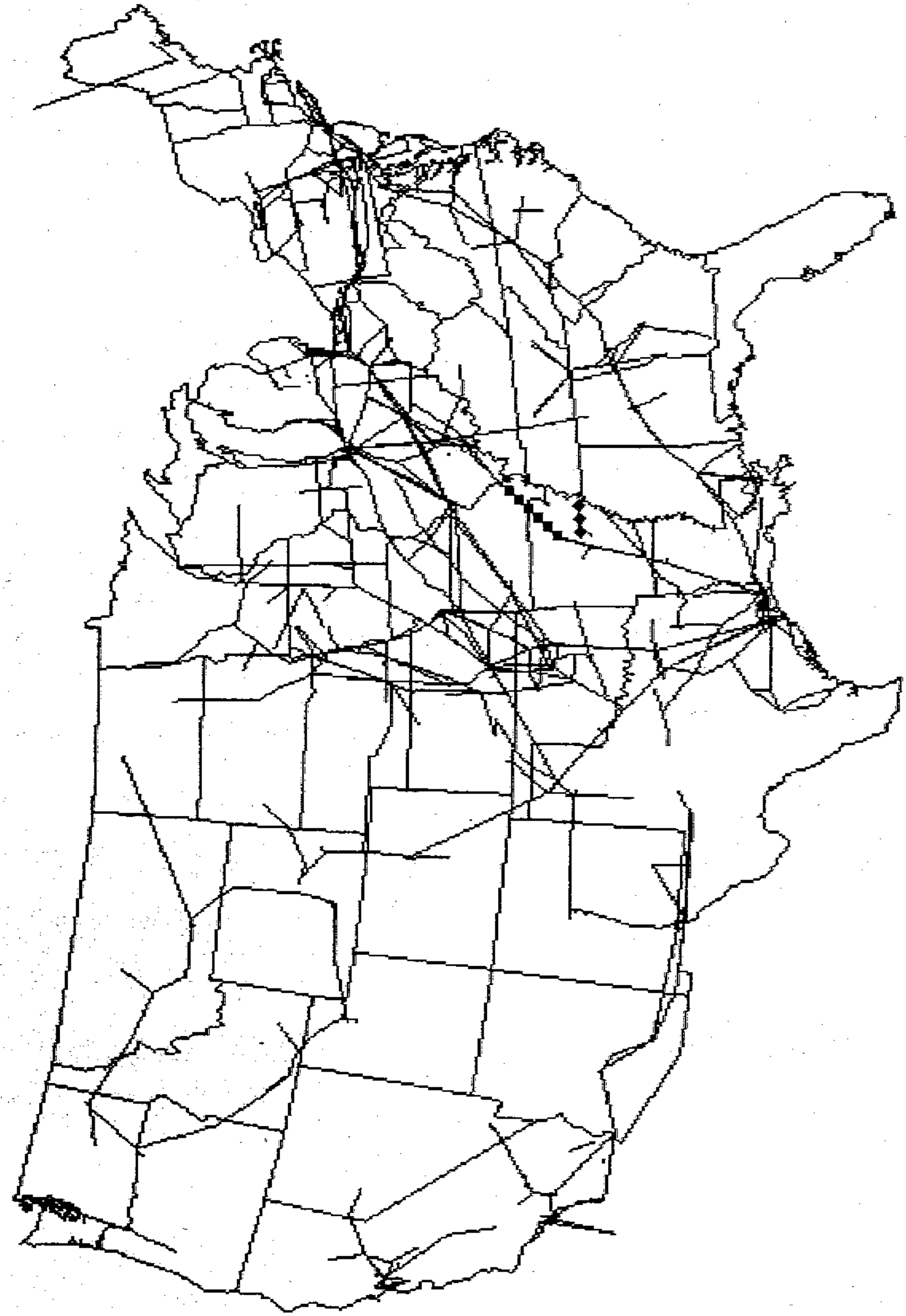


Figure 5-31 *Damage to refined oil system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

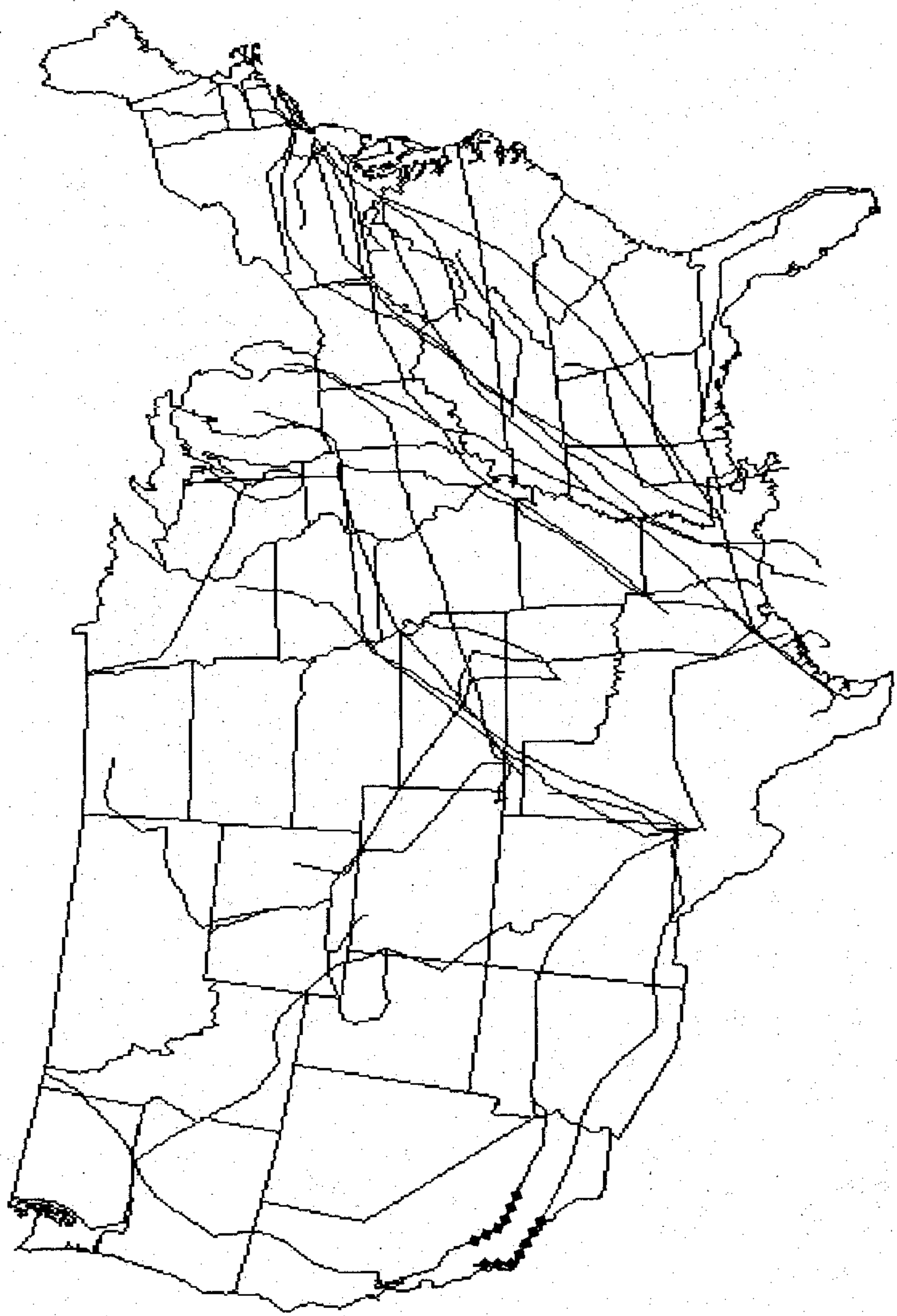


Figure 5-32 *Damage to natural gas system following Fort Tejon event (M=8.0). Broken pipelines are shown with solid diamonds.*

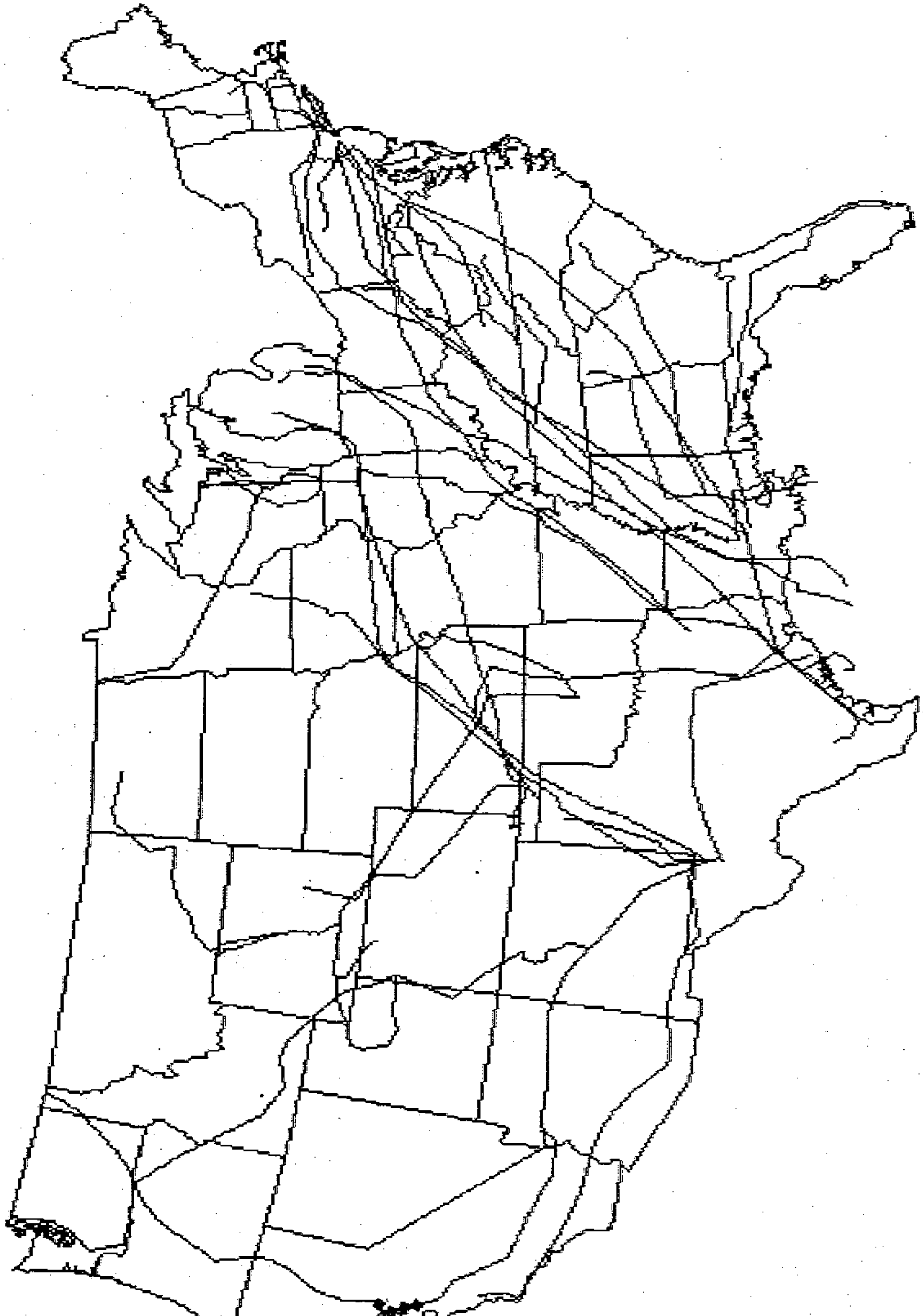


Figure 5-33 *Damage to natural gas system following Hayward event (M=7.5). Broken pipelines are shown with solid diamonds.*

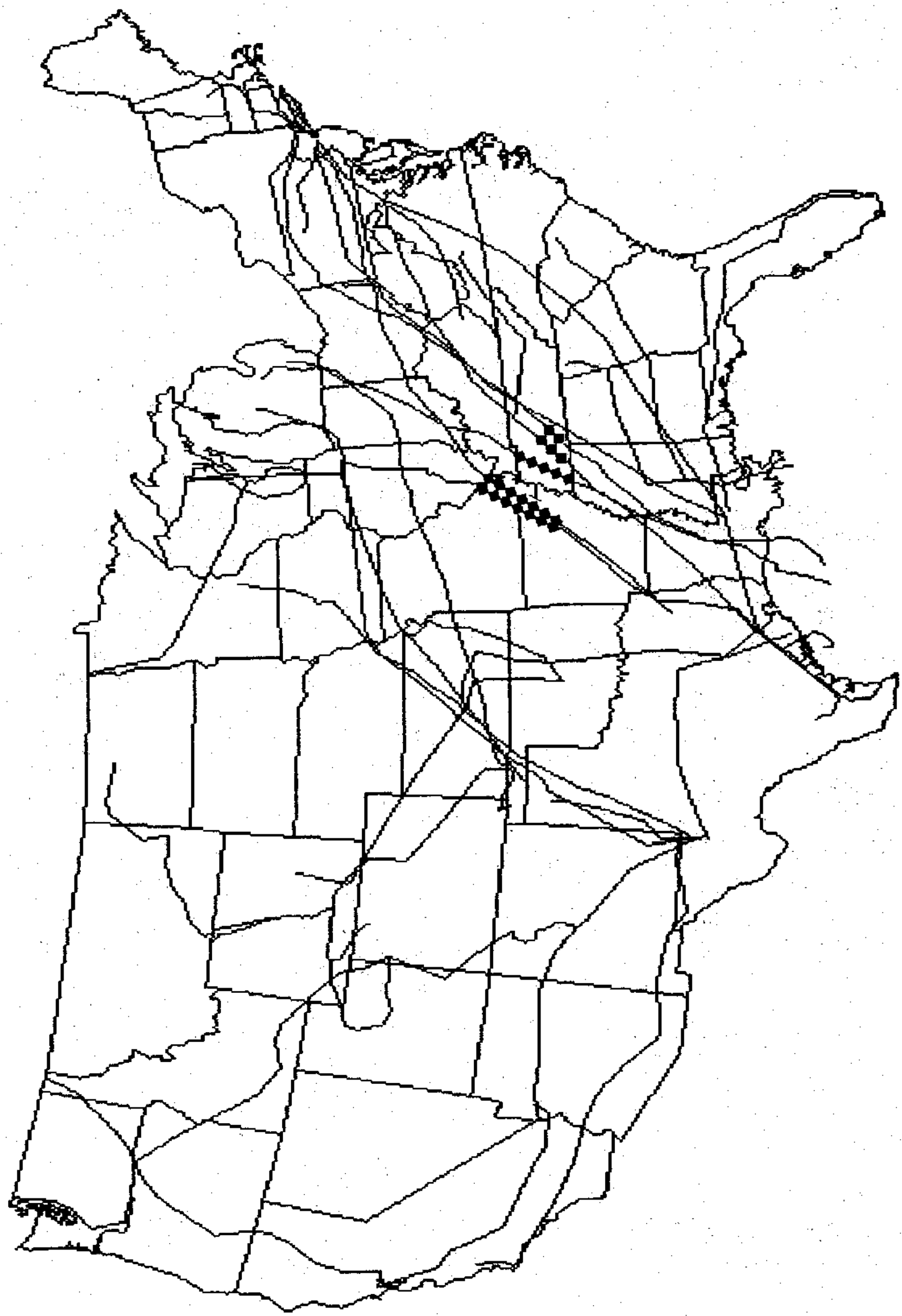


Figure 5-34 *Damage to natural gas system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

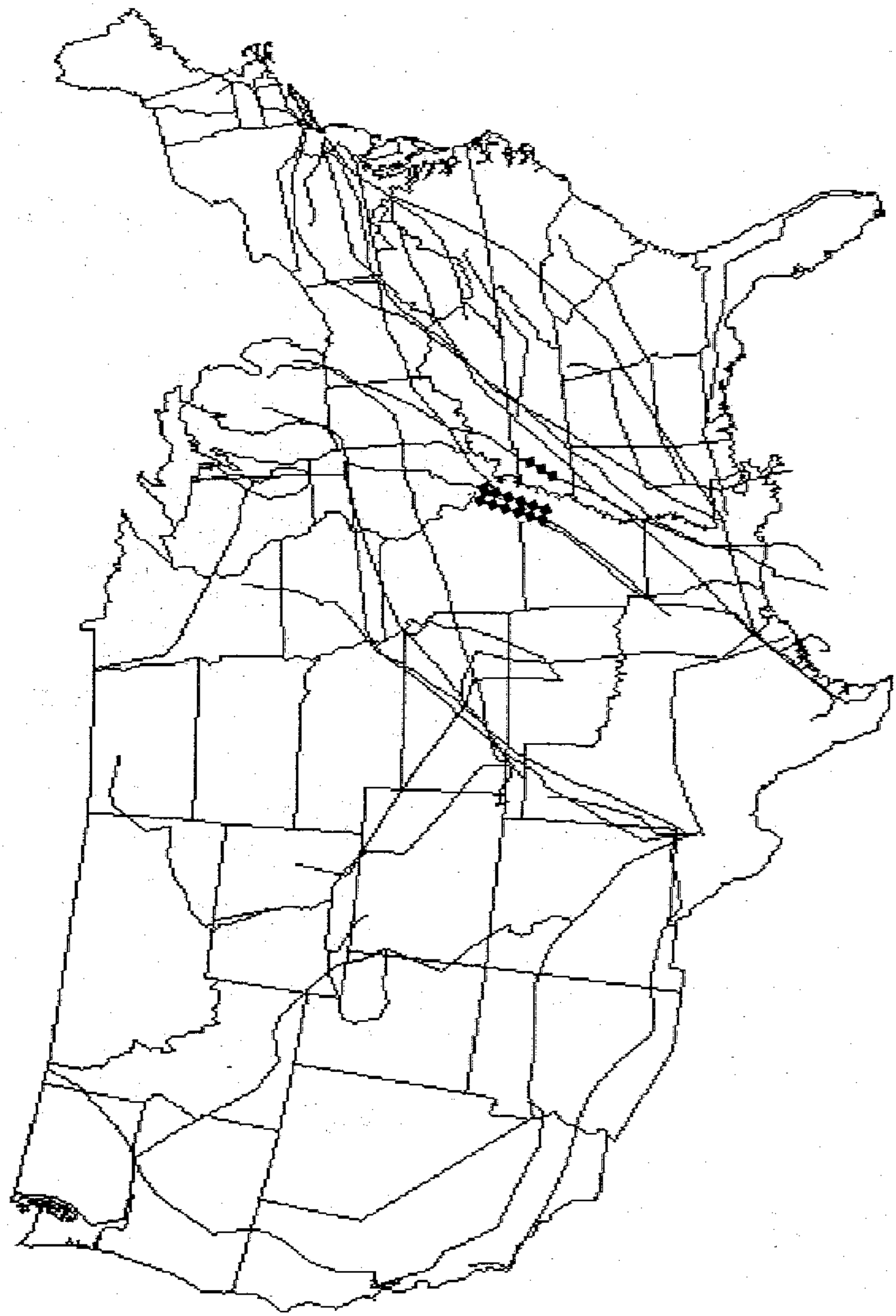


Figure 5-35 *Damage to natural gas system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

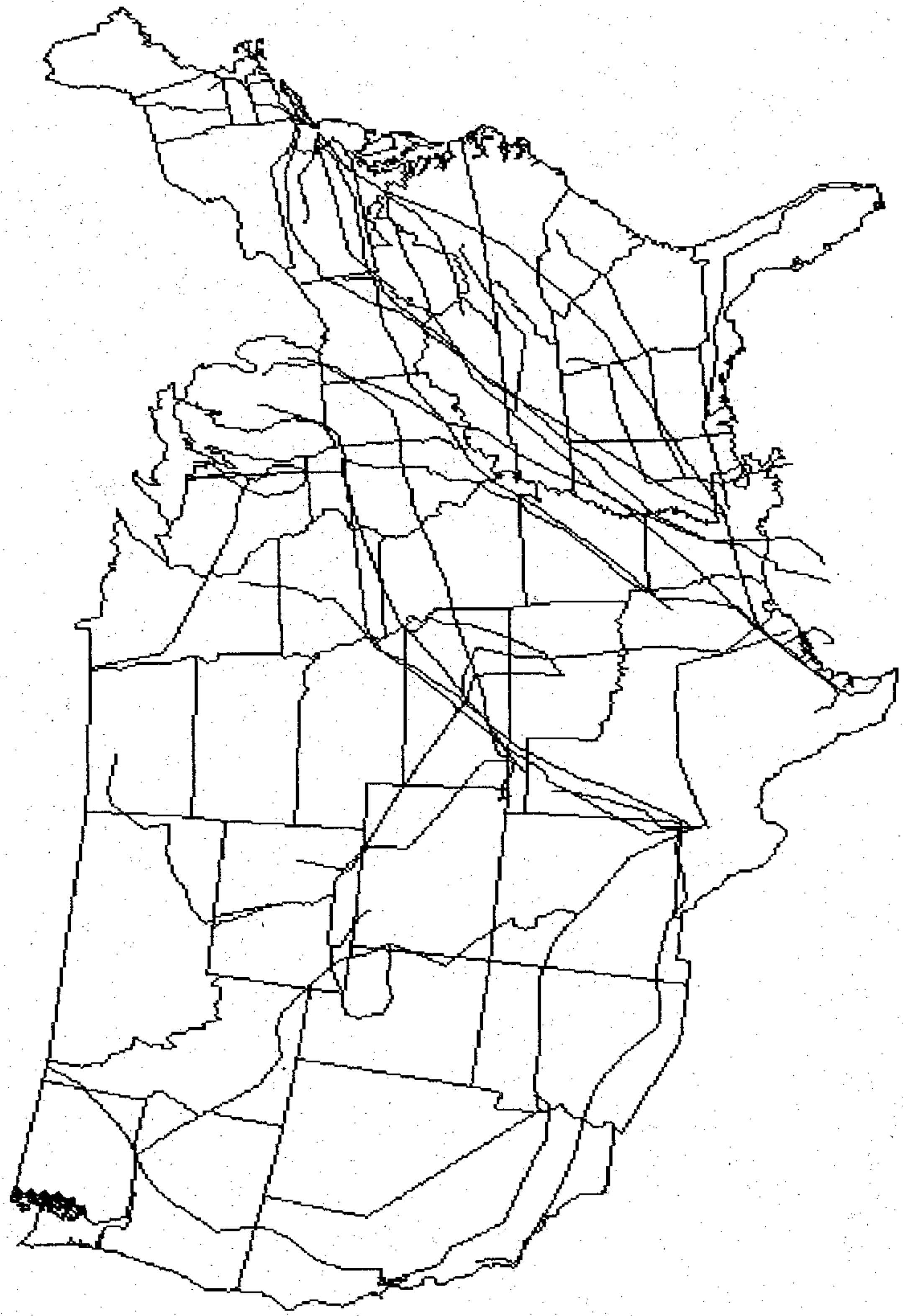


Figure 5-36 *Damage to natural gas system following Puget Sound event (M=7.5). Broken pipelines are shown with solid diamonds.*

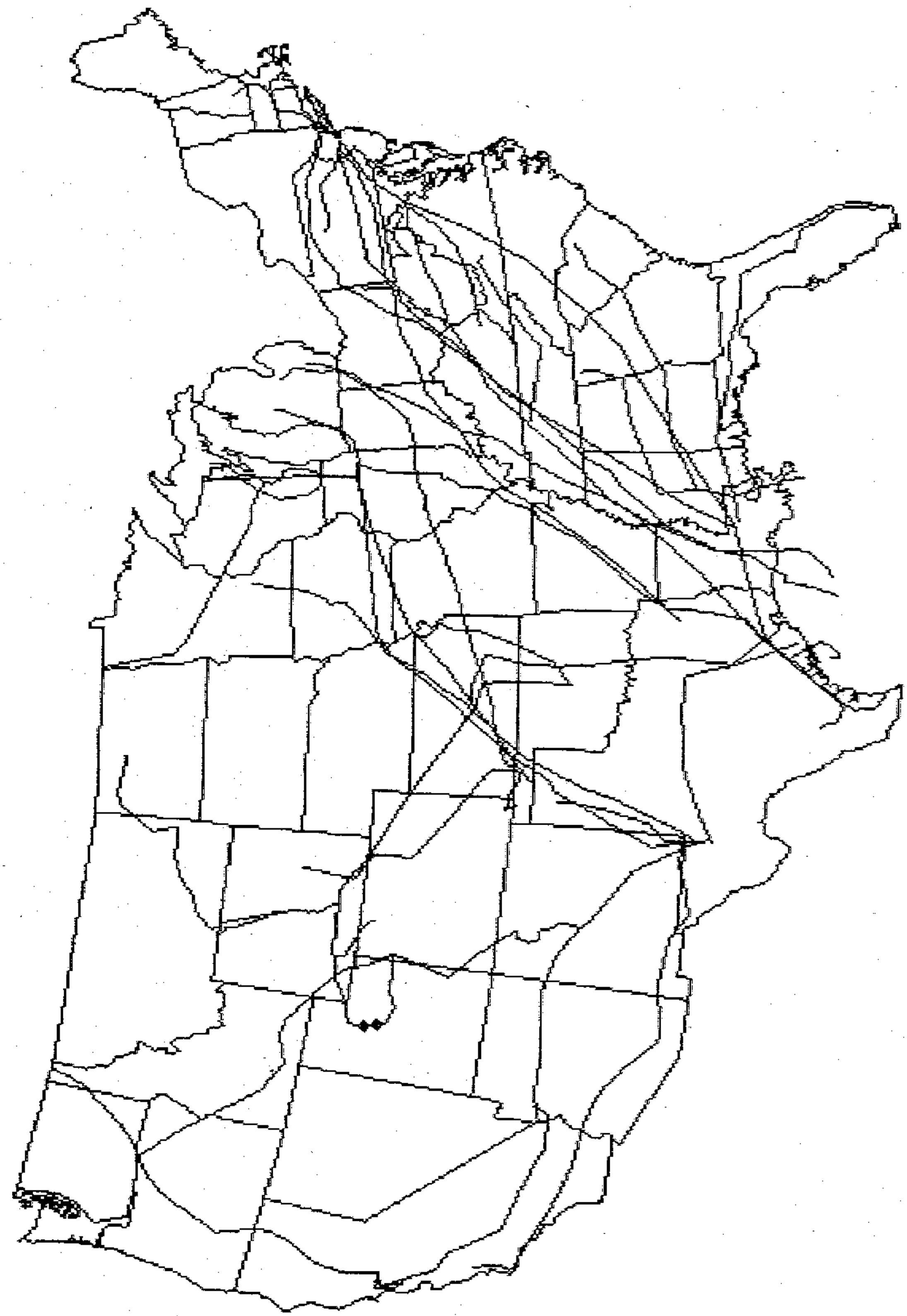


Figure 5-37 *Damage to natural gas system following Wasatch Front event. Broken pipelines are shown with solid diamonds.*

Summaries of dollar loss estimates for direct damage to site-specific systems and extended regional lifeline networks during the eight scenario earthquakes are provided in Table 5-14. Estimated dollar losses due to direct damage to local electric, water, and highway distribution systems are provided in Table 5-15. We note that damage distribution dollar loss estimates for direct damage to local distribution systems were estimated using cost data from Table 5-13 and damage curves from Appendix B for electric distribution lines, local roads, and water trunk lines. Intensities were estimated at the center of the Standard Metropolitan Statistical Areas, assuming the distribution systems were lumped at these locations.

The estimates provided in Tables 5-14 and 5-15 are based on the available inventory data and other assumptions and models described in this report. As a result, the accuracy of these estimates may vary from lifeline to lifeline. Estimates for electric systems, in particular, are believed to be more sensitive to the lack of capacity information than are the other lifelines.

By combining the data from Tables 5-14 and 5-15, we estimate the total direct damage dollar losses (in billions of U. S. dollars) for the eight scenario earthquakes as follows:

Earthquake	Direct Dollar Loss (in Billions, 1991$)
Cape Ann	$4.2
Charleston	$4.9
Fort Tejon	$4.9
Hayward	$4.6
New Madrid, M = 8.0	$11.8
New Madrid, M = 7.0	$3.4
Puget Sound	$4.4
Wasatch Front	$1.5

5.6 Comparison with Previous Studies

The foregoing presents a methodology and results for understanding the direct damage impacts of earthquakes on U.S. lifelines. No previous study has examined lifelines in comparable breadth or scale, so that comparisons are difficult. Several studies have examined the effect of earthquakes on lifelines for various regions, including:

- Earthquake Vulnerability Analysis of the Charleston, South Carolina Area (Citadel, 1988),
- Earthquake Planning Scenario for a Magnitude 7.5 Earthquake on the Hayward Fault in the San Francisco Bay Area (Steinbrugge et al., 1987) (representative of several studies in California, including others for the Newport Inglewood Fault Zone, the San Andreas Fault in northern and southern portions of California (e.g., Davis et al., 1982),
- A study of the Wasatch Front, Utah, water and gas systems (Taylor, Wiggins, Harper and Ward, 1986), and
- A pilot study on vulnerability of crude oil transmission systems in the New Madrid area (Ariman, et al., 1990).

Compared to the present study, these previous studies were typically limited in being either confined to one or a few lifelines, qualitative rather than quantitative, and/or geographically localized. Nevertheless, to the extent possible, comparison of this study's results with that of previous studies is of value, in order to compare each aspect of the methodology. The Charleston, South Carolina study is recent, probably the most comprehensive of the studies in scope, and provides quantitative results. We therefore next examine that study and its results, vis-a-vis this study.

Comparison with a study on the Charleston event. Researchers at The Citadel, the Military College of South Carolina, estimated damage to critical facilities and other resources in the epicentral region, assuming a repeat of the 31 August 1886 Charleston event. The study region comprised three counties of the Charleston, South Carolina area: Charleston County, Berkeley County, and Dorchester County. The Citadel analysis and conclusions appear in *An Earthquake Vulnerability Analysis of the Charleston, South Carolina, Area*, of July 1988. Their methodology relied significantly upon ATC-13 procedures, so The Citadel study and the present study take comparable approaches and use similar classifications for structures and

Table 5-14 Direct Damage Losses ($ Millions)

Scenario	*Highways*	*Electric*	*Fire Stations*	*Broadcasting Station*	*Medical Care*	*Ports*	*Airports*	*Railroads*	*Natural Gas*	*Refined Oil*	*Crude Oil*	*Water*	*Total*
Cape Ann	$382	$1,312	$6	$19	$490	$53	$91	$9	$0	$0	$0	$	2,362
Charleston	$773	$1,264	$9	$68	$565	$380	$142	$156	$0	$0	$0	$	$3,358
Fort Tejon	$470	$886	$48	$26	$1,431	$170	$148	$158	$11	$0	$28	$140	3,517
Hayward	$208	$1,310	$7	$17	$1,297	$115	$37	$115	$6	$0	$0	$91	3,203
New Madrid 8	$2,216	$2,786	$13	$91	$1,297	$0	$411	$458	$56	$28	$47	$	$7,403
New Madrid 7	$204	$1,077	$3	$34	$396	$0	$145	$108	$19	$9	$19	$	2,013
Puget Sound	$496	$1,834	$13	$49	$507	$196	$210	$96	$6	$0	$0	$18	3,425
Wasatch Front	$323	$90	$2	$44	$205	$0	$29	$31	$6	$0	$0	$	730

Table 5-15 Direct Losses Due to Damage to Distribution Systems

Event	Electric $ Billion	Water $ Billion	Highways $ Billion
Cape Ann	$0.89	$0.30	$0.60
Charleston	0.74	0.31	0.50
Fort Tejon	0.91	0.23	0.23
Hayward	0.90	0.20	0.25
New Madrid (M=8.0)	2.07	0.88	1.40
New Madrid (M=7.0)	0.65	0.28	0.44
Puget Sound	0.58	0.09	0.28
Wasatch Front	0.38	0.13	0.26

structural damage. The Citadel researchers studied direct damage to lifelines, as well as to housing, schools, and other components of the built environment in the three county area, but they did not investigate economic impacts as the current study does.

The following sections compare the assumptions and conclusions of the current study with those of The Citadel researchers. Note that the current study provided aggregate damage for the whole of South Carolina, and damage is not broken out by county, as it is in The Citadel study. Nonetheless, since the three counties enclose the bulk of the damaged South Carolina lifelines, the results should be comparable. The first section compares the scenario earthquake assumed by the two studies. The second section compares the results of the direct damage analyses for lifelines.

Scenario Earthquake. The Citadel researchers employed more severe ground shaking than the current study's use of the Evernden Model produced for the same event. The Citadel posted MMI IX to MMI X ground shaking within 25 miles of the epicenter, MMI VII to MMI VIII ground shaking within a 100 mile outer radius, and MMI VI or less ground shaking beyond this. This agrees well with a *broad* regional isoseismal map based on the historical record presented by Bollinger (1977). This broad map was developed by enveloping a detailed map also developed by Bollinger (1977) (i.e., the broad map was developed by the maximum MMI within a region taken from the detailed map, and using that as the MMI value for the broad map--both maps are presented in Figure 4-6). The Evernden Model used in the current study provided estimates of ground shaking on a detailed scale similar to that of the detailed map by Bollinger. In the Evernden model, MMI contours were calculated on a 25 km square basis. These contours agree fairly well with the detailed isoseismal map Bollinger presented. As a consequence of these interpretations of seismic intensity, differing results of The Citadel study tend to reflect the more conservative (i.e., higher) ground shaking estimates by generally more severe damage estimates.

Estimated Lifeline Damage. Both studies evaluated direct damage to a number of common lifeline elements. This section compares the two studies' results for direct damage to hospitals, fire stations, police stations, railroads, and electric transmission substations.

- **Hospitals.** The Citadel researchers inventoried 11 facilities in the three counties, in which 14% of the entire state population lives. They estimated a 43% probable maximum loss to hospitals, and a 21% average expected loss. The current study inventoried 91 health care facilities in South Carolina, and estimated 27 facilities would sustain light damage (damage between 1% and 10%), 6 facilities would sustain moderate damage (damage between 10% and 30%), 9 facilities would sustain heavy damage (damage between 30% and 60%) and 3 facilities would sustain major to destructive damage (damage between 60% and 100%). These figures represent an average gross dollar damage of 10%. Note that this 10% figure reflects damage to all health care facilities in South Carolina. It is to be expected that statewide average damage should be significantly less than damage within the epicentral region, which The Citadel's 21% figure reflects.

- **Airports.** The Citadel researchers inventoried 5 facilities in the three counties. They estimated functionality for operational pavements such as runways and taxiways, and for key operational vertical structures such as control towers and terminals. For runways and taxiways, The Citadel researchers estimated 30% functionality within 1 day, 60% functionality within 3 days, and full functionality within 8 days. For vertical structures, The Citadel researchers estimated 60% functionality within 2 days, and full functionality within 2-1/2 weeks. The current study inventoried 147 facilities in South Carolina, It estimated 59% functionality of South Carolina airports during the first week, 85% functionality during the second week, and full restoration during the tenth week. The present study also evaluated damage to airports as individual units, including structures and pavements, finding 49 facilities would sustain light damage, 29 facilities would sustain moderate damage, and 9 facilities would sustain major damage.

- **Fire Stations.** The Citadel researchers inventoried 55 facilities in the three counties. They estimated a 71% probable maximum loss, and a 36% expected loss. The current study estimated 275 South Carolina facilities; 50 are expected to sustain light damage (1% to 10%), 3 are expected to sustain moderate damage (10% to 30%), and 36 are expected to sustain heavy damage (30% to 60%). These figures represent an average 7% damage.

- **Police Stations.** The Citadel researchers inventoried 10 facilities in the three counties. They estimated a 69% probable maximum loss, and a 34% expected loss. The current study estimated 70 South Carolina facilities, and estimated that 10 would sustain light damage (1% to 10%), 1 would sustain moderate damage (10% to 30%), and 8 would sustain heavy damage (30% to 60%). These figures represent an average 6% damage.

- **Railroad.** The Citadel researchers inventoried 196 miles of track in the three counties. They estimated 1 mile of track would sustain 1% damage or less, 145 miles would sustain 1-to-10% damage, and 50 miles of track would sustain 10-to-30% damage. These figures would indicate an average 9% damage to railroad track in the three counties. The current study inventoried approximately 1500 miles of track in South Carolina, and estimated 550 miles of track would sustain light damage (1% to 10%), 52 miles would sustain moderate damage (10-to-30%), and 600 miles would sustain heavy damage (30-to-60%). These figures represent an average damage of 20% to South Carolina railroad track following a Charleston event. (This is a simple measure of track damage and should not be confused with residual capacity figures, which follow on network analyses (see Chapter 6)). This difference may be explained by the significant damage to railroad track outside the three counties.

- **Electric Transmission Substations.** The Citadel researchers estimated 20% of substations in the three county area would sustain light damage, 70% of substations would sustain moderate damage, and 10% of substations would sustain heavy damage. If one defines light damage as an average 5% damage, moderate damage as an average 20% damage, and heavy damage as an average 45% damage, average expected damage to transmission substations for The Citadel study would be 20%. The present study inventoried 100 substations in South Carolina, and estimated 43% sustain moderate damage (10-to-30%), 14% sustain heavy damage (30-to-60%), and 16% sustain major damage (60-to-100%). These figures represent an average 28% damage to South Carolina transmission substations following a Charleston event. The present study estimated average damage in excess of that estimated by The Citadel. An explanation can be found in that The Citadel study considered transmission and distribution substations, while the present study considered only transmission substations. Transmission substations typically sustain more damage than distribution substations; also substations outside the three counties are significantly damaged. (Note that the average damage discussed here is a simple measure of substation damage and should not be confused with residual capacity figures, which rely on network analyses (see Chapter 6).)

- **Bridges.** The Citadel researchers inventoried 3 major bridges and 216 conventional bridges in the three counties. They estimated "serious damage" to 10 bridges, "repairable damage" to 24 bridges, and "settlement damage" to 51 bridges. They defined "serious damage" as collapse of at least one span. "Repairable damage" means that the bridge could be restored within weeks, and "settlement damage" means damage to abutments. The current study inventoried 2134 bridges in South Carolina and estimated 320, 320, 128, and 20 bridges, respectively, would sustain light damage(damage between 1 and 10%), moderate damage (damage between 10 and 30%), heavy damage (damage between 30 and 60%), and major damage (damage between 60 and 100%). The current study provide an aggregate damage of about 7% for the entire state compared to about 6% given by the Citadel researchers study for the three counties. This difference may be explained by the finding that damage to bridges outside the three counties is expected to be significant.

Conclusion. The present study estimated damage between 1/2 and 1/5th of that estimated by The Citadel study in every classification except transmission substations, railroads, and bridges. These ratios seem reasonable. The Citadel researchers examined damage in a three-county epicentral region alone; while the present study considered South Carolina as a whole. One would expect average damage over the entire state to be substantially lower than average damage in the epicentral region. The exception, transmission substations, railroads, and bridges, were discussed above.

6. Estimates of Indirect Economic Losses

6.1 Introduction

Earthquakes produce both direct and indirect economic effects. The direct effects, such as dollar loss due to fires and collapsed structures, are obvious and dramatic. However, the indirect effects that these disruptions have on the ability of otherwise undamaged enterprises to conduct business may be quite significant. Although the concept of seismic disturbances and their effect on lifelines has been investigated for at least two decades, there is very little literature on indirect economic losses (Cochrane, 1975; Rose, in ASCE-TCLEE, 1981; Scawthorn and Lofting, 1984).

This study provides a first approximation of the indirect economic effects of lifeline interruption due to earthquakes. To accomplish this the relevant literature was surveyed. Then a methodology was developed to relate lifeline interruption estimates to economic effects of lifeline interruption in each economic sector. This required a two-step process:

1. Development of estimates of interruption of lifelines as a result of direct damage

2. Development of estimates of economic loss as a result of lifeline interruption

The general analytical approaches used to develop these estimates are discussed below and illustrated with example calculations. Results defining lifeline interruption and associated economic loss to specific facility types are also provided, but the bulk of this information is given in Appendices C and D. The chapter concludes with regional summaries of economic effects resulting from direct damage to the various lifelines in the eight scenario earthquakes.

6.2 General Analytical Approach for Estimating Lifeline Interruption

Lifeline interruption resulting from direct damage is quantified in this investigation in residual capacity plots that define percent of function restored as a function of time. The curves are estimated for each lifeline type and scenario earthquake using (1) the time-to-restoration curves discussed in Chapter 3 and provided in Appendix B, (2) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), and (3) inventory data specifying the location and type of facilities affected (from Chapter 2).

For site-specific systems (i.e., lifelines consisting of individual sited or point facilities, such as airports or hospitals) the time-to-restoration curves are used directly whereas for extended regional networks, special analysis procedures are used. These procedures consist of:

- connectivity analyses, and

- serviceability analyses.

Connectivity analyses measure post-earthquake completeness, "connectedness," or "cut-ness" of links and nodes in a network. Connectivity analyses ignore system capacities and seek only to determine whether, or with what probability, a path remains operational between given sources and given destinations.

Serviceability analyses seek an additional valuable item of information: If a path or paths connect selected nodes following an earthquake, what is the remaining, or residual, capacity between these nodes? The residual capacity is found mathematically by convolving lifeline element capacities with lifeline completeness.

A complete serviceability analysis of the nation's various lifeline systems, incorporating earthquake effects, was beyond the scope of this project. Additionally, capacity information was generally not available for a number of the lifelines (e.g, for the highway system, routes were available, but not number of lanes). Rather, for this project, a limited serviceability analysis has been performed, based on a set of simplifying assumptions.

The fundamental assumption has been that, on average, all links and nodes of a lifeline have equal capacities, *so that residual capacity has* *serviceable (i.e., surviving) links and nodes to the original number of serviceable links and nodes, for a given source/destination pair, or across some appropriate boundary.* For example, if the state of South Carolina has 100 airports, and 30 of these are determined to be unserviceable at some point in time following a major earthquake, then the air transport lifeline residual capacity is determined to be 70% of the initial capacity.

This assumption does not consider several important factors, including:

1. All nodes or links do not have the same capacities;

2. Links and nodes contributing most to the residual capacity are generally more distant from the heavily damaged area. Thus, the estimated lifeline residual capacity is generally overestimated in the area closest to the disaster area; and

3. Significant elasticity in capacity is generally available for most lifelines.

Factors 2 and 3 tend to offset each other. Further, factor 1 is probably acceptable for the purposes of this project, which aims to describe effects at the regional level.

The foregoing mode of analysis was employed for most of the regional network lifelines. One exception was the gas and liquid fuel transmission pipelines, where capacities were available and were employed, thus taking into account factor 1 above.

6.3 Residual Capacity Analysis of Site-Specific Systems

As indicated above, residual capacities for site specific lifelines were estimated using the restoration curves from Appendix B. For many of these facilities, only locational information was available (i.e., size or capacity information was not available). Because of this limitation, and because the general goal of this study was to determine impacts at the transmission or regional level (an approach that tends to average out differences in facility capacities), an assumption that all facilities of a particular class have the same capacity was often employed.

Using the curves provided in Appendix B, residual capacity was defined in "lifeline interruption plots" that define restoration in one-week-interval step functions. Initially, these step functions were computed for each facility in a region, and then averaged over all facilities of the same type in the region using the following equation:

$$R.C_j = \sum_{i=1}^{N} (C_i x R_i) / \sum_{i=1}^{N} C_i \qquad (6.1)$$

where $R.C_j$ is the residual capacity at time step j, C_i is the capacity of facility i, and R_i is the restoration of facility i at time step j. If all facilities have the same capacity, Equation 6.1 becomes

$$R.C_j = \sum_{i=1}^{N} R_i / N \qquad (6.2)$$

where N is the number of facilities. This calculation is illustrated in Example 6.1 (Figure 6-1).

Following is a discussion of results from the residual capacity analysis of each site-specific lifeline facility type considered in this investigation.

6.3.1 Airports

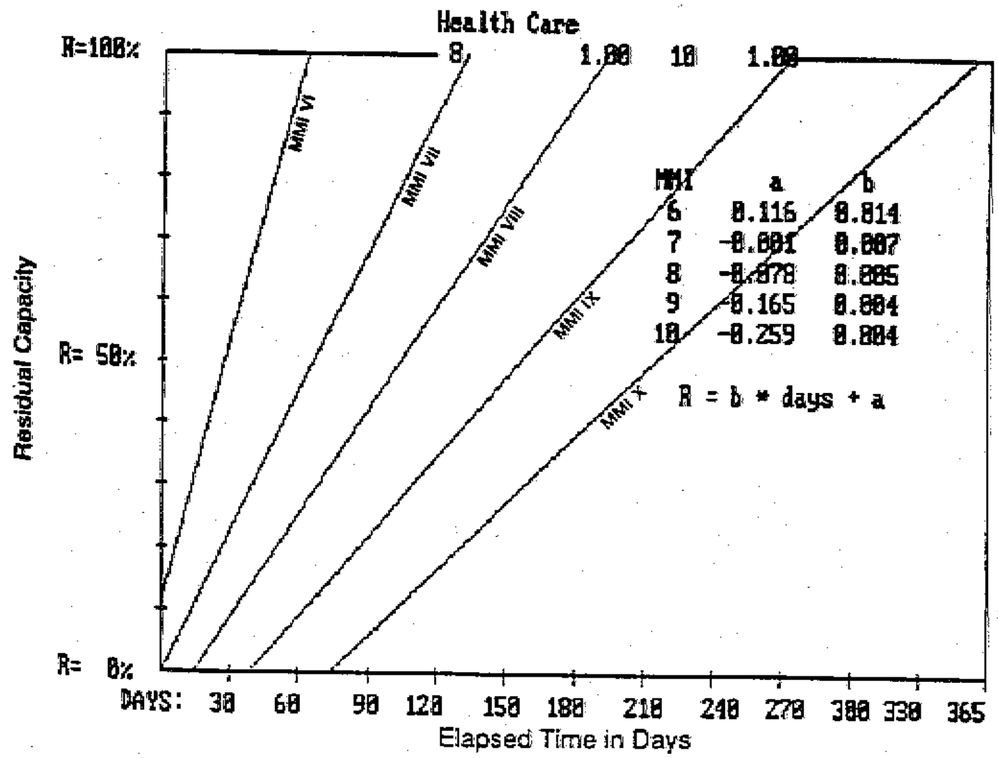
Residual capacities for airports were calculated assuming that all airports have the same capacity and the functionality of airports depends 20% on terminals and 80% on runways. The simplifying assumption that all airports have similar capacities is warranted due to the analysis seeking to determine regional air transport impacts, an approach that tends to average out extremes in airport capacities. Further rationales for this approach include: (1) the large number of general and civil aviation airports, (2) the relatively small difference in number of runways between many airports, (3) many runways have lengths sufficient for large commercial aircraft, (4) under emergency conditions, air traffic control capacity can be rapidly and significantly increased by deploying specialized military units, (5) airport through-put capacity is extremely elastic (under emergency conditions small airport cargo handling capacity can be significantly increased

Example 6.1

This example illustrates the residual capacity calculation algorithm for point source systems, using health care centers in Illinois as an example.

Assume that Illinois, located in "all other areas" of the NEHRP Map, has four health care centers. A scenario earthquake is estimated to result in shaking intensities at the four locations of MMI=5, 6, 7, and 8, respectively. Assume that no liquefaction hazard exists at the four sites. Estimate residual capacity at 0 days, 7 , 14 , 21 , 28 , and 196 days (the latter being the point of full restoration).

<u>Procedure</u>. Use the time-to-restore curve (below) for health care facilities (from Appendix B) for "all other areas" to determine the residual capacity at each health care facility.



This figure indicates residual capacities as follows:

	MMI	Elapsed time (days) 0	7	14	21	28	196
Facility 1	5	100%	100%	100%	100%	100%	100%
Facility 2	6	12%	21%	31%	41%	51%	100%
Facility 3	7	0%	5%	10%	15%	20%	100%
Facility 4	8	0%	0%	0%	3%	6%	100%
Average		**28%**	**32%**	**35%**	**40%**	**44%**	**100%**

The last row in the table provides the residual capacity of the example health care centers in Illinois, assuming that all facilities have the same capacity (i.e., per equation 6.4).

Figure 6-1: Analysis example illustrating residual capacity calculation algorithm for point source systems by staging cargo off-site, and apron space restrictions can be worked around through scheduling and staging aircraft at other airports).

Average residual capacity values over all airports in a given state at each time step were calculated using Equation 6.2. An example plot for Arkansas, one of the worst-case situations, is provided in Figure 6-2. In this example, the initial loss is approximately 31 percent of capacity, and full capacity is not restored until about day 290. Results for each state are plotted in Appendix C for each scenario earthquake (Figures C-1 through C-24). These data indicate that, of all the regional scenario events, the greatest impacts occur in the states of Arkansas, Mississippi, and Tennessee as a result of the New Madrid magnitude-8.0 event (Figures C-3, C-4, C-6). The states of Washington, Massachusetts, South Carolina, Utah, and California would experience the largest impacts due to the Seattle, Cape Ann, Charleston, Utah, and Fort Tejon, scenario events, respectively (Figures C-7, C-10, C-15, C-17, and C-18).

6.3.2 Ports

Residual capacities of Ports for all scenario events are presented in Figures C-25 to C-33. An example plot for South Carolina, the worst-case situation, is provided in Figure 6-3. In this example, the initial loss is nearly 100 percent of capacity, and full capacity is not restored until about day 200. Georgia would also experience similarly high losses due to the Charleston event (Figure C-27). Massachusetts and Rhode Island would experience the largest losses due to the Cape Ann event (Figures C-28 and C-29).

6.3.3 Medical Care Centers

Residual capacities of medical care centers were calculated using Equation 6.2 and are shown in Appendix C, Figures C-34 through C-57 for all states affected by all scenario events. All medical care centers were assumed to have the same capacity. One of the worst-case situations would occur in Arkansas for the New Madrid magnitude-8.0 earthquake (Figure 6-4). Similar long-term recovery periods are required in California for the Fort Tejon event (Figure C-51), South Carolina, for the Charleston event (Figure C-41), and in Washington, for the Puget Sound event (Figures C-52). Note also the initial high loss in capacity for medical care facilities in Massachusetts for the Cape Ann event (Figure C-44).

6.3.4 Fire Stations

Based on the assumption that fire stations have an average capacity, residual capacities of fire stations within the affected states were calculated using Equation 6.2, assuming that all fire stations are lumped at the center of Standard Metropolitan Statistical Areas (SMSAs). Results are presented in Figures C-58 through C-81. One of the worst case situations, which occurs in South Carolina as a result of the Charleston scenario event, is shown in Figure 6-5.

6.3.5 Police Stations

Residual capacities of police stations were calculated using Equation 6.2, assuming that all police stations have the same capacity and that stations were lumped at the center of the SMSAs. Results are presented in Appendix C, Figures C-82 to C-101, for all states affected by the scenario events. These plots indicate that, as in the case of fire stations, one of the worst-case situations occurs in Mississippi as a result of the New Madrid magnitude-8.0 scenario event (Figure 6-6).

6.3.6 Broadcast Stations

Based on the assumption that all broadcast stations have the same capacity, residual capacities within the affected states were calculated using Equation 6.2. For this facility type, the worst case situation occurs in South Carolina as a result of the Charleston event (Figure 6-7). See Appendix C, Figures C-102 to C-126, for plots of results for all eight scenarios and affected states.

6.4 Residual Capacity Analysis of Extended Regional Networks

In this investigation, residual capacity of extended regional networks (e.g., crude and refined oil pipelines; highways) has been estimated through the following sequence of operations:

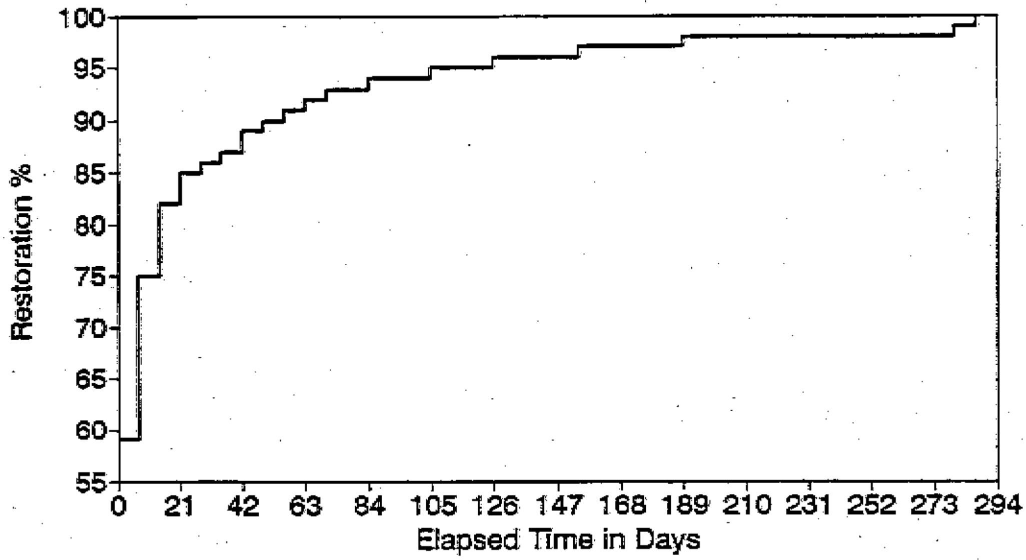


Figure 6-2 *Residual capacity of Arkansas air transportation following New Madrid event (M=8.0).*

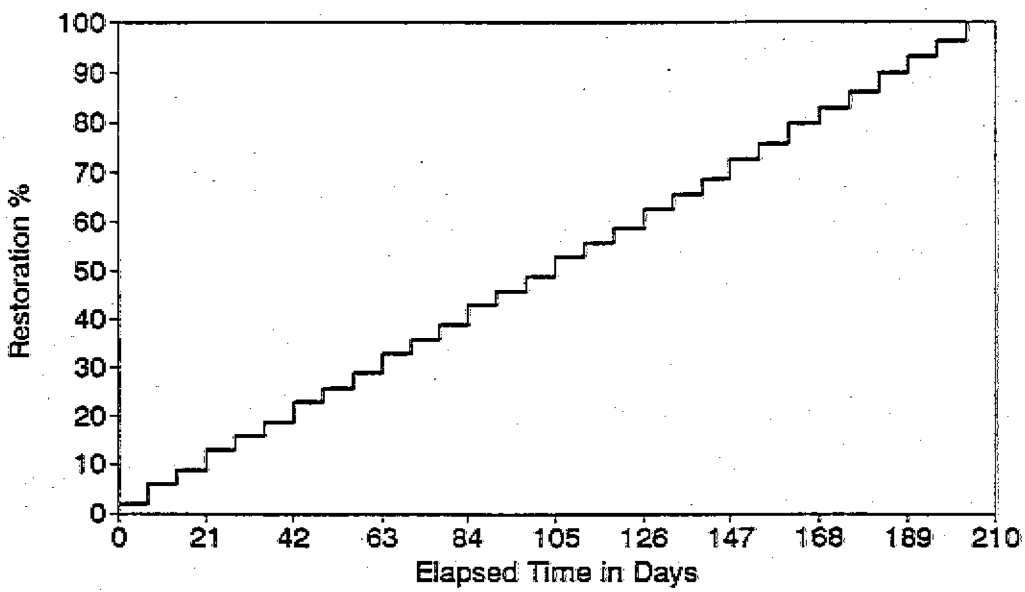


Figure 6-3 *Residual capacity of South Carolina ports following Charleston event (M=7.5).*

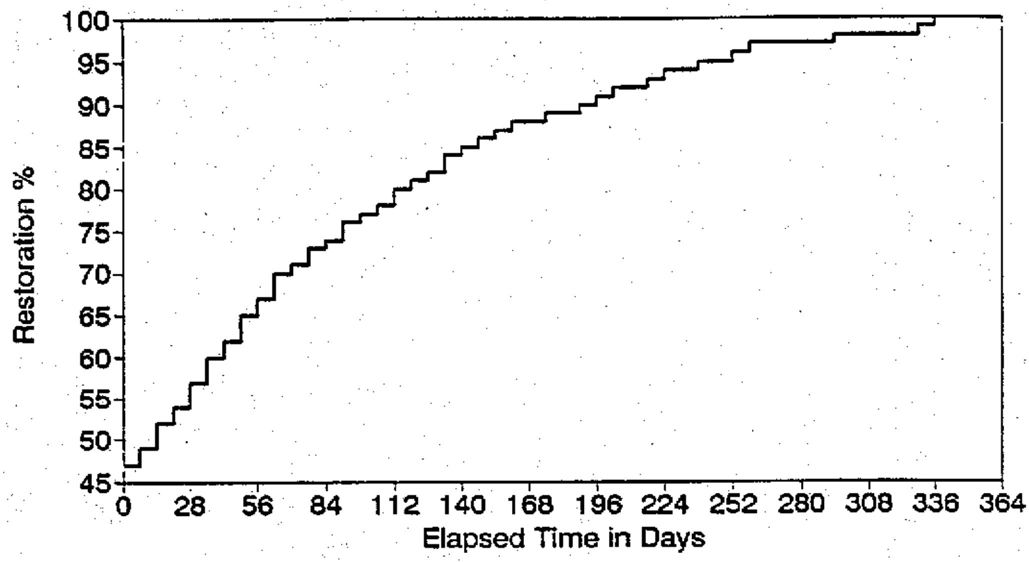


Figure 6-4 *Residual capacity of Arkansas medical care centers following New Madrid event (M=8.0).*

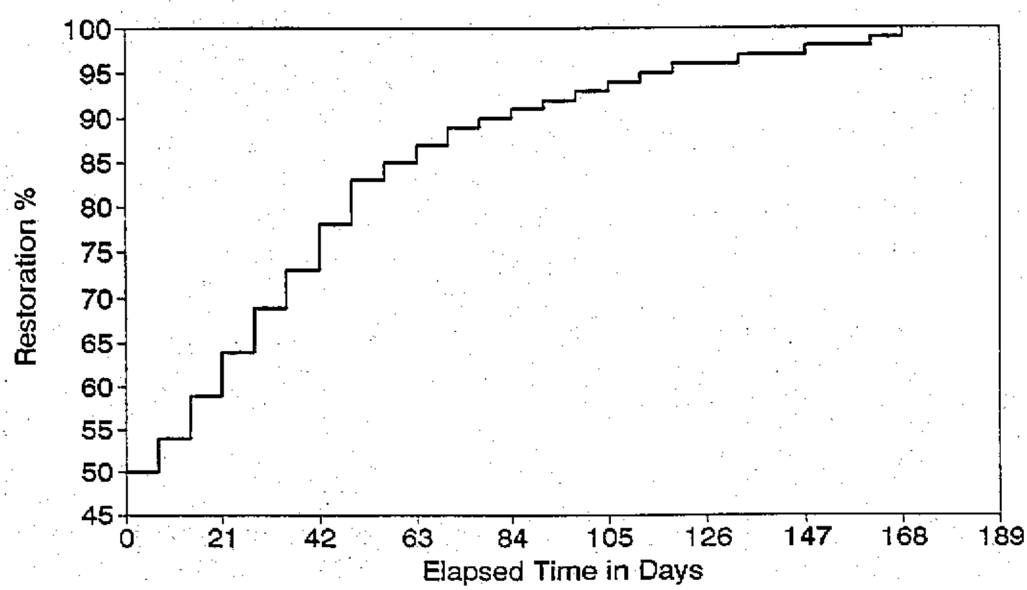


Figure 6-5 *Residual capacity of South Carolina fire stations following Charleston event (M=7.5).*

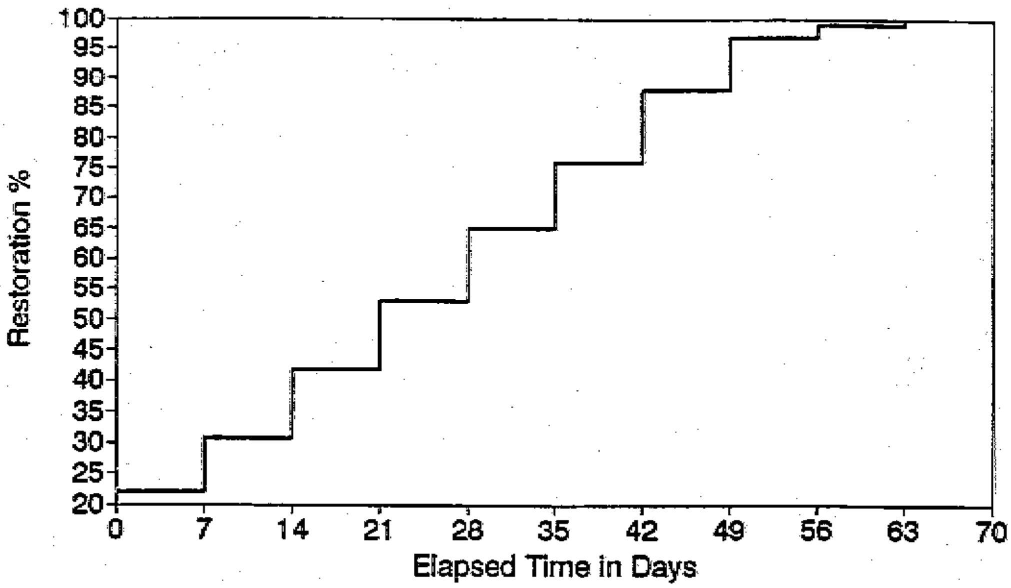


Figure 6-6 *Residual capacity of Mississippi police stations following New Madrid event (M=8.0).*

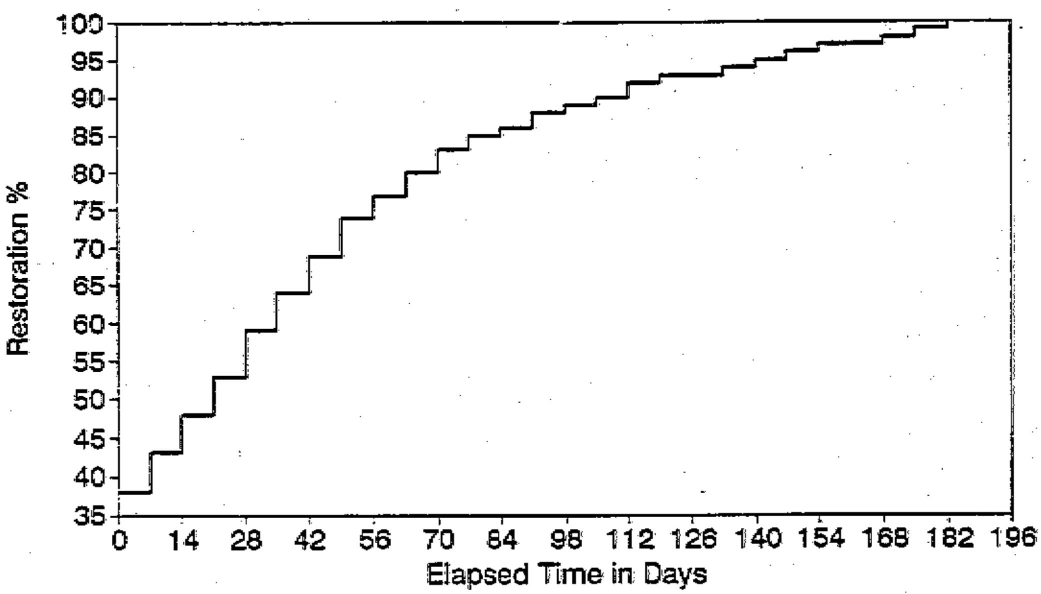


Figure 6-7 *Residual capacity of South Carolina broadcast stations following Charleston event (M=7.5).*

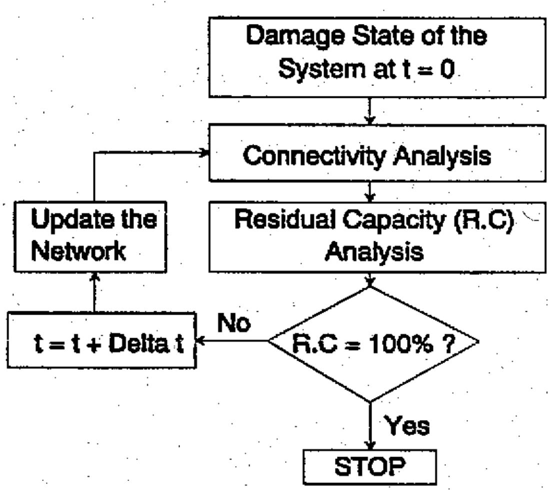
1. Maximum damage for every link in the network was first estimated using the procedures described in Chapter 5.

2. Connectivity analyses were then performed to identify nodes and links that are not connected to the source(s).

3. And finally, serviceability analyses were performed to determine residual capacity of the network as a whole, considering both damaged and undamaged links and nodes.

The networks are assumed to consist of sets of nodes and sets of links connecting these nodes. If a link has a direction, it is called a directed link; otherwise it is called an undirected link. A path is a sequence of nodes and links. The links can be directed in either direction (two-way links) or directed in one direction (one-way links).

Following is a flow chart showing the sequence of operations:



Connectivity Analyses. Connectivity analyses were performed using a technique called Depth-First-Search, or Backtracking (Tarjan, R., 1972). In this method, a network is connected if for every partitioning of the nodes of the network into subsets Y1 and Y2, there is either a link (i-j) or (j-i) between node $i \in Y1$ and node $j \in Y2$, where ε denotes membership.

For pipeline systems (crude oil and refined oil pipelines), pipeline sections (node-to-node) with probability of failure (i.e., probability of having at least one break) equal to or greater than about 60% were assumed to be closed until 100% restored. For natural gas systems, pipeline sections with probability of failure equal to or greater 30% were assumed closed until 100% restored. Bridges with more than 15% damage were also assumed out of service until fully restored.

Serviceability Analyses. Residual capacities between sources and destinations were estimated using the minimum-cut-maximum-flow theorem (Ford and Fulkerson, 1962; Hu, 1969; and Harary, 1972) which is the central theorem in network flow theory. This approach was generalized for this project to account for multiple-source multiple-destination problems.

The minimum-cut-maximum-flow theorem simply searches for the cut with the minimum capacity, i. e., the bottleneck, that completely separates the sources from the destinations. That is to say, the maximum flow in a network is always equal to the capacity of the cut that provides the minimum capacity of all cuts separating the source(s), S, and the destination(s), D.

A cut is defined by (Y1,Y2), where Y1 is a subset of nodes of the network and Y2 is its complement (i.e., the remaining subset of nodes). A cut (Y1,Y2) is a set of links (i-j) with either the node $i \in Y1$ and $j \in Y2$ or $j \in Y1$ and $i \in Y2$. Therefore, a cut is a set of links the removal of which will disconnect the network. A cut separating the source, S, and the destination, D, is a cut (Y1,Y2) with $S \in Y1$ and $D \in Y2$.

The capacity of a cut (Y1,Y2), denoted by C(Y1,Y2), is Σc_{ij} with $i \in Y1$ and $j \in Y2$, where c_{ij} is the capacity of the link (i-j). Note that in defining a cut, we count all the arcs that are between the set Y1 and the set Y2, but in calculating its capacity we count only the capacity of links from Y1 to Y2, but not the one way links from Y2 to Y1. i.e. C(Y1,Y2) not equal C(Y2,Y1). The cut with the minimum capacity is called the minimum cut.

For example, consider the network in Figure 6-8. Assume that all links are two way links, and that the numbers next to each link represent the capacity of that link. The set Y1 defined above consists of nodes S and 2, while the set Y2 consists of nodes 1 and D. The cut shown in Figure 6-8 is a minimum cut and has the capacity $C(Y1,Y2) = c_{S1} + c_{2D} = 2 + 4 = 6$, which

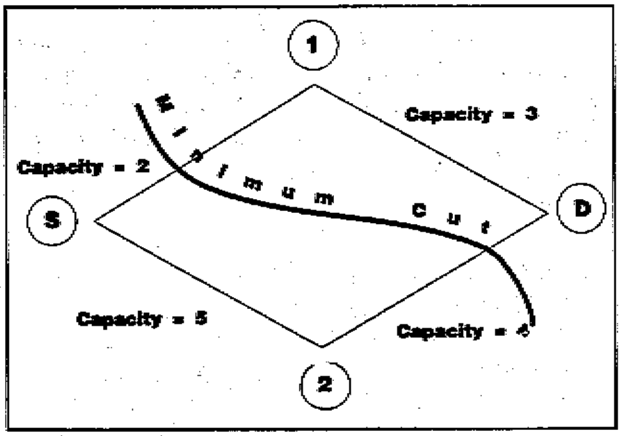


Figure 6-8 *Flow network to illustrate minimum-cut-maximum flow Theorem.*

is the maximum flow that can be delivered between the source S and the destination D.

The maximum flow is a linear programming problem with the objective function

$$Q = \Sigma X_{ij} \tag{6.3}$$

and the constraints

$$\begin{aligned} X_{ij} - X_{jk} &= -Q \text{ if } j = S \\ &= 0 \text{ if } j <> S \text{ or } D \\ &= Q \text{ if } j = D, \end{aligned} \tag{6.4}$$

and

$$0 < X_{ij} < c_{ij} \quad \text{for all } i,j \tag{6.5}$$

where Q is the out flow value and X_{ij} is the flow in link (i-j). Equation 6.4 expresses conservation of flow at every node, and Equation 6.5 states that the link flow X_{ij} is always bounded by link capacity c_{ij}.

To apply the maximum flow theorem, sources and destinations have to be defined. For the oil systems and the natural gas system, nodes in Texas and Louisiana represent the sources, while nodes in Illinois, California, Seattle, Utah, and Massachusetts represent destinations. Source and destination are more difficult to define for the highway and railroad systems. These networks are highly redundant, so damage and losses are confined to the epicentral regions. In the residual capacity calculations for highway and railroad systems, sources are defined to be the outer nodes of all links that intersect with the smallest boundary around the epicentral area, such that all intersected links remain undamaged following an earthquake. Destinations are defined to be all nodes inside the largest boundary around the epicentral area such that all intersected links are damaged (intersection is assumed at the center of the links). For damaged links, restoration of each link is estimated at each time step using the appropriate restoration curve and the maximum intensity along the link.

The residual capacity at a given destination at any time step, t, is defined to be the ratio between the maximum available flow at the destination for the damaged system, Q_t, to the maximum available flow at the destination for the undamaged system, Q_o, i.e.

$$R.C. = Q_t/Q_o \tag{6.6}$$

where Q_t and Q_o can be calculated using the min-max theorem discussed above, and R.C. is the residual capacity.

Example Calculations. Two examples are provided (Figs 6-9 and 6-10) that demonstrate residual capacity calculations for pipeline networks (Example 6.2) and for non-pipeline networks (Example 6.3).

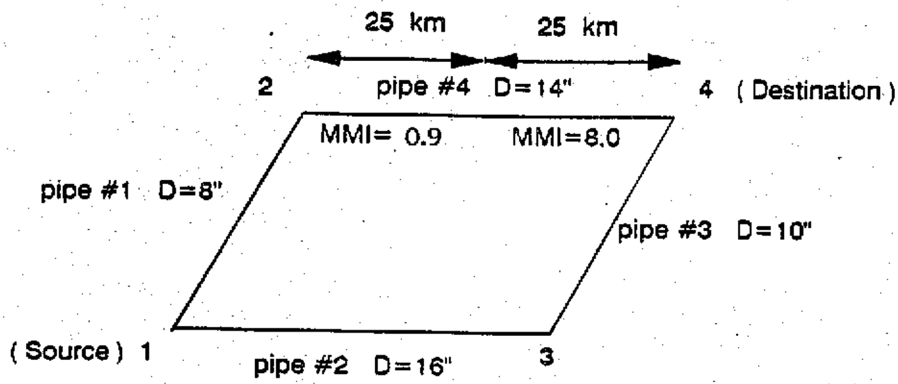
Software Employed. The calculations of damage state, connectivity, and residual capacity were performed using a proprietary computer program, *LLEQE* (*L*ife*L*ine *E*arth*Q*uake *E*ngineering). *LLEQE* employs state-of-the-art computer graphics and was developed to perform four tasks: (1) to perform seismic hazard analyses; (2) to generate lifeline damage states consistent with the calculated site-specific seismic intensities; (3) to perform connectivity analyses; and (4) to estimate residual capacities of lifeline components. Its capabilities include the following components/functions:

- Database. Database capacity can accommodate most major lifeline systems at the transmission level on the national scale, including: transportation, water, electric power generation and supply, gas and liquid fuel supply and emergency service facilities.

Example 6.2

This example illustrates the residual capacity calculation for pipelines systems (e.g., crude oil, refined oil, or natural gas).

Consider the following crude oil pipeline network:



Assume that pipe number 4 is subjected to intensity MMI = 8 along 25 km of its length, and MMI = 9 along 25 km of its length. The pipe lies in the non-California 7 portion of the NEHRP map. Assume the other pipes are unaffected and that there is no liquefaction. Find residual capacity at node 4 at the end of 7 days

Procedure. Use the damage curves for petroleum fuel transmission pipelines (from Appendix B) to determine mean break rate by intensity. Using the data on which this figure is based, the 25 km length of pipe, l_1, experiencing MMI = 8 has an expected mean break rate, λ_1, of 0.036 breaks/km. The 25 km length of pipe, l_2, experiencing MMI = 9 shaking has an expected mean break rate, λ_2, of 0.179 breaks/km. The probability of having at least one break in this pipe is given by equation 5.4, which is

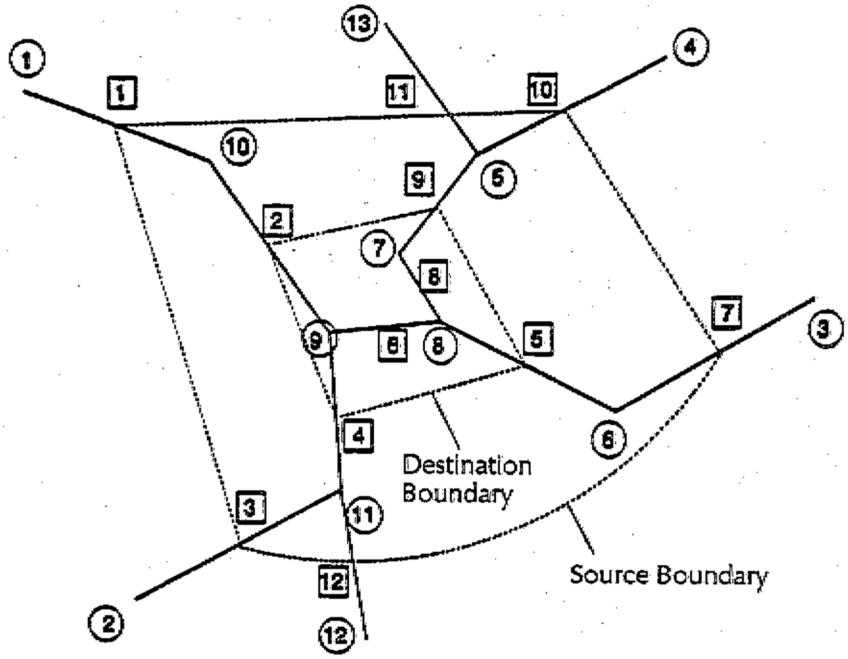
$$\begin{aligned} P_f &= 1 - \prod_{i=1}^{2} P_s \\ &= 1 - (\exp(-\lambda_1 \times l_1) \times \exp(-\lambda_2 \times l_2)) \\ &= 1 - (\exp(-0.036 \times 25) \times \exp(-0.179 \times 25)) \\ &= 0.99 \end{aligned}$$

The diameter square of each pipe will be taken as a measure of capacity of the pipe. For the undamaged system using the min-max theory, the maximum flow Q_o at the destination (i.e., node 4) is 164 (the maximum flow at node 4 equals the capacity of link number 1, i. e. 64, plus the capacity of link number 3, i.e. 100). Since the probability of failure of pipe number 4 is greater than 60%, this pipe will assumed to be closed until it will be fully restored. For the damaged system, at the first time step (i. e., t=0 days) pipe 4 will be closed and the maximum flow Q_1 at node 4 is the capacity of the remaining system, which is 100. The residual capacity at time step t=0 can be estimated using Equation 6.6 and is given by Q_1/Q_o = 61.0%. Using the time-to-restore curve for petroleum transmission lines provided in Appendix B, the time to fully restore pipe sustaining MMI = 9 is 10 days. Thus, at the second time step (t = 7 days) the maximum flow at node 4 equals 100, and the residual capacity at the destination is still 61% (pipe 4 is still closed).

Figure 6-9: Analysis example illustrating residual capacity calculation for crude oil pipeline network.

Example 6.3

This example illustrates the damage and residual capacity calculation for non-pipeline network systems (e.g., railroad or highway system). Consider the following highway network (nodes denoted by circles, links by boxes):



The network lies in the "All Other Areas" portion of the NEHRP map; the intensity distribution for a given scenario earthquake is given below. Assume liquefaction does not occur and that Links 2 and 9 contain bridges. If a bridge experiences damage of 15% or more, it is assumed closed until 100% restored. Characterize restoration at various time intervals.

	Link Number									
	1	2	3	4	5	6	7	8	9	10
length, km	5	5	5	5	5	3	5	3	5	5
MMI	5	6	5	7	8	7	5	8	7	4

Procedure. Using the damage curves provided in Appendix B for highways/freeways, damage to the highway system is estimated as follows:

	Link Number									
	1	2	3	4	5	6	7	8	9	10
Damage, %	0	0	0	1	3	1	0	3	1	0

Using the damage curves for conventional bridges, "other" areas (Appendix B), damage to the bridges in Links 2 and 9 is estimated to be 10% and 30% damage, respectively.

Due to the assumption that a bridge is closed if damage exceeds 15%, the bridges in Link 9 are closed until 100% restored, while bridges in Link 2 are not. Restoration of the network links are estimated from the restoration curves for conventional bridges, "all other areas" (Appendix B) as follows (see following page):

Figure 6-10: Analysis example illustrating the residual capacity calculation for highway networks.

- Damage State. The *LLEQE* user can specify breaks, generate random breaks, or both. To generate a break in a link the user simply select "Specify Break" option and points to the link with a mouse. To simulate a seismic event, random breaks are generated using Monte Carlo simulation and a nonhomogeneous Poisson process with mean break rate based on data from previous earthquakes.

- Connectivity Analysis. Connectivity analysis is performed to identify disconnected regions of damaged systems, tag them with coded colors, and eliminate them from subsequent system analysis. Optimum path and shortest path from source to destination can also be defined.

- Serviceability Analysis. Analysis to estimate the serviceability of lifeline systems under seismic or other events. The process involves connectivity analysis of the system in simulated damage states consistent with site seismicity and statistical analysis of residual capacities available in these damage states. It can provide fragility curves to estimate the functionality and usability of the system.

Following are summaries of residual capacity analytical results for extended regional lifeline networks.

6.4.1 Railroad System

Residual capacities of the railroad system for all scenario earthquakes were estimated using the minimum-cut-maximum-flow theorem defined above; sources and destinations were also defined as above. Residual capacity plots for the railroad system are provided in Appendix C, Figures C-127 through C-134. An example (typical) plot for the Hayward earthquake scenario is provided in Figure 6-11.

6.4.2 Highway System

Residual capacities of the highway system were estimated using the minimum-cut-maximum-flow theorem and the sources and destinations as defined above. The residual capacities are shown in Figures C-135 to C-142. An example plot for the epicentral regional of the magnitude-8.0 New Madrid event, one of the worst case situations, is provided in Figure 6-12. In this case nearly 95% of the highway system capacity is initially lost, and full restoration of the system is not achieved until about day 420. Losses in highway system capacity are similar for Utah, as a result of the Wasatch Front scenario.

6.4.3 Electric System

Residual capacities of the electric system were estimated taking into account nodes only (i.e., transmission substations). The residual capacity for each node was estimated at each time step using the time-to-restore curves for transmission substations from Appendix B. Averages over all nodes in each state affected by the scenario events were calculated using Equation 6.2 and are plotted in Figures C-143 to C-166. One of the worst case situations occurs in Mississippi following the magnitude-8.0 New Madrid event (Figure 6-13). In this case, the initial loss is approximately 75% of capacity, and full restoration is not achieved until about day 130. Losses for Arkansas for this same event are similar.

6.4.4 Water System

Residual capacities of the water system (Figures C-167 to C-169) were estimated using the minimum-cut-maximum-flow theorem discussed above. For the Hayward event the San Francisco Bay area was assumed to be the destination and the outside world, the source. For the Fort Tejon event Los Angeles was assumed to be the destination and the Colorado River Aqueduct (1056 hm^3), California Aqueduct South Coast (692 hm^3), and Los Angeles Aqueduct (574 hm^3) were assumed to be the sources. The worst case situation occurs in Los Angeles as a result of the Fort Tejon event (Figure 6-14).

6.4.5 Crude Oil System

For the residual capacity calculations for the crude oil system, Texas and Louisiana were assumed to represent the source region, while Chicago, Southern and Northern California represented the destinations. Residual capacities of the crude oil system were estimated using the minimum-cut-maximum-flow theorem discussed above. Links with probability of failure greater than or equal to 60% were assumed closed until 100% restored.

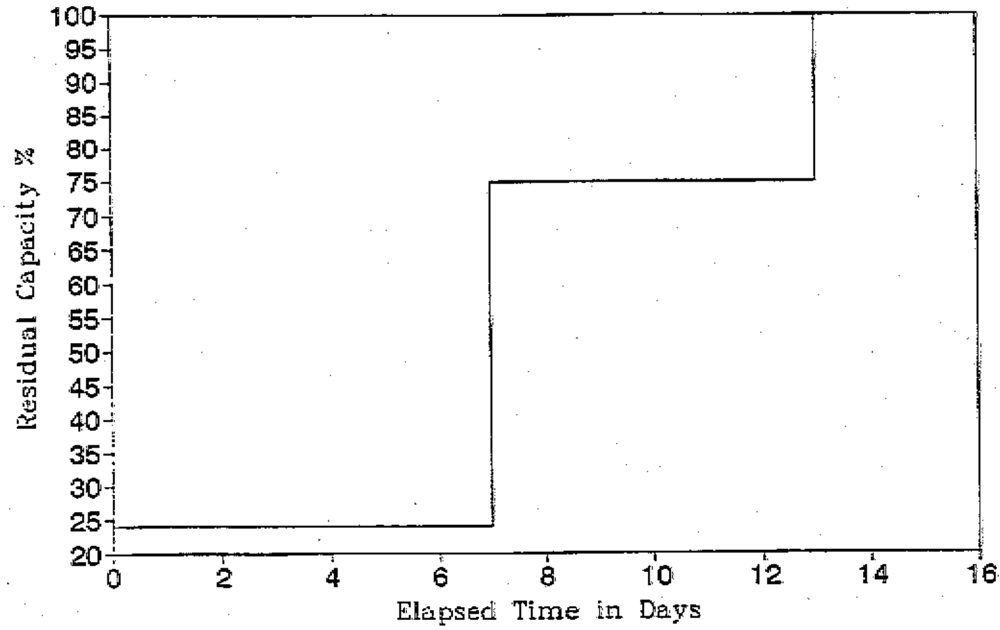


Figure 6-11 *Residual capacity of San Francisco Bay area railroad system following Hayward event (M=7.5).*

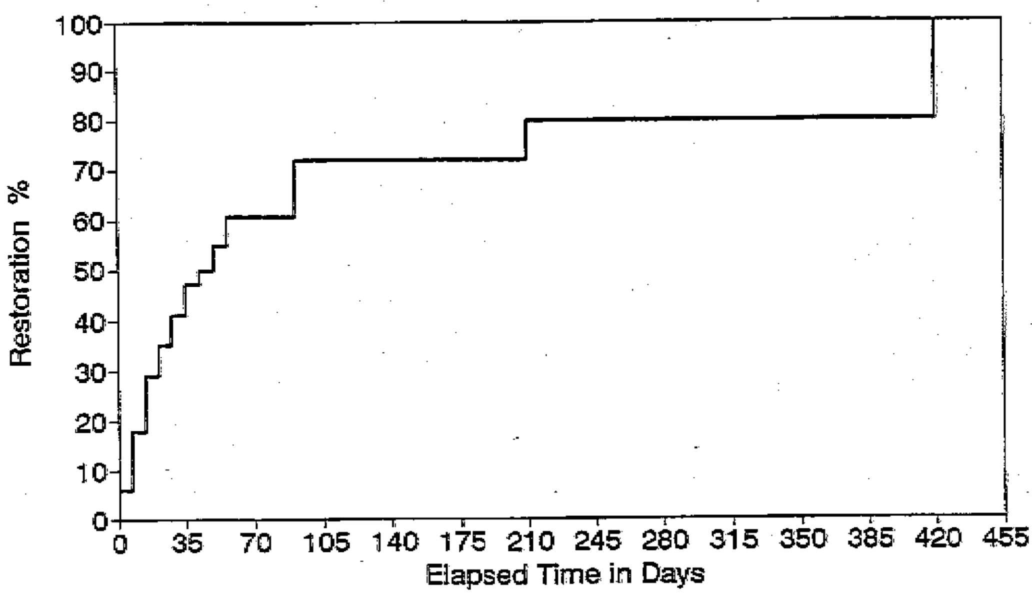


Figure 6-12 *Residual capacity of epicentral region highways following New Madrid event (M=8.0).*

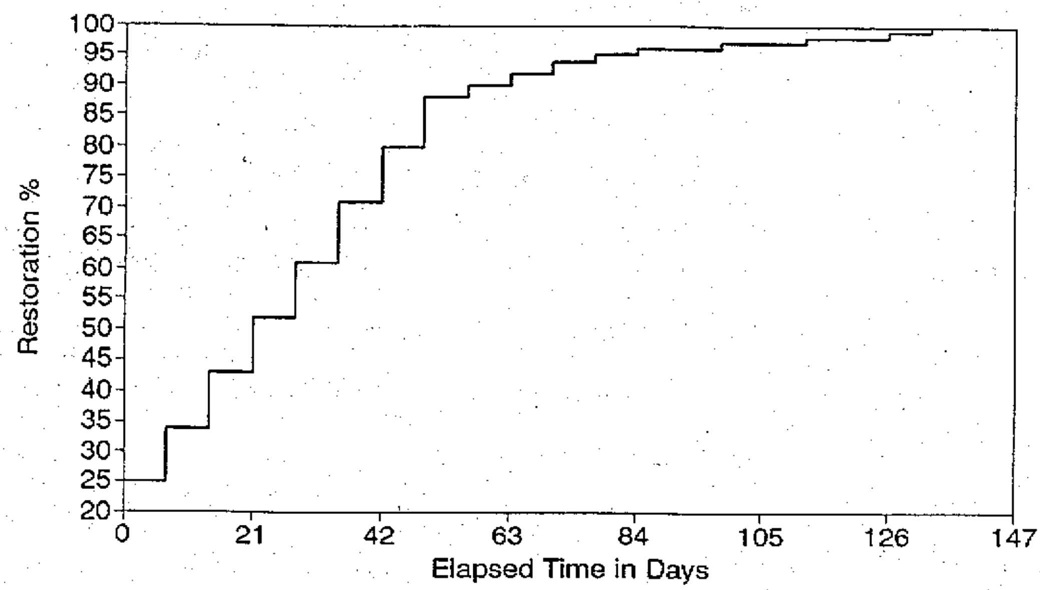


Figure 6-13 *Residual capacity of Mississippi electric system following New Madrid event (M=8.0).*

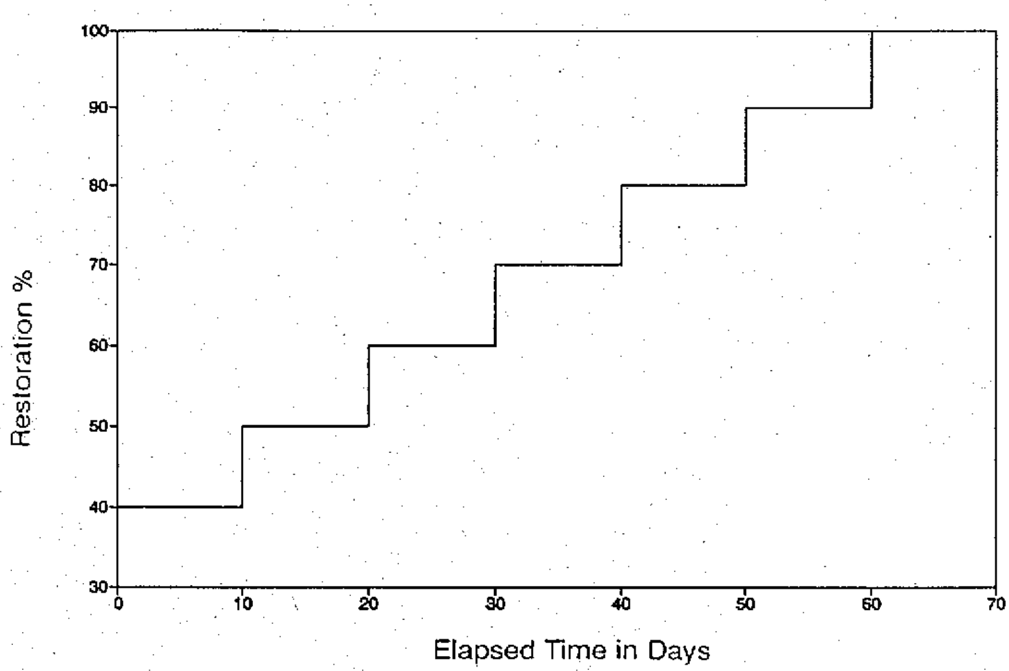


Figure 6-14 *Residual capacity of epicentral region water system following Fort Tejon event (M=8.0).*

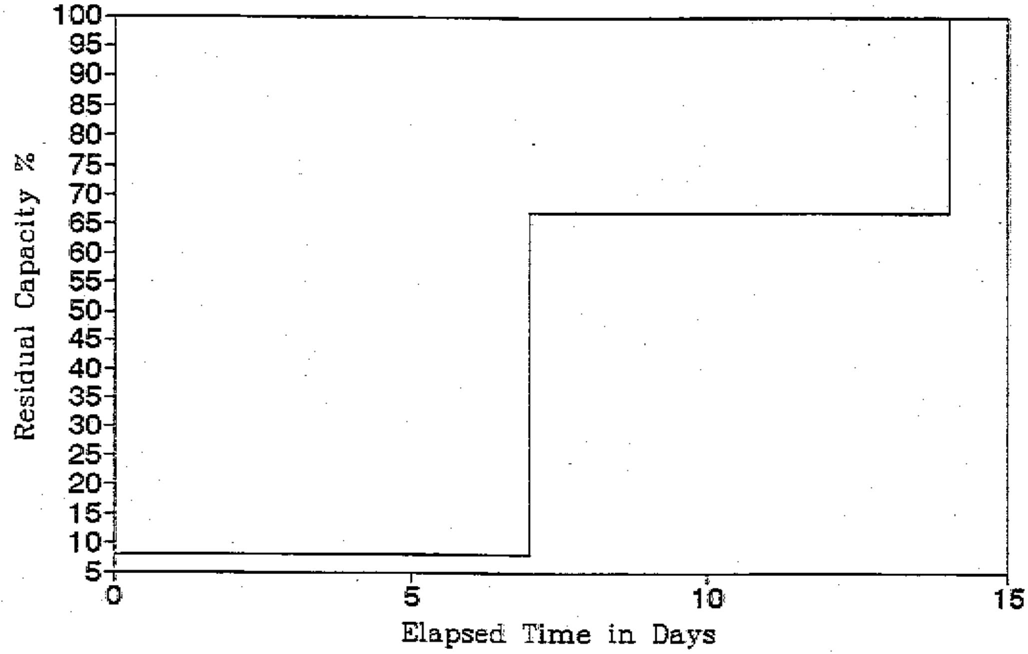


Figure 6-15 *Residual capacity of crude oil delivery system from Texas to Northern California following Fort Tejon event (M=8.0).*

The residual capacities are shown in Figures C-170 to C-173. One of the worst-case situations occurs in California as a result of the Fort Tejon earthquake scenario (Figure 6-15). In this case crude oil delivery capacity from Texas to Northern California is initially reduced to less than 10 percent, and full restoration of capacity is not achieved until about day 14. A similar situation occurs in this same scenario earthquake for crude oil delivery from Texas to Southern California.

6.4.6 Refined Oil System

For the residual capacity calculations for the refined oil system, Texas was assumed to be the source, and Chicago was the destination. Residual capacities were estimated using the minimum-cut-maximum-flow theorem discused above. Links with probability of failure greater than or equal to 60% were assumed closed until 100% restored. The residual capacities are shown in Figures C-174 and C-175. Residual capacity plots for the two New Madrid events considered are similar. The plot for the New Madrid magnitude-8.0 event is provided in Figure 6-16.

6.4.7 Natural Gas System

For the residual capacity calculations for the natural gas system, Texas and Louisiana were considered as the sources, and Illinois, Massachusetts, Utah, Washington, and California represented the destinations. Residual capacities of the natural gas system were estimated using the minimum-cut-maximum-flow theorem discused above. The residual capacities are shown in Figures C-176 through C-184. An example plot for the Hayward scenario, one of the worst case situations, is provided in Figure 6-17. In this case the capacity for natural gas delivery from Texas to Northern California is reduced to zero for the first seven days after the earthquake; full capacity is restored at about day 14. Losses in delivery capacity to Seattle from Texas, as a result of the Puget Sound scenario, and to California from Texas, as a result of the Fort Tejon event, are similar.

6.4.8 Distribution Systems

Residual capacities of the electric, water, and highway distribution systems were estimated using the time-to-restore curves provided in

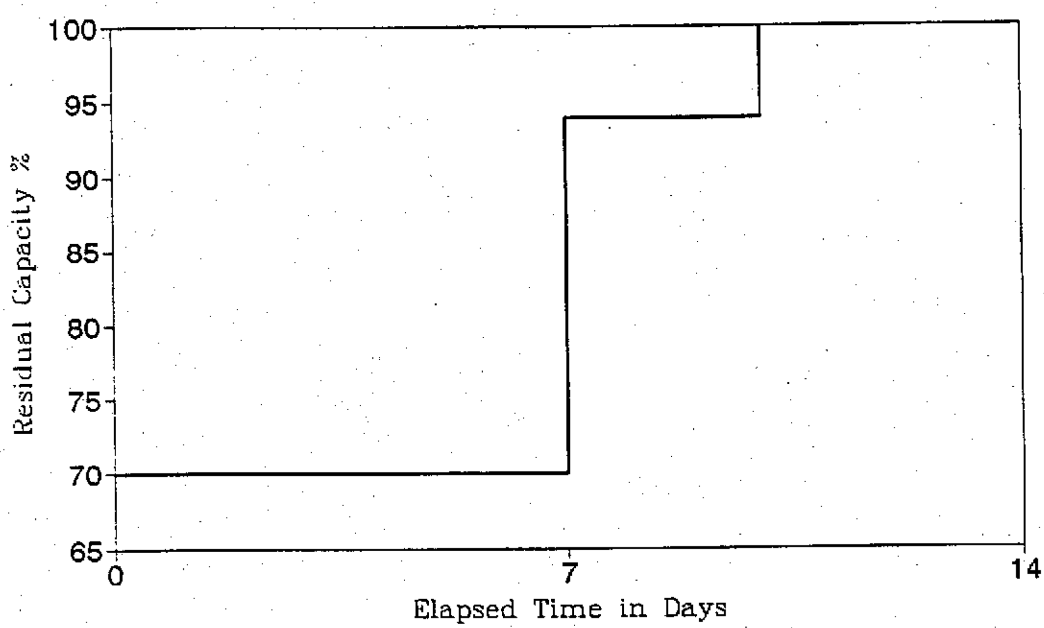


Figure 6-16 *Residual refined oil delivery from Texas to Chicago following New Madrid event (M=8.0).*

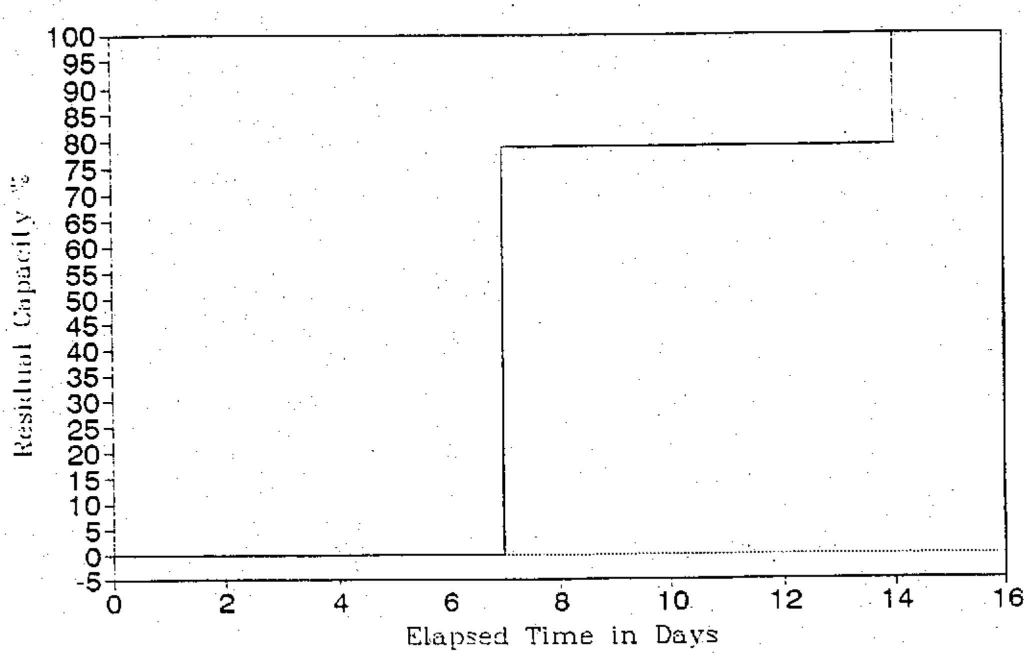


Figure 6-17 *Residual capacity of natural gas delivery from Texas to Northern California following Fort Tejon event (M=8.0).*

Appendix B. Distribution systems were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas (SMSAs), and intensities were estimated at each SMSA for every scenario event. Residual capacity plots for distribution systems have not been included in this report. Economic losses resulting from damage to these systems, however, are included in the summaries provided later in this chapter.

6.5 General Analytical Approach for Estimating Indirect Economic Losses

In order to develop the relationship between lifeline interruption and indirect economic losses it was necessary to generate a set of simplifying assumptions. The general assumptions that apply to all lifelines are listed below.

6.5.1 General Assumptions

1. Duration. The interruption of the lifeline element/system that gives rise to the economic loss is assumed to extend over one or more consecutive month-long time periods. The functionality loss assigned to each month is the average for that month.

2. Independence. Lifeline elements are assumed to be independent. Interruptions in elements of one lifeline do not produce interruptions in other lifeline elements. That is, we ignore lifeline interaction effects, which are sometimes non-trivial.

3. Lifeline Functionality. The quantity under examination here is lifeline functionality as opposed to lifeline capacity. For example, assume the water supply lifeline sustains a loss of 20 percent of its capacity locally, but, because of redundancy and looping, water remains fully available. The functionality loss and consequent indirect economic loss would both be zero. Conversely, if all water supply and transmission facilities remain intact, but damage to the distribution system cuts off water to 20 percent of the industries served, the functionality loss is 20 percent.

4. Distribution of Incidence of Interruption. Lifeline interruptions are assumed to be prioritized as follows:

   Primary: Emergency response and human needs

   Secondary: Industrial needs (Within this class non-interruptible service customers share the loss in capacity equally)

   Tertiary: Interruptible service customers

5. Secondary Impacts Ignored. The loss of capacity in one (non-lifeline) industry would likely reduce the productivity of other industries that obtain inputs from the first industry. These reverberations, which are typically measured using input-output analysis, will be ignored for this first approximation. To the extent that these reverberations are ignored, impacts are understated.

6. Functional Relationships. Each industrial sector of the economy was considered separately with respect to each lifeline. The maximum impact, which would be expected to result from a prolonged total lifeline failure was estimated for each lifeline/sector pair. The effect of less-than-total failure of the lifeline was estimated using the following assumptions:

   - The first 5% interruption could be absorbed without economic loss

   - Subsequent losses would result in proportionate economic losses. Thus as lifeline capacity falls from 95 to 0%, the economic impact is assumed to increase linearly from zero to the maximum effect for each sector/lifeline pair.

   - The product of the percent loss of value added for each sector was summed over all sectors for each decile and lifeline. This sum represents the value-added weighted average of the economic impact of the lifeline for that decile.

7. Linearity. The linearity assumption mentioned above implies that remaining lifeline capacity could be used productively; limited lifeline damage would not cause a complete cessation of economic activity in

the sector. This assumption may unrealistically underestimate the effects of lifeline interruptions in industries (such as primary metals) that might be unable to scale back operations or to close and restart operations in response to reduction and restoration of lifeline capacity.

6.5.2 Data Sources and Methodology

Value Added Data. Economic activity within each industrial sector was measured in terms of value added. Value added refers to the value of shipments (products) less the cost of materials, supplies, contract work and fuels used in the manufacture or cultivation of the product. The United States Bureau of Economic Analysis publishes annual data for value added for each industrial sector. For simplicity, data from the 99 sectors were collapsed into 36 sectors. Data for 1983 were the latest available (published by BEA, 1989), and were used in this study.

As a first approximation, data on the national economy were used to assess the relative economic importance of each sector. The value added for each of the 36 sectors of the economic model is expressed as a percentage of the nationwide total. These data are presented in Table 6-1. For comparison, comparable data for the local San Francisco Bay Area economy (which comprises Santa Clara County and parts of Alameda County) are shown on the same table.

Lifeline Importance Factors. The economic impact of each lifeline was estimated by modifying estimates from ATC 13 (ATC, 1985). Table 9.8 of ATC 13 presents the lifeline importance factors for each social function. To adapt these estimates to the present study, the "social functions" were assigned to each industrial sector. The importance weights provided in ATC-13 distinguish between main and distribution systems for each lifeline. For the present study, the two figures were averaged to produce an importance weight for the entire lifeline system. Further modification of the ATC-13 estimates were made to reflect the difference between the importance of the lifeline and its impact on the economy if it were totally disrupted. These modifications, generally in the upward direction, constitute first approximations of economic impacts. The maximum impact estimates by sector and lifeline are shown in Table 6-2.

Reduction in Value Added Due to Lifeline Interruption. Table 6-3 presents the percent reduction in value added for each sector resulting from increasingly severe crude oil lifeline interruptions. (Similar tables are shown for all lifelines in Appendix D.) Values are shown for each decile of lifeline interruption and are assumed to pertain to *monthly* Gross National Product (GNP). As noted in the assumptions cited above, these percentages are linearly interpolated between the reduction in value added when the lifeline experiences 5% interruption (for a 5% lifeline interruption, there is no reduction in value added) to the reduction in value added when the lifeline experiences 100 percent interruption (maximum impact).

Table 6-4, also assumed to pertain to *monthly* GNP, presents the remaining value added of each sector under alternative levels of crude oil lifeline interruption. Similar tables are shown for all lifelines in Appendix D. These value added estimates are calculated by finding the percent value added of the sector within the total economy (Table 6-1, right column) and the percentage reductions in value added (e.g., Table 6-3 for oil supply). The product of these two variables is subtracted from the uninterrupted value-added for each decile. In the case of oil supply and the livestock sector, the residual valued-added after 10% of loss of capacity = (0.45%) - ((0.45%) x (2.63%)) = (0.45) - (.01) = 0.44% These sums thus represent the weighted average of the sectorial impacts of interruptions to the lifeline.

Figure 6-18 illustrates the value added weighted average economic impacts of crude oil lifeline interruptions (taken from totals at bottom of Table 6-4). Similar figures are shown for all lifelines in Appendix D. The Y-intercept reflects the estimate of the maximum impact, due to total disruption of the lifeline for an extended period of time.

Further Refinements. As noted at the outset, this brief study constitutes a first approximation of the economic effects of lifeline interruption. A number of explicit and implicit assumptions were made in order to simplify the analysis. Using these assumptions limits the accuracy of

Table 6-1 Relative Importance of Industry Sections--U. S. and Santa Clara County, California

	Sector	Santa Clara & Part Alameda Value Added (Mil $1986)	U.S. Econ Value Added (Mil $1983)	U.S. Econ. Value Added Pct. of Tot.	U.S. Econ. Value Added Pct. of Tot.
1	Livestock	4	0.01%	15,227	0.45%
2	Agr. Prod.	78	0.13%	35,567	1.06%
3	AgServ For. Fish	115	0.20%	3,705	0.11%
4	Mining	92	0.16%	130,577	3.89%
5	Construction	1,973	3.39%	185,326	5.52%
6	Food Tobacco	593	1.02%	80,810	2.41%
7	Textile Goods	10	0.02%	12,515	0.37%
8	Misc Text. Prod.	11	0.02%	24,397	0.73%
9	Lumber & Wood	50	0.09%	17,319	0.52%
10	Furniture	60	0.10%	11,378	0.34%
11	Pulp & Paper	153	0.26%	29,253	0.87%
12	Print & Publish	413	0.71%	44,053	1.31%
13	Chemical & Drugs	492	0.84%	47,144	1.40%
14	Petrol. Refining	3	0.01%	32,332	0.96%
15	Rubber & Plastic	127	0.22%	34,579	1.03%
16	Leather Prods.	1	0.00%	4,119	0.12%
17	Glass Stone Clay	199	0.34%	20,758	0.62%
18	Prim. Metal Prod	95	0.16%	34,951	1.04%
19	Fab. Metal Prod.	538	0.92%	55,094	1.64%
20	Mach. Exc. Elec.	5,789	9.95%	52,384	1.56%
21	Elec. & Electron	5,603	9.63%	84,697	2.52%
22	Transport Eq.	924	1.59%	87,942	2.62%
23	Instruments	1,416	2.43%	22,807	0.68%
24	Misc. Manufact.	113	0.19%	23,080	0.69%
25	Transp & Whse.	533	0.92%	116,193	3.46%
26	Utilities	1,173	2.02%	197,676	5.89%
27	Wholesale Trade	4,034	6.93%	189,178	5.63%
28	Retail Trade	2,567	4.41%	189,178	5.63%
29	F.I.R.E. *(Finance, Insurance, Real Estate)*	10,250	17.62%	558,851	16.64%
30	Pers./Prof Serv.	8,755	15.05%	269,683	8.03%
31	Eating Drinking	1,556	2.67%	71,217	2.12%
32	Auto Serv.	1,137	1.95%	36,761	1.09%
33	Amuse & Rec.	223	0.38%	23,385	0.70%
34	Health Ed. Soc.	4,650	7.99%	211,503	6.30%
35	Govt & Govt Ind.	3,870	6.65%	395,936	11.79%
36	Households	574	0.99%	8,442	0.25%
	Inventory & Leak	0.00%	39,135		
	TOTAL	58,174	100.00%	3,397,151	100.00%

Sources: Santa Clara: Dames & Moore, 1987. Regional Economics Of Water Supply Shortages in the South Bay Contractors' Service Area U.S.: U.S. Dept. of Comm. Bureau of Econ. Analysis, 1989 Suvey of Current Business. Input Output Accounts of the U.S. Economy, 1983 Collapsed from 99 to 36 sectors.

Table 6-2 Importance Weights of Various Lifeline Systems on Economic Sectors (Modified ATC-13 Table 9.8 (ATC, 1985))

	Water	*Waste*	*Electric*	*Natural Gas*	*Oil*	*Highway*	*Railways*	*Air Transportation*	*Water Transportation*	*Phone*
1 Livestock	0.45	0.20	0.50	0.10	0.50	0.50	0.40	0.10	0.40	0.20
2 Agr. Prod.	0.70	0.50	0.50	0.30	0.80	0.80	0.40	0.10	0.40	0.20
3 AgServ For. Fish	0.45	0.50	0.50	0.30	0.80	0.80	0.40	0.10	0.40	0.20
4 Mining	0.15	0.10	0.90	0.10	0.90	0.35	0.35	0.10	0.20	0.10
5 Construction	0.50	0.20	0.40	0.00	0.90	0.40	0.05	0.00	0.20	0.10
6 Food Tobacco	0.70	0.70	0.90	0.25	0.50	0.80	0.20	0.20	0.20	0.15
7 Textile Goods	0.70	0.70	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
8 Misc Text. Prod.	0.70	0.70	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
9 Lumber & Wood	0.50	0.50	1.00	0.20	0.50	0.90	0.40	0.20	0.20	0.15
10 Furniture	0.50	0.50	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
11 Pulp & Paper	0.60	0.80	1.00	0.40	0.50	0.80	0.45	0.10	0.30	0.10
12 Print & Publish	0.30	0.30	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
13 Chemical & Drugs	0.80	0.80	0.90	0.90	0.50	0.80	0.20	0.20	0.20	0.15
14 Petrol. Refining	0.50	0.50	1.00	0.50	1.00	0.90	0.40	0.00	0.80	0.10
15 Rubber & Plastic	0.50	0.50	1.00	0.50	0.50	0.75	0.20	0.20	0.20	0.15
16 Leather Prods.	0.50	0.50	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
17 Glass Stone Clay	0.50	0.50	1.00	0.50	0.50	0.75	0.20	0.20	0.20	0.15
18 Prim. Metal Prod.	0.90	0.80	0.90	0.50	0.90	0.80	0.50	0.10	0.20	0.15
19 Fab. Metal Prod.	0.80	0.80	1.00	0.50	0.50	0.80	0.45	0.10	0.30	0.10
20 Mach. Exc, Elec.	0.60	0.80	1.00	0.50	0.50	0.80	0.45	0.20	0.30	0.10
21 Elec. & Electron	0.90	0.90	1.00	0.50	0.50	0.75	0.20	0.30	0.20	0.15
22 Transport Eq.	0.60	0.80	1.00	0.50	0.90	0.80	0.45	0.30	0.30	0.10
23 Instruments	0.90	0.60	1.00	0.75	0.50	0.80	0.05	0.40	0.10	0.30
24 Misc. Manufact.	0.60	0.60	1.00	0.50	0.50	0.75	0.20	0.20	0.20	0.15
25 Transp & Whse.	0.20	0.10	0.30	0.00	0.90	0.80	0.30	0.30	0.30	0.30
26 Utilities	0.40	0.24	0.80	0.40	0.50	0.40	0.00	0.00	0.00	0.30
27 Wholesale Trade	0.20	0.10	0.90	0.10	0.50	0.70	0.15	0.20	0.20	0.50
28 Retail Trade	0.20	0.20	0.90	0.20	0.90	0.55	0.20	0.20	0.00	0.50
29 F.I.R.E.	0.20	0.20	0.90	0.20	0.60	0.45	0.10	0.20	0.00	0.60
30 Pers./Prof Serv.	0.20	0.20	0.90	0.20	0.60	0.45	0.10	0.20	0.00	0.40
31 Eating Drinking	0.80	0.80	0.80	0.40	0.80	0.50	0.05	0.40	0.00	0.40
32 Auto Serv.	0.10	0.20	0.90	0.05	0.90	0.55	0.00	0.00	0.00	0.40
33 Amuse & Rec.	0.80	0.80	0.80	0.40	0.90	0.50	0.05	0.40	0.00	0.40
34 Health Ed. Soc.	0.40	0.80	0.80	0.20	0.20	0.55	0.05	0.10	0.00	0.15
35 Govt & Govt Ind.	0.25	0.20	0.60	0.20	0.20	0.30	0.10	0.20	0.00	0.20
36 Households	0.40	0.75	0.80	0.35	0.50	0.40	0.00	0.00	0.00	0.20
TOTAL	0.51	0.51	0.86	0.32	0.62	0.67	0.22	0.18	0.19	0.22

Table 6-3 Percent Value-Added Lost Due to Specified Percent Loss of Oil Supply Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod.	1.06%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
3 AgServ For. Fish	0.11%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
4 Mining	3.89%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
5 Construction	5.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
6 Food Tobacco	2.41%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
7 Textile Goods	0.37%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
8 Misc Text. Prod.	0.73%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
9 Lumber & Wood	0.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
10 Furniture	0.34%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
11 Pulp & Paper	0.87%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
12 Print & Publish	1.31%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
13 Chemical Drugs	1.40%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
14 Petrol. Refining	0.96%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
20 Mach. Exc. Elec.	1.56%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
21 Elec. & Electron	2.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
22 Transport Eq.	2.62%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
23 Instruments	0.68%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
24 Misc. Manufact.	0.69%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
25 Transp & Whse.	3.46%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
26 Utilities	5.89%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
27 Wholesale Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
28 Retail Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
29 F.I.R.E.	16.64%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
30 Pers./Prof. Serv.	8.03%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
33 Amuse & Rec.	0.70%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
34 Health Ed. Soc.	6.30%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
TOTAL	100.00%	3.25% Avg.	9.74% Avg.	16.23% Avg.	22.72% Avg.	29.21% Avg.	35.70% Avg.	42.19% Avg.	48.68% Avg.	55.18% Avg.	61.67% Total V.A Pct. V.A.

Table 6-4 **Residual Value-Added After Loss of Capacity of Oil Supply Lifeline**

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.44%	0.42%	0.39%	0.37%	0.35%	0.32%	0.30%	0.27%	0.25%	0.23%
1.06%	1.01%	0.93%	0.84%	0.75%	0.66%	0.57%	0.48%	0.39%	0.30%	0.21%
0.11%	0.11%	0.10%	0.09%	0.08%	0.07%	0.06%	0.05%	0.04%	0.03%	0.02%
3.89%	3.70%	3.34%	2.97%	2.60%	2.23%	1.86%	1.49%	1.13%	0.76%	0.39%
5.52%	5.26%	4.73%	4.21%	3.69%	3.17%	2.64%	2.12%	1.60%	1.07%	0.55%
2.41%	2.34%	2.22%	2.09%	1.96%	1.84%	1.71%	1.58%	1.46%	1.33%	1.20%
0.37%	0.36%	0.34%	0.32%	0.30%	0.28%	0.26%	0.25%	0.23%	0.21%	0.19%
0.73%	0.71%	0.67%	0.63%	0.59%	0.55%	0.52%	0.48%	0.44%	0.40%	0.36%
0.52%	0.50%	0.48%	0.45%	0.42%	0.39%	0.37%	0.34%	0.31%	0.29%	0.26%
0.34%	0.33%	0.31%	0.29%	0.28%	0.26%	0.24%	0.22%	0.21%	0.19%	0.17%
0.87%	0.85%	0.80%	0.76%	0.71%	0.66%	0.62%	0.57%	0.53%	0.48%	0.44%
1.31%	1.28%	1.21%	1.14%	1.07%	1.00%	0.93%	0.86%	0.79%	0.72%	0.66%
1.40%	1.37%	1.29%	1.22%	1.15%	1.07%	1.00%	0.92%	0.85%	0.78%	0.70%
0.96%	0.91%	0.81%	0.71%	0.61%	0.51%	0.41%	0.30%	0.20%	0.10%	0.00%
1.03%	1.00%	0.95%	0.89%	0.84%	0.79%	0.73%	0.68%	0.62%	0.57%	0.51%
0.12%	0.12%	0.11%	0.11%	0.10%	0.09%	0.09%	0.08%	0.07%	0.07%	0.06%
0.62%	0.60%	0.57%	0.54%	0.50%	0.47%	0.44%	0.41%	0.37%	0.34%	0.31%
1.04%	0.99%	0.89%	0.79%	0.70%	0.60%	0.50%	0.40%	0.30%	0.20%	0.10%
1.64%	1.60%	1.51%	1.42%	1.34%	1.25%	1.17%	1.08%	0.99%	0.91%	0.82%
1.56%	1.52%	1.44%	1.35%	1.27%	1.19%	1.11%	1.03%	0.94%	0.86%	0.78%
2.52%	2.46%	2.32%	2.19%	2.06%	1.92%	1.79%	1.66%	1.53%	1.39%	1.26%
2.62%	2.49%	2.25%	2.00%	1.75%	1.50%	1.25%	1.01%	0.76%	0.51%	0.26%
0.68%	0.66%	0.63%	0.59%	0.55%	0.52%	0.48%	0.45%	0.41%	0.38%	0.34%
0.69%	0.67%	0.63%	0.60%	0.56%	0.52%	0.49%	0.45%	0.42%	0.38%	0.34%
3.46%	3.30%	2.97%	2.64%	2.31%	1.99%	1.66%	1.33%	1.00%	0.67%	0.35%
5.89%	5.73%	5.42%	5.11%	4.80%	4.49%	4.18%	3.87%	3.56%	3.25%	2.94%
5.63%	5.49%	5.19%	4.89%	4.60%	4.30%	4.00%	3.71%	3.41%	3.11%	2.82%
5.63%	5.37%	4.83%	4.30%	3.77%	3.23%	2.70%	2.16%	1.63%	1.10%	0.56%
16.64%	16.12%	15.07%	14.01%	12.96%	11.91%	10.86%	9.81%	8.76%	7.71%	6.66%
8.03%	7.78%	7.27%	6.76%	6.26%	5.75%	5.24%	4.73%	4.23%	3.72%	3.21%
2.12%	2.03%	1.85%	1.67%	1.50%	1.32%	1.14%	0.96%	0.78%	0.60%	0.42%
1.09%	1.04%	0.94%	0.84%	0.73%	0.63%	0.52%	0.42%	0.32%	0.21%	0.11%
0.70%	0.66%	0.60%	0.53%	0.47%	0.40%	0.33%	0.27%	0.20%	0.14%	0.07%
6.30%	6.23%	6.10%	5.97%	5.83%	5.70%	5.57%	5.44%	5.30%	5.17%	5.04%
11.79%	11.67%	11.42%	11.17%	10.92%	10.67%	10.43%	10.18%	9.93%	9.68%	9.43%
0.25%	0.24%	0.23%	0.22%	0.21%	0.19%	0.18%	0.17%	0.15%	0.14%	0.13%
100.00%	96.94%	90.83%	84.71%	78.60%	72.48%	66.37%	60.25%	54.14%	48.02%	41.91%
100%	97%	91%	85%	79%	72%	66%	60%	54%	48%	42%

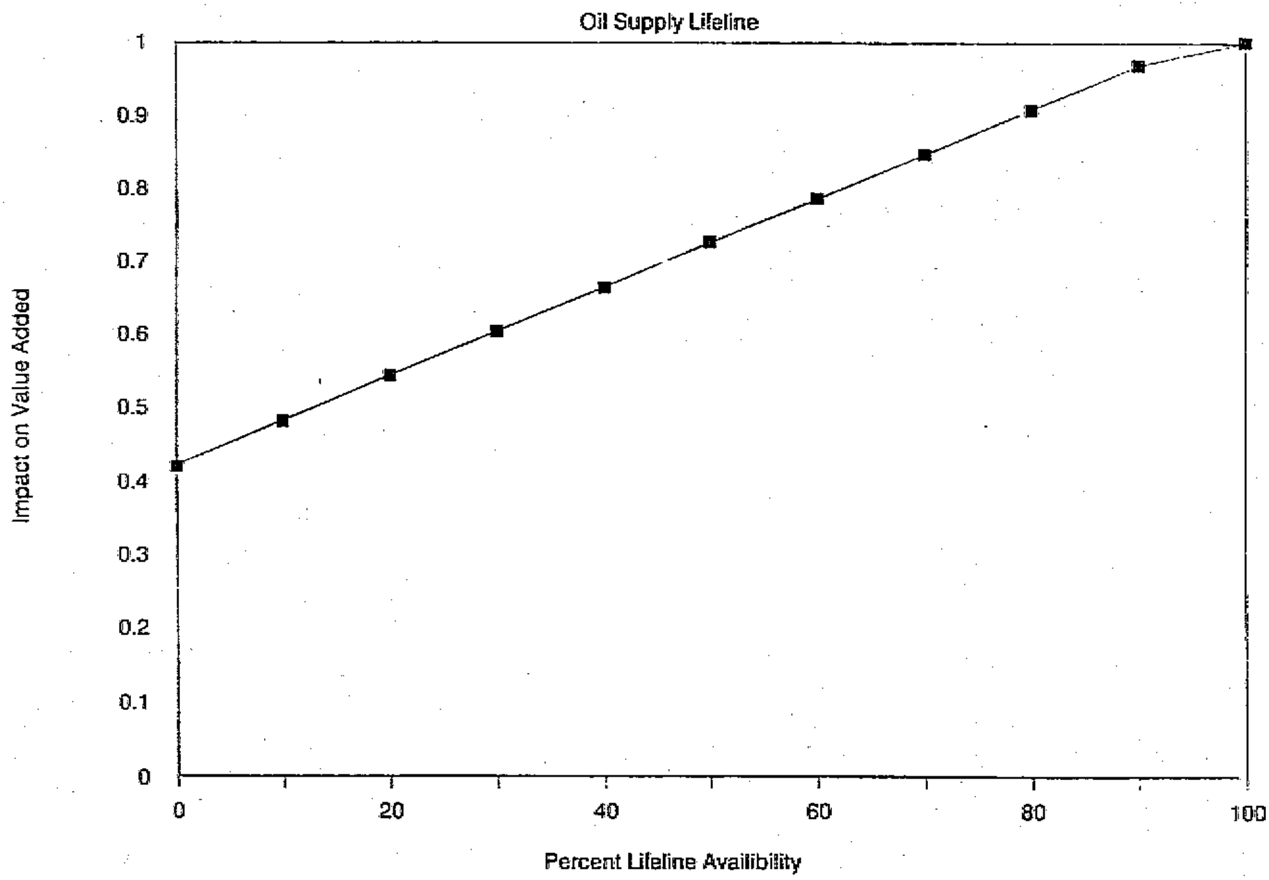


Figure 6-18 Residual Value Added as a function of crude oil lifeline residual capacity

the results. However, the model's parameters could be refined to produce more accurate results, which might also better represent regional and local economic diversity. The following refinements are suggested:

- Regionalization. Data on value added are available on a county-by-county basis for the entire United States. This data could be used in place of the national data presented here to produce local area models of county or multiple-county areas. Such a localized model would more accurately reflect the impacts weighted by the local importance of each of the industrial sectors.

- Maximum Economic Impacts. The estimates of the maximum impacts of lifeline disruptions were modified from the ATC-13 data, based on the judgment of the authors. These estimates could be improved by research into the use of each of the lifeline inputs within each of the economic sectors.

- Linearity Assumption. The economic impact of lifeline interruption was assumed to vary linearly between no impact at 5% interruption, to maximum impact at 100% interruption. This assumption could be investigated and modified as appropriate. Some industries may require uninterrupted use of lifelines in order to operate; they may be unable to operate under certain conditions of reduced lifeline capacity. The linearity assumption ignores these possible threshold effects. Furthermore, many or all industries might respond non-linearly to interruptions. Smaller percentage interruptions might cause a less than proportional impact on value added as lower valued functions or product line are cut first, or as other factors of production are substituted for the damaged lifeline. At high percent interruptions, the response might be more than proportional, as vital functions cannot be maintained. Further research into industry response to scarcity might suggest a convex rather than linear response function.

- Interindustry Effects. The scarcity of productive factors other than lifelines could have major impacts on a regional economy. These interactions were ignored in the present study, thus understating impacts of lifeline interruptions. As noted in Scawthorn and Lofting (1984), input-output economic models could be used to solve for these interactions. Building such a model would be difficult because the impacts caused by lifeline disruptions and the non-lifeline scarcity impacts would have to be solved simultaneously. However, the basic modeling approach proposed in this study is consistent with the type of regional data necessary to drive an input-output model.

6.6 Indirect Economic Loss Estimates

Indirect economic losses were estimated for each lifeline system and scenario event using the residual capacity plots provided in Appendix C and the economic tables described above. The calculation procedure was as follows:

1. Determine the monthly loss in capacity for the lifeline and scenario earthquake under consideration using the appropriate residual capacity plot (Appendix C).

2. Determine Percent-Value-Added Lost for each month and sector of the economy for the lifeline under consideration, using the estimates obtained from Step 1 above and the Percent-Value-Added Lost Tables provided in Appendix D (Table 6-3 is an example). Sum the percentages for all months in each sector to obtain the total Value-Added-Lost in that sector during the time period the lifeline had loss in capacity. Multiply this sum by the percent U. S. Economic Value Added for that sector.

3. Sum the products calculated in Step 2 for each sector to estimate the total percentage value added lost for all economic sectors; multiply this percentage by the percent of U. S. population affected and by the monthly Gross National Product to obtain the total indirect economic loss for the lifeline and earthquake scenario under consideration.

The equation used to calculate indirect economic losses (IEL) is as follows:

$$\text{IEL} = \sum_{i=1}^{N1} \sum_{j=1}^{N2} \sum_{k=1}^{N3} (A)(B)(C)(D) \qquad (6.7)$$

where:
- IEL = Indirect Economic Loss
- N1 = number of affected regions
- N2 = number of economic sectors
- N3 = number of months the lifeline has a loss in capacity
- A = percent Value-Added-Lost per month
- B = percent U. S. Economy Value Added
- C = percent of U. S. population affected
- D = monthly Gross National Product

We note that an average value of loss of functionality during each month of the restoration period is used when estimating the overall indirect economic impact (from Table 6-3 and similar tables in Appendix D). This aspect of the computation is illustrated in Example 6.4 (Figure 6-19), which illustrates the economic loss calculation for a specific lifeline, economic sector, and hypothetical earthquake. Shown in Example 6.5 (Figure 6-20) is an example calculation for estimating total indirect dollar loss in all economic sectors due to damage of the electric system in the state of Utah as a result of the Wasatch Front scenario event.

We have also calculated values of "Percent of Monthly Economic Loss" in each economic sector due to interruption to each lifeline system for each scenario earthquake using the "Residual Capacity Plots" provided in Appendix C and the "Percent Value Added Lost" tables provided in Appendix D. These data are provided in Tables 6-5 through 6-11. Values in these tables are percentage of the monthly GNP of each economic sector that is lost due to the

Example 6.4

For the pipeline network described in Example 6.2 and using the residual capacity results determined there, determine indirect economic losses to the livestock sector for the first month.

Procedure. Immediately following the earthquake, this network experiences a 39% loss of functionality. Ten days later the loss of functionality is 0%. Thus, the average loss of functionality during the first 10 days is about 20%, and for the first month it is 20%/3, or 7%. From Table 6-3, which pertains to average loss of functionality for one month, the Value Added lost for a 7% loss in functionality for the live stock sector of the economy is 1.8%, i.e., 0.7 of 2.63% corresponding to 10% loss of oil supply lifeline for one month. To determine the economic losses in dollars, this percentage would first need to be multiplied by the percent U. S. Economy Value Added for the livestock sector (0.45%) and then prorated by the percent of the national population affected. Actual economic losses in this economic sector due to loss of functionality of this particular pipeline would then be determined by multiplying this prorated percentage by the monthly gross national product

Figure 6-19. Analysis Example Illustrating Economic Loss Calculation for Crude Oil Pipeline Network.

scenario earthquake and resulting lifeline interruption. In Table 6-6, for example, 141% of the monthly GNP of livestock is lost as a result of damage to water transportation systems during the Charleston earthquake scenario. The actual dollar loss would be the product of 1.41 x .0045 x monthly national GNP x percent of national population affected.

Summaries of the total indirect economic losses resulting from damage to site-specific systems and extended regional networks, based on 1986 GNP data, are provided in Table 6-12. Total indirect economic losses resulting from damage to local distribution systems are presented in Table 6-13. We note that Table 6-12 contains total loss amounts expressed in terms of lower bound, upper bound, and best estimate. The lower bound represents economic loss caused by the singular lifeline system causing the greatest loss; the upper bound is the sum of losses caused by all systems; and the best estimate is the square root of the sum of the squares (SRSS) of losses caused by each lifeline. We note also that the SRSS procedure was used to estimate total indirect economic losses resulting from damage to local distribution networks (Table 6-13).

By combining like system data from Tables 6-12 and 6-13 in a least squares (SRSS) fashion, we estimate the total indirect economic losses for the eight scenario earthquakes as follows:

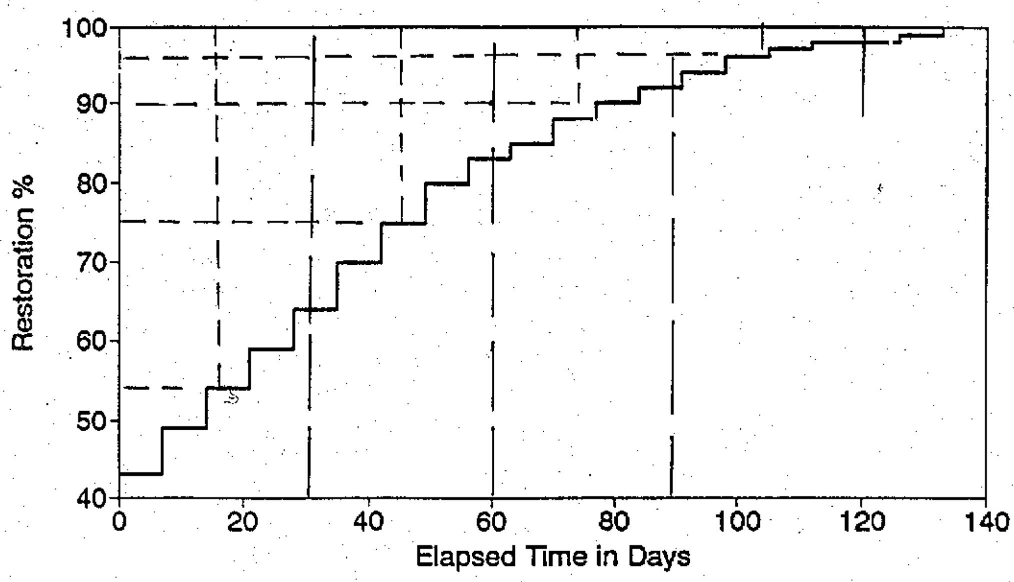
Earthquake	Indirect Loss (in Billions, 1991$)
Cape Ann	$9.1
Charleston	$10.2
Fort Tejon	$11.7
Hayward	$11.1
New Madrid, M = 8.0	$14.6
New Madrid, M = 7.0	$4.9
Puget Sound	$6.1
Wasatch Front	$3.9

Bar charts showing the indirect losses caused by transmission lines (upper bound data) by state for each scenario earthquake are provided in Figures 6-21 through 6-28. We note that estimates of indirect economic losses for each state are sensitive to the assumed location of the source zone for large-magnitude events (e.g., had the assumed source zone for the magnitude-8 New Madrid event been located further north, estimates of direct damage in Missouri would have been substantially larger). Estimates of direct damage (Chapter 6) are similarly affected.

The data provided in Figures 6-21 through 6-28 suggest that Massachusetts would experience the highest indirect losses due to the Cape Ann event with the electric system contributing the highest portion; Mississippi and Arkansas would experience the highest indirect losses due to the magnitude-8.0 New Madrid event; and South Carolina, Utah, Washington, Northern and Southern California would experience the highest indirect losses due to the Charleston, Utah, Seattle, Hayward, and Fort Tejon events, respectively. The electric system contributes the highest indirect losses, among all systems, for most of the events.

Example 6.5

Using the Restoration Capacity Plot shown below for Utah electric power following the scenario Wasatch Front event, estimate the indirect economic losses due to damage of the electric system in the state of Utah.



<u>STEP 1</u>: Estimate the average loss for each month, which is as follows:

Month	Percent Loss
1	45%
2	25%
3	10%
4	5%

<u>STEP 2</u>: From Table D-2, *Percent Value-Added Lost Due to Specified Percent Loss of Electricity Lifeline*, extrapolate percent Value Added Lost for each sector of the economy for each month and sum the results to obtain the estimated percent of Value Added Lost for the entire period. For the livestock sector, this calculation is as follows:

(23.68+18.42)/2 + (13.16+7.89)/2 + 2.63 + 2.63/2 =

21.05 + 10.53 + 2.63 + 1.32 = 35.53%

Figure 6-20. Analysis Example Illustrating Economic Loss Calculation for Electric System in State of Utah for the Wasatch Front Scenario Event.

STEP 3: Multiply the sum from Step 2 by the percent of the economy for that sector and sum the products for all economic sectors to obtain the total Percent-Value-Added lost (for all economic sectors):

	Economic Sector	(1) U. S. Economy Value-Added (percent)	(2) Utah Value-Added Lost (percent)	(3) Product of (1)x(2) (percent)
1	Livestock	0.45	35.53	0.16
2	Agr. Prod.	1.06	35.53	0.38
3	AgServ. For. Fish	0.11	35.53	0.04
4	Mining	3.89	63.95	2.49
5	Construction	5.52	28.42	1.57
6	Food Tobacco	2.41	63.95	1.54
7	Textile Goods	0.37	71.05	0.26
8	Misc. Text. Prod.	0.73	71.05	0.52
9	Lumber & Wood	0.52	71.05	0.37
10	Furniture	0.34	71.05	0.24
11	Pulp & Paper	0.87	71.05	0.62
12	Print & Publish	1.31	71.05	0.93
13	Chemical & Drugs	1.40	63.95	0.90
14	Petrol. Refining	0.98	71.05	0.68
15	Rubber & Plastic	1.03	71.05	0.73
16	Leather Prods.	0.12	71.05	0.09
17	Glass Stone Clay	0.62	71.05	0.44
18	Prim. Metal Prod.	1.04	63.95	0.67
19	Fab. Metal Prod.	1.64	71.05	1.17
20	Mach. Exc. Elec.	1.56	71.05	1.11
21	Elec. & Electron	2.52	71.05	1.79
22	Transport Eq.	2.62	71.05	1.86
23	Instruments	0.68	71.05	0.48
24	Misc. Manufact.	0.69	71.05	0.49
25	Transp & Whse.	3.46	21.32	0.74
26	Utilities	5.89	56.84	3.35
27	Wholesale Trade	5.63	63.95	3.60
28	Retail Trade	5.63	63.95	3.60
29	F.I.R.E.	16.64	63.95	10.64
30	Pers./Prof. Serv.	8.03	63.95	5.14
31	Eating Drinking	2.12	56.84	1.21
32	Auto Serv.	1.09	63.95	0.70
33	Amuse & Rec.	0.70	56.84	0.40
34	Health Ed. Soc.	6.30	56.84	3.58
35	Govt & Govt Ind.	11.79	42.63	5.03
36	Households	0.25	56.84	0.14
	Total			**57.63**

The total indirect economic loss resulting from damage to the electric system in the state of Utah is computed as follows:
= 57.63% (Utah population/U.S. population) (U.S. GNP)/12
= 57.63% (1.68/242) ($4,881/12) = $1.63 Billion
where U.S. GNP = $4,881 Billion (1986)

Figure 6-20 (Continued)

Table 6-5 Indirect Economic Loss due to Damage to the Air Transportation Lifeline (Percent Monthly GNP)

			NEW MADRID (M=8.0)				CHARLESTON (M=7.5)		CAPE ANN	WASATCH	HAYWARD	FORT TEJON	PUGET SOUND	NEW MADRID (M=7.0)
		U.S. Econ. Value Added (Percent)	Arkansas	Tennessee	Kentucky	Mississippi	South Carolina	Georgia	Massachusetts	Utah	California	California	Washington	Arkansas
1	Livestock	0.45%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
2	Agr. Prod.	1.06%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
3	AgServ For. Fish	0.11%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
4	Mining	3.89%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
5	Construction	5.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6	Food Tobacco	2.41%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
7	Textile Goods	0.37%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
8	Misc Text. Prod.	0.73%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
9	Lumber & Wood	0.52%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
10	Furniture	0.34%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
11	Pulp & Paper	0.87%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
12	Print & Publish	1.31%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
13	Chemical & Drugs	1.40%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
14	Petrol. Refining	0.96%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
15	Rubber & Plastic	1.03%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
16	Leather Prods.	0.12%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
17	Glass Stone Clay	0.62%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
18	Prim. Metal Prod.	1.04%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
19	Fab. Metal Prod.	1.64%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
20	Mach. Exc. Elec.	1.56%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
21	Elec. & Electron	2.52%	14.21%	4.74%	1.11%	10.26%	6.32%	3.16%	8.84%	5.37%	1.58%	5.37%	9.47%	6.32%
22	Transport Eq.	2.62%	14.21%	4.74%	1.11%	10.26%	6.32%	3.16%	8.84%	5.37%	1.58%	5.37%	9.47%	6.32%
23	Instruments	0.68%	18.95%	6.32%	1.47%	13.68%	8.42%	4.21%	11.79%	7.16%	2.11%	7.16%	12.63%	8.42%
24	Misc. Manufact.	0.69%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
25	Transp & Whse.	3.46%	14.21%	4.74%	1.11%	10.26%	6.32%	3.16%	8.84%	5.37%	1.58%	5.37%	9.47%	6.32%
26	Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27	Wholesale Trade	5.63%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
28	Retail Trade	5.63%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
29	F.I.R.E.	16.64%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
30	Pers./Prof Serv.	8.03%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
31	Eating Drinking	2.12%	18.95%	6.32%	1.47%	13.68%	8.42%	4.21%	11.79%	7.16%	2.11%	7.16%	12.63%	8.42%
32	Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33	Amuse & Rec.	0.70%	18.95%	6.32%	1.47%	13.68%	8.42%	4.21%	11.79%	7.16%	2.11%	7.16%	12.63%	8.42%
34	Health Ed. Soc.	6.30%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
35	Govt & Govt Ind.	11.79%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
36	Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 6-6 Indirect Economic Loss due to Damage to the Water Transportation Lifeline (Percent Monthly GNP)

	U.S. Econ. Value Added (Percent)	CHARLESTON			CAPE ANN			HAYWARD	FORT TEJON	PUGET SOUND
		South Carolina	North Carolina	Georgia	Massachussetts	Rhole Island	New Hampshire	California	California	Washington
1 Livestock	0.45%	141.05%	5.47%	103.16%	14.74%	12.63%	1.58%	11.58%	21.05%	27.37%
2 Agr. Prod.	1.06%	141.05%	5.47%	103.16%	14.74%	12.63%	1.58%	11.58%	21.05%	27.37%
3 AgServ For. Fish	0.11%	141.05%	5.47%	103.16%	14.74%	12.63%	1.58%	11.58%	21.05%	27.37%
4 Mining	3.89%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
5 Construction	5.52%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
6 Food Tobacco	2.41%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
7 Textile Goods	0.37%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
8 Misc Text. Prod.	0.73%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
9 Lumber & Wood	0.52%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
10 Furniture	0.34%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
11 Pulp & Paper	0.87%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
12 Print & Publish	1.31%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
13 Chemical & Drugs	1.40%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
14 Petrol. Refining	0.96%	282.11%	10.95%	206.32%	29.47%	25.26%	3.16%	23.16%	42.11%	54.74%
15 Rubber & Plastic	1.03%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
16 Leather Prods.	0.12%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
17 Glass Stone Clay	0.62%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
18 Prim. Metal Prod.	1.04%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
19 Fab. Metal Prod.	1.64%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
20 Mach. Exc. Elec.	1.56%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
21 Elec. & Electron	2.52%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
22 Transport Eq.	2.62%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
23 Instruments	0.68%	35.26%	1.37%	25.79%	3.68%	3.16%	0.39%	2.89%	5.26%	6.84%
24 Misc. Manufact.	0.69%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
25 Transp & Whse.	3.46%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
26 Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27 Wholesale Trade	5.63%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
28 Retail Trade	5.63%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
29 F.I.R.E.	16.64%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30 Pers./Prof Serv.	8.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
31 Eating Drinking	2.12%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
32 Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33 Amuse & Rec.	0.70%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
34 Health Ed. Soc.	6.30%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
35 Govt & Govt Ind.	11.79%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
36 Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 6-7 Indirect Economic Loss due to Damage to the Oil System (Percent Monthly GNP)

			CRUDE OIL				REFINED OIL	
			New Madrid		Fort Tejon		New Madrid	
		U.S. Econ. Value Added (Percent)	(M=8.0) Chicago	(M=7.0) Chicago	(M=8.0) South California	(M=8.0) North California	(M=8.0) Chicago	(M=7.0) Chicago
1	Livestock	0.45%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
2	Agr. Prod.	1.06%	4.21%	1.05%	12.63%	14.32%	2.11%	1.47%
3	AgServ For. Fish	0.11%	4.21%	1.05%	12.63%	14.32%	2.11%	1.47%
4	Mining	3.89%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
5	Construction	5.52%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
6	Food Tobacco	2.41%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
7	Textile Goods	0.37%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
8	Misc Text. Prod.	0.73%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
9	Lumber & Wood	0.52%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
10	Furniture	0.34%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
11	Pulp & Paper	0.87%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
12	Print & Publish	1.31%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
13	Chemical & Drugs	1.40%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
14	Petrol. Refining	0.96%	5.26%	1.32%	15.79%	17.89%	2.63%	1.84%
15	Rubber & Plastic	1.03%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
16	Leather Prods.	0.12%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
17	Glass Stone Clay	0.62%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
18	Prim. Metal Prod.	1.04%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
19	Fab. Metal Prod.	1.64%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
20	Mach. Exc. Elec.	1.56%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
21	Elec. & Electron	2.52%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
22	Transport Eq.	2.62%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
23	Instruments	0.68%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
24	Misc. Manufact.	0.69%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
25	Transp & Whse.	3.46%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
26	Utilities	5.89%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
27	Wholesale Trade	5.63%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
28	Retail Trade	5.63%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
29	F.I.R.E.	16.64%	3.16%	0.79%	9.47%	10.74%	1.58%	1.11%
30	Pers./Prof Serv.	8.03%	3.16%	0.79%	9.47%	10.74%	1.58%	1.11%
31	Eating Drinking	2.12%	4.21%	1.05%	12.63%	14.32%	2.11%	1.47%
32	Auto Serv.	1.09%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
33	Amuse & Rec.	0.70%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
34	Health Ed. Soc.	6.30%	1.05%	0.26%	3.16%	3.58%	0.53%	0.37%
35	Govt & Govt Ind.	11.79%	1.05%	0.26%	3.16%	3.58%	0.53%	0.37%
36	Households	0.25%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%

Table 6-8 Indirect Economic Loss due to Damage to the Natural Gas System (Percent Monthly GNP)

	U.S. Econ. Value Added (Percent)	NEW MADRID (M=8.0)		WASATCH	HAYWARD		FORT TEJON		NEW MADRID (M=7.0)	
		Texas to Chicago	Louisiana to Northeast	Utah	Texas to North Carolina	Texas to Washington	Texas to California	Texas to Seattle	Texas to Chicago	Louisiana to Northeast
1 Livestock	0.45%	0.26%	0.53%	0.74%	2.11%	0.37%	2.11%	2.11%	0.21%	0.26%
2 Agr. Prod.	1.06%	0.79%	1.58%	2.21%	6.32%	1.11%	6.32%	6.32%	0.63%	0.79%
3 AgServ For. Fish	0.11%	0.79%	1.58%	2.21%	6.32%	1.11%	6.32%	6.32%	0.63%	0.79%
4 Mining	3.89%	0.26%	0.53%	0.74%	2.11%	0.37%	2.11%	2.11%	0.21%	0.26%
5 Construction	5.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6 Food Tobacco	2.41%	0.66%	1.32%	1.84%	5.26%	0.92%	5.26%	5.26%	0.53%	0.66%
7 Textile Goods	0.37%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
8 Misc Text. Prod.	0.73%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
9 Lumber & Wood	0.52%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
10 Furniture	0.34%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
11 Pulp & Paper	0.87%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
12 Print & Publish	1.31%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
13 Chemical & Drugs	1.40%	2.37%	4.74%	6.63%	18.95%	3.32%	18.95%	18.95%	1.89%	2.37%
14 Petrol. Refining	0.96%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
15 Rubber & Plastic	1.03%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
16 Leather Prods.	0.12%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
17 Glass Stone Clay	0.62%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
18 Prim. Metal Prod.	1.04%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
19 Fab. Metal Prod.	1.64%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
20 Mach. Exc. Elec.	1.56%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
21 Elec. & Electron	2.52%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
22 Transport Eq.	2.62%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
23 Instruments	0.68%	1.97%	3.95%	5.53%	15.79%	2.76%	15.79%	15.79%	1.58%	1.97%
24 Misc. Manufact.	0.69%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
25 Transp & Whse.	3.46%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
26 Utilities	5.89%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
27 Wholesale Trade	5.63%	0.26%	0.53%	0.74%	2.11%	0.37%	2.11%	2.11%	0.21%	0.26%
28 Retail Trade	5.63%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
29 F.I.R.E.	16.64%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
30 Pers./Prof Serv.	8.03%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
31 Eating Drinking	2.12%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
32 Auto Serv.	1.09%	0.13%	0.26%	0.37%	1.05%	0.18%	1.05%	1.05%	0.11%	0.13%
33 Amuse & Rec.	0.70%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
34 Health Ed. Soc.	6.30%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
35 Govt & Govt Ind.	11.79%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
36 Households	0.25%	0.92%	1.84%	2.58%	7.37%	1.29%	7.37%	7.37%	0.74%	0.92%

Table 6-9 Indirect Economic Loss due to Damage to the Railroad Lifeline (Percent Monthly GNP)

	U.S. Econ. Value Added (Percent)	*(M=8.0) New Madrid*	*Charleston*	*Cape Ann*	*Utah*	*Hayward*	*Fort Tejon*	*Seattle*	*(M7=.0) New Madrid*
1 Livestock	0.45%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
2 Agr. Prod.	1.06%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
3 AgServ For. Fish	0.11%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
4 Mining	3.89%	3.68%	6.63%	6.63%	2.95%	4.79%	6.63%	6.63%	2.95%
5 Construction	5.52%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
6 Food Tobacco	2.41%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
7 Textile Goods	0.37%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
8 Misc Text. Prod.	0.73%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
9 Lumber & Wood	0.52%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
10 Furniture	0.34%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
11 Pulp & Paper	0.87%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
12 Print & Publish	1.31%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
13 Chemical & Drugs	1.40%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
14 Petrol. Refining	0.96%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
15 Rubber & Plastic	1.03%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
16 Leather Prods.	0.12%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
17 Glass Stone Clay	0.62%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
18 Prim. Metal Prod.	1.04%	5.26%	9.47%	9.47%	4.21%	6.84%	9.47%	9.47%	4.21%
19 Fab. Metal Prod.	1.64%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
20 Mach. Exc. Elec.	1.56%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
21 Elec. & Electron	2.52%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
22 Transport Eq.	2.62%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
23 Instruments	0.68%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
24 Misc. Manufact.	0.69%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
25 Transp & Whse.	3.46%	3.16%	5.68%	5.68%	2.53%	4.11%	5.68%	5.68%	2.53%
26 Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27 Wholesale Trade	5.63%	1.58%	2.84%	2.84%	1.26%	2.05%	2.84%	2.84%	1.26%
28 Retail Trade	5.63%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
29 F.I.R.E.	16.64%	1.05%	1.89%	1.89%	0.84%	1.37%	1.89%	1.89%	0.84%
30 Pers./Prof Serv.	8.03%	1.05%	1.89%	1.89%	0.84%	1.37%	1.89%	1.89%	0.84%
31 Eating Drinking	2.12%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
32 Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33 Amuse & Rec.	0.70%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
34 Health Ed. Soc.	6.30%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
35 Govt & Govt Ind.	11.79%	1.05%	1.89%	1.89%	0.84%	1.37%	1.89%	1.89%	0.84%
36 Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 6-10 Indirect Economic Loss due to Damage to the Electric System (Percent Monthly GNP)

		U.S. Econ. Value Added (Percent)	NEW MADRID (M=8.0)						CHARLESTON			CAPE ANN		
			Illinois	Missouri	Arkansas	Tennessee	Kentucky	Mississippi	South Carolina	North Carolina	Georgia	Massachusetts	Connecticut	Delaware
1	Livestock	0.45%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
2	Agr. Prod.	1.06%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
3	AgServ For. Fish	0.11%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
4	Mining	3.89%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
5	Construction	5.52%	3.16%	5.26%	26.32%	10.53%	10.53%	35.79%	36.84%	6.32%	14.74%	35.79%	12.63%	8.42%
6	Food Tobacco	2.41%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
7	Textile Goods	0.37%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
8	Misc Text. Prod.	0.73%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
9	Lumber & Wood	0.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
10	Furniture	0.34%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
11	Pulp & Paper	0.87%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
12	Print & Publish	1.31%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
13	Chemical & Drugs	1.40%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
14	Petrol. Refining	0.96%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
15	Rubber & Plastic	1.03%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
16	Leather Prods.	0.12%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
17	Glass Stone Clay	0.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
18	Prim. Metal Prod.	1.04%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
19	Fab. Metal Prod.	1.64%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
20	Mach. Exc. Elec.	1.56%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
21	Elec. & Electron	2.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
22	Transport Eq.	2.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
23	Instruments	0.68%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
24	Misc. Manufact.	0.69%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
25	Transp & Whse.	3.46%	2.37%	3.95%	19.74%	7.89%	7.89%	26.84%	27.63%	4.74%	11.05%	26.84%	9.47%	6.32%
26	Utilities	5.89%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
27	Wholesale Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
28	Retail Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
29	F.I.R.E.	16.64%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
30	Pers./Prof Serv.	8.03%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
31	Eating Drinking	2.12%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
32	Auto Serv.	1.09%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
33	Amuse & Rec.	0.70%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
34	Health Ed. Soc.	6.30%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
35	Govt & Govt Ind.	11.79%	4.74%	7.89%	39.47%	15.79%	15.79%	53.68%	55.26%	9.47%	22.11%	53.68%	18.95%	12.63%
36	Households	0.25%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%

Table 6-10 Indirect Economic Loss due to Damage to the Electric System (Percent Monthly GNP) (Continued)

	U.S. Econ. Value Added (Percent)	CAPE ANN		WASATCH	CALIFORNIA		PUGET SOUND	NEW MADRID (M=7.0)			
		Rhode Island	New Hampshire	Utah	Hayward	Fort Tejon	Washington	Arkansas	Tennessee	Kentucky	Mississippi
1 Livestock	0.45%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
2 Agr. Prod.	1.06%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
3 AgServ For. Fish	0.11%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
4 Mining	3.89%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
5 Construction	5.52%	33.68%	11.58%	28.42%	18.95%	10.53%	37.89%	18.95%	6.32%	3.16%	3.16%
6 Food Tobacco	2.41%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
7 Textile Goods	0.37%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
8 Misc Text. Prod.	0.73%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
9 Lumber & Wood	0.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
10 Furniture	0.34%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
11 Pulp & Paper	0.87%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
12 Print & Publish	1.31%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
13 Chemical & Drugs	1.40%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
14 Petrol. Refining	0.96%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
15 Rubber & Plastic	1.03%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
16 Leather Prods.	0.12%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
17 Glass Stone Clay	0.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
18 Prim. Metal Prod.	1.04%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
19 Fab. Metal Prod.	1.64%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
20 Mach. Exc. Elec.	1.56%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
21 Elec. & Electron	2.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
22 Transport Eq.	2.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
23 Instruments	0.68%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
24 Misc. Manufact.	0.69%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
25 Transp & Whse.	3.46%	25.26%	8.68%	21.32%	14.21%	7.89%	28.42%	14.21%	4.74%	2.37%	2.37%
26 Utilities	5.89%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
27 Wholesale Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
28 Retail Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
29 F.I.R.E.	16.64%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
30 Pers./Prof Serv.	8.03%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
31 Eating Drinking	2.12%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
32 Auto Serv.	1.09%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
33 Amuse & Rec.	0.70%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
34 Health Ed. Soc.	6.30%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
35 Govt & Govt Ind.	11.79%	50.53%	17.37%	42.63%	28.42%	15.79%	56.84%	28.42%	9.47%	4.74%	4.74%
36 Households	0.25%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%

Table 6-11 Indirect Economic Loss due to Damage to the Highway System (Percent Monthly GNP)

	U.S. Econ Value Added (Percent)	*New Madrid (M8.0)*	*Charleston*	*Cape Ann*	*Wasatch*	*Hayward*	*Fort Tejon*	*Puget Sound*	*New Madrid (M=7.0)*
1 Livestock	0.45%	85.53%	36.84%	78.95%	83.96%	42.11%	52.63%	60.53%	63.16%
2 Agr. Prod.	1.06%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
3 AgServ For. Fish	0.11%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
4 Mining	3.89%	59.87%	25.79%	55.26%	58.77%	29.47%	36.84%	42.37%	44.21%
5 Construction	5.52%	68.42%	29.47%	63.16%	67.17%	33.68%	42.11%	48.42%	50.53%
6 Food Tobacco	2.41%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
7 Textile Goods	0.37%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
8 Misc Text. Prod.	0.73%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
9 Lumber & Wood	0.52%	153.95%	66.32%	142.11%	151.13%	75.79%	94.74%	108.95%	113.68%
10 Furniture	0.34%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
11 Pulp & Paper	0.87%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
12 Print & Publish	1.31%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
13 Chemical & Drugs	1.40%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
14 Petrol. Refining	0.96%	153.95%	66.32%	142.11%	151.13%	75.79%	94.74%	108.95%	113.68%
15 Rubber & Plastic	1.03%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
16 Leather Prods.	0.12%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
17 Glass Stone Clay	0.62%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
18 Prim. Metal Prod.	1.04%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
19 Fab. Metal Prod.	1.64%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
20 Mach. Exc. Elec.	1.56%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
21 Elec. & Electron	2.52%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
22 Transport Eq.	2.62%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
23 Instruments	0.68%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
24 Misc. Manufact.	0.69%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
25 Transp & Whse.	3.46%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
26 Utilities	5.89%	68.42%	29.47%	63.16%	67.17%	33.68%	42.11%	48.42%	50.53%
27 Wholesale Trade	5.63%	119.74%	51.58%	110.53%	117.54%	58.95%	73.68%	84.74%	88.42%
28 Retail Trade	5.63%	94.08%	40.53%	86.84%	92.36%	46.32%	57.89%	66.58%	69.47%
29 F.I.R.E.	16.64%	76.97%	33.16%	71.05%	75.56%	37.89%	47.37%	54.47%	56.84%
30 Pers./Prof Serv.	8.03%	76.97%	33.16%	71.05%	75.56%	37.89%	47.37%	54.47%	56.84%
31 Eating Drinking	2.12%	85.53%	36.84%	78.95%	83.96%	42.11%	52.63%	60.53%	63.16%
32 Auto Serv.	1.09%	94.08%	40.53%	86.84%	92.36%	46.32%	57.89%	66.58%	69.47%
33 Amuse & Rec.	0.70%	85.53%	36.84%	78.95%	83.96%	42.11%	52.63%	60.53%	63.16%
34 Health Ed. Soc.	6.30%	94.08%	40.53%	86.84%	92.36%	46.32%	57.89%	66.58%	69.47%
35 Govt & Govt Ind.	11.79%	51.32%	22.11%	47.37%	50.38%	25.26%	31.58%	36.32%	37.89%
36 Households	0.25%	68.42%	29.47%	63.16%	67.17%	33.68%	42.11%	48.42%	50.53%

Table 6-12 Indirect Economic Losses Due to Damage to Lifeline Transmission Systems

Scenario Earthquakes	*Natural Gas*		*Crude Oil*		*Refined Oil*		*Air Transportation*		*Railroads*		*Ports*		*Electric*		*Water*		*Highways*	
	%	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*
Cape Ann		$0.00		$0.00		$0.00	0.12	$0.49	0.01	$0.02	0.11	$0.45	2.20	$8.95	N/A	N/A	0.16	$0.65
Charleston		$0.00		$0.00		$0.00	0.11	$0.45	0.01	$0.02	1.21	$4.92	2.15	$8.75	N/A	N/A	0.08	$0.33
Fort Tejon	0.41	$1.67	1.07	$4.35		$0.00	0.35	$1.42	0.06	$0.25	0.61	$2.48	1.90	$7.73	1.2	$4.88	1.10	$4.47
Hayward	0.22	$0.89		$0.00		$0.00	0.10	$0.41	0.03	$0.11	0.33	$1.34	2.43	$9.88	1	$4.07	0.50	$2.03
Madrid, MO M=8	0.07	$0.28	0.10	$0.41	0.05	$0.20	0.2	$0.81	0.06	$0.25		$0.00	2.55	$10.37	N/A	N/A	2.30	$9.36
Madrid, MO M=7	0.04	$0.16	0.03	$0.11	0.04	$0.15	0.04	$0.16	0.01	$0.04		$0.00	0.81	$3.29	N/A	N/A	0.84	$3.42
Puget Sound	0.05	$0.20		$0.00		$0.00	0.10	$0.41	0.03	$0.11	0.13	$0.53	1.43	$5.82	0.19	$0.77	0.27	$1.10
Wasatch Front	0.01	$0.38		$0.00		$0.00	0.02	$0.08	0.01	$0.02		$0.00	0.40	$1.63	N/A	N/A	0.80	$3.25

Scenario Earthquakes	*ESTIMATED TOTAL ECONOMIC LOSS/EVENT*		
	Lower Bound	*Upper Bound*	*Best Estimate*
Cape Ann	$8.95	$10.56	$9.00
Charleston	$8.75	$14.46	$10.05
Fort Tejon	$7.73	$27.26	$11.56
Hayward	$9.88	$18.73	$11.01
Madrid, MO M=8	$10.37	$21.69	$14.00
Madrid, MO M=7	$3.42	$7.33	$4.76
Puget Sound	$5.82	$8.94	$6.01
Wasatch Front	$3.25	$5.02	$3.64

Table 6-13 Indirect Economic Losses Due to Damage to Lifeline Distribution Systems

	Electric		Water		Highways		
Scenario Earthquakes	%	$ Bil	%	$ Bil	%	$ Bil	SRSS
Cape Ann	0.32	$1.3	0.15	$.61	0.21	$0.86	$1.6
Charleston	0.27	$1.1	0.15	$.63	0.17	$0.71	$1.4
Fort Tejon	0.34	$1.4	0.11	$.47	0.08	$0.33	$1.5
Hayward	0.37	$1.5	0.10	$.41	0.09	$0.36	$1.6
New Madrid, M=8	0.76	$3.1	0.44	$1.8	0.49	$2.0	$4.1
New Madrid, M=7	0.23	$1.0	0.14	$.57	0.15	$0.63	$1.3
Puget Sound	0.22	$0.9	0.04	$.18	0.10	$0.40	$1.0
Wasatch Front	0.15	$0.6	0.06	$.27	0.09	$0.37	$1.25

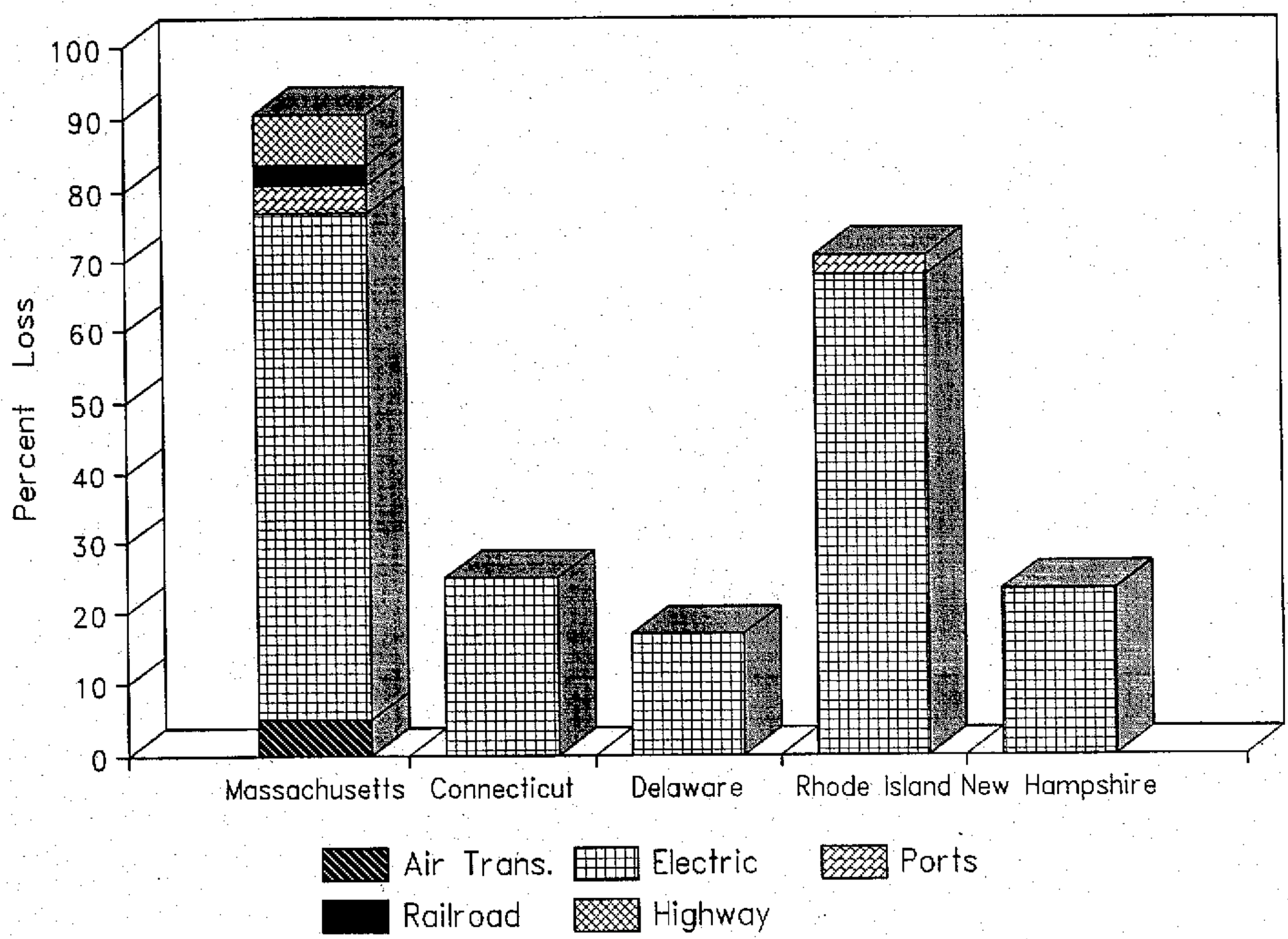


Figure 6-21 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, Cape Ann event (M=7.0).*

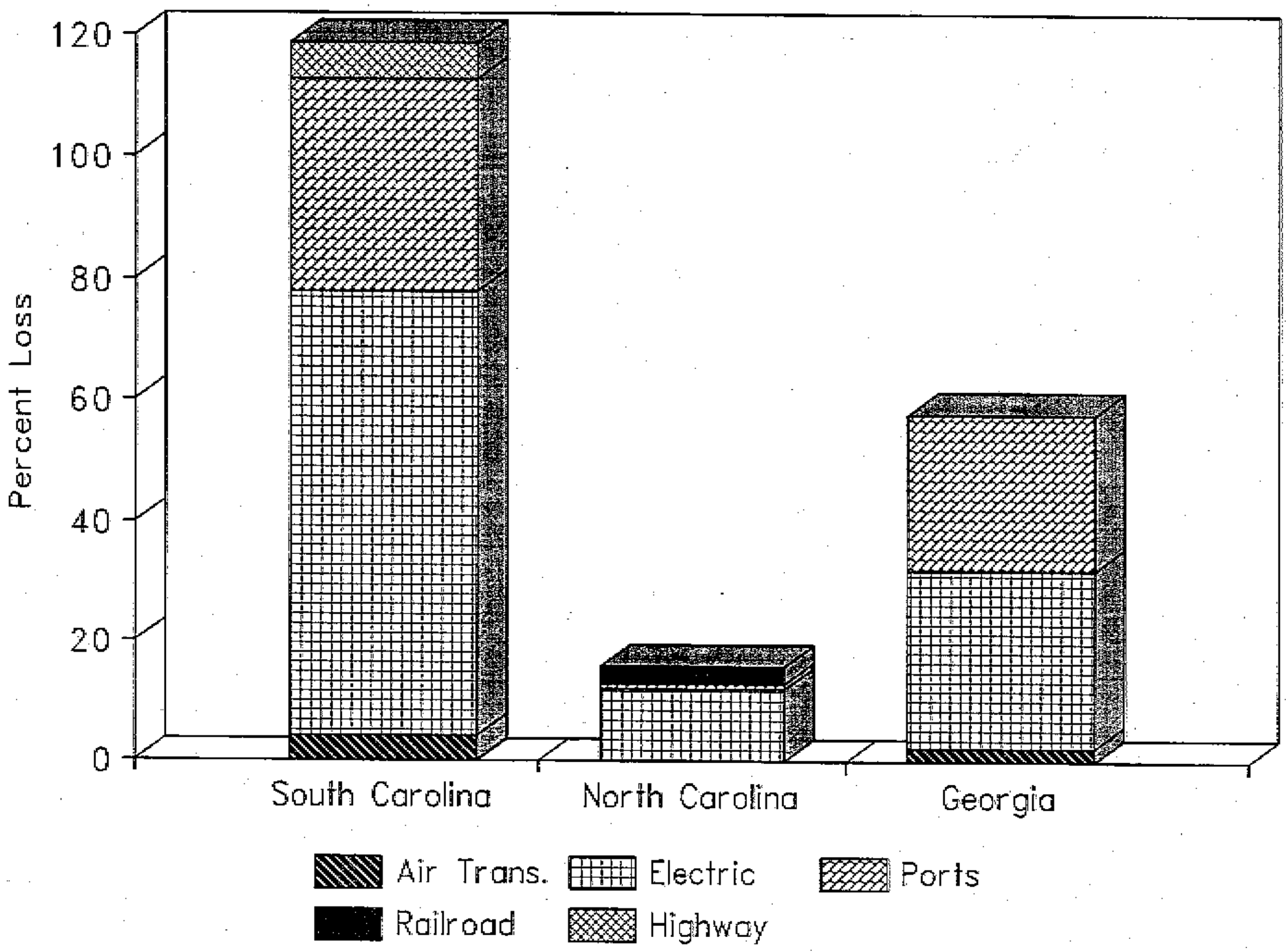


Figure 6-22. Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, Charleston event (M=7.5).

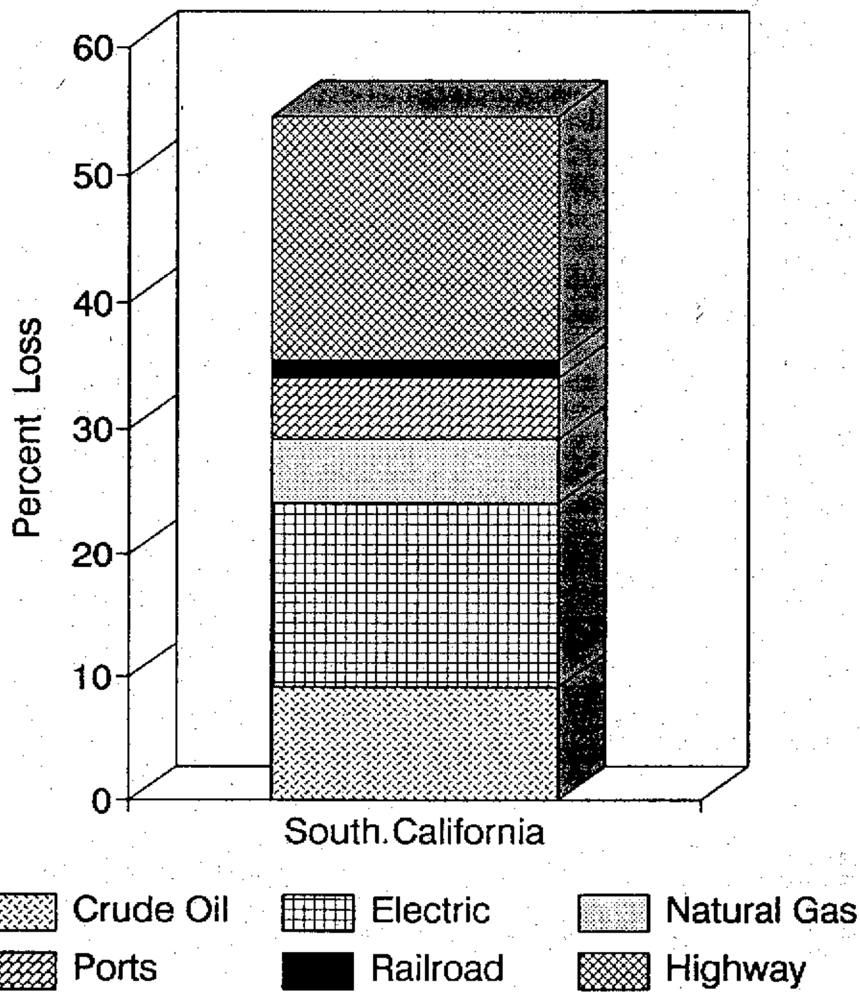


Figure 6-23 *Percent indirect economic loss in Southern California (monthly GNP) resulting from damage to various lifelines, Fort Tejon event (M=8.0).*

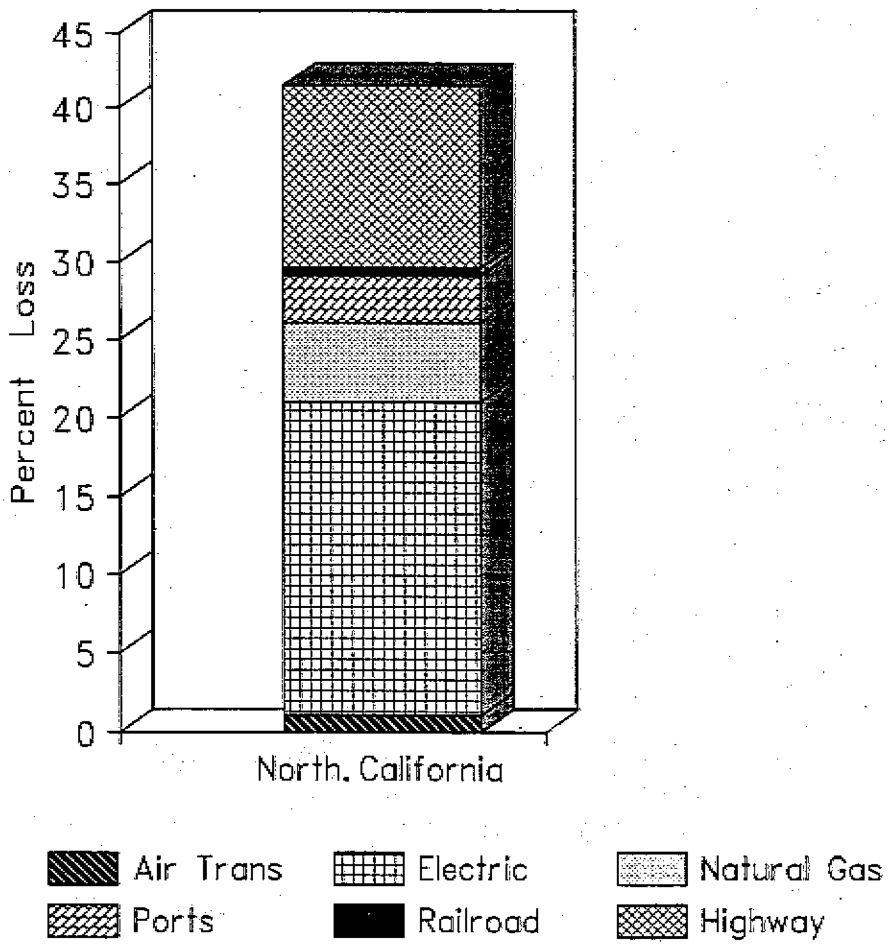


Figure 6-24 *Percent indirect economic loss in Northern California (monthly GNP) resulting from damage to various lifelines, Hayward event (M=7.5).*

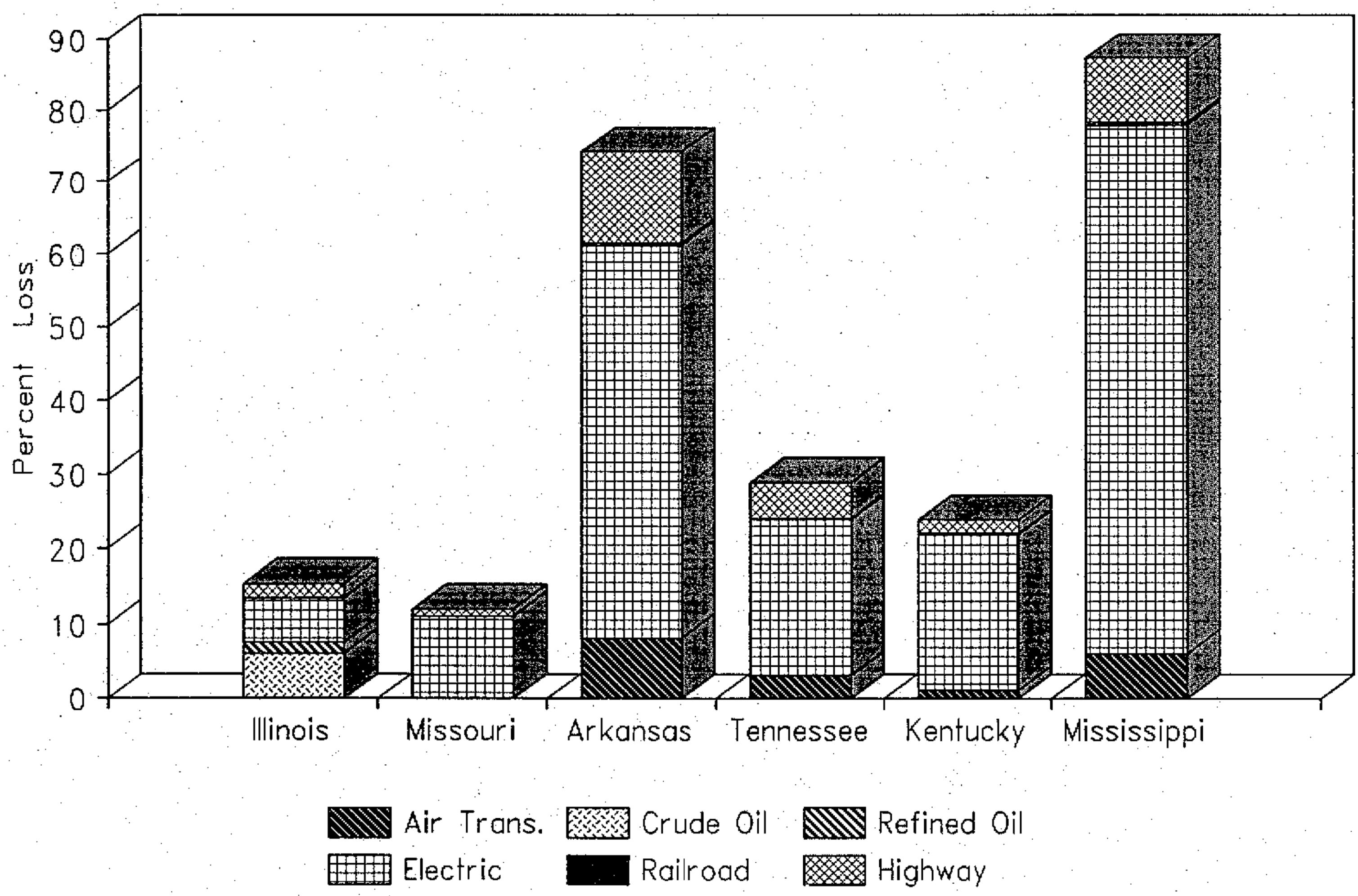


Figure 6-25 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, New Madrid event (M=8.0). Note that the relatively low losses for Missouri reflect the assumed location of the scenario earthquake source zone and the estimated distribution of intensity (see Figure 4-17).*

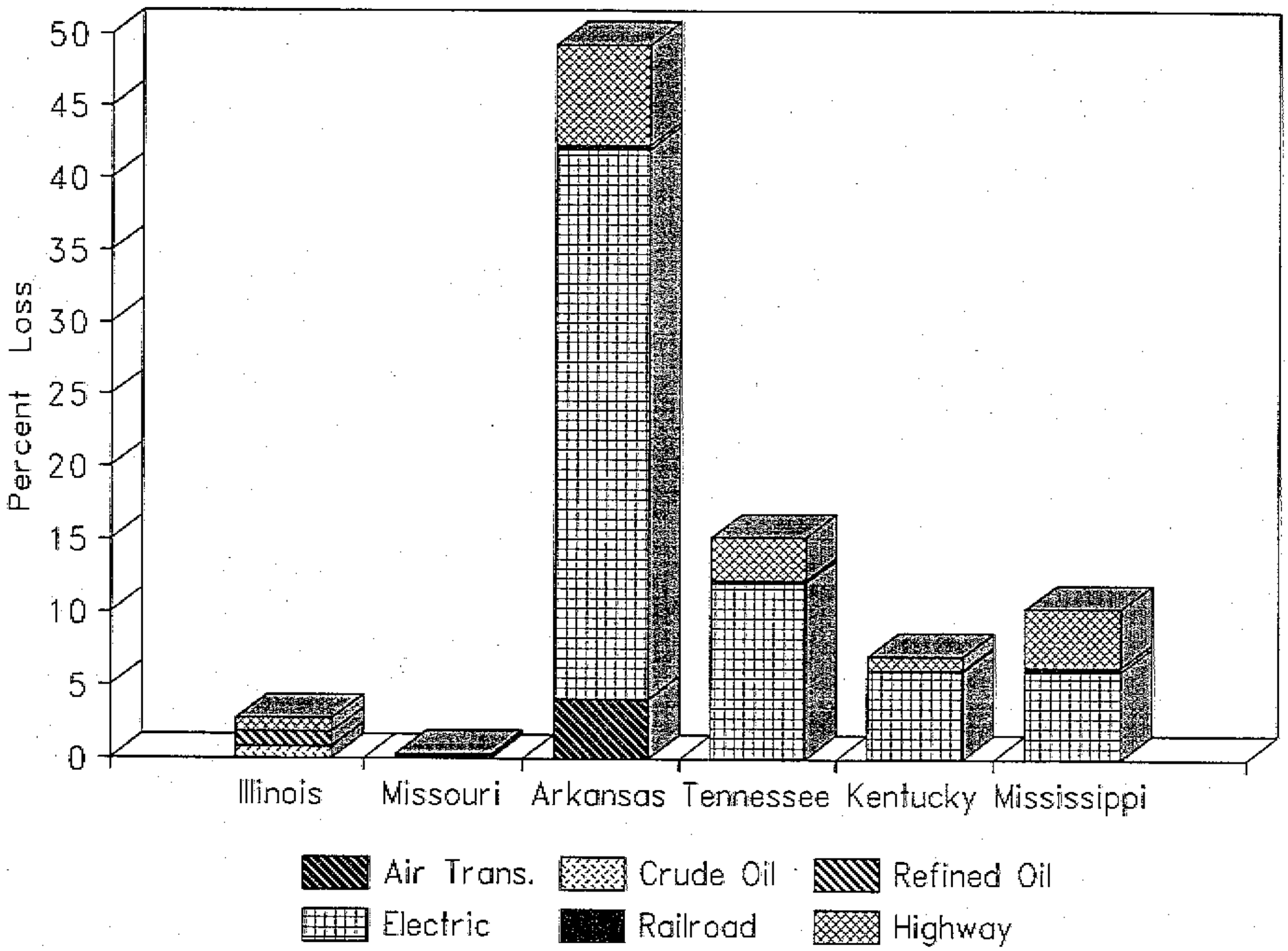


Figure 6-26 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, New Madrid event (M=7.0). Note that the relatively low losses for Missouri reflect the assumed location of the scenario earthquake source zone and the estimated distribution of intensity (see Figure 4-18).*

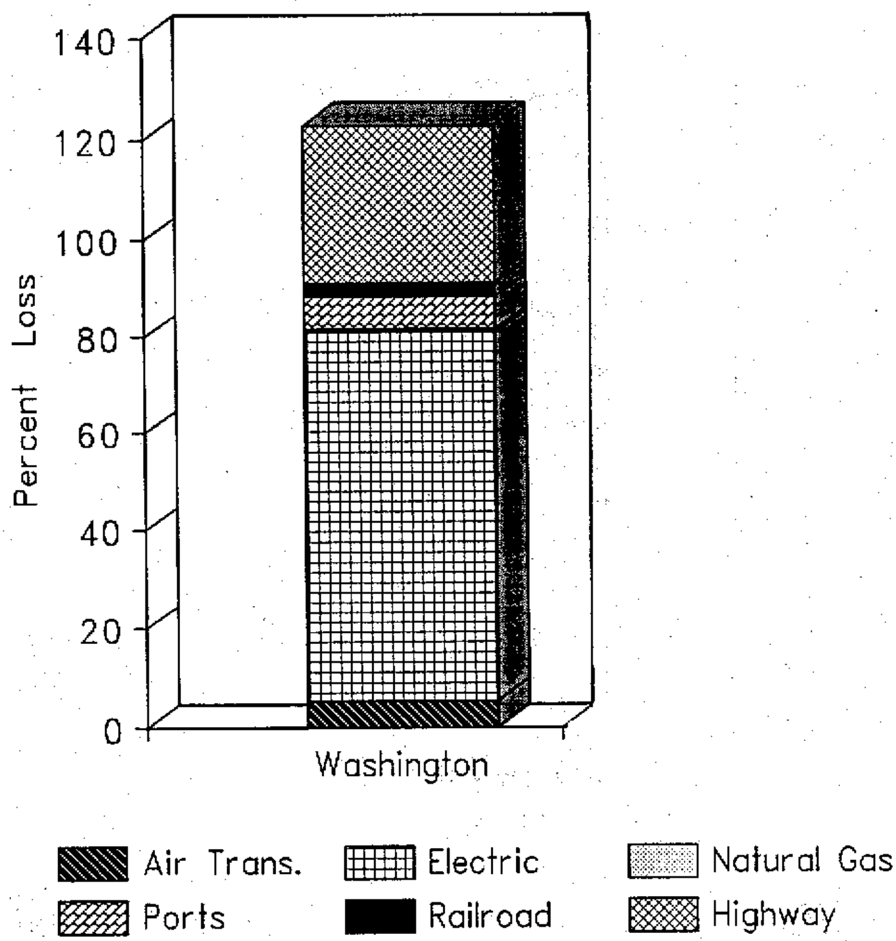


Figure 6-27 *Percent indirect economic loss in state of Washington (monthly GNP) resulting from damage to various lifelines, Puget Sound event (M=7.5).*

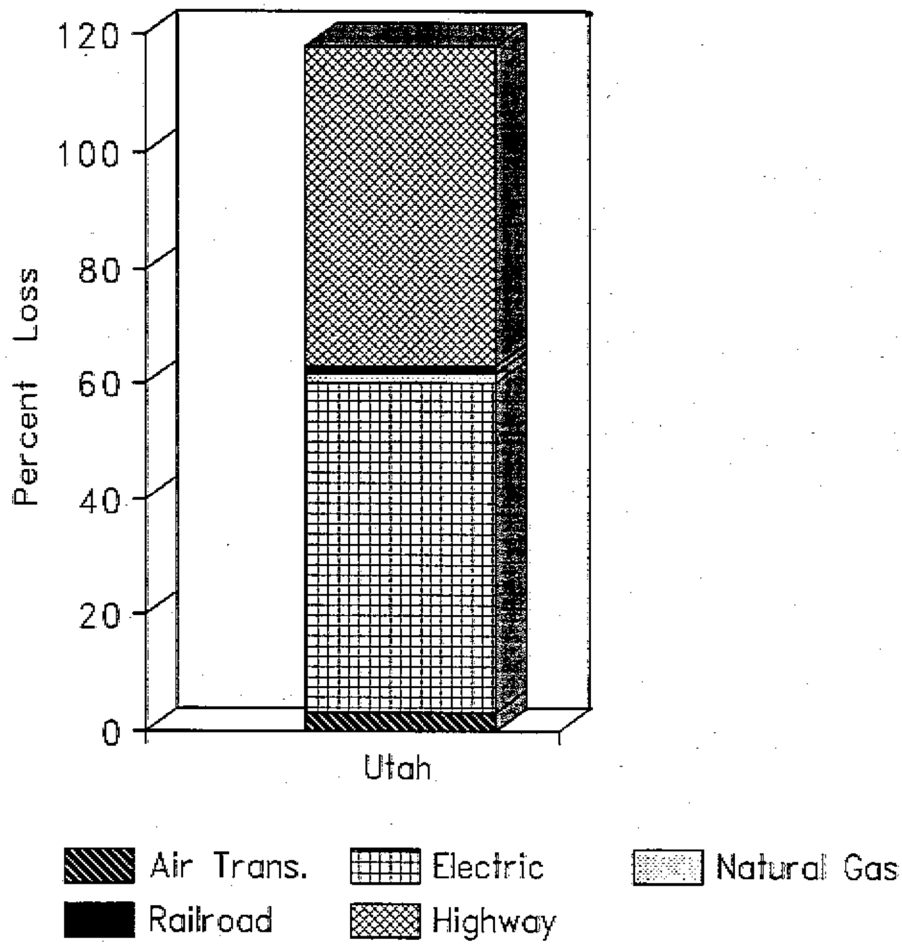


Figure 6-28 *Percent indirect economic loss in state of Utah (monthly GNP) resulting from damage to various lifelines, Wasatch Front event (M=7.5).*

7. Combined Economic Losses, Deaths, and Injuries

7.1 Introduction

In this chapter we provide an overview of combined economic losses, consisting of direct and indirect economic losses, and a discussion of deaths and injuries.

At this point it is important to reiterate the purposes and key limitations of this study. As previously indicated, the overall purpose is to provide an overview of the national economic impact resulting from the seismic vulnerability of lifelines and the impact of their disruption. The Federal Emergency Management Agency is planning to use this report to emphasize the importance of maintaining functionality of lifelines after earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies.

Lifelines considered are transportation systems, energy systems, emergency service facilities, and water systems. Excluded from consideration because of the unavailability of inventory data or the need for more in-depth studies are telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain highway, electric, and water facilities at the local distribution level.

Also excluded from consideration in the results are interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslide (due to lack of inventory data nationwide). These limitations and others described in Chapters 2, 4, and 5 tend to underestimate losses; other limitations (e.g., application of ATC-13 vulnerability functions to a relatively few structures) tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, due primarily to the exclusion of systems (e.g., dams and telecommunication systems), we believe the estimates presented in this report are, in fact, quite conservative.

This report is a macroscopic investigation at the national level and the results should not be used for microscopic interpretations. The results are not intended to be used to evaluate any particular regional utility or lifeline and no specific information on such specific facilities has been included.

7.2 Human Death and Injury

It is generally felt that lifeline performance and continuity of operation is vital to human survival in the modern, urban, world. Most observers believe that damage to lifelines would result in human death and injury. Analogous to direct damage to property and indirect economic losses, human death and injury resulting from lifeline damage can be categorized as follows:

1. Human death and injury caused by lifeline functional curtailment, where persons suffer as a result of deprivation of vital services; and

2. Human death and injury resulting from direct damage to lifelines (e.g., occupant injuries resulting from the collapse of an air terminal building).

Analysis and data on both of these aspects are virtually nonexistent. Following are discussions of these death and injury causes:

7.2.1 Casualties Due to Lifeline Functional Curtailment

Without the benefit of hard data it is difficult to estimate with high confidence the number of casualties that will result from curtailment of lifeline function. Our preliminary assessment is that human death and injury due to functional curtailment of lifelines can generally be expected to be very low. This is a fundamental assumption of this study, and will probably cause some debate. Each lifeline was considered, and this conclusion was found to hold, based on the following assumptions: (1) most vital installations that normally require a lifeline service have back-up emergency supplies, and (2) most lifelines have considerable elasticity in demand, and the level of service necessary for life maintenance is very low. Examples follow:

- Electricity. Persons can survive without power, even in the Northeast in the winter. Most hospitals and similar installations have emergency generators. Those that lack emergency generators can transfer patients to other sites.

- Water. Water for human survival is very minimal. Humans can survive without water for 48 or more hours, and water for human survival can be imported if necessary.

- Gas and Liquid Fuels. Gas and liquid fuel systems are probably the most critical of all lifelines, yet capacity is very elastic, and only short-term shortages are expected. Fuel for heating in the Northeast in the winter can be conserved if necessary by clustering people in school gymnasia, national guard armories, and so on.

- Rail, Air, and Highway Transportation. Transportation lifelines are highly redundant and thus very elastic; emergency food and medicines would be expected to be deliverable regardless of earthquake damage.

7.2.2 *Casualties Resulting From Lifeline Direct Damage*

Casualties can result from direct damage, especially catastrophic collapse, of lifeline components. Although few deaths occurred directly as a result of lifeline damage in U. S. earthquakes prior to 1989, life-loss due to lifeline failure was tragically demonstrated during the October 17, 1989, Loma Prieta, California, earthquake. Approximately two thirds of the 62 deaths from this earthquake resulted from the failure of a lifeline component--partial collapse of the Cypress structure, a double-decked highway viaduct in Oakland approximately 100 km from the earthquake source zone.

Although it can be argued that the deaths and injuries caused by lifeline failure in the Loma Prieta earthquake were the exception, not the rule, the vulnerability functions developed for this project suggest that substantial life-loss from lifeline component failure should be anticipated. Lifeline failures that could cause substantial life loss or injury include bridge failure, railroad derailment, and pipeline failure.

Unfortunately, data necessary for estimating life loss associated with these component failures are not readily available, precluding development of reliable casualty estimation methodology and data for lifeline structures.

7.3 Combined Direct and Indirect Economic Losses

Total dollar losses from direct damage and indirect economic losses have been taken from Chapters 5 and 6 and are combined and summarized herein for each scenario earthquake and lifeline in Table 7-1. The total losses for each scenario earthquake are as follows:

Earthquake	Direct Plus Indirect Losses (in Billions, 1991$)
Cape Ann	$13.3
Charleston	$15.1
Fort Tejon	$16.6
Hayward	$15.7
New Madrid, M = 8.0	$26.4
New Madrid, M = 7.0	$8.3
Puget Sound	$10.5
Wasatch Front	$5.4

Table 7-1 Total Direct Plus Indirect Dollar Losses for Each Scenario Earthquake and Lifeline (Billions of Dollars)

Scenario	*Electric*	*Highways*	*Water*	*Medical Care*	*Ports*	*Railroads*	*Airport*	*Natural Gas*	*Crude Oil*	*Refined Oil*	*Broadcasting Stations*	*Fire Stations*	*Total*
Cape Ann	$11.24	$2.06	$0.91	$0.49	$0.50	$0.03	$0.58	$0.00	$0.00	$0.00	$0.02	$0.01	$13.25
Charleston	$10.82	$2.05	$0.94	$0.57	$5.30	$0.18	$0.59	$0.00	$0.00	$0.00	$0.07	$0.01	$15.11
Fort Tejon	$9.66	$5.18	$5.27	$1.43	$2.65	$0.41	$1.57	$1.68	$4.38	$0.00	$0.03	$0.05	$16.58
Hayward	$12.21	$2.52	$4.38	$1.30	$1.46	$0.22	$0.44	$0.09	$0.00	$0.00	$0.02	$0.01	$15.66
New Madrid 8	$15.68	$13.19	$2.68	$1.30	$0.00	$0.71	$1.22	$0.34	$0.46	$0.23	$0.09	$0.01	$26.37
New Madrid 7	$5.17	$4.12	$0.85	$0.40	$0.00	$0.15	$0.31	$0.18	$0.13	$0.16	$0.03	$0.00	$8.29
Puget Sound	$8.29	$1.95	$0.90	$0.51	$0.73	$0.21	$0.62	$0.21	$0.00	$0.00	$0.05	$0.01	$10.48
Wasatch Front	$2.21	$3.85	$0.40	$0.20	$0.00	$0.05	$0.11	$0.04	$0.00	$0.00	$0.04	$0.00	$5.41

8. Hazard Mitigation Measures and Benefits

8.1 Introduction

A primary objective of this study is to identify the most critical lifelines and develop a prioritized series of steps for reduction of lifeline seismic vulnerability, based on overall benefits. In this chapter we identify the most critical lifelines and provide a relative ranking of the criticality of these different lifelines in terms of the estimated impact of damage and economic disruption. Also included are recommended key measures for reducing the earthquake vulnerability of these lifeline systems, and results from analytical computations to illustrate the reduction in losses if such hazard mitigation strategies are employed.

8.2 Identification of Critical Lifelines

Based on the combined direct and indirect economic losses presented in Chapter 7 and with due consideration of the assumptions and limitations expressed throughout this report, we offer the following relative ranking of the criticality of different lifelines in terms of the estimated impact of damage and disruption:

Rank	Lifeline	Event/Location
1.	Electric System	New Madrid (M=8.0)
		Hayward
		Cape Ann, Charleston, Fort Tejon
2.	Highways	New Madrid (M=8.0)
		Fort Tejon
		Hayward, New Madrid (M=7.0)
3.	Water System*	Fort Tejon
4.	Ports	Charleston
5.	Crude Oil	Fort Tejon

*The ranking for the water system may be underestimated because critical components such as pumping stations and dams were not included in the study.

8.3 Measures for Reducing Vulnerability of Lifeline Systems

The seismic vulnerability of lifeline systems, from the point of view of fulfilling function, can be reduced through three primary approaches:

1. **Damage reduction measures.** In this approach reliability of function is enhanced by reducing damage. This approach may take the form of :

    - Strengthening a building, bracing equipment, or performing other corrective retrofit measures to mitigate shaking effects;
    - Densifying the soil beneath a structure, or placing a structure on piles, or using other techniques to mitigate hazardous geotechnical conditions, e.g., liquefaction potential,
    - Other component improvements, depending on the component and potential earthquake impacts, e.g., replacement of vulnerable systems/components with new systems/components that will provide improved seismic resistance.

2. **Provision for system redundancy.** In this approach, reliability of function is enhanced by providing additional and alternative links (e.g., new highways, pipelines, other transmission or distribution links). Because earthquake damage is fundamentally a random phenomena, addition of system links will tend to increase system reliability.

3. **Operational improvements.** In this approach reliability of function is enhanced by providing emergency response planning and the capability to rapidly and effectively repair damage, redirect functions, or otherwise mitigate earthquake damage impacts on system operations and thereby re-establish system function.

Of these measures, the most common are component strengthening/retrofit measures, which are discussed at length in Appendix B of this report. The proposed measures (Appendix B) include generic solutions, such as designing structures to meet current seismic design or retrofit standards of the local community, or anchoring equipment. In addition, there are numerous specific measures that relate to unique systems or components within each lifeline. Special attention should be directed to those systems and conditions that are of greatest concern, such as porcelain components in electric substations.

Following are recommended steps when implementing a program to reduce seismic hazards of existing lifelines:

1. Review existing descriptions of seismic performance and rehabilitation measures for the lifeline(s) of concern, i.e., familiarize yourself and your organization with the overall problem. Sources include Appendix B and Chapter 10 (References) of this report.

2. Conduct an investigation of the seismic vulnerability and impact of disruption for the lifeline(s) and region(s) of concern. Lifeline seismic evaluation methodologies and other potential resources for this purpose have been developed by the ASCE Technical Council for Lifeline Earthquake Engineering (see references, Chapter 10), the Applied Technology Council (ATC, in preparation) and others.

3. Focus first on the most vulnerable lifelines, components, and conditions (e.g., liquefaction or landslide potential). Vulnerable components include:

   For electric systems:
   - Substations
   - Power stations

   For water systems:
   - Pumping stations
   - Tanks and reservoirs
   - Treatment plants
   - Transmissions aqueducts

   For highway systems
   - Bridges
   - Tunnels
   - Roadbeds

   For water transportation systems:
   - Port/cargo handling equipment
   - Inland waterways

   For gas and liquid fuels:
   - Distribution storage tanks
   - Transmission pipelines
   - Compressor, metering and pressure reduction stations

4. Conduct cost-benefit studies to determine the most cost effective measures. We note that, in some cases, retrofit measures may not be very cost effective. In regions where the return period for large earthquakes is quite long, for example, replacement over the life cycle of the facility or component may be a reasonable approach.

5. Implement the selected hazard reduction measures.

8.4 Estimated Overall Benefits of Implementing Hazard Reduction Measures

In order to provide an indication of the overall benefit of implementing hazard mitigation measures, we have computed and compare estimated direct damage and indirect economic losses for the existing and an upgraded extended regional electric network, with specific focus on the most vulnerable component for this lifeline--substations. Estimated direct damage and indirect economic losses for the existing network are taken from Chapters 5 and 6, respectively. Estimated direct damage and indirect economic losses for the hypothetical upgraded network have been computed using the same techniques and data as used for the existing network, but seismic intensities have been shifted downward two units to reflect the improved performance of the upgraded system. While this is a rather simplistic approach, we believe the results reasonably indicate the extent of benefit provided by rehabilitation.

Direct Damage Comparisons. Percentages of substations in the existing and upgraded system in the various damage states are provided in Tables 8-1 and 8-2 respectively. With the exception of 1% of the upgraded substations in Missouri and Tennessee that would sustain major-to-destructive damage in the magnitude-8.0 New Madrid event, none of the substations in other locations for this event or in other events would sustain damage this severe. In contrast, 43 percent of the transmission substations in Washington, 29 percent in Arkansas, 16 percent in South Carolina, 13 percent in California, 10 percent in Utah, 8 percent in Missouri, and 6 percent in Tennessee would sustain damage in this range in the various earthquake scenarios. Trends for lower damage states are similar, as are trends for transmission lines (not shown here).

Indirect Economic Loss Comparisons. Indirect economic losses resulting from damage to the existing and upgraded systems are provided in Tables 8-3 and 8-4. Table 8-3 includes data for all affected states, whereas Table 8-4 does not include data for states for which damage to the upgraded system was zero or insignificant. Data for the upgraded system are based on residual capacity plots provided in Appendix C (Figures C-185 through C-200).

By comparing the results in Tables 8-3 and 8-4, it is clear that indirect economic losses are substantially reduced through seismic upgrade measures. For example, the ratio of indirect economic loss to the retail trade sector resulting from damage to the existing system versus loss resulting from damage to the upgraded system ranges from 2.5 to 34 for the 7 events and 8 states considered in both analyses. A comparison of data for the other economic sectors shows similar trends.

Table 8-1 Damage Percent for Existing Electric Transmission Substations for Each Scenario Earthquake (Percent of Substations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Indiana 89	Mississippi 93	South Carolina 100	North Carolina 76	Georgia 86
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	14%	8%	22%	16%	24%	2%	63%	43%	20%	33%
Heavy 30-60 %	0%	0%	10%	9%	7%	0%	8%	14%	0%	3%
Major to Destructive 60-100 %	0%	8%	29%	6%	1%	0%	10%	16%	1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 153	Connecticut 69	Delaware 3	Rhode Island 22	New Hampshire 22	Utah 10
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	82%	42%	33%	100%	45%	30%
Heavy 30-60 %	0%	0%	0%	0%	0%	20%
Major to Destructive 60-100 %	5%	0%	0%	0%	0%	10%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 205	California 205	Washington 155	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Mississippi 93
Light Damage 1-10 %	8%	11%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	13%	6%	12%	0%	2%	21%	16%	16%	14%
Heavy 30-60 %	14%	< 1%	3%	0%	0%	16%	0%	0%	2%
Major to Destructive 60-100 %	13%	12%	43%	0%	6%	6%	3%	0%	0%

Table 8-2 Damage Percent for Upgraded Electric Transmission Substations for Each Scenario Earthquake (Percent of Substations in State)

	NEW MADRID (M=8.0)						
Total Number	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Indiana 89	Mississippi 93
Light 0-10 %	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	0%	0%	21%	11%	9%	0%	10%
Heavy 30-60 %	0%	7%	8%	1%	0%	0%	0%
Major to Destructive 60-100 %	0%	1%	0%	1%	0%	0%	0%

	CHARLESTON (M=7.5)		
Total Number	South Carolina 100	North Carolina 76	Georgia 86
Light 0-10 %	0%	0%	0%
Moderate 10-30 %	24%	1%	1%
Heavy 30-60 %	6%	0%	1%
Major to Destructive 60-100 %	0%	0%	0%

	CAPE ANN (M=7.0)				
Total Number	Massachusetts 153	Connecticut 69	Delaware 3	Rhode Island 22	New Hampshire 22
Light 0-10 %	0%	0%	0%	0%	0%
Moderate 10-30 %	1%	0%	0%	0%	0%
Heavy 30-60 %	5%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%

	WASATCH FRONT (M=7.5)
Total Number	Utah 10
Light 0-10 %	0%
Moderate 10-30 %	30%
Heavy 30-60 %	0%
Major to Destructive 60-100 %	0%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 205	California 205	Washington 155	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Mississippi 93
Light 0-10 %	12%	6%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	21%	11%	21%	0%	3%	6%	1%	0%	0%
Heavy 30-60 %	0%	1%	22%	0%	3%	0%	1%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 8-3 Indirect Economic Loss Due to Damage to the Existing Electric System (Percent Monthly GNP)

		U.S. Econ. Value Added (Percent)	NEW MADRID (M=8.0)						CHARLESTON			CAPE ANN		
			Illinois	Missouri	Arkansas	Tennessee	Kentucky	Mississippi	South Carolina	North Carolina	Georgia	Massachusetts	Connecticut	Delaware
1	Livestock	0.45%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
2	Agr. Prod.	1.06%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
3	AgServ For. Fish	0.11%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
4	Mining	3.89%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
5	Construction	5.52%	3.16%	5.26%	26.32%	10.53%	10.53%	35.79%	36.84%	6.32%	14.74%	35.79%	12.63%	8.42%
6	Food Tobacco	2.41%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
7	Textile Goods	0.37%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
8	Misc Text. Prod.	0.73%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
9	Lumber & Wood	0.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
10	Furniture	0.34%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
11	Pulp & Paper	0.87%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
12	Print & Publish	1.31%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
13	Chemical & Drugs	1.40%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
14	Petrol. Refining	0.96%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
15	Rubber & Plastic	1.03%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
16	Leather Prods.	0.12%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
17	Glass Stone Clay	0.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
18	Prim. Metal Prod.	1.04%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
19	Fab. Metal Prod.	1.64%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
20	Mach. Exc. Elec.	1.56%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
21	Elec. & Electron	2.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
22	Transport Eq.	2.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
23	Instruments	0.68%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
24	Misc. Manufact.	0.69%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
25	Transp & Whse.	3.46%	2.37%	3.95%	19.74%	7.89%	7.89%	26.84%	27.63%	4.74%	11.05%	26.84%	9.47%	6.32%
26	Utilities	5.89%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
27	Wholesale Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
28	Retail Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
29	F.I.R.E.	16.64%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
30	Pers./Prof Serv.	8.03%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
31	Eating Drinking	2.12%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
32	Auto Serv.	1.09%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
33	Amuse & Rec.	0.70%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
34	Health Ed. Soc.	6.30%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
35	Govt & Govt Ind.	11.79%	4.74%	7.89%	39.47%	15.79%	15.79%	53.68%	55.26%	9.47%	22.11%	53.68%	18.95%	12.63%
36	Households	0.25%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%

Table 8-3 Indirect Economic Loss Due to Damage to the Existing Electric System (Percent Monthly GNP) (Continued)

	U.S. Econ. Value Added (Percent)	CAPE ANN		WASATCH	CALIFORNIA		PUGET SOUND	NEW MADRID (M=7.0)			
		Rhode Island	New Hampshire	Utah	Hayward	Fort Tejon	Washington	Arkansas	Tennessee	Kentucky	Mississippi
1 Livestock	0.45%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
2 Agr. Prod.	1.06%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
3 AgServ For. Fish	0.11%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
4 Mining	3.89%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
5 Construction	5.52%	33.68%	11.58%	28.42%	18.95%	10.53%	37.89%	18.95%	6.32%	3.16%	3.16%
6 Food Tobacco	2.41%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
7 Textile Goods	0.37%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
8 Misc Text. Prod.	0.73%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
9 Lumber & Wood	0.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
10 Furniture	0.34%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
11 Pulp & Paper	0.87%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
12 Print & Publish	1.31%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
13 Chemical & Drugs	1.40%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
14 Petrol. Refining	0.96%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
15 Rubber & Plastic	1.03%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
16 Leather Prods.	0.12%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
17 Glass Stone Clay	0.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
18 Prim. Metal Prod.	1.04%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
19 Fab. Metal Prod.	1.64%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
20 Mach. Exc. Elec.	1.56%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
21 Elec. & Electron	2.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
22 Transport Eq.	2.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
23 Instruments	0.68%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
24 Misc. Manufact.	0.69%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
25 Transp & Whse.	3.46%	25.26%	8.68%	21.32%	14.21%	7.89%	28.42%	14.21%	4.74%	2.37%	2.37%
26 Utilities	5.89%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
27 Wholesale Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
28 Retail Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
29 F.I.R.E.	16.64%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
30 Pers./Prof Serv.	8.03%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
31 Eating Drinking	2.12%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
32 Auto Serv.	1.09%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
33 Amuse & Rec.	0.70%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
34 Health Ed. Soc.	6.30%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
35 Govt & Govt Ind.	11.79%	50.53%	17.37%	42.63%	28.42%	15.79%	56.84%	28.42%	9.47%	4.74%	4.74%
36 Households	0.25%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%

Table 8-4 Indirect Economic Loss Due to Damage to the Upgraded Electric System (Percent Monthly GNP)

			NEW MADRID (M=8.0)		*CHARLESTON*	*CAPE ANN*	*WASATCH*	*HAYWARD*	*FT. TEJON*	*WASHINGTON*
		U.S. Econ. Value-Added (Percent)	*Arkansas*	*Tennessee*	*S Carolina*	*Massachusetts*	*Utah*	*California*	*California*	*Washington*
1	Livestock	0.45%	13.16%	5.26%	15.79%	1.32%	10.53%	5.26%	2.63%	18.42%
2	Agr. Prod.	1.06%	13.16%	5.26%	15.79%	1.32%	10.53%	5.26%	2.63%	18.42%
3	AgServ For. Fish	0.11%	13.16%	5.26%	15.79%	1.32%	10.53%	5.26%	2.63%	18.42%
4	Mining	3.89%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
5	Construction	5.52%	10.53%	4.21%	12.63%	1.05%	8.42%	4.21%	2.11%	14.74%
6	Food Tobacco	2.41%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
7	Textile Goods	0.37%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
8	Misc Text. Prod.	0.73%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
9	Lumber & Wood	0.52%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
10	Furniture	0.34%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
11	Pulp & Paper	0.87%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
12	Print & Publish	1.31%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
13	Chemical & Drugs	1.40%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
14	Petrol. Refining	0.96%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
15	Rubber & Plastic	1.03%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
16	Leather Prods.	0.12%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
17	Glass Stone Clay	0.62%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
18	Prim. Metal Prod.	1.04%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
19	Fab. Metal Prod.	1.64%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
20	Mach. Exc. Elec.	1.56%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
21	Elec. & Electron	2.52%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
22	Transport Eq.	2.62%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
23	Instruments	0.68%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
24	Misc. Manufact.	0.69%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
25	Transp & Whse.	3.46%	7.89%	3.16%	9.47%	0.79%	6.32%	3.16%	1.58%	11.05%
26	Utilities	5.89%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
27	Wholesale Trade	5.63%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
28	Retail Trade	5.63%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
29	F.I.R.E.	16.64%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
30	Pers./Prof Serv.	8.03%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
31	Eating Drinking	2.12%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
32	Auto Serv.	1.09%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
33	Amuse & Rec.	0.70%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
34	Health Ed. Soc.	6.30%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
35	Govt & Govt Ind.	11.79%	15.79%	6.32%	18.95%	1.58%	12.63%	6.32%	3.16%	22.11%
36	Households	0.25%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%

9. Recommendations for Further Work

9.1 Introduction

The ATC-25 project has raised a number of questions and indicated areas in which knowledge is inadequate or nonexistent with respect to the impact of lifeline disruption due to earthquake. Following is a discussion of recommendations for further research and other efforts. This list is not meant to be all inclusive but rather an overview of some of the more important issues that should be pursued.

9.2 Lifeline Inventory

This project has initiated the development of a comprehensive national lifelines inventory database. Completion of this monumental task will require many person-years of effort. Organizations such as the Federal Emergency Management Agency, Department of Transportation, and American Society of Civil Engineers Technical Council of Lifeline Earthquake Engineering are encouraged to build on the work performed in this project, develop standards for complete lifeline inventories, and coordinate the acquisition of the needed additional and updated data from various lifeline owners. Capacity data in the National Petroleum Council's oil/gas transmission line inventory is an example of the kind and extent of information that is needed in lifeline inventory databases. An integral part of any project to augment the existing ATC-25 lifeline database should be its wide availability in the public domain.

9.3 Lifeline Component Vulnerability

This project employed lifeline component vulnerability functions developed in the ATC-13 project (ATC, 1985) on the basis of expert opinion obtained by surveys. While the ATC-13 expert-opinion data are extremely useful, comprehensive information based on hard field data would provide an improved basis for estimating lifeline vulnerability. We recommend a major effort to acquire data on lifeline seismic performance and damage, and conduct analysis towards the development of improved component vulnerability functions. This effort should also investigate lifeline recovery data, and incorporate the extensive experience realized during the 17 October 1989 Loma Prieta, California, earthquake, as well as from other damaging earthquakes.

9.4 Seismic Hazard Data

The project has uncovered the relative paucity of seismic hazard models and resources at the regional/national scale. Only two models are available, those of Evernden and Thompson (1985) and Algermissen et al. (1990), the latter of which does not incorporate a soils database. While a nationally agreed upon seismic hazard model may be desirable, this is less of a priority than the need for a digitized soils database. That is, existing models (e.g., attenuation relations, seismicity databases, seismotectonic models) are sufficient for a number of site-specific purposes, and can be expanded to regional modeling, given an adequate soils database. We suggest that the U. S. Geological Survey develop, or coordinate through the various states' Office of Geologists, a series of digitized soils/geologic databases.

9.5 Economic Analysis and Impacts Data and Methodology

This project has presented a rational comprehensive model for the estimation of the economic impacts due to lifeline disruption. Many steps of the process necessarily involved approximations and limited analyses. We recommend further research, especially in economic areas such as:

- Economic impacts associated with lifeline disruption,
- Second-order economic effects (e.g., interaction between lifelines, such as the effect of disrupted electric power on the water supply),
- Elasticities of demand, or substitution of a lesser disrupted lifeline (e.g., fuel oil) for a more disrupted lifeline (e.g., natural gas),

- Inter-regional impacts (e.g., economic impacts in New York due to disruption in California), and

- So-called "benefits," such as increased economic activity associated with repair, or replacement of older equipment with new technology.

Lastly, we note that this study did not address environmental consequences associated with lifeline disruption, especially the potential for oil spills from broken pipelines in the nation's waterways following a New Madrid event. Investigation of this issue is critically important.

10. References

AIRAC, 1987, "Fire Following Earthquake--Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco," All-Industry Research Advisory Council, Oak Brook, Illinois.

Aki, K., 1982, "Strong Motion Prediction Using Mathematical Modeling Techniques," Bull. Seis. Soc. Am., Vol. 72, pp. 529-541.

Aki, K., and Richards, P. G., 1980, *Quantitative Seismology*, W. H. Freeman, San Francisco.

Algermissen, S.T., 1969, "Seismic Risk Studies in the United States," In *Proc. 4th World Conf. on Earthquake Engineering*, Santiago, Chile, Vol. 1, pp. 14-27.

Algermissen, S.T., and D.M. Perkins, 1976, *A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States*, U.S. Geological Survey Open-File Report 76-416.

Algermissen, S.T., R. J. Brazee, C.W. Stover, and L.C. Pakiser, 1977, "Maximum Intensity of the Washington Earthquake of December 14, 1872," Report of USGS/NOAA Ad Hoc Working Group on Intensities of Historic Earthquakes.

Algermissen, S.T., D.M. Perkins, P.C. Thenhaus, S.L. Hanson, and B.L. Bender, 1982, *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States*, U.S. Geological Survey Open-File Report 82-1033.

Algermissen, S.T., 1983, "An Introduction to the Seismicity of the United States," Earthquake Engineering Research Institute, Berkeley, Calif, 148 pp.

Algermissen, S. T. et al., 1990, "Probabilistic Earthquake Acceleration and Velocity for the United States and Puerto Rico," U. S. Geological Survey Map MF-2120.

American Society of Civil Engineers (ASCE-TCLEE), 1977, *Conference on Current State of Knowledge of Lifeline Earthquake Engineering*, New York, NY.

American Society of Mechanical Engineers, 1979, "National Congress on Pressure Vessels and Piping" (3rd: 1979: San Francisco, Calif.); "Lifeline Earthquake Engineering--Buried Pipelines, Seismic Risk, and Instrumentation," Presented at the Third National Congress on Pressure Vessels and Piping, San Francisco, California, June 25-29, 1979, New York.

American Society of Mechanical Engineers, 1980, *Symposium on Recent Advances in Lifeline Earthquake Engineering in Japan* (San Francisco, Calif.), "Recent Advances in Lifeline Earthquake Engineering in Japan,".

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering, 1980, *Annotated Bibliography on Lifeline Earthquake Engineering*, Prepared by Technical Council on Lifeline Earthquake Engineering, American Society of Engineers.

American Society of Civil Engineers (ASCE-TCLEE), 1981, "Lifeline Earthquake Engineering: The Current State of Knowledge," in *Proceedings of the Second Specialty Conference of the Technical Council on Lifeline Earthquake Engineering*, Oakland Hyatt House, Oakland, New York, N.Y.

American Society of Civil Engineers, 1983, "Advisory Notes on Lifeline Earthquake Engineering," New York, NY.

American Society of Civil Engineers (ASCE-TCLEE), Technical Council on Lifeline Earthquake Engineering, 1983, "Advisory Notes on Lifeline Earthquake Engineering," A Report Prepared by the Technical Committees, New York, N.Y.

American Society of Civil Engineers, Technical Council on Lifeline Earthquake

Engineering, 1984, "Lifeline Earthquake Engineering: Performance, Design, and Construction," in *Proceedings of a Symposium Sponsored by the Technical Council on Lifeline Earthquake Engineering of the American Society of Civil Engineers*, New York, N.Y.

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering, 1986, "Lifeline Seismic Risk Analysis--Case Studies," in *Proceedings of the Session Sponsored by the Technical Council of Lifeline Earthquake Engineering of the American Society of Civil Engineers in Conjunction with the ASCE*, New York, N.Y.

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering, 1986, "Seismic Evaluation of Lifeline Systems--Case Studies" in Proceedings of a Session Sponsored by the Technical Council on Lifeline Earthquake Engineering of the American Society of Civil Engineers, New York, N.Y.

American Society of Civil Engineers, 1988, "Seismic Design and Construction of Complex Civil Engineering Systems." in *Proceedings of a Symposium Sponsored by the Technical Council on Lifeline Earthquake Engineering of the American Society of Civil Engineers*, New York, N.Y.

Anderson, J.G., 1984, Synthesis of Seismicity and Geological Data in California, USGS Open-file Rept. 84-424.

Applied Technology Council (ATC 3-06), 1978, *Tentative Provisions for the Development of Seismic Regulations for Buildings*, Report ATC 3-06, Palo Alto, Calif.

Applied Technology Council (ATC-6), 1981, *Seismic Design Guidelines for Highway Bridges*, Report ATC-6, Palo Alto, Calif.

Applied Technology Council (ATC-6-2), 1983, *Seismic Retrofit Design Guidelines for Highway Bridges*, Report ATC-6-2, Palo Alto, Calif.

Applied Technology Council (ATC-13), 1985, *Earthquake Damage Evaluation Data for California*, Report ATC-13, Redwood City, Calif.

Applied Technology Council (ATC-21), 1988, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, Report ATC-21, Redwood City, Calif.

Applied Technology Council (ATC-23), 1991, *General Acute Care Hospital Earthquake Survivability Inventory for California*, Report ATC-23, Redwood City, Calif.

Applied Technology Council (ATC-25-1), in preparation, *A Model Methodology for Assessment of Seismic Vulnerability and Impact of Disruption of Water Supply Systems*. Report ATC-25-1, Redwood City, Calif.

Arabasz, W. J. and Smith, R. B., 1979, *Earthquake Studies in Utah: 1850-1978*, University of Utah Seismograph Station.

Ariman, T., ed, 1987, *Recent Advances in Lifeline Earthquake Engineering*, Amsterdam; New York: Elsevier; Southampton, U.K.; Boston: Computational Mechanics Publications; New York, N.Y.: Distributors for the U.S. and Canada, Elsevier Science Pub. Co., Series Title: Developments in Geotechnical Engineering; 49 pp.

Ariman, T., ed, 1983, "Earthquake Behavior and Safety of Oil and Gas Storage Facilities, Buried Pipelines and Equipment," Am. Soc. Mech. Engrs., New York, NY.

Ariman, T., Dobray, R. Grigoriu, M., Cozen, F., O'Rourke, M., O'Rourke, T., and Shinozuka, M., 1990, *A Pilot Study of Seismic Vulnerability of Crude Oil Transmission Systems*, National Center for Earthquake Engineering Report 90-0008, Buffalo, NY.

BEA, February 1989, "Survey of Current Business," Vol. 69, No. 2, pp. 21-36, Input-Output Accounts of the U.S. Economy, 1983.

Binder, R.W., 1952, *Engineering Aspects of the 1933 Long Beach Earthquake, in Earthquake and Blast Effects on Structures*, Duke, C.M. and Feigen, M., eds, Earthquake Engineering Research Institute, Los Angeles, Calif.

Blackmon, Greg, July-August 1985, "How to Reduce Business Interruption Following Catastrophic Property Loss, *Journal of Property Management*, Indianapolis, Vol. 50, No. 4.

Bollinger, G.A., 1973, "Seismicity and Crustal Uplift in the Southeastern United States," *American Jnl. Science*, Vol. 273A, pp. 396-408.

Bollinger, G.A., 1977, "Reinterpretation of the Intensity Data for 1886 Charleston, South Carolina Earthquake," *Studies Related to the Charleston, South Carolina Earthquake of 1886--A Preliminary Report*, D. W. Rankin, ed, U.S. Geological Survey Prof. Paper 1028, pp 17-32.

Bollinger, G.A., 1983, "Seismicity of the Southeastern United States," *Bull. Seis. Soc. Amer.*, Vol. 63, No. 5, pp. 1785-1808.

BSSC, 1987, "Abatement of Seismic Hazards to Lifelines," in *Proceedings of a Workshop held in Denver*, in Seven Volumes, available from the Federal Emergency Management Agency (EHRS 26 - 32), Washington, DC.

BSSC, 1988, *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*, Federal Emergency Management Agency, Eaerthquake Hazard Reduction Series Report 95, Washington, DC.

Bureau, G., Scawthorn, C., Gates, W.E., and Myksvoll, K., 1985, "Seismic Safety of the Lower Crystal Springs Reservoir Outlet System," *Paper Presented at the 4th Intl. Conf. of Structural Safety and Reliability*, Kobe.

Calif. Division of Mines and Geology (CDMG), 1982, *Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in the San Francisco Bay Area*, Special Publ. 61, Sacramento, Calif.

GLFC, 1984, *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, Committee on Gas and Liquid Fuel Lifelines*, Am. Soc. Civil Engrs., New York, NY.

Citadel (Military College of South Carolina), 1988, *An Earthquake Vulnerability Analysis of the Charleston, South Carolina, Area*, Report CE-88-1, Charleston, S. Carolina.

Cochrane, H. C. et al., 1975, *Social Science Perspectives on the Coming San Francisco Earthquake: Economic Impact, Prediction, and Reconstruction*, Series title: Natural Hazards Research Working Paper; No. 25, University of Colorado, Env Design HC79.E3S6, Boulder.

Cochrane, H., 1975, "Predicting the Economic Impact of Earthquakes," in *Social Science Perspectives on the Coming San Francisco Earthquake: Economic Impact, Prediction, and Reconstruction*, University of Colorado, Boulder.

Coffman, J. L., and Von Hake, C.A., 1982, *Earthquake History of the United States*, NOAA, Pub. 41-1, Washington, DC.

Cooper, J.D. ed, 1984, *Lifeline Earthquake Engineering: Performance, Design and Construction*, Am. Soc. Civil Engrs., New York, NY.

Cornell, C.A., 1968, "Engineering Seismic Risk Analysis," *Bulletin of the Seismological Society of America*, Vol. 58, No. 5.

Dames & Moore, 1984, *Seismic Evaluation, Outlet System, Lower Crystal Springs Reservoir*, Phase II, Report to San Mateo County, Calif.

Davis, J., et al., 1982, *Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in Southern California*, Calif. Division of Mines and Geology Special Publ. 60, Sacramento, Ca.

Douty, C.M., 1970, *The Economics of Localized Disasters*, Arno Press, New York, NY.

Eguchi, R.T., ed, 1986, *Lifeline Seismic Risk Analysis - Case Studies*, Am. Soc. Civil Engrs., New York, NY.

EQE Engineering, 1983, *Coalinga Earthquake of May 2, 1983, A Reconnaissance Report*, San Francisco, Calif.

EQE Engineering, 1986, *North Palm Springs Earthquake, a Reconnaissance Report*, San Francisco, Calif.

EQE Engineering, 1988, *Seismic Analysis, San Francisco Fire Department Facilities*, Report to the San Francisco Fire Department, San Francisco, Calif.

Evernden, J.F., Kohler, W.M., and Clow, G.D., 1981, "Seismic Intensities of Earthquakes of Conterminous United States - Their Prediction and Interpretation," U.S. Geological Survey Prof. Paper 1223, Reston, Virginia.

Evernden, J. F., and J. M. Thomson, 1985, "Predicting Seismic Intensities, in Evaluating Hazards in the Los Angeles Region--An Earth Science Perspective," J. I. Ziony, ed., U. S. Geological Survey Prof. Paper 1360, U. S. GPO, Washington, DC.

FEMA, 1985, FEMA Database Catalog, FEMA Manual 1520.8 (interim), Washington, DC.

Freeman, J.R., 1932, *Earthquake Damage and Earthquake Insurance*, McGraw-Hill, New York, NY.

Ford, L.R., and D.R. Fulkerson, 1962, *Flow in Networks*, Princeton University Press.

Gates, J. H., 1987, "Available Criteria, Methods and Techniques for the Design and Construction of New Transportation Facilities in California," in BSSC (1987), Vol. 2.

Gates, W.E. and Scawthorn, C., 1983, "Mitigation of Earthquake Effects on Data Processing and Telecommunications Equipment," Chapter in Earthquake Damage Mitigation for Computer Systems, in *Proceedings of Workshop Sponsored by Finance, Insurance and Monetary Services Committee*, Governor's Task Force (Thiel, C. and Olson, R., eds), San Francisco, Calif.

Gerlach, A. C., ed, no date, *National Atlas of the United States of America*, Dept. of the Interior, U. S. Geological Survey, Washington, DC.

Glendening, Frank S., 1980, *Business Interruption Insurance: What is Covered*, 1st ed, Cincinnati, Ohio., National Underwriter Co., UCLA AGS Mgmt HG 9970 B85 G53.

Gori, P.L. and Hays, W.W., 1983, A Workshop on *Continuing Actions to Reduce Losses from Earthquakes in the Mississippi Valley Area*, USGS Open-File Report 83-157,

Hanks, T. C., and Kanamori, H., 1979, "A Moment Magnitude Scale," *J. Geophys. Res.*, Vol. 84, pp. 2348-2350.

Harary, F., 1972, *Graph Theory*, Addison-Wesley.

Hays, W.W., and Gori, P.L., 1983, A Workshop on *The 1886 Charleston, South Carolina, Earthquake and Its Implications for Today*, USGS Open-File Report 83-843.

Heaton, T.H., and Hartzell, S.H., 1986, *Estimation of Strong Ground Motion for Hyothetical Earthquakes on the Cascadia Subduction Zones, Pacific Northwest*, USGS Open-File Rpt. 86-328.

Hopper M. G., 1985, *Estimation of Earthquake Effects Associated with Large Earthquakes in the New Madrid Seismic Zones*, U.S. Geological Survey Open-File Report 85-457, Denver Colorado.

Hu, T.C., 1969, *Integer Programming and Network Flows*, Addison-Wesley.

International Conference of Building Officials, 1982, 1985, 1988, 1991, *Uniform Building Code*, Whittier, Calif.

International Symposium on Lifeline Earthquake Engineering, 1983, "Earthquake Behavior and Safety of Oil and Gas Storage Facilities, Buried Pipelines, and Equipment", Presented at 1983 International Symposium on Lifeline Earthquake Engineering, New York, N.Y.

Iwasaki, T. et al., 1984, "Report on Damages to Civil Engineering Structures Due to the Nihonkai-Chubu Earthquake of 1983," 16th Jt. Meeting, Wind and Seismic Effects, UJNR.

Japan Society of Civil Engineers, 1980, *Earthquake Resistant Design for Civil Engineering Structures*, Tokyo, Japan.

Jorgensen, James R., 1983, *Standard Forms of Business Interruption Insurance*, 3rd ed, San Antonio, Texas.

Jorgensen, James R., 1983, *Business Interruption Insurance, How It Works: A Non-technical Description of the Coverage and Pricing of Standard Forms of Business Interruption Insurance*, 3rd ed, San Antonio, Texas.

Johnsen, K.E., 1984, "An Overview of Earthquake Design Requirements at Pacific Bell," (in Cooper, 1984).

Kahler, Clyde McCarty, 1930, *Business Interruption Insurance: A Survey of the Coverage of Business Interruption Losses caused by Fire and Allied Hazards, Other than Marine*, Philadelphia.

Kawasumi, H., 1968, *General Report on the Niigata Earthquake of 1964*, Tokyo, Japan.

Khater, M.M., M.D. Grigoriu, and T.D. O'Rourke, 1989, "Serviceability Measures and Sensitivity Factors for Estimating Seismic Performance of Water Supply Systems," in *Proceedings of the 9th World Conference on Earthquake Engineering*, Tokyo, Japan, Vol. VII, pp. 123-128.

Khater, M.M. and M.D. Grigoriu, August 1989, "Graphical Demonstration of Serviceability Analysis," in *Proceedings of the International Conference on Structural Safety and Reliability*, San Francisco, Calif., pp. 525-532.

Khater, M.M., Scawthorn, C., Isenberg, J., Lund, L., Larsen, T., and Shinozuka, 1990, "Lifelines Performance During the October 17, 1989, Loma Prieta Earthquake," Wind and Seismic Effects Proceedings of the 22nd UJNR Joint Meeting, NIST, Special Publication 79.

Klein, Henry C., 1886, "Business Interruption Insurance and Extra Expense Insurance as Written by Fire Insurance Companies in the United States and Canada," Rev. by Wallace L. Clapp, Jr., [5th ed. Indianapolis] Rough Notes Co. 1964].

Kockelman, W.J., 1984, "Use of Geologic and Seismologic Information for Earthquake-Hazard Reduction by Planners and Decision-makers in Southern California," In *Proc. Eighth World Conference on Earthquake Engineering*, Vol. VII, p. 744-752, Earthquake Engineering Research Institute, Berkeley, Calif.

Kubo, K., and Jennings, P., eds, 1976, in *Proc. of US-Japan Seminar on Earthquake Engineering Research with Emphasis on Lifeline Systems*, Tokyo, Japan.

Kubo, K., and Shinozuka, M., eds, 1981, in *Proc. of Review Meeting of US-Japan Cooperative Research on Seismic Risk Analysis and its Application to Reliability-based Design of Lifeline Systems*, Honolulu, Hawaii.

Lawson, A. C., 1908, *The California Earthquake of April 18, 1906*, State Investigation Commission Report, Carnegie Institution, Washington, DC.

Lindh, A.G., *Preliminary Assessment of Long-Term Probabilities for Large Earthquakes Along Selected Fault Segments of the San Andreas Fault System in California*, USGS Open-File Report 83-63.

McGuire, R. K., 1974, *Seismic Structural Response Risk Analysis Incorporating Peak Trespone Regressions on Earthquake Magnitude and Distance*, Mass. Inst. of Technology Publication R74-51, Cambridge, Mass.

Miyasato, G.H. et al., 1986, "Implementation of a Knowledge Based Seismic Risk Evaluation System on Microcomputers," *J. Artificial Intelligence in Engineering*, Vol. 1, No. 1.

Monbusho, 1979, "Investigation of Disasters Caused by the 1978 Miyagiken-oki Earthquake," *Natural Hazards Special Research No. 1*, Tokyo, Japan (in Japanese).

Morrison, R. M., A. G. Miller & S. J. Paris, 1986, *Business Interruption Insurance: Its Theory and Practice*, Cincinnati, Ohio: National Underwriter.

NBFU, 1933, *Report on the Southern California Earthquake of March 10, 1933*, by the National Board of Fire Underwriters, New York, NY.

National Petroleum Council, 1989, *Petroleum Storage and Transportation*, Washington, DC.

National Research Council, 1982, *Earthquake Engineering Research-1982*, Washington, D.C.

Nuttli, O.W., 1974, *The Mississippi Valley Earthquakes of 1811 and 1812*, Earthquake Information Bull., Vol. 6, No. 2, U.S. Geological Survey, pp. 8-13.

Nuttli, O.W., 1979, "Seismicity of the Central United States," *Geology in the Siting of Nuclear Power Plants*, A. W. Hatheway and C.R. McClure, eds, Geological Society of America, Reviews in Engineering Geology, Vol. 4, pp. 67-94.

Nuttli, O.W., 1981, "Similarities and differences between western and eastern United States earthquakes, and their consequences for earthquake engineering," in *Proceedings of Conference on Earthquakes and Earthquake Engineering: The Eastern U.S.*, Knoxville, Tenn, pp. 24-51.

Nuttli, O.W., et al., 1984, *Strong Ground Motion Studies for S. Carolina Earthquakes*, U.S. Nuclear Regulatory Commission, NUREG/CR-3755.

O'Rourke, T.D., M.D. Grigoriu, and M.M. Khater, 1985, "Seismic Response of Buried Pipes," *Pressure Vessel and Piping Technology - A Decade of Progress*, C. Sundararajan, ed., ASME, New York, NY, pp. 281-323.

Phelan, John D., and James R. Gregory, 1951, *Business Interruption Primer*, [Indianapolis] Rough Notes.

Poppe, B. B., 1979, "Historical Survey of U. S. Seismograph Stations," U. S. Geological Survey Prof. Paper 1096.

Reichle, Michael S., "Mexico Earthquake Damage: Lifeline Performance," in California Geology, Vol. 39, N. 4 (Apr. 1986).

Reitherman, R., 1985, "A Review of Earthquake Damage Estimation Methods," *Earthquake Spectra*, Vol. 1, No. 4, pp. 805-848.

Richter, C. F., "Seismic Regionalization," *Bull. Seis. Soc. Amer.*, 49:2, April 1959, pp. 123-162.

Richter, C. F., 1958, *Elementary Seismology*, W. H. Freeman Co., San Francisco, Calif.

Riley, Denis, 1985, "Riley on Business Interruption and Consequential Loss Insurance Claims," ed. by David Cloughton, London: Sweet & Maxwell.

Scawthorn, C., ed, 1985a, *Proceedings, US-Japan Workshop on Urban Earthquake Hazards Reduction*, Stanford University, Earthquake Engineering Research Institute.

Scawthorn, C., 1985b, "Fire Following Earthquake-Two Recent Earthquakes Indicate the Variety of Demands Placed upon Fire Services," in Fire Engineering (April).

Scawthorn, C., 1986a, "Use of Damage Simulation in Earthquake Planning and Emergency Response Management," Chapter in Terminal Disasters: The Use of Computers in Emergency Management, Marston, S., ed, *Monographs in Environment and Behavior Series*, No. 39, Institute of Behavioral Sciences, University of Colorado, Boulder.

Scawthorn, C., 1986b, "Fire-related Incidents," section in Report on the North Palm Springs, California, Earthquake-July 8, 1986, Special Earthquake Report in the Earthquake Engineering Research Institute *Newsletter*, A.G. Brady, ed.

Scawthorn, C., 1986c, "Lifeline Aspects of Fire Following Earthquake," Workshop on Abatement of Seismic Hazards to Lifelines, Building Seismic Safety Council, Washington.

Scawthorn, C., 1986d, Simulation Modeling of Fire Following Earthquake, *Proc. Third U.S. National Conference on Earthquake Engineering*, Charleston, South Carolina.

Scawthorn, C., Bouhafs, M., Segraves, D.W., and Unnewehr, D.L., 1986, "Fire Losses from Earthquakes: Los Angeles Region, Future Earthquake Losses in the Los Angeles, California Region," Seminar sponsored by the Committee on Seismic Risk of E.E.R.I., Santa Monica, Calif.

Scawthorn, C., Bureau, G., Jessup, C., and Delgado, R., 1985, "Fire-related Aspects of 24 April 1984 Morgan Hill Earthquake," *Earthquake Spectra*, Vol. 1, No. 3.

Scawthorn, C. and Donelan, J., "Fire-Related Aspects of the Coalinga Earthquake," Chapter in the Earthquake Engineering Research Institute report on the Coalinga Earthquake of May 2, 1983.

Scawthorn, C. and Gates, W.E., February 1985, "Secure Data Centers from Seismic Disturbances," in Data Management.

Scawthorn, C. and E.M. Lofting, 1984, "Earthquake Recovery--Analytically Based Economic Policies for Reconstruction." *International Symposium on Earthquake Relief in Less Industrialized Areas*, Zurich.

Scawthorn, C., Yamada, Y., and Iemura, H., 1978, Seismic Risk Analysis of Urban Regions," 5th Japan Earthquake Engineering Symposium, Tokyo, Japan.

Seed, H.B. and Idriss, I.M., 1971a, "Simplified Procedure for Evaluating Soil Liquefaction Potential," Am. Soc. Civil Engrs., *J. Soil Mech.*, Vol. 97, No. SM9.

Seed, H.B. and Idriss, I.M., 1971b, "Influence of Soil Conditions on Building Damage Potential During Earthquakes," Am. Soc. Civil Engrs, *J. Struct. Div.*, Vol. 97, No. ST2.

Smethurst, H., 1933, "Data Collected as Result of Southern California Earthquake, March 10, 1933," The Travelers Fire Insurance Company, Eng. and Insp. Div., Los Angeles (manuscript).

Smith, D.J., ed, 1981, "The Current State of Knowledge," *Lifeline Earthquake Engineering*, Am. Soc. Civil Engrs., New York.

Steinbrugge, K.V. et al., 1980, *Metropolitan San Francisco and Los Angeles Earthquake Loss Studies: 1980 Assessment*, USGS Open-File Report 81-113.

Steinbrugge, K.V., 1982, *Earthquakes, Volcanoes and Tsunamis*, Skandia-America Group, 392 pp., New York.

Steinbrugge, K. V., et al., 1987, *Earthquake Planning Scenario for a Magnitude 7.5 Earthquake on the Hayward Fault in the San Francisco Bay Area*, California Division of Mines and Geology Report, Sacramento, Calif.

Swan, F. H., Schwartz, D. P., and Cluff L. A., 1980, "Recurrence of Moderate-to-Large Magnitude Earthquakes Produced by Surface Faulting on the Wasatch Fault Zone, Utah", *Bull. Seis. Soc. Am.*, Vol. 70, No. 5, pp. 1431-1462.

Tarjan, R., 1972, "Depth-first Search and Linear Graph Algorithms," *SIAM Journal of Computers*, Vol. 1, pp. 146-160.

Taylor, C., Wiggins, J., Harper, G., and Ward, D., 1986, *A Systems Approach to Wasatch Front Seismic Risk Problems*, U. S. Geological Survey Report, Contract #140800122013, Reston, Virginia.

TIPS Property Insurance Law Committee Meeting, 1987, "Business Interruption Coverage: A Basic Primer," From Papers Presented at the TIPS Property Insurance Law Committee Midyear Meeting, March 8-11, 1984, Pebble Beach, Calif., [Chicago]: Tort and Insurance Practice Section, American Bar Association.

"The Current State of Knowledge of Lifeline Earthquake Engineering,", 1977, in *Proceedings of the Technical Council on Lifeline Earthquake Engineering Specialty Conference*, University of California, Los Angeles, California, August, New York

The Society, 1977; Thenhaus, P.C. et al., 1980, *Probabilistic Estimates of Maximum Seismic Horizontal Ground Motion on Rock in Coastal California and the Adjacent Outer Continental Shelf*, USGS Open-File Report 80-924.

Toppozada, T.P et al., 1981, *Preparation of Isoseismal Maps and Summaries of Reported Effects for Pre-1900 California Earthquakes*, Calif. Div. Mines and Geology, Open-File Report 81-11 SAC, Sacramento, Calif.

Trautmann, C.H., and O'Rourke, T.D., 1983, "Load Displacement Characteristics of a Buried Pipe Affected by Permanent Earthquake Ground Movements," in Ariman, 1983.

Uda,T., May 1984, "Inundation Damages Due to the 1983 Nihonkai-Chubu Earthquake Tsunami," 16th Jt. Meeting, Wind and Seismic Effects, UJNR.

Univ. of Alaska and URR, 1984, "Seismic Hazard Mitigation: Planning and Policy Implementation, The Alaska Case," Lidia L. Selkregg, Principal Investigator.

U. S. Geological Survey, 1990, *Probabilities of Large Earthquakes in the San Francisco Bay Region*, U. S. G. S. Circule 1053.

Wang, Leon RuLiang, et al., 1981, *Lifeline Earthquake Engineering Literatures in Japan*, School of Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma, Technical Report No. LEE-001.

Whitman, R.V., 1973, *Damage Probability Matrices for Prototype Buildings*, Rept. No. 8, SDDA, MIT, Cambridge, MA.

Whitman, R.V., 1974, "Earthquake Damage Probability Matrices," In *Proc. 5th World Conf. Earthquake Engr.*, Rome.

Whitman, R.V. et al., 1975, "Seismic Design Decision Analysis," In *Proc., Am. Soc. Civil Engrs.*, Vol. 101, No. ST5.

Whitmore, R. S., 1952, "Your Insurance Program; Charts of Exposures, Insurance as a Factor in Credit, Fire, Extended Coverage, Earthquake, Relation of Insurance to Value, Blanket Insurance, Coinsurance Clause, Prorata Distribution...," Culver City, Calif., Murray & Gee.

Wiegel, R.L., ed, 1970, *Earthquake Engineering*, Prentice-Hall, Englewood Cliffs, NJ.

Withers, Kennett Woodson, 1893, *Business Interruption Insurance: Coverage and Adjustment*, Berkeley, Calif., Howell-North, 1957.

Wiggins, J.H., 1981, *Earthquake Hazard and Risk Mitigation*, J.H. Wiggins Company, Rept. No. 80-1371-1.

Wood H. O., and Newmann, F., 1931, "Modified Mercalli Intensity Scale of 1931," *Bull. Seis. Soc. Am.*, Vol. 21, No. 4, pp. 277-283.

Yanev, P.I. ed, 1978, *Reconnaissance Report, Miyagiken-oki Earthquake, June 12, 1978*, Earthquake Engineering Research Institute, Berkeley, Calif.