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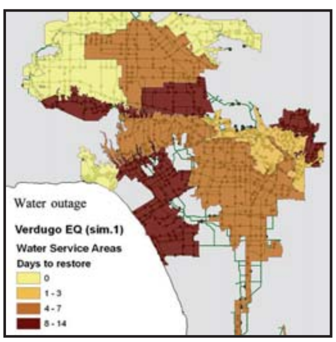

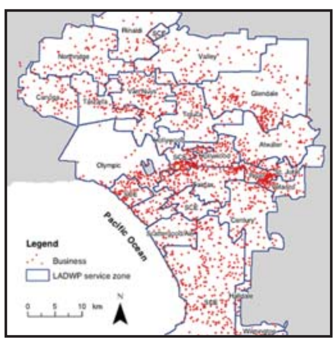

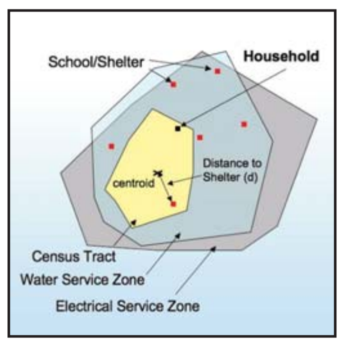

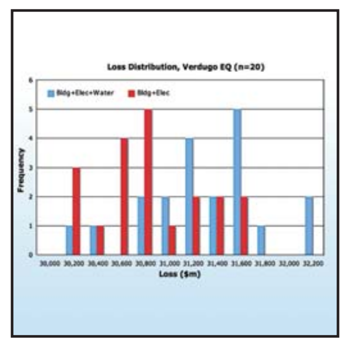

Technical Report MCEER-08-0004

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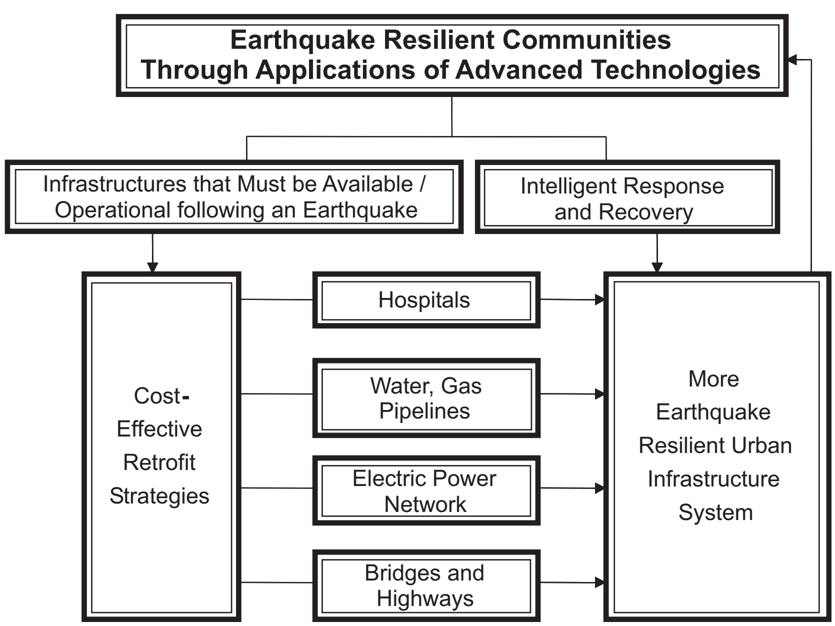
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

This report examines how lifeline infrastructure performance in disasters can be linked to communities' disaster resilience. The scope is limited to the social and economic dimensions of resilience, and focuses on the case of the Los Angeles Department of Water and Power (LADWP). The research links infrastructure performance and community resilience through two channels: first, through quantitative modeling and development of decision-support tools, and second, through exploring the role of community engagement in defining performance goals. The research develops a new simulation model of direct economic loss from lifeline disruption in disasters. It further develops a model to estimate the demand for public shelter in a disaster. A second line of research then explores issues related to how such socio-economic impacts can be considered in utilities' mitigation decision-making, what are appropriate seismic performance goals for utilities, and by what processes these can be determined. The issues are explored through a literature review of participatory processes in environmental risk management and a series of interviews with experts, utilities, and representatives from a broad range of community stakeholder groups. This research provides background, quantitative models, preliminary community input, and recommendations for a process by which utilities and communities can assess and improve their disaster resilience.

ABSTRACT

This report examines how lifeline infrastructure performance in disasters can be linked to communities' disaster resilience. The scope is limited to the social and economic dimensions of resilience, and focuses on the case of the Los Angeles Department of Water and Power (LADWP). The research links infrastructure performance and community resilience through two channels: first, through quantitative modeling and development of decision-support tools, and second, through exploring the role of community engagement in defining performance goals. The research develops a new simulation model of direct economic loss from lifeline disruption in disasters. It further develops a model to estimate the demand for public shelter in a disaster. A second line of research then explores issues related to how such socio-economic impacts can be considered in utilities' mitigation decision-making, what are appropriate seismic performance goals for utilities, and by what processes these can be determined. The issues are explored through a literature review of participatory processes in environmental risk management and a series of interviews with experts, utilities, and representatives from a broad range of community stakeholder groups. This research provides background, quantitative models, preliminary community input, and recommendations for a process by which utilities and communities can assess and improve their disaster resilience.

ACKNOWLEDGEMENTS

This project benefited from data, suggestions, and collaboration from numerous colleagues and professionals in the field. We thank in particular Professors M. Shinozuka, T. O'Rourke, R. Davidson, K. Tierney, and A. Rose (and their graduate students) for sharing data, modeling results, and ideas. We are very grateful to R. Tognazzini, G. Singley, C. Davis, and others at LADWP for hosting research progress meetings, sharing data, and providing valuable feedback. We also appreciate advice from E. Stanley (L.A. City Emergency Management) in developing the Los Angeles stakeholder survey, and all of the experts and community representatives who participated in our surveys.

Several graduate research assistants made valuable contributions to various aspects of this project. Cathy Pasion developed the Shelter Model for her master's project, and developed building damage data using HAZUS-MH. Kristi Tatebe conducted the Los Angeles stakeholder interviews as part of her master's project. Sanjay Coehlo conducted the utility/expert interviews. Rana Ahmad undertook the literature review of participatory processes. Chris Chamberlin and Line Bang Christensen worked on computer coding and model development. Enru Wang worked on developing the Los Angeles business database.

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SECTION 1
INTRODUCTION

This technical report describes an effort to develop decision-support tools that focus on lifeline infrastructure performance in disasters and how this affects community resilience, specifically in its social and economic dimensions. This multi-year effort is part of a larger, coordinated research project by MCEER researchers ("the L.A. Lifelines Project") to develop new methods, tools, and models to support risk reduction decision-making by critical infrastructure providers, with particular application to the case of the Los Angeles Department of Water and Power (LADWP). The L.A. Lifelines Project, in turn, is related to broader MCEER efforts to develop new conceptual and measurement frameworks for community resilience (e.g., Bruneau et al., 2003). The overall goal of the L.A. Lifelines project is to improve the seismic resilience of communities through substantial improvements in the earthquake reliability of critical lifeline systems. Other research teams within the L.A. Lifelines Project have focused on modeling lifeline damage and service outage (M. Shinozuka, T. O'Rourke), restoration (R. Davidson), and higher-order economic impacts and resilience (A. Rose). The effort described in this technical report focuses on direct, or first-order, economic impacts and certain social impacts related to lifeline disruption.

As the concept of disaster resilience gains prominence in the research and practice of disaster management, it becomes increasingly important to develop systematic approaches to quantify and evaluate resilience. In the last decade, the concept of resilience has figured prominently or implicitly in efforts by the Federal Emergency Management Agency (FEMA) such as Project Impact, the Disaster Resistant Universities program, and the Disaster Mitigation Act of 2000. The academic literature on resilience has also been rapidly expanding. While numerous definitions of resilience have been proposed, they generally agree with the concept offered in the 2nd Assessment of Hazards and Disasters, in which a disaster-resilient community as one that “can withstand an extreme natural event with a tolerable level of losses” and one that “takes mitigation actions consistent with achieving that level of protection.” (Mileti, 1999, p.5)

The increasing acceptance of this concept requires new research on how disaster resilience can be quantitatively evaluated. Evaluation methods are important for understanding, as well as improving, disaster resilience. Quantitative measures can help address such questions as which communicates are more disaster resilient than others, and why? Is a community becoming more resilient over time? And, what risk reduction efforts can most effectively move a community towards disaster resilience? Bruneau et al. (2003), and related efforts by MCEER researchers, have made key contributions to the resilience literature by providing frameworks for systematically and quantitatively assessing resilience.

Earthquake loss estimation models provide a natural starting point for attempts to implement the community resilience concept. These models broadly quantify the potential impacts of earthquakes on a region. They combine extensive spatial databases (e.g., of regional soil conditions, populations, and buildings) with computational algorithms for physical damage, monetary loss, and-often-human casualties and economic disruption. A well-known example is HAZUS-MH, FEMA's nationally applicable loss estimation methodology and software. A number of loss estimation models have also been developed that specifically address losses from lifeline infrastructure disruption (e.g., Cho et al. 2001, Chang et al. 2002, Kim et al. 2002). But while loss estimation models are clearly related to community resilience, they do not provide direct measures of resilience. As noted in Bruneau et al. (2003, p. 734), "the notion of seismic resilience suggests a much broader framework than the reduction of monetary losses alone. Equally important, in addition to focusing on losses earthquakes produce, research must also address the ways in which specific pre- and post- event measures and strategies can prevent and contain losses."

The current study builds on MCEER's research on quantifying resilience and on lifeline loss estimation to develop new models of lifeline resilience in its economic and social dimensions, with the following specific objectives:

- To develop a decision-support tool for the Los Angeles lifelines study that focuses on social and economic dimensions of community resilience;
- To produce scenario results for the LADWP case;
- To explore a process for framing lifeline performance objectives for disaster management and planning from a community resilience perspective; and
- To engage end users (LADWP) and community stakeholders in this process.

This research ultimately aims to contribute toward comprehensive assessments of lifeline disruption risk in earthquakes, to provide tools for evaluating loss reduction mitigations and strategies (from the perspective of social and economic impacts and resilience), and to help utilities and the communities they serve to make rational decisions about the allocation of resources necessary to achieve community goals in earthquake resilience.

1.1 Lifeline Resilience Framework

Bruneau et al. (2003) proposed a conceptual and measurement framework for seismic resilience (referred to hereafter as the MCEER Resilience Framework) that is taken as the point of departure for the current work. In the MCEER Resilience Framework, resilience is defined as "the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes." (Bruneau et al., p.735) More specifically, a resilient system should demonstrate three characteristics: reduced failure probabilities, reduced consequences from failures, and reduced time to recovery.

In the MCEER Resilience Framework, resilience can be conceptualized along four inter-related dimensions: technical, organizational, social and economic (TOSE). Technical resilience refers to how well physical systems perform when subjected to earthquake forces. Organizational resilience refers to the ability of organizations to respond to emergencies and carry out critical functions. Social resilience refers to the capacity to reduce the negative societal consequences of loss of critical services in earthquakes. Economic resilience refers to the ability to reduce the direct and indirect economic losses resulting from earthquakes. While technical and organizational resilience are, in the case of lifeline infrastructures, appropriately assessed at the level of each infrastructure system, evaluating economic and social resilience should be conducted at the community scale. This evaluation should, moreover, closely consider the effects of lifeline instructure disruptions – that is, it should integrate infrastructure-scale performance with community-scale effects.

The MCEER Resilience Framework also identifies four main properties of resilience: robustness, rapidity, redundancy, and resourcefulness (4 R's) (Bruneau et al., p.737). Robustness refers to "strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function. Rapidity is the "capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption." Redundancy refers to the availability of substitutable elements or systems that can be activated when earthquake-related disruptions occur. Resourcefulness is the capacity to mobilize and apply material and human resources to achieve goals in the event of disruptions. It is useful to view robustness and rapidity as the desired ends of resilience-enhancing measures. Redundancy and resourcefulness are some of the means to these ends.

Because resilience is a multidimensional concept, it is difficult to develop measures that are simultaneously quantifiable, succinct, and meaningful. Bruneau et al. (2003) offer a set of 80 illustrative measures set out in five tables. They relate to the four dimensions of resilience (TOSE), the four properties of resilience (4R's), and five systems ("global", electric power, water hospital, and response and recovery systems). For example, a social performance measure for rapidity of the hospital system might be defined as "all injuries treated in first day."

While Bruneau et al. (2003) set out the MCEER framework for evaluating community resilience, with appropriate emphasis on lifeline infrastructure systems, it stopped short of actual implementation; however, Chang and Shinozuka (2004) provided a refinement of the framework and applied it to the Memphis, Tennessee, water delivery system. The latter study demonstrated how loss estimation models could be used as a starting point for assessing resilience.

A key refinement proposed by Chang and Shinozuka to the MCEER Resilience Framework involves the introduction of explicit performance standards or objectives. This is illustrated in Figure 1-1, which follows system performance before, during, and after an earthquake or other disaster. Loss of system performance in the disaster is compared with predefined performance standards of robustness (r^*) and rapidity (t^*). The initial loss (r_o) is compared with r^*, an absolute level of loss that can be some prespecified "maximum acceptable loss." The time to full recovery t_1 is compared with t^*, an absolute duration of loss that can be some pre-specified "maximum acceptable disruption time." Figure 1-1 illustrates the case where, in the particular scenario earthquake, the system meets the rapidity performance standard ($t_1 < t^*$) but not the robustness standard ($r_o > r^*$). The outcomes of a particular earthquake scenario can be assessed in the context of multiple scenarios, each with a specified likelihood of occurrence, in order to fully represent the risk faced by the system.

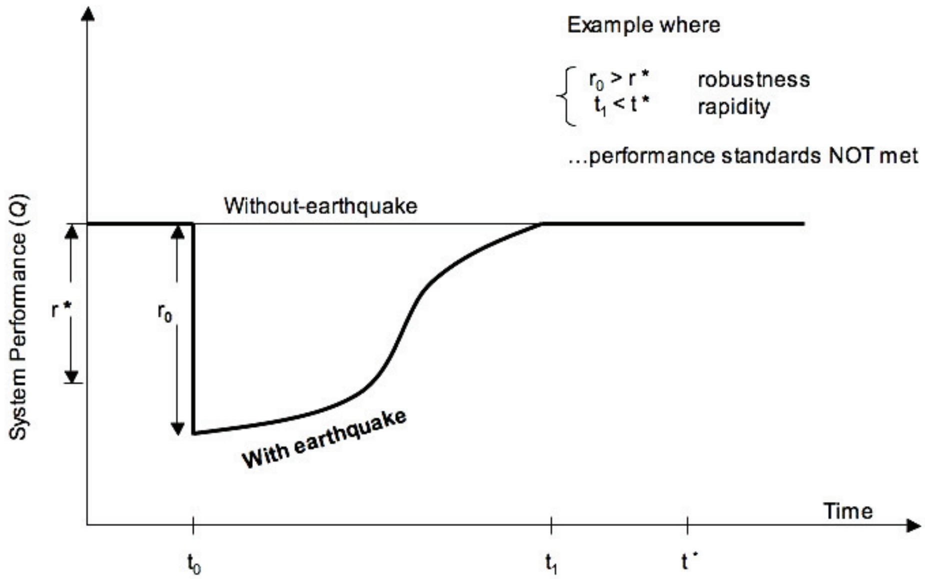

Figure 1-1 Resilience Measurement Framework
(source: Chang and Shinozuka, 2004)

Resilience is then defined as the probability that the system will meet predefined performance objectives. These objectives may refer to robustness and rapidity (i.e., r^* and t^*) in deterministic scenario events, which may be useful for planning and decision-making purposes. The performance objectives can be specified probabilistically with reference to a reliability goal R^*, in which "resilience" is indicated by the system meeting the robustness and rapidity goals with a certain level of probability for the scenario event. More broadly, system performance could also be assessed against a general system resilience goal, expressed in terms of the entire range of potential seismic events. Different goals could also be specified for different levels of hazards – e.g., higher levels of performance goals for more frequent, less severe events. Clearly, the definition of performance measures and standards is central to this proposed approach to quantifying resilience. Ideally, these definitions should be developed in consultation with decision makers, the public, and other potential end users.

Chang and Shinozuka (2004) provide an example of a water lifeline system and its role in broader community resilience. “Technical” and “organizational” performance standards are defined at the level of the water system. Technical performance refers to the extent of physical damage to the network, measured in this case by the number of major pumping stations lost and the percentage of pipes broken. Organizational performance refers to the extent of service disruption, which can be measured as the percentage of population losing water service. Note that organizational performance depends not only on the extent of physical damage, but also on network flow conditions. This in turn reflects the degree of network redundancy. Moreover, in principle, network flow should also reflect the utility agency's degree of organizational resourcefulness. This refers to the ability of the utility to respond to the emergency by rapidly detecting damage, efficiently deploying repair crews, using shutoff valves to isolate damage, implementing mutual aid agreements to speed up repairs, and so on.

"Social" and "economic" measures are defined at the level of the community as a whole. Social performance could refer to the population displaced from their homes – that is, forced to seek emergency shelter – due to the disaster. (Another possible measure might refer to the population needing medical attention.) Loss of water service to residences could be a main source of population displacement. A complete analysis should also consider other factors such as housing damage that could also force people to seek emergency shelter. Similarly, economic performance refers to the loss of gross regional product (GRP) due to the disaster and should consider water outage to businesses along with other sources of economic disruption.

To assess resilience in this framework, then, requires loss models that estimate the impacts of interest as well as performance goals that indicate the level of impacts that are considered acceptable. Both of these dimensions are pursued further in the effort documented in this technical report.

Figure 1-2 summarizes the overall framework for the L.A. Lifelines research on economic and social dimensions of resilience modeling. The earthquake event is first assessed in terms of physical damage to buildings and water and electric power lifelines (and potentially damage to other physical systems) through models of damage, disruption, and restoration. The outcomes of these models are data on the status of service from each of these systems over time. These data serve, in turn, as inputs to economic and social models, along with other data that characterize the economic and social systems at risk. Notably, the effects of disruptions to buildings and lifelines are considered simultaneously in assessing the consequent impacts. The economic and social models produce estimates of economic and social impacts, respectively, that then feed into a general model or assessment of resilience. As discussed above, resilience is assessed in the current framework by comparing impacts with performance goals.

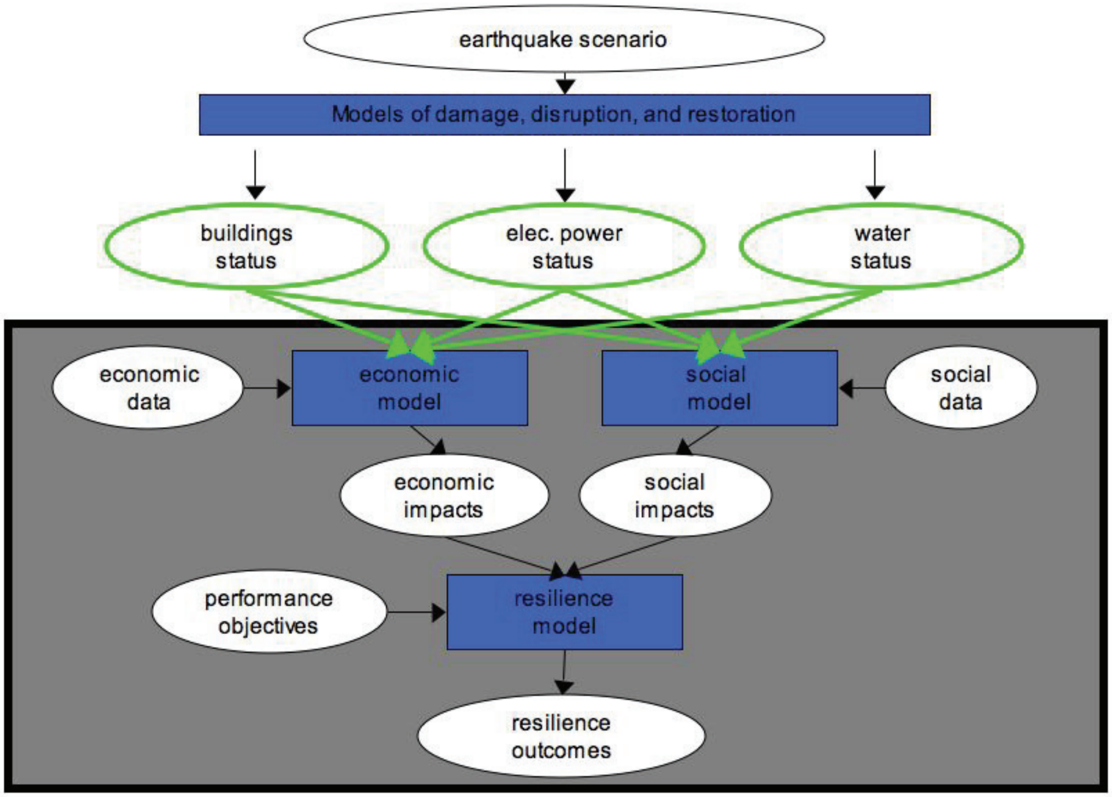

Figure 1-2 Overall Framework for Resilience Modeling Efforts

1.2 Scope and Objectives

The current research extends the work of Chang and Shinozuka (2004) in three principal directions: economic loss modeling, social loss modeling, and defining performance objectives. The economic loss modeling effort sought to: (1) make key methodological refinements to the lifeline loss estimation model that had been developed for the Memphis case (e.g., Shinozuka et al., eds., 1998; Chang et al. 2002), (2) apply the revised model to the Los Angeles Department of Water and Power System, and (3) implement the model for a scenario earthquake. Two key methodological refinements include changing the unit of analysis from census tracts to individual agents (businesses), and assessing economic impacts from lifeline disruptions in the context of other earthquake-related sources of disruption (specifically, building damage). This effort involved coordination with other MCEER researchers working on the L.A. Lifelines Project.

The social loss modeling effort focused on populations that might be displaced from their homes due to water and power outage in earthquakes. It sought to develop a model to estimate the number of persons displaced and seeking public shelter, and to apply this model to two earthquakes: the 1994 Northridge earthquake and a second, hypothetical event. The Northridge application would provide an opportunity to test and validate the model. (The social loss modeling effort also involved a second focus, estimating how loss of water and power would lead to disruption of hospitals and health care services in the Los Angeles region. This research will be described in forthcoming papers; however, it is not included in this technical report because the research eventually determined that lack of data precluded detailed assessment of lifeline-hospital interactions, and so the study ultimately focused on other dimensions of modeling regional health care disruption.)

The performance objectives research effort focused on addressing the issue of identifying lifeline performance objectives for seismic decision-making and mitigation planning. This topic has been identified as a critical research need at numerous stages of the L.A. Lifelines Project, including in Chang and Shinozuka (2004) as mentioned above, and in a joint Workshop on Performance Criteria held in June 2004 by MCEER and LADWP. The effort taken here involved first conducting a series of interviews with lifeline representatives and experts; findings are briefly summarized in this report but more fully reported in Chang and Coehlo (2006). A key outcome of that initial phase was the need for more participatory processes that involved a broad range of stakeholders. Subsequent efforts therefore involved a literature review on stakeholder participation processes and cases from the environmental and risk management literatures, and finally a series of interviews with representatives of a range of community stakeholder groups in the Los Angeles region.

Section 3 of this technical report describes the L.A. Lifelines economic loss modeling effort. Section 4 describes the L.A. shelter model and its links to the lifeline models. Section 5 describes the efforts associated with defining performance objectives for Los Angeles lifelines from the perspective of community resilience. Section 6 concludes with a general discussion of innovations, limitations, and further research suggested by this research.

SECTION 2
ECONOMIC LOSS MODEL

This section describes the L.A. Lifelines Project effort to model direct economic loss from water and electric power disruption in disasters ("economic loss model"). The model is based conceptually on an earlier model of lifeline economic loss that was implemented for the case of the Memphis Light, Gas and Water Division ("Memphis model") (Shinozuka et al., eds., 1998; Chang et al., 2002; Chang and Shinozuka, 2004). Key methodological refinements are made, however, including: changing the unit of analysis from spatial units to individual businesses; considering the impacts of building damage and lifeline outages simultaneously; and extending the empirical basis to include data from the 1994 Northridge and 1989 Loma Prieta earthquakes. Section 2.1 describes the economic loss model, including its conceptual and empirical bases. Section 2.2 describes the Los Angeles implementation and simulation results for a hypothetical earthquake on the Verdugo fault.

2.1 Model Development

2.1.1 Methodological advances

Traditionally, the unit of analysis in loss estimation models has been some spatial unit of analysis, such as the census tract, census block, or some spatial unit customized for the analysis. HAZUS-MH (which assesses economic impact of building damage but not lifelines disruption), the original ATC-25 model of lifeline economic impact (ATC, 1991), and many more recent lifeline impact models (e.g., Cho et al. 2001, Chang et al. 2002) are examples of models that take this approach. Modeling at the spatial unit scale has many advantages, including most notably, consistency with common datasets on social and economic aspects of communities (e.g., census data) and the ease of synthesizing multiple data inputs through spatial overlays in GIS. A key disadvantage, however, is the inability to account for correlations and interactions that occur at the individual agent level.

Modeling losses at the individual level allows for accounting of these correlations and interactions, with several important benefits, as described below. The overall effect of these benefits is that agent-level modeling should allow for greater detail, accuracy, flexibility, and conceptual clarity.

First, this approach improves consistency between the model and conceptual frameworks regarding business vulnerability to disasters. In particular, it is well-established in the theoretical and empirical literatures on disaster vulnerability that factors influencing vulnerability of businesses – such as business size, sector, and quality and condition of building – are not independent, but rather, highly correlated. The approach can therefore account for the observation that locally-oriented retail businesses also tend to be small businesses with limited financial resources that rent their space and often occupy more seismically vulnerable types of buildings – all factors that increase vulnerability to economic loss.

Second, it improves consistency between the model and the empirical databases that are used to implement the model. The primary data source consists of business surveys, which provide information on correlations between variables, as well as impacts, at the level of the individual business.

Third, it facilitates modeling the simultaneous effects of multiple sources of disruption. Multiple source modeling is important because an earthquake will cause disruption to more than just a single system. Modeling a single source of disruption, such as loss of water, involves making the unrealistic assumption that building damage and other lifeline disruption has no significant effect on losses. Yet if a business is forced to close because it has suffered extensive building damage, its loss of water is actually irrelevant as a source of loss. Attributing its loss to water disruption would amount to inflating or double-counting losses. On the other hand, it is possible that a business may be able to withstand water disruption alone, but cannot function without both water and electric power. Considering only water-related losses in this case would underestimate losses. Modeling the simultaneous effects of multiple sources of disruption thus allows more accurate statements about economic losses and the loss reduction benefits of mitigation measures.

2.1.2 Data sources

Like the Memphis model, the primary data source for model development is the Northridge earthquake business survey conducted by K. Tierney (1997) and colleagues at the Disaster

Research Center (DRC) at the University of Delaware. (The DRC's data collection effort was supported in part by MCEER. The survey datasets were generously provided for analysis in this project by K. Tierney.) In the L.A. economic loss model, the Northridge data is supplemented to the extent possible with information from a Santa Cruz business survey that the DRC conducted after the Loma Prieta earthquake. The data were pooled to get larger sample sizes for analysis.

Businesses are grouped according to major industry. The number of businesses by industry grouping are shown in Table 2-1.

Table 2-1 Sample Sizes in DRC Business Survey Databases, by Major Industry

Industry Group	Northridge database	Loma Prieta database
1. AGR (agriculture)	24	31
2. MCT (mining, construction, transport, communications, utilities)	146	98
3. MFG (manufacturing)	116	97
4. TRD (wholesale and retail trade)	279	289
5. FIR (finance, insurance, real estate)	144	93
6. HTH (health services)	87	87
7. SVC (all other services)	314	238
TOTAL	1,110	933

These are large, unique databases that provide highly valuable information on losses that businesses actually suffered in these major earthquakes, as well data on attributes of these businesses and factors that may have contributed to the losses.

A second major data source pertained to information on businesses in the Los Angeles region, included the distribution of businesses by size and sector. Because census and other similar public data sources did not provide sufficiently detailed information for this study, commercially available data from Dun & Bradstreet (D&B) were obtained on the population of businesses in Los Angeles. D&B data indicate that there are some 372,000 businesses in Los Angeles County, accounting for some 3.4 million jobs. Table 2-2 shows the distribution by the industry classification used in the model. Note that the vast majority of businesses in all industries are small (i.e., with less than 20 employees).

Table 2-2 Businesses and Employment in Los Angeles County

Industry Group	Number of Employees	Number of Businesses	Percent Small Businesses[1]
Agriculture	20,263	3,564	94%
Mining, construction, transportation, communications, utilities	341,594	33,358	91%
Manufacturing	500,045	23,860	79%
Wholesale and retail trade	821,125	105,046	92%
Finance, insurance, real estate	237,697	32,280	93%
Health services	259,578	24,608	94%
All other services	1,222,791	149,675	93%
TOTAL	3,403,093	372,391	92%

Note: (1) less than 20 employees
source: Dun & Bradstreet database (December 2003)

Information on individual businesses is available from D&B; however, this database is prohibitively expensive. Instead, a partially aggregated database was obtained with information for each census tract in the county. Data include the number of jobs and businesses by industry and size class.

From this database, a "pseudo-sample" was created of 3,724 businesses, or 1% of the total population of businesses in L.A. County. The Dun & Bradstreet database was aggregated from 4-digit Standard Industrial Classification (SIC) codes to the 7-industry grouping shown in Table 2-2 above. Each of the 3,724 "business objects" in the model corresponds to a hypothetical business. Each was assigned to an industry such that the sample would have the same industry distribution as the population as a whole. Assigning numbers of employees to the businesses was more complicated since the D&B database only contained aggregate data by business size class. A lognormal curve of business size distribution was therefore generated for each industry, such that it matched the benchmark size class subtotals in the D&B database. Each business object was then assigned a number of employees using the appropriate lognormal curve and a random number generator. Further, for each business subtype, the spatial distribution across census tracts was calculated. Each business object was then assigned a census tract location using the appropriate spatial distribution and a random number generator.

Based on this procedure, a stratified 1% business sample was developed that reflects the total business population in terms of industry, size, and spatial distributions. As noted earlier, the model evaluates earthquake losses for each business, then scales up to the entire study area. The study area is LADWP's service territory, which constitutes the majority of L.A. County.

2.2 Methodology

Figure 2-1 outlines the core structure of the economic loss model. The first set of calculations for each business involve evaluating the independent disruptiveness levels to the business's operations resulting from building damage, electric power outage, and water outage, respectively. Disruptiveness from building damage is evaluated as if there were no lifeline outages, and so on. "Disruptiveness" is measured in terms of four qualitative categories, as defined in the DRC business surveys. The categories are: not at all disruptive (NAA), not very disruptive (NV), disruptive (D), and very disruptive (VD).

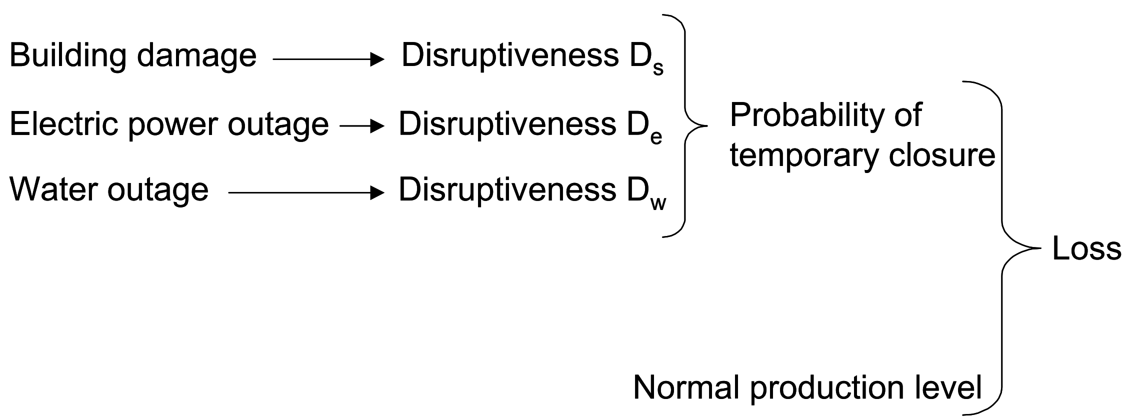

Figure 2-1 Outline of Economic Loss Model

The second step involves integrating across these three sources of disruption to develop an overall indicator of disruption, measured in terms of probability of temporary closure. This probability, together with data on baseline or normal production levels, is used to calculated expected business disruption loss (i.e., direct economic loss). Each of these steps is described in greater detail below. Calculations for individual businesses are then aggregated to the region as a whole.

2.2.1 Disruptiveness from building damage

Unfortunately, neither the Northridge nor the Loma Prieta datasets had enough information to ascertain the degree of physical damage suffered by the businesses to their buildings and contents. Data was available on whether such damage occurred, but did not include data on its severity. They did, however, contain data on the associated disruptiveness. Within the Loma Prieta and Northridge surveys the following question asked was: "How disruptive was this physical damage to your ability to do business? (Question 14 of the survey instrument)" Physical damage was defined in Question 12 as structural damage to the building, damage to the building's nonstructural elements (windows, light fixtures, partitions, water pipes, etc.), damage to furnishings (desks, cabinetry, etc.), damage to equipment (computers, machinery, etc.), and damage to inventory or stock.

For purposes of the model, the deterministic mapping shown in Table 2-2 was judgmentally developed to translate building damage states from the HAZUS-MH building damage categorization to the DRC Disruptiveness Scale. Consequently, a business estimated to have suffered "slight" building damage is assumed to suffer "not very disruptive" building-related disruptiveness (D_s).

Table 2-3 Building-Related Disruptiveness Mapping

Building damage state	Disruptiveness Level
None	Not at all disruptive
Slight	Not very disruptive
Moderate	Disruptive
Extensive	Very disruptive
Complete	Very disruptive

2.2.2 Disruptiveness from electric power outage

The model algorithm for estimating disruptiveness from electric power outage (D_e) was developed using DRC Northridge and Loma Prieta survey data in which businesses responded to the question: “As a result of the earthquake, did the business lose electrical service? “ (Response Yes or No) and “How disruptive was the loss of electricity to your ability to do business?” (4-category Disruptiveness Scale noted above.)

In the Loma Prieta survey, 837 of 933 businesses reported that they did lose electricity, while in the Northridge survey, 667 of 1,110 said they did. The samples were pooled to develop the model algorithm for electric power disruptiveness. Table 2-3 shows the resulting distribution of businesses among disruptiveness categories. This distribution includes only those that indicated they had lost electric power. It does not distinguish businesses according to the duration of outage. The Loma Prieta survey did not inquire about the duration of outage, and in the Northridge earthquake, power outage regionally lasted not more than a day or two.

Table 2-4 Disruptiveness of Loss of Electric Power

	Disruptiveness Level[1]				
Industry	NAA	NV	D	VD	Sample size
AGR	9 %	22 %	31 %	38 %	45
MCT	11 %	22 %	26 %	41 %	164
MFG	3 %	16 %	18 %	63 %	147
TRD	4 %	17 %	27 %	52 %	419
FIN	4 %	15 %	26 %	56 %	169
HTH	4 %	19 %	19 %	57 %	124
SVC	7 %	19 %	20 %	54 %	400
All industries	6 %	18 %	24 %	53 %	1,468

Note: (1) Row sums add to 100%, except in cases of rounding error.

Because the sensitivity of business operations to electric power depends largely on the type of business, disruptiveness outcomes were assessed by major industry group. For example, it can be seen from Table 2-3 that the Agriculture sector is the least sensitive to electric power outage, while manufacturing is the most dependent on electricity.

Within the model, data from Table 2-3 are used in the following manner: for each business object at time t=0, it is determined whether the electric power service area in which the business is located has suffered power outage. If it has not, the business is assigned a disruptiveness level

D_e=NAA. If it has, a random number between 0 and 1 is generated. This random number is used to select a discrete disruptiveness level according to the distribution of disruptiveness levels indicated in Table 2-3 for the business's industry. For example, if industry=AGR and the random number=0.09, then D_e=NAA ("not at all disruptive") is assigned; if the random number is 0.10, then D_e=NV ("not very disruptive") is assigned. For each subsequent timestep of analysis, it is determined if electric power is still unavailable. If the outage in that area continues, the previously assigned disruptiveness level is retained. If outage has ended, disruptiveness D_e is reset to NAA.

2.2.3 Disruptiveness of water outage

A somewhat similar procedure was used to develop the model algorithm for disruptiveness from water outage (D_w). Data were taken from the following questions in the DRC surveys for Loma Prieta and Northridge: "As a result of the earthquake, did the business lose water service? " (Response Yes or No) and "How disruptive was the loss of water service to your ability to do business?" (Disruptiveness Scale noted above.)

In the Loma Prieta survey, 360 of 933 businesses said they lost water while in Northridge, 207 of 1,110 lost water. The two samples were pooled to develop the model algorithms. Table 2-4 shows the resulting distribution of businesses among disruptiveness categories. This distribution includes only those that indicated they had lost water. It does not distinguish businesses according to the duration of outage. The Loma Prieta survey did not inquire about the duration of outage, and in the Northridge earthquake, the Los Angeles Department of Water and Power was able to restore water service to all areas within a week.

Table 2-5 Disruptiveness of Loss of Water Service

Industry	Disruptiveness Level[1]				Sample size
	NAA	NV	D	VD	
AGR	8 %	15 %	42 %	35 %	26
MCT	8 %	31 %	37 %	24 %	51
MFG	0%	35 %	26 %	39 %	54
TRD	10 %	23 %	26 %	41 %	169
FIN	5 %	24 %	29 %	43 %	63
HTH	2 %	6 %	22 %	70 %	50
SVC	7 %	29 %	24 %	41 %	147
All industries	7 %	25 %	27 %	42 %	560

Note: (1) Row sums add to 100%, except in cases of rounding error.

In the model, Table 2-4 is used in the same manner as Table 2-3 to assign the disruptiveness of water outage D_w. Note that as with electric power, this approach assumes that water will be either available or unavailable. Further refinements could consider partial water service, deteriorated water quality, and other intermediate levels of water service.

2.2.4 Probability of temporary closure

After estimating disruptiveness from building damage and lifeline outages, the model then translates these qualitative, independent measures into an overall indicator of economic disruption loss. The model uses whether or not a business closes temporarily as the impact measure. While other measures would have been preferable in principle, this measure was selected because the DRC surveys did not contain enough data to estimate alternatives such as percent of revenue lost.

The model algorithm for overall loss was developed using data from the DRC Northridge survey. (Only the Northridge data was used in this step because the Loma Prieta survey contained slightly different questions and did not gather information on the reason for temporary closure.) Responses to the following survey questions were first used to identify businesses with relevant experiences for the model:

Q.43 Was your business closed or inactive for any period of time as a result of the earthquake? (Yes or No)
Q.45 Next, looking again at the list [of reasons] in Question 44, please write the letters that correspond to the most important, second most important, and third most important reasons why your business was forced to close.

For those businesses that did close for a time (Q43=Y), the subset that primarily closed because of building-related damage, electric power outage, or water outage were used, i.e., that gave any of the following reasons in response to Q45: building declared unsafe; building needed to be structurally assessed; need to repair building; need to clean up damage to interior, contents of building; loss of inventory/stock; loss of machinery/office equipment; loss of electricity; loss of water. Businesses that did not close, as well as those that closed for other reasons (e.g., "couldn't afford to pay employees"), were excluded from the subsequent analysis. There were 850 businesses in the Northridge database retained in the analysis dataset.

Next, businesses in the analysis dataset were grouped according to their self-reported disruptiveness levels D_s, D_e, and D_w. For each group, the percentage of businesses that reported closing for a time was calculated. Since there are 4 possible disruptiveness levels, there are 64 (4x4x4) possible combinations of these three disruptiveness variables. Many of these categories had no data or very few observations. After combining some of the categories and checking for logical consistency across categories (e.g., the percent of businesses closing temporarily should increase as the disruptiveness levels D_s, D_e, and D_w increase), the algorithms summarized in Table 2-5 were developed. Table 2-5 indicates, for each of 6 mutually exclusive cases (a~f) of building and lifeline disruptiveness, the percentages of businesses that closing temporarily. For example, of businesses that reported one source (building damage, power outage, or water outage) as "very disruptive" and none as "disruptive" (case *c*), 63% closed temporarily. This percentage was much higher, 80%, for those businesses that additionally reported one source as being "disruptive" (case *b*).

Table 2-6 Temporary Business Closures from Multiple Sources of Disruption

Case	Number of sources[1] in each disruptiveness category				Percent closed	Sample size[3]
	NAA	NV	D	VD		
a				2+	90 %	115
b			1+	1	80 %	55
c			0	1	63 %	114
d			1+	0	54 %	133
e		1+	0	0	30 %	128
f	3	0	0	0	4 %[2]	268

Notes: (1) 3 possible sources total: building-related damage D_s, electric power outage D_e, and water outage D_w. Shaded boxes denote categories that are not used in defining the cases. (2) Interpreted as 0% in the model implementation. (3) Total sample size = 813 businesses.

Note that this approach is based on the number of sources (0~3) in each disruptiveness category. It does not distinguish between the actual sources. Thus case *c*, for example, applies whether it is building damage or electric power outage that the business has found to be "very disruptive." Note also that this approach assumes that the disruptiveness categories VD, D, NV, and NAA can be interpreted similarly for businesses in different industries. Industry differences are presumed to be adequately captured in the previous step, mapping damage/outage into disruptiveness categories.

In the model, the information in Table 2-5 is used to indicate the likelihood that businesses in various cases (*a~f*) would close temporarily. That is, the "percent closed" in Table 2-5 is interpreted as the probability of closure. For each business at time t=0 (immediately after the earthquake), a random number ranging from 0~1 is generated and compared with the probability of closure in order to assign a deterministic state of "open" or "closed." If the business is modeled as "open," it is then assumed that it will remain open in subsequent time periods. If it is "closed," then for time t=1, the model checks if the sources D_s, D_e, and D_w have changed in value. If they have not changed, it is assumed that the business remains closed. If they have changed, the procedure described above is repeated to assign a state of "open" or "closed" at t=1. The approach is repeated for subsequent time periods.

In implementing the model to an actual region and disaster event, at any time period *t*, there will be a certain percentage of businesses in each industry that are temporarily closed. These percentages are interpreted as an aggregate loss factor for the respective industries. The loss factor is multiplied by normal industry production levels (in dollars) to derive a quantitative estimate of aggregate economic disruption loss. Note that this methodological approach indicates a lower-bound estimate of economic loss, as it does not consider losses suffered by businesses that remain open but at reduced functionality levels.

The simulator for the model is implemented in the object-oriented programming language C++. (The earlier loss model of the Memphis water system had been implemented in Fortran.) Each key component of the model has a corresponding object (C++ class) in the simulation software. An object-oriented environment is useful for this type of model implementation because it enables clearly defined relationships between the various components, and protects data that should be static from modification. Further, the C++ inheritance mechanism makes it straightforward to add modified or improved components of the model without affecting the rest of the code.

2.2.5 Model Inputs and Outputs

Inputs to the model include electric, water and building damage data for the disaster being modeled. Electric power and water data are specified in terms of days of outage. Building damage data is generated in FEMA's HAZUS-MH software. HAZUS-MH allows the user to input a user-defined, historical, or source earthquake scenario within the earthquake model. The model then generates building damage results based on an inventory of building type. The data is reported at the level of the census tract. Building damage is reported for each census tract according to the occupancy use of the building, for example residential, agricultural or commercial. The building damage levels are "none", "slight", "moderate", "extensive", and "complete". The user also specifies the number of simulations to be run for the earthquake being modeled.

The data produced by the simulator correspond to industry loss factors at each timestep (taken in the Los Angeles implementation to be one day), for each simulation of the earthquake and averaged over all simulations. These results can then be converted to dollar losses as described above.

2.3 Scenario Applications

The economic loss model was applied to a number of hypothetical earthquake scenarios for the Los Angeles study area. Three sets of results are presented and discussed here. The first (section 2.3.1) consists of simulation results for a suite of 47 earthquakes, in which analysis was limited to exploring the effects of electric power disruption only. Water outages and building damage were not considered in this analysis. The intent here was to develop and test the model, paying particular attention to linkages with other MCEER research and exploring the probabilistic outcomes of the model. Second (section 2.3.2), an application to a hypothetical earthquake on the Newport-Inglewood fault was developed in order to explore linking the loss model to the resilience framework and resilience assessment. Multi-source loss modeling was considered to a limited extent here; specifically, electric power and building damage were considered as sources of loss. Third (section 2.3.3), an application to a hypothetical earthquake on the Verdugo fault was developed, in coordination with the larger MCEER L.A. Lifelines Project, in which the multi-source aspect of the model was fully explored. Thus the latter effort included effects of building damage, water, and electric power outage simultaneously.

2.3.1 Modeling economic loss: multiple earthquake scenarios

The economic loss model was first tested for the case of electric power outage using the suite of 47 earthquakes proposed in Chang et al. (2000). These earthquakes collectively represent the range of damaging earthquakes that may occur in the Los Angeles region. (Although a suite of 59 earthquakes has since been developed by MCEER researchers in conjunction with URS Corporation, this latter set was not available in time for the initial testing of the model described in this section. One of the 59, a Verdugo fault event, was used in the subsequent analysis described in section 2.3.2).

Figure 2-2 shows a series of intermediate and final results for scenario #1 of the suite of 47, a M7.1 earthquake on the Elysian Park fault. The results illustrate the sequence of computations, linkages with other efforts in the overall MCEER L.A. Lifelines Project, and types of results obtained. The first phase of the analysis, estimating damage, was conducted by M. Shinozuka and colleagues at the University of Southern California (and later the University of California at Irvine) (see Dong 2002, Shinozuka and Chang 2004). For each of the 47 earthquakes, their analysis developed estimates of transmission substation damage for LADWP's transmission network, taking into account such factors as ground motions, the physical vulnerability of equipment at the substations, connectivity between the equipment, and power flow analysis. Monte Carlo simulation was conducted, with 20 damage simulations being run for most of the scenarios and 10 damage simulations for a few of them. As shown in Figure 2-2 for the Elysian Park scenario, there is considerable uncertainty involved in the damage modeling, so that depending on the simulation, the number of transformers damaged system-wide in this earthquake could range from 25 to 37 transformers.

In the second phase, R. Davidson and colleagues at Cornell University applied a system restoration model to translate each of the damage simulations for each scenario into estimates of the duration of power outage across LADWP's service area (Çag˘nan et al., 2006). This restoration model considered such factors as the location and types of damage, repair requirements, and the availability and locations of repair resources in simulating post-earthquake damage restoration. Figure Figure 2-2 shows the results (in terms of days to restore power to the entire service area) for one of the damage simulation cases (a case where 34 transformers were damaged). While results typically indicated about a week's restoration time, depending on the restoration simulation, the restoration timeframe could vary from 1 to 19 days. Thus the restoration modeling, too, involves considerable uncertainty.

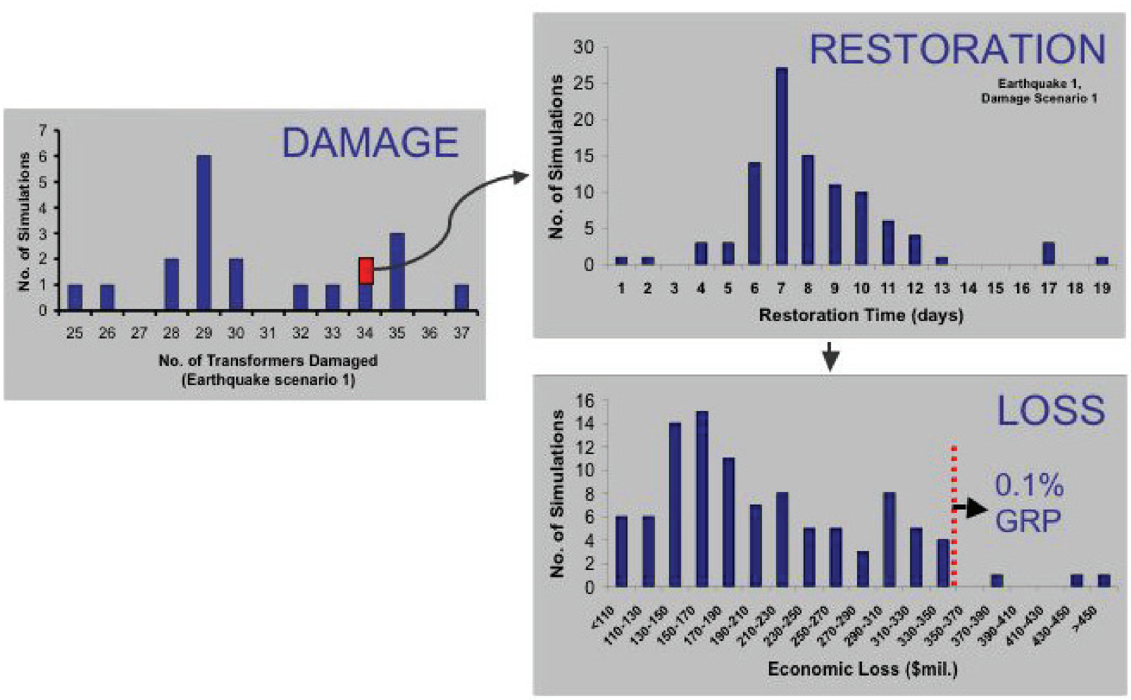

Figure 2-2 Simulation Results for M7.1 Elysian Park Scenario (power outage only)

Finally, Figure 2-2 shows the outage and restoration time data translated into loss results using the economic loss model described in this technical report. The figure indicates the distribution of loss results for 2,000 simulations of the Elysian Park earthquake (20 damage simulations x 100 restoration simulations x 1 loss simulation). Loss is measured in millions of dollars of reduced economic production activity. Results exhibit considerable variability across simulations, as a consequence of the accumulation of damage modeling uncertainty, restoration modeling uncertainty, and economic loss modeling uncertainty.

A key advantage of the simulation approach is that allows quantification of the range and probabilities associated with loss levels, rather than simply a single expected value. This allows some insight into the likelihoods of extreme loss values that may be of concern to decision-makers and planners. For example, the dotted line in the loss figure in Figure 2-2 indicates the level of economic loss that would be equivalent to 0.1% of gross regional product (GRP). If this were the performance threshold of interest for decision-makers, the modeling effort would be able to indicate that (in this case) there is a 3% chance of exceeding this level of loss. While 0.1% of GRP was chosen arbitrarily as a threshold for this illustration, an important planning and policy consideration is what that threshold should be, and by what process this should be determined. These issues are addressed in Section 4 later in this report.

Table 2-6 summarizes loss results for the suite of 47 earthquakes, with analysis limited to the economic losses resulting from electric power damage. Those earthquakes for which the Shinozuka et al. group estimated no damage are excluded from the table, as no restoration or economic loss modeling was conducted for them. Mean values and standard deviations are reported for the 2,000 (in some cases 1,000) simulations for each earthquake. As indicated in the table, the average losses resulting from electric power disruption range from \$0 to \$318 million (scenario #2). Moreover, the variability within each event can also be significant. In a few cases (scenarios #4, 18, 27, 32, and 35), the coefficient of variation (standard deviation over mean) exceeds 1.0.

While opportunities for model validation and calibration are limited, it is useful to compare these results to estimates made by A. Rose and colleagues at the Pennsylvania State University on the economic disruption losses caused by electric power disruption in the Northridge earthquake (Rose and Lim 2002). Through a modeling exercise that adopted a different methodology, although also referencing the DRC Northridge survey database, Rose et al. estimate that as a first approximation, electric power in the Northridge earthquake would have caused $88 million in total gross output losses, in the absence of any adjustments that businesses might make to respond to the situation. Note that power outage in Northride, although affecting the entire LADWP service area, lasted less than 24 hours for the vast majority of customers and less than 36 hours for virtually all customers. Moreover, Rose's results are expressed in gross output terms (total sales), rather than final demand terms that are consistent with GRP measures. Gross output measures of economic activity are higher than GRP measures because they include intermediate sales, in addition to sales to final demand. Moreover, if many types of "resilience" measures such as shifting time-of-day of production activities are considered that can reduce actual losses, Rose et al. estimate that total gross output losses from electric power outage in the Northridge earthquake could be as low as $5 million. Thus the results indicated in Table 2-6 for the smaller magnitude events seem to be consistent, in terms of order-of-magnitude, with the $5~$88 million range indicated by the Rose et al. study (with adjustments for gross output v. GRP basis and for potential "business resiliency" adjustments).

Table 2-7 Loss Results for Multiple Scenarios (Electric Power Outage)

Scenario no.	Magnitude	Fault	Loss ($mil.) average	Loss ($mil.) standard deviation
1	7.1	Elysian Park	171.08	77.44
2	7.3	Malibu Coast	318.24	82.18
3	7.0	Newport-Inglewood (N.)	127.81	58.15
4	7.0	Newport-Inglewood (S.)	9.44	9.48
5	7.2	Palos-Verdes	36.38	26.75
6	6.7	Raymond	99.79	60.88
8	7.5	San Jacinto	0.00	0.00
9	6.9	Santa Susana	52.17	29.39
10	7.4	Sierra Madre	138.48	83.52
11	7.5	Santa Rosa	163.18	90.55
12	6.8	Verdugo	193.16	81.79
13	7.5	Whittier	73.75	66.10
15	6.0	Malibu Coast	0.00	0.00
16	6.0	Malibu Coast	48.13	38.18
17	6.0	Newport-Inglewood	0.00	0.00
18	6.0	Newport-Inglewood	57.31	60.91
19	6.0	Newport-Inglewood	0.00	0.00
22	6.0	Palos-Verdes	14.90	12.15
27	6.0	San Fernando	18.14	18.59
31	6.5	Malibu Coast	0.00	0.00
32	6.5	Malibu Coast	4.96	5.82
33	6.5	Malibu Coast	172.75	27.97
34	6.5	Newport-Inglewood	100.16	57.53
35	6.5	Newport-Inglewood	0.59	1.12
40	6.5	San Fernando	49.66	16.99
42	7.0	Malibu Coast	258.72	40.31
43	7.0	Malibu Coast	277.75	65.79
47	7.0	Whittier	3.92	0.65

2.3.2 Modeling resilience: Newport-Inglewood earthquake scenario

In a second application, a hypothetical M6.5 Newport-Inglewood earthquake is modeled (scenario #35 of the set of 47) to explore how the loss model can be applied to assessing community resilience, as discussed conceptually in Section 1 of this technical report. Table 2-7 summarizes results for simulations associated with one of the 20 damage simulations by Shinozuka et al. (damage simulation #8), in which economic loss results associated with 100 restoration simulations by Davidson et al. were calculated. The economic loss model was applied in two modes: first, by considering losses from electric power outage only (i.e., as if there were no other sources of loss), and second, by considering losses from power outage and building damage simultaneously.

Moreover, comparisons were made between losses given the current state of the LADWP electric power network and losses if a certain level of seismic mitigation were implemented. Specifically, a mitigation case is considered where system robustness is increased by 50%. In other words, if with the current system state 5 of 100 simulation cases can be expected to indicate no power outage, in the "mitigation" case, there would be 10 simulation cases with no power outage. (The specific technologies, methods, or designs of such a mitigation are unspecified in this illustration, and do not affect the outcomes.)

The first row of Table 2-7 reports average loss over the 100 simulations for the current state of the LADWP electric power network. As expected, in comparison with the "electric power only" case, losses are several times greater when both power outage and building damage are considered. The mitigation case (increasing robustness by 50% for the electric power system) reduces losses in both cases. Interestingly, the loss reduction benefit in the case considering both power and buildings ($135m.) is greater than that for the case of electric power only ($94m.). It is possible that this result is an artifact of the sizable uncertainties involved in the modeling effort. A more likely explanation, however, is that there are measurable "interaction effects" between power outage and building damage. Businesses are more likely to suffer economic losses from power outage if they have already suffered some building damage than if they had not. While in theory, considering electric power alone could inflate losses and loss reduction benefits (over-attributing some losses to electric power), this inflation or double-counting effect appears to be small in comparison with the interaction effects. In the Newport-Inglewood scenario, at least, modeling electric power losses while neglecting building damage actually underestimates, rather than overestimates, losses attributable to power outage.

Table 2-8 Resilience Benefits of Hypothetical Mitigation, Newport-Inglewood Scenario

	Loss Source(s)	
	Electric Power Only	Electric Power and Buildings
Average Loss		
Current state	$191 m.	$1,659 m.
Robustness +50%	$97 m.	$1,524 m.
Loss reduction benefit	$94 m.	$135 m.
Probability of L>L*	L*=$100 m.	L*=$1,000 m.
Current state	99%	83%
Robustness + 50%	50%	70%
Resilience benefit	49%	13%

Table 2-7 also measures model outcomes in terms of resilience. As discussed in Section 1 above, one approach to quantifying resilience is to measure the likelihood of a system exceeding some tolerable threshold of loss (L^*), which can be considered a performance goal for the system. In Table 2-7, two arbitrary performance goals are considered: L_1^*=$100 million in economic disruption loss (in the case where electric power alone is considered), and L_2^*=$1,000 million (when both power outage and building damage are considered). Probabilities of exceeding these thresholds are evaluated over the 100 simulations of each case. Results indicate that the "mitigation" modeled here reduces the probability of exceeding L_1^* from 99% to 50%, for a resilience benefit of 49%. In the case of L_2^*, the resilience benefit is 13%. While this again raises the issue of appropriate performance goals (to be discussed in Section 4 below), it demonstrates how the economic loss model can readily be applied to assessing resilience according to the proposed resilience framework.

2.3.3 Modeling multiple loss sources: Verdugo earthquake scenario

Section 2.2 above described the data requirements and integration in the economic loss model. Figure 2-3 provides illustrations of some of the key datasets in map form in the case of a scenario M6.8 Verdugo fault earthquake (one of the suite of 59 earthquakes developed by MCEER and URS). Figure 2-3(a) shows that data on water outage and restoration are required by water service area. In this case, T. O'Rourke and colleagues at Cornell University estimated water flow results for the earthquake-damaged water delivery system at each demand node on the network. They then assessed water serviceability for each of the 15 LADWP water services areas at time t=0 immediately after the earthquake, and provided this information for the current loss modeling effort.

In order to develop estimates of the number of days required to restore water in each service area, a very approximate method was applied. (At the time this analysis was conducted, results were not yet available from the extensive restoration modeling effort by R. Davidson and colleagues for the LADWP water system. The approximation applied here was intended as a placeholder to allow the economic loss model to be tested. The placeholder data can readily be replaced by more reliable restoration data, such as that developed by the Davidson group.) The approximation applied here consisted of (i) estimating the number of days for complete system restoration by comparing the severity of water outage in the simulation with that in the Northridge earthquake, in which the system was restored within 7 days; (ii) assuming a functional form (S-shaped curve) for the system-aggregate restoration curve (in terms of % of customers restored), (iii) scaling the restoration curve based on the number of days to complete system restoration, and (iv) applying this scaled system restoration curve to each water service area that suffered outage; and (v) assuming that a water service area was fully restored when it had less than 1% water loss in comparison with normal volumes.

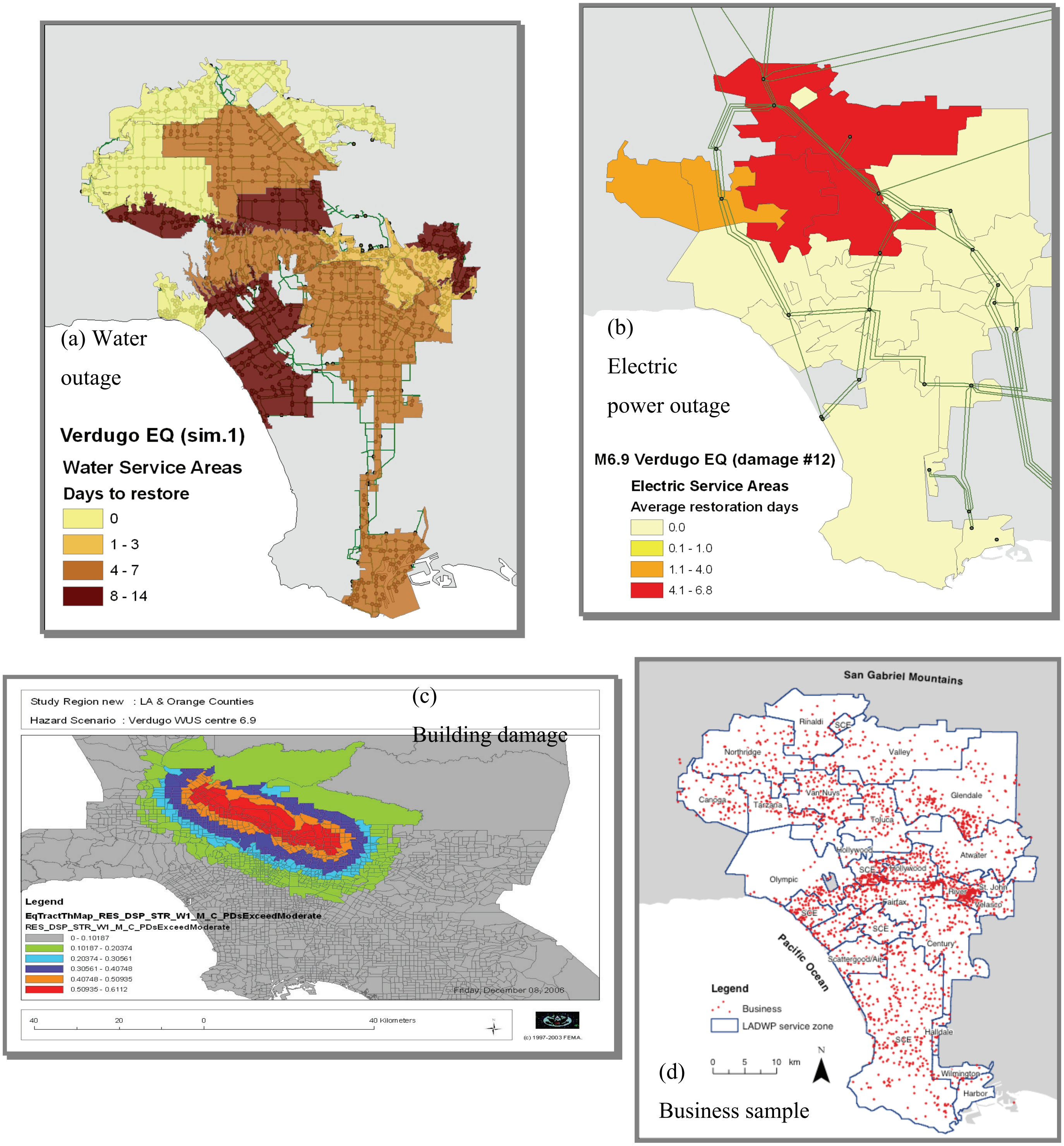

Figure 2-3 Spatial Distribution of Data Inputs, Verdugo earthquake scenario.

(a) water outage, (b) electric power outage, (c) building damage, (d) business sample.

Figure 2-3(b) shows electric power restoration days by LADWP's electric power service areas. In this case, the best available data pertained to an M6.9 Verdugo earthquake scenario that was from the original set of 47 earthquakes (scenario #12) and had been modeled in terms of damage by the Shinozuka group and in terms of restoration by the Davidson group. At the time of this analysis, similar results were not available for the Verdugo scenario from the set of 59 earthquakes. This introduces some inconsistency with the water outage data described above, but the inconsistency was considered to be relatively minor.

Figure 2-3(c) shows building damage results for the M6.9 Verdugo earthquake as modeled in HAZUS-MH, which are produced at the census tract level. This scenario was specified in consultation with URS Corporation, and ground motions were checked across census tracts to ensure that they closely matched (with 99% accuracy) the ground motions for the scenario used in the electric power modeling. The figure maps one dimension of detailed tabular results that were used in the current loss modeling effort.

Figure 2-3(d) provides a dot-density map of the locations of the 1% sample of businesses in the study area. For the derivation of this sample, see Section 2.1.2 above.

Figure 2-4 below shows the distribution of economic loss results for two sets of runs from the Verdugo application: the case where all three sources of disruption (buildings, electric power, and water) are considered ("BEW"), and the case where only buildings and electric power are modeled ("BE"). Each set consists of 20 simulations (each corresponding to one of the Shinozuka et al. electric power damage simulations) of the Verdugo earthquake. Average losses are $31.2 billion in the BEW case, with a standard deviation of $518 million and a coefficient of variation of 0.017. In the BE case, average losses are $30.7 billion, the standard deviation is $449 million, and the c.o.v. is 0.015.

The difference between them indicates the economic losses that can be attributable to water outages in the context of these other sources of earthquake damage and disruption. Taking the difference between the mean values of the two cases, about $467 million in economic disruption losses can be attributed to water disruption in the Verdugo scenario earthquake. This amounts to 1.5% of total economic disruption losses.

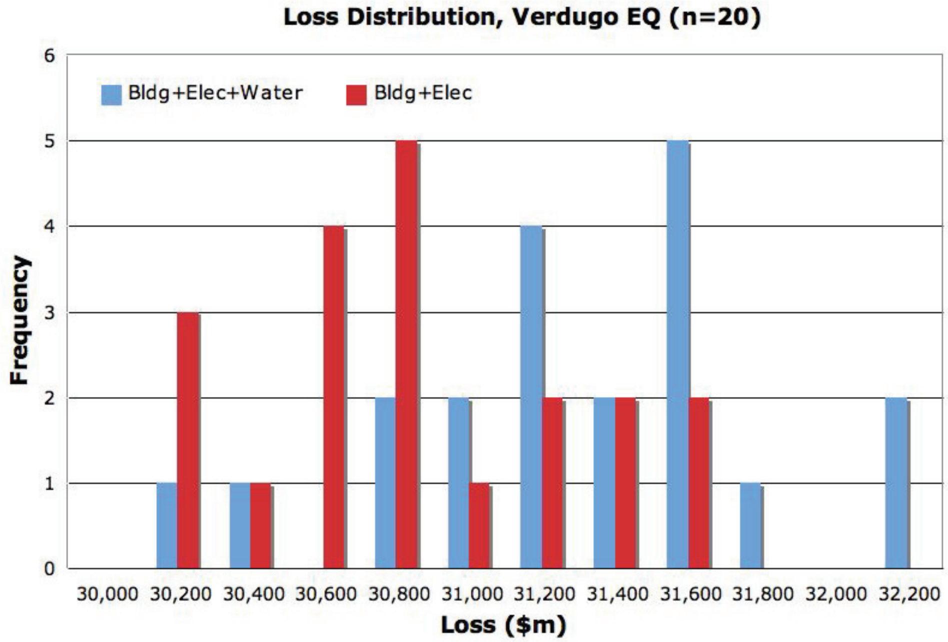

Figure 2-4 Loss Distribution Results for Verdugo Scenario

2.4 Conclusions

This section describes the development of an economic loss model for water and electric power systems, applied to the Los Angeles study area. The model constitutes one element of a larger multi-investigator effort to study seismic resilience for the Los Angeles Department of Water and Power (LADWP) infrastructure system and service area. The model is distinguished from other models in the literature, including the predecessor model applied to the Memphis study area, in several key respects: (1) It is agent-based, rather than area-based; (2) it makes extensive use of large survey datasets (developed by K. Tierney and colleagues) on business impacts in the Northridge and Loma Prieta earthquakes; (3) it considers how multiple sources of earthquake damage (specifically, to buildings, electric power, and water systems) affect losses simultaneously. Moreover, as a probabilistically-based simulation model, it provides results in terms of loss distributions (rather than point estimates alone). This allows insights into the magnitudes, sources, and effects of the multiple sources of uncertainty that are inherent in such a modeling effort. The loss distribution results are also important for linking the loss modeling to assessment of resilience. Specifically, the likelihood of losses exceeding certain threshold levels ("performance goals") can readily be assessed. The degree to which mitigations could reduce this likelihood – i.e., increase resilience – can similarly be assessed. Thus the economic loss model described here contributes to the literature on methods for quantifying communities' disaster resilience.

Many further refinements, extensions, and applications can be made to this model. A particularly key refinement would be to expand the model to more fully account for other types of earthquake damage – most notably, damage to regional transport networks – that affect economic loss simultaneously with damage to buildings and utility infrastructures.

SECTION 3
SHELTER MODEL

3.1 Objectives

A second emphasis of the project concerned the social consequences of infrastructure disruption in disasters, specifically on populations seeking emergency shelter. Loss of basic services such as water and electric power not only causes hardship, but may force households to temporarily leave their homes and seek other forms of shelter – even if the home itself has not suffered significant damage and is otherwise inhabitable. Anticipating the numbers and locations of these displaced populations is important for local emergency planners, governmental agencies such as the Federal Emergency Management Agency (FEMA), and non-governmental organizations such as the Red Cross. Previous studies yield some insights into the factors that influence people's propensities to seek emergency shelter.

Yet estimating these populations in relation to lifeline service disruptions poses several key challenges. Many of the factors identified in the social science literature are difficult to quantify and model (for example, transport access to shelter and perceived safety). Existing pertinent data are sparse. Only a portion of persons displaced from their homes are likely to seek emergency public shelter, with many persons choosing to stay with friends or family instead. Moreover, it is important to avoid double-counting potential displaced persons: modeling households displaced by infrastructure loss should account for those that have simultaneously been displaced by damage to the home itself.

This section describes an effort to model the numbers, types, and locations of persons likely to seek emergency public shelter as a result of water and electric power outages. The specific research objectives of this effort include the following:

- To develop a shelter model that includes the influence of lifeline disruption in the context of other factors, including key variables accounting for structural damage, socio-economic attributes, and household demographics;
- To utilize a unit of analysis (i.e., household) that appropriately characterizes how decisions are made in seeking public shelter;

- To develop a model that estimates a household's propensity to seek shelter based on a successive assessment of decisions, all leading to the final decision to choose public shelter; and
- To create a shelter model in a format that is transparent, flexible, and easy for planners and decision-makers to utilize.
-

Section 3.2 reviews existing models and empirical literature on shelter populations, including the Shelter Module of FEMA's HAZUS-MH loss estimation program. Section 3.3 then outlines a methodological approach that is distinctive in adopting households, rather than spatial units such as census tracts, as the unit of analysis. Section 3.4 describes the shelter model in greater detail. Sections 3.5 and 3.6 respectively describe results of the model for two earthquakes – the 1994 Northridge earthquake, and a hypothetical Verdugo fault scenario. Section 3.7 investigates model sensitivity to key parameters, and Section 3.8 provides brief conclusions, including implications for improving the HAZUS-MH shelter module.

3.2 Literature on Shelter Populations

3.2.1 Socio-economic and demographic factors

Both impacts to physical infrastructure and socio-economic and demographic characteristics influence a household's decision to choose public shelter. Therefore, research within both the physical and social sciences is important for estimating public shelter demand. Post-disaster sheltering and housing has been conceptualized in terms of four stages: emergency sheltering, temporary sheltering, temporary housing, and permanent housing (Tierney et al, 2001). Emergency shelter is shelter that is sought in the immediate timeframe of the disaster. Temporary sheltering involves accommodations that provide food, sleeping facilities, and similar services, and is intended to be used only briefly. It may be provided formally by the Red Cross or other relief organizations, or informally by relatives, friends, or neighbors. Temporary shelters include tents provided in public parks, open spaces and athletic fields. The present study focuses on public shelter, which is considered for present purposes to include both emergency sheltering and transitional sheltering. Temporary and permanent housing – which involve "the reestablishment of household routines" (Tierney et al. 2001, p.101) – is beyond the scope of this study. The following is a review of existing literature on post-disaster shelter and factors influencing shelter needs.

Findings from various earthquake events in the past suggest that the decision to leave home and to seek public shelter is influenced by a range of factors. Such factors include the actual and perceived structural condition of the victim's house, access to options for shelter (ranging from emergency shelters in nearby schools and churches to the homes of friends and relatives), the ability to access these shelter options via a car or transport infrastructure, and behavioral influences such as avoiding certain shelters because that area of the city has been rumored as highly at risk or under the threat of danger.

Much work has been done in predicting the structural damage to housing in earthquake events through engineering analyses. Generally speaking, damage is dependent upon the intensity and duration of local ground shaking and the structural type of the building. Local ground shaking is a function of four parameters in addition to the magnitude of the earthquake: the underlying geology, the depth of the epicenter, the duration of the earthquake and the distance from the fault (Harrald and Al-Hajj, 1992). In addition to the effects of an earthquake on the structural integrity and safety of one's home, the loss of utilities such as electrical power, water, and natural gas can make it difficult to engage in essential life-support activities such as food preparation (Chang and Chamberlin, 2004). These factors largely influence a household's decision to leave home. However, it has been shown that many will also seek alternative forms of shelter for other reasons, even if their home is deemed habitable (Harrald and Al-Hajj 1992; EQE International, 1997).

The roles of socio-economic and demographic factors on the decision to use public shelter – including notably socio-economic status, income, ethnicity, housing tenure, and age – have been discussed by a variety of authors (Mileti et. al., 1992; Harrald and Al-Hajj,1992; Fothergill et. al., 1999). Socio-economic status can be measured by education, income, wealth and relative position within a hierarchy of social class. Research has shown in the US that those with lower socio-economic status levels are more likely to seek refuge in mass shelters (Bolin and Bolton, 1986; Mileti et al. 1992, Yelvington, 1997).

Lack of preparedness for earthquakes has also been correlated with lower socio-economic status. Turner et al. (1986) noted that education, income, and ethnicity are related to earthquake preparedness and found that preparedness increases with higher income levels. Vaughan (1995) stated that those living in poverty or those with inadequate resources may be less likely to perform prescribed or necessary actions to mitigate the effects of hazardous agents because of a lack of a sense of personal control over potential outcomes. At the community level, preparedness activities may include devising community disaster plans, gathering emergency supplies, training response teams, and educating residents about a potential disaster (Mileti et al., 1992). Many preparedness activities and the ability to evacuate require access to economic and social resources that the poor may not readily possess.

Income plays a major role in influencing shelter use. Fothergill et al. (2004) found that higher-income families were less likely to stay at mass evacuation shelters than lower-income individuals and families after the Grand Forks flood of 1997. People of lower income are constrained by transportation options (Dash and Gladwin, 2005). Limited income also decreases people's ability to choose the option of a motel room because of limited funds. Housing tenure is also correlated with income, where those with lower incomes tend to be renters rather than homeowners. Rental housing is often not as well-maintained as owner-occupied housing, and often performs more poorly in an earthquake (Tierney et al., 2001). As a result, much low-income housing is at greater risk of becoming uninhabitable in the event of an earthquake.

Age also plays a role in influencing shelter use. The extremes of the age spectrum, both the young and the elderly, are in general more vulnerable to disaster events (Morrow, 1999). The vulnerability of the elderly in disaster events has been discussed by a number of researchers (Cutter et. al., 2003; Mileti et al., 1992; Turner et. al., 1986). Earthquake studies have found that families with young children or elderly members are more likely to perceive their homes to be uninhabitable and more likely to choose to evacuate their homes (Comerio, 1997). This is in contrast to observations made of hurricane events. Dash and Gladwin (2005) have found that in hurricanes, families headed by aged persons, or extended family households containing aged persons, are less likely to evacuate in response to hazard warnings. In particular, they note that difficulties associated with evacuation, particularly to shelters, are greater for older people.

Ethnicity played a major role in public shelter use during the Northridge Earthquake (1994), the Whittier Earthquake (1987), and the Loma Prieta Earthquake (1989) (Tierney, 1996). Because of past experiences with disasters, many ethnic groups have shown a heightened perception of risk (Fothergill et. al., 1999). For instance, during the Whittier earthquake many of the Southern

California ethnic groups, a significant number of whom were of Latino origin, insisted on staying outdoors in public parks or in yards and many slept in their cars on street curbs (Comerio, 1997). Those who experienced earthquakes in the past, especially destructive earthquakes in Central and South America, feared their lives would be endangered if they stayed indoors because of aftershocks. The same use of outdoor space was seen during the Loma Prieta (1989) and Northridge (1994) Earthquakes. Immigration status also played a role in public shelter use. Many illegal immigrants refused to use public shelters because they believed that applying for disaster assistance could jeopardize their plans for obtaining citizenship (Tierney et al., 2001).

In summary, socio-economic factors and demographics have been found to significantly influence people's propensity to seek public shelter. It is clear that estimates of shelter use based solely on structural damage will not be accurate. The empirical literature indicates that models of public shelter use should account for the effects of income level, housing tenure, car ownership, age, ethnicity, Hispanic origin, and immigration status.

3.2.2 Models of Shelter Use

Few models exist that predict public shelter demand in the event of an earthquake. The most widely used model is the software HAZUS-MH, developed by the Federal Emergency Management Agency (FEMA) of the United States. HAZUS-MH is a risk assessment software program that analyzes potential losses from floods, hurricanes and earthquake disasters. The potential loss estimates analyzed in HAZUS-MH include physical damage to infrastructure, economic losses and social impacts. HAZUS-MH predicts shelter use within its social impacts module and provides estimates for shelter requirements and displaced households in the event of an earthquake. Their model includes work performed by Harrald and Al-Hajj (1992) at George Washington University for the Association of Bay Area Governments (ABAG) in their development of a shelter model (1996 and 2000).

The HAZUS-MH shelter model provides two outputs: the number of displaced households (due to loss of habitability), and the number of people requiring short-term shelter**.** The model recognizes that only a portion of those displaced from their homes will seek public shelter and some will seek public shelter even though their homes may not be significantly damaged. Input variables include single-family versus multi-family dwelling type, damage state probabilities of structural damage, household income distribution, ethnicity distribution, tenure distribution, and age distribution.

The HAZUS-MH public shelter model is useful in that it does incorporate socio-economic variables in addition to physical structural variables that influence public shelter needs. However, it does have certain key limitations. For instance, the unit of analysis is the census tract. The model is thus unable to differentiate between households within a census tract. For example, it assumes that the proportions of people with given socio-economic characteristics are uniform across all building types and all building damage levels. This method also ignores the locations of different households relative to shelter locations and the effect on accessibility. Moreover, because the model uses regular data from the census, it ignores factors such as car ownership for which data are not available. A further limitation is that the model algorithms are based on expert judgments, in which it is presumed that experts are able to consider the effects of the different socio-economic variables independently, therefore ignoring correlations between ethnicity, age, income etc. As a result, they assume that considering the variables independently would not introduce significant computational error.

3.3 Methodological approach

The approach adopted in this study takes the household as the unit of analysis. This approach has two primary advantages: (1) it allows the model to account for correlations between different household-level attributes (e.g., income and housing tenure), which is an important refinement over area-based models such as HAZUS-MH, and (2) it allows the model to more accurately reflect decision-making about shelter use, which occurs at the household level. It is therefore more amenable to exploring the effects of public policies, plans, and actions that influence household decision-making.

The proposed public shelter model is structured as shown in Figure 3-1. This Figure illustrates the decision process that a household might go through when faced with an earthquake event. The starting point within the model is the occurrence of an earthquake. From this point forward, structural characteristics (i.e. building damage and power/water outage), along with characteristics of the household agent, influence whether the household will choose to seek public shelter through a series of preliminary decisions. The outcome of each preliminary decision determines the process direction within the model. For instance if, based on the data variables, the outcome of the decision “Do you perceive it desirable to leave home?” is estimated to be “no”, the model predicts that the household agent will stay home. If the predicted outcome is “yes”, the next decision in the model, “Can you physically access another form of shelter?” is assessed. The decision to “Leave Home” is an interim outcome within the model.

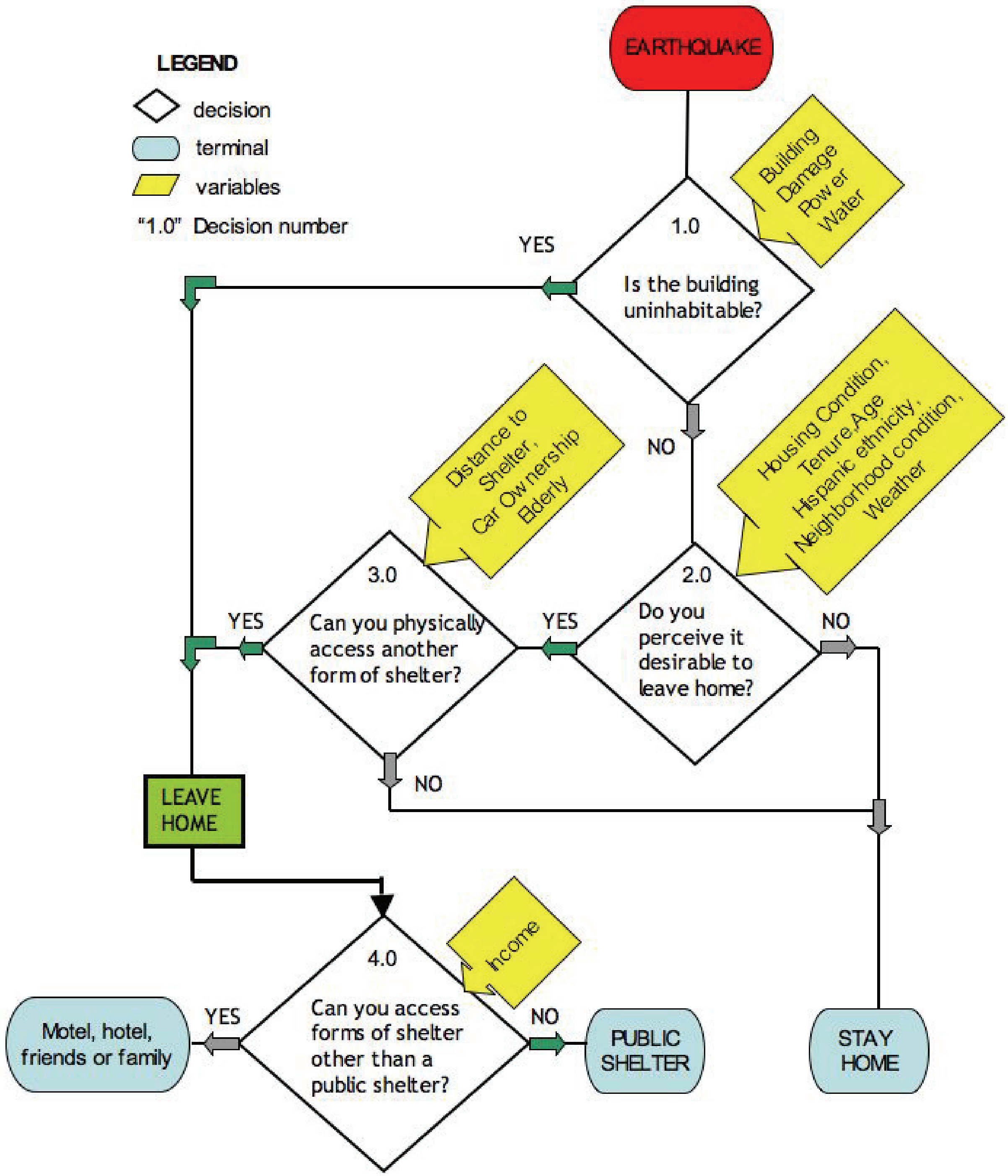

Figure 3-1 Flowchart of Decision Process in the Proposed Shelter Model

3.4 Data Collection

The public shelter model was applied to two earthquake scenarios: the Northridge Earthquake of 1994, and a simulated earthquake on the Verdugo fault. The study area of interest is the city of Los Angeles.

3.4.1 Socio-Economic Data

Socio-economic data were obtained through IPUMS, the Integrated Public Use Microdata Series. The variable data collected include income, tenure, car ownership, Hispanic ethnicity, and age. IPUMS is census microdata, meaning that it provides information about individual persons and households. The data differ from the regular census bureau data because all socio-economic data associated with each household are given. The IPUMS microdata are confidential and therefore no names, addresses or identifying information are included in the sample set. The sample set used for the model was the 1% sample set for the year 2000. This is a 1 in 100 national random sample of the population. For the 1% sample set for the year 2000 the smallest identifiable geographic unit is the Super-PUMA (PUMA indicates Public Use Microdata Area), where each Super-PUMA contains at least 400,000 persons. The IPUMS data used for this project was accessed through the IPUMS USA website: http://usa.ipums.org/usa/.

3.4.2 Geographical Locations of Households

As described above, each household agent in the IPUMS sample is not given a location within the Super-PUMA. However, it is essential for the shelter model that the households have location information, so that the output of the model can offer some understanding of the influence of geographical distribution on shelter demand. The census provides information on which census tracts comprise each Super-PUMA. The households were assigned to one of the census tracts within their Super-PUMA using the procedure described below.

The assignment of households to census tracts (for purposes of the model) is keyed on what the literature indicates to be a major factor in shelter use, household income. In effect, households are randomly assigned to census tracts according to probabilities that reflect the spatial pattern of income distribution in the Super-PUMA. That is, the probability that a household will be assigned to a given census tract is determined by the household's own income level as well as how all households with that income level are distributed across the census tracts comprising the Super-

PUMA. The incomes of the households in the IPUMS dataset are reported. Data on number of households and income distribution by census tract are available from the Census. For each census tract, the number of households within a given income range (e.g., less than $10,000) is given. This number was divided by the total number of households of that same income range in the corresponding Super-PUMA to determine, for each census tract, the percent proportion of households of that income range in the entire Super-PUMA. Each household of a given income range was then assigned a random number, and assigned to a census tract using this random number based on the percent proportion of households of that income range in that census tract over the entire super-PUMA. For example, if a census tract contains 30% of the Super-PUMA's population in the $30,000 to $40,000 income range, then a household with an income of $35000 had a 30% chance of being assigned to that census tract.

3.4.3 Distance to Shelter

As discussed above, the locations of households are inferred at the census tract level. In the model, one of the predictive variables for shelter use is the household's distance to the nearest shelter. This "distance to shelter" is defined as the distance from the centroid of the census tract within which the household is located to the shelter that is closest to this point. Refer to Figure 3-2. The set of shelters that were in operation during the Northridge earthquake of 1994 are used in the distance-to-shelter calculations (EQE International, 1997). It should be noted that transitional shelters, including tent cities, are included in the estimate. Because of the lack of published guidelines on how many and where shelters will be set up in future earthquakes (which will vary in location within the L.A. region, extent of damage, and extent of need), predicting shelter locations is difficult. Thus for the hypothetical Verdugo earthquake scenario explored in this project, the actual 1994 Northridge shelters were used. Note that the model can readily incorporate a different set of shelters (e.g., specified by Red Cross planners), and indeed, a potential use of the model is to facilitate planning for shelter provision.

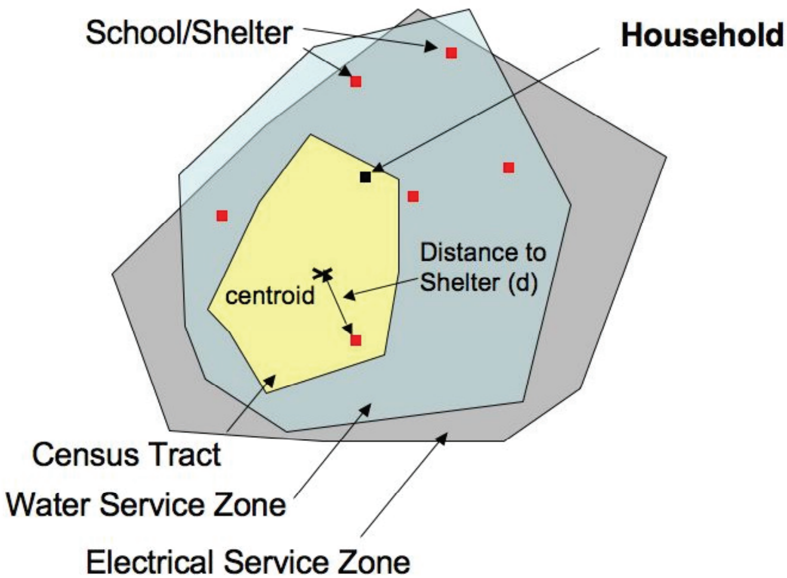

Figure 3-2 Geographical relationships between the locations of households, shelters, water service zones, and electric service zones.

The distance used is "as the crow flies" and does not take into account the road network. While this is a simplifying approximation, it is reasonable given that the location of the household (assumed to be the census tract centroid) is itself a rough approximation. Ideally, the distance from each household's actual location to the nearest shelter using the road network would be used. However, actual location is not available in the IPUMS data, and furthermore, the households were assigned to the census tracts within each Super-PUMA based on income distribution.

3.4.4 Building Damage

Building damage data are generated in FEMA's HAZUS-MH software. The software version used in this research was HAZUS-MH MR1 Version1.1. HAZUS-MH allows the user to input a user-defined, historical, or source earthquake scenario within the earthquake model. The model then generates building damage results based on an inventory of buildings by type. The data is reported at the level of the census tract. Building damage is reported for each census tract according to the occupancy use of the building; for example residential, agricultural or commercial. Specifically, building damage is reported as a probability by level of damage to the building, by building type. The building damage levels are “none”, “slight”, “moderate”, “extensive” and “complete”.

As discussed earlier, household agents were assigned to census tracts based on income distribution across the census tracts. The household agents in each census tract are randomly distributed across the building damage levels predicted by HAZUS-MH. Building damage levels were assigned to households within each census tract by assigning each household a random number, and using this random number to distribute the households amongst each category of building damage to satisfy the percent distribution of building damage across each census tract as predicted by HAZUS-MH. This method potentially presents a significant source of error, as in reality income level and level of building damage are correlated.

3.4.5 Power and Water Data

Power and water outage data were obtained differently for each of the two earthquake events modeled in this study. For the hypothetical Verdugo fault earthquake, outage results were obtained from the MCEER L.A. Lifelines modeling effort, specifically from R. Davidson's research team at Cornell University (see discussion in Section 2 above). For a simulation of the actual 1994 Northridge earthquake, electric power and water outage data for that event were obtained from the Los Angeles Department of Water and Power (Davis, 2005). Figure 3-2 above describes the relationship between the locations of households, water service zones and electric service zones. The data used for the model are reported as the number of days needed to restore power and electricity, in the household’s water service zone and electric power service zone, respectively.

3.5 Shelter model

As previously discussed, the purpose of this research is to develop a model that estimates emergency public shelter demand immediately following an earthquake. This model consists of a linear set of decisions. As such, the importance of each decision is determined by its placement in the sequence of decisions. For instance, the first decision is to determine if the structure is uninhabitable and is therefore given the highest level of importance. Building damage and structural habitability, or housing condition, are the most influential variables and are given the most weight in determining the number of displaced households.

While some displaced households will seek to use public shelter, others will access other forms of shelter such as staying with friends or family, or in motels or hotels. Income is the only variable used as an indicator of socioeconomic access to such other forms of shelter for displaced households. Although ethnicity and age are also indicators of public shelter use, these variables are highly correlated with income. Studies have shown that income is a strong indicator of accessibility to alternative options of shelter (Morrow, 1999; Turner et al., 1997; Tierney et al., 2001). Therefore income is used to determine the number of displaced households who will seek public shelter.

3.5.1 Unit of Analysis – the Household

The chosen unit of analysis for the shelter model is the household. The household agent was thought to best represent the model and its variables for a number of reasons. First, the damage to a building affects all members within a household and will be the same value for all individuals in that household. Secondly, decisions made in the event of a disaster will likely be made at the household level for families, or groups of people, living in the same household.

3.5.2 Model Inputs

The variables used in the public shelter model and their data sources are summarized in Table 3.1. Model variables are defined in the following way:

- **Building damage (BD)**: Building damage is defined as the probability of damage to a structure of a certain type of use (e.g., single family home or apartment building), within ranges of damage, i.e., none (**BDN**), slight (**BDS**), moderate (**BDM**), complete (**BDC**) or extensive (**BDE**).
- **Water (W)**: Water outage is defined as the number of days a household's home is without potable water prior to water restoration.
- **Power (P)**: Similarly to the water outage data, power outage is defined as the number of days a household's home is without electrical power prior to restoration of electricity.

- **Car Ownership (C)**: Defined as whether or not a household owns a car. A car provides a household with a means to get to different forms of shelter, including emergency shelters or to the homes of family or friends. The car could also serve as a shelter itself.
- **Tenure (T)**: Defined as whether a household rents or owns their home. This has been highly correlated to shelter use. Renters tend to live in multiple family dwellings rather than single-family homes. Renters also tend to have lower incomes, another variable that is correlated with shelter use.

Table 3-1 Public Shelter Model Input Variables and Data Sources[1]

Model Variable	Data Source
Building Damage (BD)	HAZUS-MH
- None (BDN)	
- Slight (BDS)	
- Moderate (BDM)	
- Complete (BDC)	
- Extensive (BDE)	
Water (W)	MCEER Lifelines
Power (P)	MCEER Lifelines
Car Ownership (C)	IPUMS
Tenure (T)	IPUMS
Hispanic Variable (H)	IPUMS
Neighbourhood Condition (NC)	HAZUS-MH
Weather Condition (WC)	Supplied by user
Distance to Shelter (D)	Calculated
Income (I)	IPUMS
Elderly (E)	IPUMS
Age (A)	IPUMS

[1] See text for details.

- **"Hispanic Variable" (H):** The Hispanic variable accounts for the heightened perception of risk of ethnic groups that have experienced earthquake disasters in the past, especially highly destructive ones, in Central or South America. The Hispanic variable is reported as "yes" for Hispanic origin and "no" otherwise.
- **Neighborhood Condition (NC):** Neighborhood condition describes the influence of the overall condition of a neighborhood on a household's decision to leave home. Neighborhood condition is approximated by the average building damage across a census tract. The variable is reported as low, moderate or high where NC = low if the average building damage across

the census tract is "none" or "slight", NC = moderate if the average building damage is moderate, and NC = high if the average building damage is complete or extensive.

- **Weather condition (WC):** Weather is reported as bad or good. Rain and cold are considered bad weather. The user of the model will input this variable in order to observe the effect of weather condition on the decision to leave home.
- **Distance (D)**: Distance is defined as the walkable distance to a shelter. In the model distance is approximated by the distance between the centroid of the census tract in which the household resides and the location of the shelter closest to this point. Within the model 2 km is considered a walkable distance.
- **Income (I)**: Household income has been found in previous studies to be a strong indicator of the accessibility of different options to a household in a disaster situation. Household income is assigned to levels of high, medium or low income based on the distribution of incomes in Los Angeles County. Low household income is defined as $0 to $40,000; medium income is defined as $40,000 to $90,000; and high income is defined as $90,000 and above.
- **Age (A):** If households have children or elderly members, they are likely to be less tolerant of reduced housing conditions and more likely to seek alternative shelter. This variable is assigned "yes" if at least one household member is less than 18 years of age or greater than 65 years of age. The variable is assigned "no" otherwise.
- **Elderly (E):** This variable is assigned "yes" if all members of the household are greater than 65 years in age. The variable is assigned "no" otherwise. If the household does not own a car, consists of all elderly members greater than 65 years of age, and the distance to shelter is greater than 2 km, it is assumed that they will not be able to physically access alternative shelter.

3.5.3 Calculating Decision Outcomes

The outcome of each decision within the model is calculated based on a series of variables. The model uses a spreadsheet format and all calculations are made in Microsoft Excel. The outcome of each decision is either "yes" or "no". The following discussion describes the inputs and outputs of each decision and how each "yes" or "no" outcome is determined.

Decision 1: Is the building uninhabitable?

The input variables for this decision are building damage (**BD**), Power (**P**), and Water (**W**). An interim variable is created within this decision, called housing condition (**HC**). This variable is given the values of low, medium or high to represent the likelihoods of uninhabitable building conditions for the given household agent. **HC** is passed on to the next decision in the model to contribute to the overall risk perception of the household. The values of **HC** are based on the values of **BD**, **P** and **W**. The following conditions are applied:

- Housing condition (**HC**) is "very low" if building damage (**BD**) is complete (**BDC**)
- Housing condition (**HC**) is "low" if one of the following are satisfied:

- Building damage (**BD**) is extensive (**BDE**)
- Water (**W**) is out of service for more than 4 days
- Power (**P**) is out of service for more than 4 days
- Building damage (**BD**) is moderate (**BDM**) and both water (**W**) and power (**P**) are out of service for more than 4 days.

- Housing condition (**HC**) is "high" if building damage (**BD**) is negligible (**BDN**) and both water (**W**) and power (**P**) are out of service for no more than 2 days**.**
- **HC** = "mod" otherwise.

The outcome of Decision 1 ("Is the building uninhabitable?") is "yes" if housing condition (**HC**) is "very low". The outcome is "no" if housing condition (**HC**) is "low" or "mod" or "high". If the outcome is "yes", that household is assumed to "Leave Home" and is considered a displaced household. If the outcome is "no", the household is modeled to consider Decision 2, "Do you perceive it desirable to leave home?"

Decision 2: Do you perceive it desirable to leave home?

This decision is meant to reflect the household's risk perception. The variables considered in this decision include housing condition (**HC**), tenure (**T**), age (**A**), Hispanic ethnicity (**H**), neighbourhood condition (**NC**), and weather condition (**WC**). The decision outcomes "yes" or "no" are determined by combinations of the input variables.

The outcome of Decision 2 is "yes" if one of the following combinations is satisfied:

- Housing condition (**HC**) is "low", tenure (**T**) is "rent" and the household is Hispanic (**H**=yes).
- Housing condition (**HC**) is "low", tenure (**T**) is "rent" and the neighborhood condition (**NC**) is "high" (i.e., there is extensive damage in the neighborhood).
- Housing condition (**HC**) is "low", tenure (**T**) is "rent" and at least one member of the household is less than 18 years of age or more than 65 years of age (**A**=yes).

- Housing condition (**HC**) is “low”, the household is Hispanic (**H**=yes) and at least one member of the household is less than 18 years of age or more than 65 years of age (**A**=yes).
- Housing condition (**HC**) is “mod”, the neighborhood condition (**NC**) is “high,” and the weather condition (**WC**) is “bad”.

The outcome of Decision 2 is “no” otherwise. If the outcome of the decision is “no” the household is assumed to stay home and is not considered a displaced household. If on the other hand the outcome is “yes” the household is modeled to consider Decision 3, “Can you physically access another form of shelter?”

Decision 3: Can you physically access another form of shelter?

Once a household perceives it desirable to leave home, the next decision considered is “can you physically access another form of shelter?” The variables considered in this decision include distance to shelter (**D**), car ownership (**C**), and elderly (**E**). The outcome of the decision is “yes” if one of the following is satisfied:

- The household owns a car (**C** = yes).
- The distance to shelter (**D**) is less than 2 km away from home and the household does not consist entirely of members greater than 65 years in age, i.e. the variable elderly (**E**) is assigned “no”.

The outcome of the decision is “no” otherwise. If the outcome of the decision is “yes”, the household is considered a displaced household and is assumed to “Leave Home”. If the outcome of the decision is “no”, the household is assumed to stay home.

At this point in the model the total number of households that are thought to leave home, or the number of displaced households, is determined by summing the number of households displaced at each of the three decision steps. These households then continue to Decision 4 to determine how many of them will seek public shelter.

Decision 4: Can you access forms of shelter other than public shelter?

It is assumed that households with the means (in particular, the financial resources) to arrange for non-public shelter will choose this over public shelter. The variable used as a proxy for means is income (**I**). The outcome of this decision is “yes” if income (**I**) is “moderate” or “high”. The outcome of this decision is “no” if income (**I**) is “low”. Households for whom the outcome of the decision is “no” are modeled as seeking public shelter.

3.6 Northridge scenario

The results of running the public shelter model for the Northridge Earthquake of 1994 and the Verdugo fault simulation are summarized in Figures 3-3 and 3-4, respectively. The total numbers of households with “yes” or “no” outcomes, respectively, are shown for each decision.

The Northridge Earthquake of 1994 is considered an earthquake of moderate impact, and as shown, a small portion of the total number of households is deemed to be in uninhabitable buildings. The model predicts that homes for 0.10 % of the households (3,183 households) are uninhabitable. The Northridge Earthquake also did not impact utilities severely. All power was restored to essentially all households within a period of 24 hours. As well, households within the Northridge area were without water for a range of 0 to 7 days. This data was obtained from the Los Angeles Department of Water and Power (Davis, 2005) and used as inputs in the model. As a result, 73.7% of the households were categorized as having a housing condition (**HC**) of “high”. This portion of the population is assumed to “Stay Home”.

As summarized in Figure 3-3, the public shelter model predicts that of the 3,136,279 households in Los Angeles, 25,472 households will leave their home and 14,983 of these households will seek public shelter. The 14,893 households seeking public shelter corresponds to 0.48% of the total number of households in Los Angeles County. As reported by EQE International (1997), 11,088 households were registered with the Red Cross after the Northridge Earthquake of 1994.

It should be noted that the HAZUS-MH software predicts a total shelter population for the Northridge earthquake in Los Angeles of 12,416 people. By using the average household size for Los Angeles of 3.037 people per household (Census 2000), the approximate number of households that make up this predicted shelter population is 4,088 households. This number is substantially less than both the estimated number from the proposed public shelter model (14,983 households) and the actual number reported by the Red Cross (11,088 households). This result may indicate that the HAZUS-MH software does not adequately account for all influential variables within its shelter model.

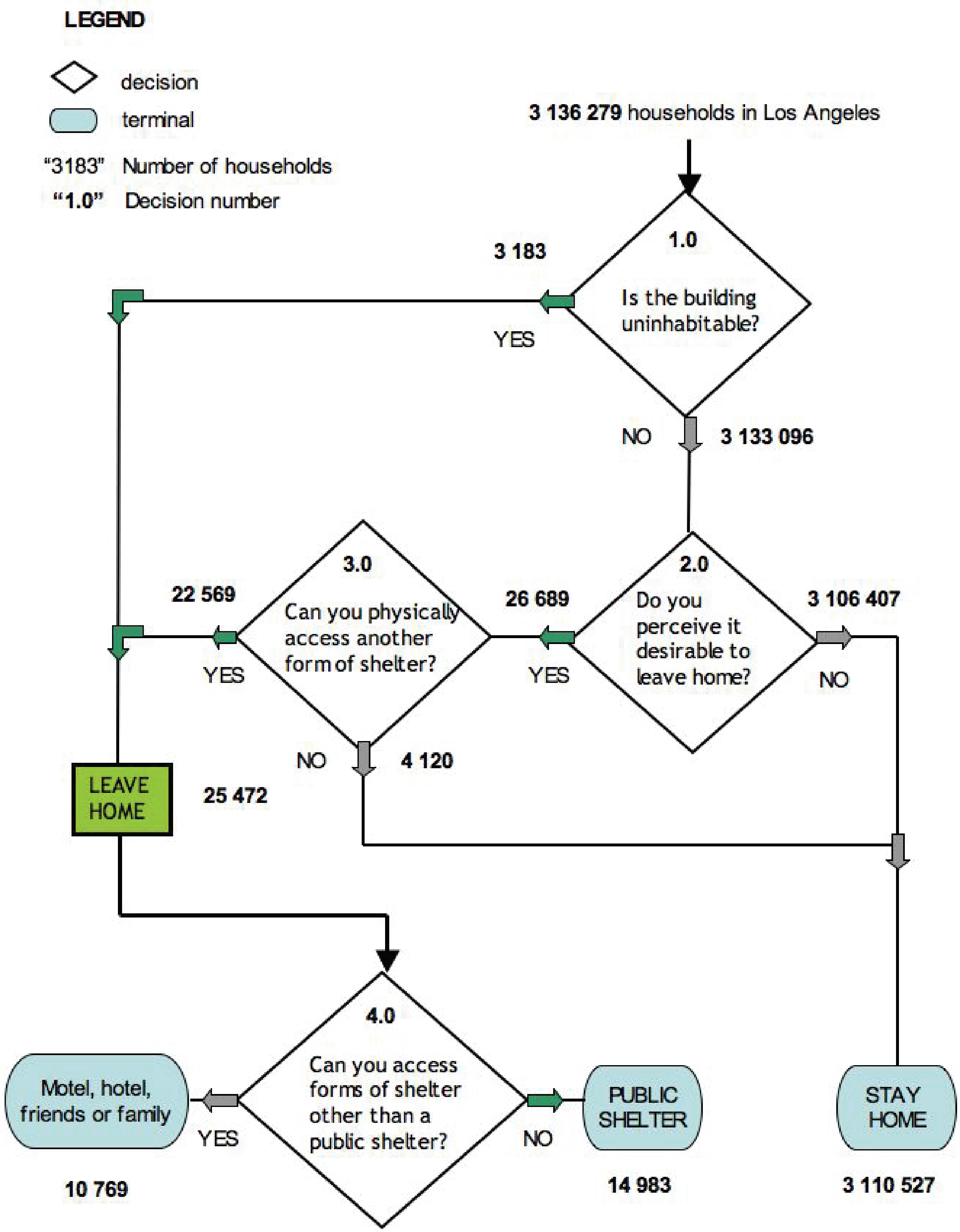

Figure 3-3 Shelter Model Results for the 1994 Northridge Earthquake Simulation

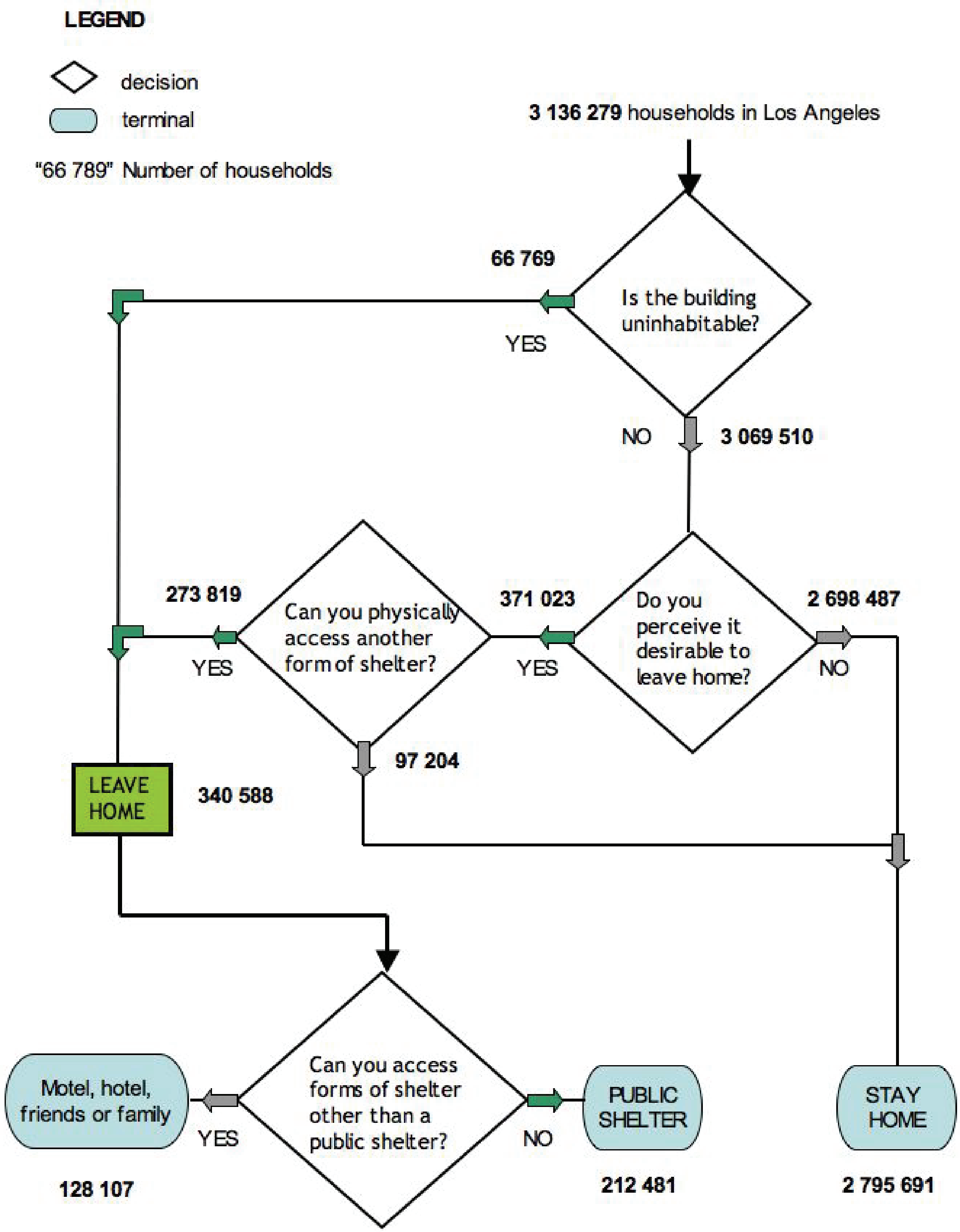

Figure 3-4 Shelter Model Results for the Verdugo Fault Earthquake Simulation

3.7 Verdugo Earthquake Simulation

The public shelter model for the Verdugo simulation, as shown in Figure 3-4 above, predicts that of the 3,136,279 households in Los Angeles, 340,588 households will leave home and 212,481 households will seek public shelter. This corresponds to 6.77% of the total number of households in Los Angeles. There are two reasons why there are a greater predicted number of households seeking public shelter for the Verdugo simulation in comparison to the Northridge run. First, the Verdugo Earthquake simulation resulted in a higher level of building damage than the Northridge Earthquake. Secondly, the days without power or water utilities in the Verdugo simulation are greater than in the Northridge Earthquake run. The Verdugo simulation was run with water outages that ranged from 0 to 14 days, and days without power that ranged from 0 to 13 days. These building damage and utilities data significantly impacted the predicted number of households seeking public shelter.

3.8 Sensitivity Analysis

The sensitivity of the model to variations in the decision calculations was investigated by varying the values of chosen variables and monitoring the model outcomes. It should be noted that the analysis conducted does not fully investigate the model's sensitivity; however, the outcomes do suggest some findings. More extensive sensitivity analysis should be conducted in further research.

Figure 3-3 above showed the resulting number of households seeking public shelter for the Northridge Earthquake simulation using the variable definitions and decision calculations described in Section 3.5 above. The sensitivity of the model to altering the influence of the variables Power (P) and Water (W) within the model calculations is illustrated in Figure 3-5.

The tolerable thresholds of days without Power (P) and Water (W) were altered in the calculations of Decision 1 "Is the building uninhabitable?" Within this decision housing condition (HC) is defined as "low" if one of the following are satisfied: building damage (BD) is extensive (BDE); days without water are greater than 4 days (W>=4 days); days without power are greater than 4 days (P>=4); *or*, building damage (BD) is moderate and W >= 4 days and P>=

4 days are all satisfied. Within the definition of housing condition (HC), the limiting number of days for the variables water (W) and power (P) were varied from 2 to 7 days.

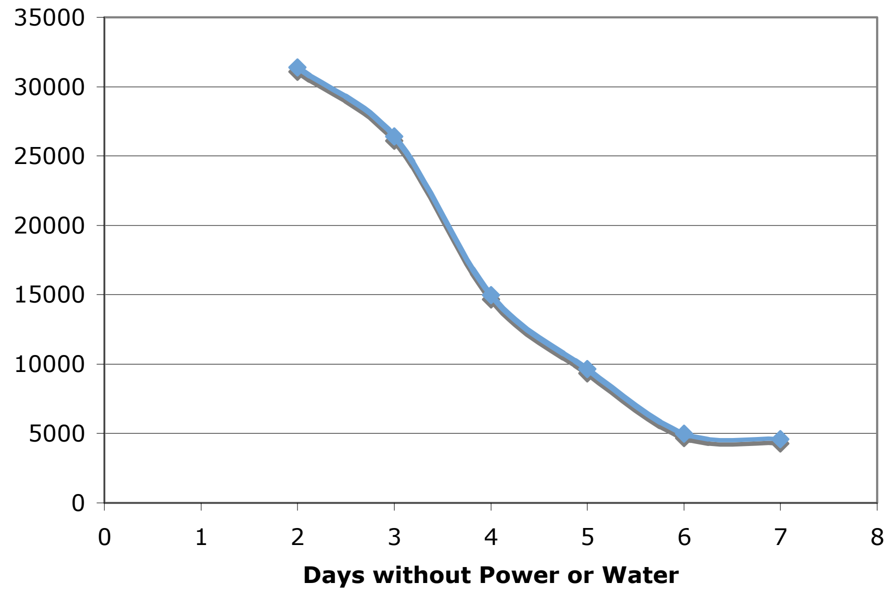

Figure 3-5 Sensitivity of model results to tolerance thresholds for lifeline disruption

As shown in the figure, increasing the tolerance threshold from 2 to 7 days resulted in a reduction in households seeking public shelter from approximately 32,000 to approximately 5,000 households. Given that power was restored to all households in the Northridge earthquake within 1 day and water was restored to all households within about 7 days, it is expected that the impact of the number of days taper off at 7 days. The influence of the water and power variables are substantial in this model because their values are used in determining the value of housing condition (HC) and therefore determine the outcomes of both Decision 1 and Decision 2. As discussed earlier in this section, the total number of households seeking public shelter in the Northridge earthquake was reported by the Red Cross to be 11,088 households. Based on this number of households, the limiting number of days without power (P) and water (W) set to 4 days within the model best corresponds to this result. Five days was not considered in order to avoid underestimating the total number of households seeking public shelter.

3.9 Discussion

- Based on the results of the Northridge and Verdugo Earthquake applications of the public shelter model, the following observations are made:
- Approximately 50% of the households that are estimated as displaced are predicted to be public shelter users for the city of Los Angeles. This is directly reflective of the income distribution of the population as income is the only variable considered in determining the number of displaced households that actually seek public shelter.
- A significantly larger proportion of the population will seek public shelter than that predicted by building damage alone. Based on the model, approximately three times the number of households deemed to have come from uninhabitable homes will seek public shelter. This corresponds to much of the disaster literature that has discussed the high proportion of public shelter users who do not come from structurally uninhabitable homes.
- The days without power and water play an influential role in determining the number of displaced households within this model. Further studies into the behavior of households in the event of an earthquake and the choices they make with regards to the amount of time they can tolerate without power and water before seeking alternative forms of shelter are needed, and should be integrated into the model.
- The HAZUS-MH model substantially underestimates the number of households seeking public shelter for the Northridge Earthquake. The public shelter model developed here is an improvement upon the HAZUS-MH model in terms of accuracy.
- Moreover, the public shelter model is conceptual advantageous, as it is based on a decision-making framework that is implemented at the household level, and further integrates a greater number of variables identified in the literature as influencing public shelter use.
- It would be very useful to run the public shelter model for another earthquake, besides the Northridge earthquake, where the number of persons seeking public shelter use is known and recorded. Running the public model for two earthquakes with known public shelter use outcomes would help better determine the relevant variable values and appropriate decision calculations for determining public shelter use in the city of Los Angeles.

SECTION 4
PERFORMANCE OBJECTIVES

This section describes the effort conducted in the L.A. Lifelines project on investigating performance objectives for lifeline infrastructure systems in earthquake contexts. The centrality of performance objectives to the resilience framework adopted in this study has been described earlier, in Section 1. The research here began with a survey of experts (Section 4.1). A key result from the survey was the consensus that performance objectives should be determined through a participatory process that involves a broad range of stakeholder groups. Consequently, a literature review was conducted on studies in the literature on environmental risk management, including but not limited to natural hazards, that employed participatory processes (Section 4.2). Following a recommendation from the literature review, a survey of key stakeholder group representatives in the L.A. region was then conducted (Section 4.3). Section 4.4 concludes with recommendations for further research.

4.1 Experts survey

While the current state of loss modeling allows analysis of the economic disruption and other broad societal impacts of utility outages on communities, questions remain as to whether, how, and to what extent such community impacts should be incorporated into mitigation decision-making; in particular, through utilities' performance objectives. To address these questions, some 20 structured, in-depth interviews were conducted with upper-level technical managers and consultants working in water and electric power utilities in seismically vulnerable communities in the United States and Canada. These practitioners are considered experts who have some (and in many cases substantial) specialized knowledge of seismic mitigation practices for water and electric power systems. In total, 27 practitioners participated in these interviews.

Open-ended questions were asked with regard to the following topics: Background and technical expertise of respondent; recent examples where utilities had used system performance objectives to guide decision-making for seismic mitigation; benefits, drawbacks, and challenges associated with using broad system performance objectives that take into account community impacts; possible uses and users for modeled estimates of how seismic mitigation could reduce the social and economic impacts of utility outages; performance metrics that would be most useful to utilities and other stakeholders; and suggestions regarding a process for involving stakeholder groups in developing performance objectives for utilities.

As details can be found in Chang and Coehlo (2006), only the main findings are presented here. The interviews found that a broad range of performance objectives are currently used in practice, and that utilities are primarily interested in technical and economic measures of performance. With regard to considering broad community impacts, beyond losses that might be suffered to the utility itself, water utilities were generally more open and interested than the electric power sector. There was, however, broad support for community-based performance objectives, which were considered useful not only for specific mitigation decision-making, but also for general policy-setting and communication with the public.

A surprising finding was the widespread inability or reluctance on the part of practitioners to quantify specific performance objectives. The practitioners generally felt that some form of consultation with other stakeholder groups (i.e., a multi-stakeholder process) was needed for such quantification. But while there was consensus regarding the need for some form of broader consultation, there was also considerable disagreement regarding who should be consulted. All of the respondents felt that the utility itself should be involved in creating performance objectives, with other frequently mentioned groups included emergency managers, politicians, police and fire departments (particularly for water utilities), the business community, and researchers. Some respondents also mentioned that other utilities should be involved, because of inter-utility dependence (i.e. mutual aid and infrastructure failure interdependencies). Interestingly, most respondents felt that the public should be involved to some capacity, but some mentioned that they should have an intentionally limited role, or even no direct role.

There was also disagreement about the process by which broader stakeholder input should be considered. Interviewees generally felt that the utility should take the primary technical role in the process and assume responsibility for gathering and incorporating feedback from other stakeholders. But suggested roles for non-utility stakeholders ranged from helping the utility write the performance goals, to having some responsibility in approving them, to simply being allowed to provide feedback at certain points in the process.

A key conclusion from the expert interviews was therefore the need for further research into appropriate processes for multi-stakeholder involvement in discussions regarding seismic performance goals for utilities.

4.2 Stakeholder participation: literature review

A literature review was conducted to investigate stakeholder participation processes, with a focus on case studies that could help inform the L.A. Lifelines project. The scope of the literature search was defined to include not only the natural hazards area, but also environmental risk assessment and health risk assessment. The search identified ten relevant case studies, together with some technical reports and theoretical background on the participatory process. The ten case studies presented here address different aspects of the process; however they were thought to provide a general overview of both the participatory process motivations, methods, challenges and overall success. This section provides a summary of the key findings from the literature review. (A complete version of the literature review is available upon request.)

4.2.1 Participatory Process Background

Participatory processes are utilized in a variety of disciplines to inform a diverse set of issues. (It should be noted that the term "participatory process" is synonymous with "participatory democracy", "public consultation" and "public participation". In the hazard literature, the participatory process typically includes discussions with stakeholders, whereas in other literatures, the goal is often to get the public involved in decision-making. In both cases, however, the methodology is the same, in that both approaches use focus groups, telephone surveys, workshops, etc.) In the case of environmental risk management, the participatory process attempts to gauge stakeholder views and to provide much needed information to the stakeholders. Once collected, these views are helpful in formulating risk management plans. They also serve as a source of information for service providers and can be used to inform public policy.

The participatory process is more involved than merely collecting stakeholders' views on a particular issue, however. It is a process that allows interested parties or stakeholders to actively participate in the development of policies or practices, express their views and concerns, and receive important information they might otherwise not have access to. The process also allows decision-makers to ensure they are meeting the needs of stakeholders. It helps to avoid charges of bias in decisions, improve the understanding and thus tolerance of a greater number of people in terms of what can be expected and delivered after a natural hazard, and finally, to reduce costly mistakes caused by oversight in planning or mitigation.

There are a variety of methods used to collect information from stakeholders such as phone and written surveys, public forums, workshops, focus groups, town hall meetings, and deliberative discussions. All of these methods are thought to provide an accurate account of issues and needs outside academic or industry concerns. This literature review found that participatory research was recognized widely to be a key element in improving the efficacy in risk management. Objectivity and representation are two of the key elements to a successful process since the participatory process attempts to get non-technical, non-expert attitudes, views and input. Problems with bias, specifically in the form of the self-selection bias where participants are those who volunteer or have an interest in the issue at hand, ultimately call into question the objectivity of the data or information produced by the participatory process. Additionally, as the trend in public participation in decision making continues to increase, it becomes more important for those in industry to ensure that public opinion does not go unheard. With a more informed and less deferential group of stakeholders, the methods used to elicit their participation must satisfy both their needs as well as those of the decision makers or researchers.

4.2.2 Research Questions and Motivations

A hazard mitigation program that includes an account of stakeholders' views serves to address both structural damage but also economic, social and environmental damage as the result of a natural hazard. (See Flax et al, (2002) for an account of the role of community stakeholders in hazard mitigation.) As the public becomes more aware of issues surrounding community resiliency, and thus more motivated to be involved in hazard mitigation programs, the composition of stakeholder groups becomes more diverse as do their interests, expectations and concerns.

This literature review is focused on a set of questions formulated to assist in developing an effective strategy for stakeholder involvement in the L.A. Lifelines project. The list of questions includes:

- How are the stakeholder groups to be identified and representatives recruited?
- What participatory environments (e.g. focus groups, workshops etc) are most appropriate?
- How should the interaction between researchers and stakeholders (e.g. in a workshop setting) be structured?
- How should the discussion be framed?
- How should computer-based models (i.e. MCEER's integrated lifeline model) be used in this setting?
- How should technical information be presented?

Defining the appropriate stakeholders and recruiting them will have a significant effect on the overall effectiveness of any participatory process. Once identified, it is then critical to use the most appropriate participatory environment. For example, for the participatory process to be inclusive and representative, it is unlikely that a telephone survey will be sufficient in reaching a diverse cross-section of the population or produce very deep, informed answers given that most respondents will have very limited access to pertinent information.

The literature also suggests that the interaction between researchers and stakeholders can sometimes be prohibitive to open discussion, as most laypeople tend to defer to the opinions of the 'experts'. It is therefore important to understand how this interaction should be structured. This is also true for framing discussions that may occur in workshops and focus groups.

Incorporation of the MCEER computer-based model is a key component to the overall aim of this project and it is helpful to see whether various approaches to incorporating simulation models met with success or left room for improvement. Finally, the literature also suggests that the presentation of technical information can either enrich discussions or produce more thoughtful and informed opinions, or it can overwhelm stakeholders and limit interactions between participants. Presenting unfamiliar technical information in a way that is both informative and non-threatening is of particular importance when the issues to be discussed, as in the case of hazard risk management, are unfamiliar to most stakeholders.

4.2.3 Case Study Summaries

This section provides an annotated review of the most relevant and informative case studies found in the literature review. Each summary describes the case briefly and attempts to situate its role in the overall goal of informing the participatory process. The first four cases focus on methodology, the next three address the use of models, and the final three discuss results of the participatory process. After a brief summary, a short assessment (reasons why the case was included here) is made of each case and, where appropriate, successes as well as challenges are identified.

Case Study 1. "Vulnerability Assessment of a Port and Harbor Community to Earthquake and Tsunami Hazards: Integrating Technical Expert and Stakeholder Input" (Wood et.al, 2004)

This case describes an initiative to increase the resiliency of Pacific Northwest ports and harbors to earthquake and tsunami hazards by developing a natural hazard mitigation and emergency preparedness planning process that combines technical expertise with local stakeholder values and perceptions. The vulnerability assessment methodology was used in a case study of Yaquina River, Oregon to assess local vulnerability. The paper argues that an effective vulnerability assessment tool must include the incorporation of the community by involving stakeholders in preparedness planning efforts which will result in a greater public interest and increased plan implementation.

The primary focus of the paper is on the workshops and various participatory methods employed in the community planning process which included workshops, group discussions and a questionnaire. The participants were composed of a diverse group of stakeholders who attended a workshop designed to assess the issues that were of most concern to the community as well as other objectives. The results of the workshop and the assessment questionnaire at the end of the workshop suggest that most participants found the exercise to be very useful, with hands-on learning rated as particularly helpful when trying to master new information quickly (i.e. descriptive maps, field trips to affected sites, interaction with technical advisors and presentations by the project team).

This is the most comprehensive account of a participatory method involving hazards. Stakeholders are defined specifically. Participant selection and recruitment is described in detail as is participant attendance and the way interactions between stakeholders and experts were approached. The methodology seemed to prove effective, but was very time-consuming. A preparatory workshop was held for 1 day before the 2-day workshop, which itself was followed up with another 1-day workshop, however the authors suggest this was not a problem.

Field trips to affected sites were thought to be highly effective. Field trips will not always be possible or relevant but it suggests that tangible data or local reference points are beneficial to the participatory process. One problem, as outlined by the authors, was a poor representation by key public sector departments and environmental organizations. This is possibly due to the methods of recruitment used which involved individual invitations. A second problem is that technical advisors tended to dominate the discussions which are also problematic in a stakeholder engagement workshop. A balance needs to be struck between information-giving and information gathering. There is no mention of the cost of the entire process nor do the authors suggest that cost-effectiveness was a factor in the design of the participatory process. It seems that the participants were voluntary and received no compensation which could account for some of the poor representation.

Case Study 2. "Maximizing Multi-Stakeholder Participation in Government and Community Volcanic Hazard Management Programs: A Case Study from Savo, Solomon Islands" (Cronin et.al., 2004)

This case study demonstrates an effective method to facilitate the interaction between diverse groups of participants in a participatory process. Specifically, it targets the difficulties inherent in engaging participants with significant disparity in terms of technical and scientific knowledge of the issues involved in natural hazard risk management, as well as cultural and social customs. Participatory rural appraisal methods (PRA) were trialed in volcanic risk management planning and awareness activity for Savo Island in the Solomon Islands. The roles of the facilitators and educators were combined and the input of stakeholders (from the community to the national government) was involved in the process of volcanic risk management. Although the population in the case study was very small (2,549 people) the participatory methods used are applicable since the focus groups and workshops incorporate the same number of people which might be sampled in a larger population. It provides a good account of how to incorporate the expertise of both technical and cultural representatives and get them discussing a common topic and contributing to making an effective risk management plan.

Stakeholders are clearly defined in this paper, and are very diverse, although there is no description of recruitment. The methodology is described in detail and includes: two 3-day workshops (the first was a briefing session). Specifically the Participatory Rural Appraisal method was used to 'level' the discussions and to address the diversity of participants. A comprehensive table of vulnerabilities is produced from the workshop. Workshop exercises and results are explained in detail. Hands-on tasks are considered very effective. The benefits of this study are in two areas. First, it provides insight into effectively engaging technical and non-technical participants in discussions of natural hazard risks. Second, it provides an assessment of areas for improvement which include: facilitators need to act as educators, scientific/technical information needs to be expressed in terms that are locally relevant rather than as abstract and purely rationally based, respecting cultural norms but not deferring to them, follow-up is essential or the benefits of the process can be lost or forgotten. This study demonstrates that a long-term view might be necessary to adequately engage stakeholders (i.e. one workshop will not suffice). However, the length of the 6-day workshop described is prohibitive in a larger community and unlikely to generate much interest in terms of participants. Issues of cost were not addressed.

Case Study 3. "Public Support for Earthquake Risk Mitigation in Portland Oregon" (Flynn et al, 1999)

This study also focuses on the methods of public participation; however it specifically discusses the process in terms of creating an earthquake hazard mitigation policy for the city of Portland and the state of Oregon. In order to develop an effective public policy, a task force of stakeholders was formed to examine a range of problems. A survey was administered to measure for the public's response to a proposed plan to issue public bonds. This study is useful in that it provides a detailed account of how to formulate and administer a survey to stakeholders (i.e. the public) to obtain their views, provide information and collect pertinent demographic data. The survey results are reported on in detail.

It should be noted that the target population was very limited and randomly selected. This case study demonstrates the use of a telephone survey as a means of stakeholder engagement. The benefit of a survey is its cost-effectiveness (the authors hired a company to design the survey although cost is not specifically mentioned), the large sample it generates (400 respondents) and the large amount of data it produces in a very efficient format. Problems with relying on a survey include: limited stakeholder representation and self-selection bias, potential of uninformed responses since little information can be provided by phone, and there was little or no opportunity for unstructured responses which could be beneficial to decision makers.

Case Study 4. "Participatory evaluations of trachoma control programmes in eight countries" (Kuper et al, 2005)

This case involves an initiative to conduct participatory evaluations of the trachoma control programmes receiving support from the International Trachoma Initiative in eight countries. It is an examination of participatory processes in health risk management. Its value comes from its detailed account of the participatory processes used in gathering data from stakeholders, who were defined as health care professionals, administrators and patients. The processes used included structured and semi-structured interviews, focus groups, questionnaires, and direct observations. Additionally, it provides some insight into the way participants from diverse backgrounds can participate and contribute to decisions about a common issue.

Interestingly, this is the only case study in which external evaluators were included in order to maintain objectivity throughout the process and to mitigate the interests of the team members. Although this was a helpful addition to the process, it also proved to have drawbacks as it resulted in less staff available for ongoing activities creating a conflict of interest. Costs of the project were not mentioned.

Case Study 5. "Experiment with Simulation Models in Water-Resources Negotiations" (Reitsma et al., 1996)

This case study provides insight into how simulation models might be utilized effectively in participatory methods to deliver technical information to participants. Although the topic at hand is a non-hazard water negotiation, it provides a useful template for how to incorporate models into the process. Specifically the case involves an experiment designed to investigate the effects of simulation models on water-resource negotiation using a mock water-resource negotiation. The use of models was integral as they were thought to confer a number of benefits on the participants and the decision making process as a whole. The authors argue that increased availability of simulation models allows stakeholders to more effectively become involved in the negotiation process. It was found, however, that the benefit of the models in terms of imparting knowledge and producing a final policy based on consensus was offset by the burden of direct use of the model. Participants required much guidance and direction to employ the models which decreased the efficiency of the task and increased frustration among the participants.

Overall, use of a simulation model in the participatory process was found to be very effective. This study suggests that if models are used, participants should be well-informed about the purpose of the model and how it is used. If participants are to actually use the model, supervisors should be close at hand to avoid frustration. This case focuses on generating consensus among stakeholders; however, based on the literature, this is problematic and perhaps counter-productive. This will be discussed further in the recommendations section below.

<u>Case Study 6</u>. "Decision Support System for Stakeholder Involvement" (Chen et al, 2004)

This case study focuses on the use of technical models and their ability to provide technical information for stakeholders who subsequently contribute to management decisions. A simulation model was used which supported the negotiation and compromise among stakeholders. The tool was developed to guide stakeholders through the calculation for the total acceptable amount of pollutant that can be discharged without violating water quality and to vote for alternatives where relevant. The authors conclude that their tool allows stakeholders a more active role in risk management decision-making and is accessible to a wider range of people.

This case study shows that there is an alternative to traditional participatory methods which are time consuming, costly and often not effective. Having stakeholders use this tool has its limitations as well but it provides further information for decision makers in a much more user friendly form. One of the limitations of this method is the amount of information a stakeholder would need to make informed and thoughtful decisions but this could be addressed in a brief workshop or briefing session before using the model. Also note that the composition of the stakeholder group is not mentioned, nor is recruitment or background. From the study, it is not apparent how familiar the participants were with the model or would need to be before using it. Cost is not mentioned in this study, however use of a an online tool like this one is a step toward defraying the expense of multi-day workshops.

<u>Case Study 7</u>. "Interplay of Science and Stakeholder Values in Neuse River Total Maximum Daily Load Process" (Maguire, 2003)

This case study is similar to the first case study in the amount of detail it provides on participatory methodology, from recruitment and definition of stakeholders to how the stakeholders were engaged (i.e. description of the participatory methods used) and analysis of results. This case is an evaluation of stakeholder interactions with water quality models and modelers in the Neuse River total maximum daily load process. A general analysis of the interactions is provided (i.e. between stakeholders and models, modelers and stakeholders). Participatory methods included public meetings, written and phone surveys, interviews and meetings. The meetings and interviews provided an opportunity for stakeholders to interact with technical experts during the model development process. It was noted that stakeholders must perceive the models as unbiased if they are to function as arbiters in collective decision making.

The significance of this particular case study is the involvement of stakeholders in the development of some models used to generate data about water quality. Regulatory agencies accepted stakeholder input as having a significant advisory role. One problem with the process was that the TMDL was defined too narrowly and thus did not address the broad concerns of the stakeholders such as equity, cost effectiveness, costs vs. benefits calculations, and social, economic and cultural concerns). This narrowness was attributed to the regulatory process and its narrow structure. Although this is a non-hazard case study, it serves to highlight the effective use of stakeholder input in environmental policy issues and regulatory decision making. Another valuable aspect of this case study to the LA lifelines project is the integration of stakeholder values with science. The model in the LA Lifelines project does not involve stakeholders in the development stage, but the information it produces will be used to inform stakeholders and must therefore be understood as unbiased as possible in order to function optimally. Cost was not mentioned in this case study.

Case Study 8. "Public Involvement in the Red River Basin management decisions and preparedness for the next flood" (Haque et al, 2002)

This case explores the importance, feasibility and effectiveness of public participation in the case of the Red River Basin in Manitoba after the flood of the Red River in 1997. The objective of this study is to explore the roles and degree of actual influence of public participation. Following the flood, a task force (the International Joint Commission (IJC)) was set up which conducted hearings for the public and stakeholders. The study found that there are different degrees of efficacy associated with various techniques of public involvement. The most effective techniques from the users' (stakeholders') perspective need to be inclusive, flexible, iterative and informative. Public hearings were the method used in this case and the researchers arrived at a number of conclusions about their efficacy. For example, it was concluded that public involvement in decision making needs to be part of the emergency management plan laid out well before a situation arises. Conclusions include: public hearings are only effective in raising awareness but may not produce the representative outcomes desired, effective public participation in hearings require adequate resources, information and time, emergency preparations must be made well ahead of time (ahead of the disaster) in order to improve the relations between public input and emergency management decisions, transparency, respectful communication and trust are all essential elements in establishing a close link between stakeholders and corporate or government decision making.

In order to make environmental hazard management projects and programs more socio-economically and politically feasible, the views of the public and stakeholders must be incorporated in decision making. The authors argue that the IJC programs were more sensitive to the views of the public and stakeholders whereas the Red River Basin Task force was not. Advertising the public forums through flyers and newspaper ads seemed a relatively successful method of getting more people to participate. There is a difference between rural and urban stakeholders in that rural stakeholders are more likely to participate. However, in the case of a city that has a very real hazard threat, perhaps this is not an insurmountable problem. Adequate resources (both time and information) were identified as necessary to an effective participatory process.

Case Study 9. "Disaster Management and Community Planning and Public Participation: How to Achieve Sustainable Hazard Mitigation" (Pearce, 2003)

This study provides not only a brief historical overview of disaster management planning but also a review of Australian and American research that suggests a shift in the focus of disaster management planning from response and recovery to sustainable hazard mitigation which necessitates both community planning and local decision making. The case describes methodological strategies for a successful participatory process which emphasize the importance of inviting citizens/stakeholders to participate in the most effective way, the benefits of multi-stakeholder consensus processes, and the problems inherent in traditional approaches to the participatory process. The author draws these conclusions based on their examination of the results of a hazard mitigation project for landslides in the Portola Valley, California. She suggests that based on the results of their analysis, any successful approach to sustainable hazard mitigation must be participatory in nature and linked with the local decision-making process.

The author claims that how citizens (stakeholders) are invited to participate is fundamental to the success of the process. Informational brochures and pamphlets were thought to be necessary but not sufficient means of recruitment. However, the author does not suggest any other tangible methods of recruitment, other than making sure the results of the process are actually used in decision making. This is a long-term strategy and probably an effective one, but it does not address the immediate need of effective recruitment.

Case Study 10. "Seismic Evaluation Program: Final Report" and "Communications Summary Report" East Bay Municipal Utility District, (1994)

These reports present the results of the Seismic Evaluation Program (SEP) conducted by the East Bay Municipal Utility District. The SEP covers the essential components of the water system within the District's Service Area. The report describes how the performance of the established service goals for the water system compares with how the system may perform after earthquakes. More significant for this review is the evolution of the Capital Improvement Program (CIP) packages (strategies for mitigating the effects of an earthquake on water system performance) which are evaluated in terms of their benefits and costs and serve as the means of evaluative comparison for the water system service goals. The CIP packages were developed through the use of a very extensive participatory process. Specifically, a series of workshops were held with the District which resulted in four packages of varying levels of improved earthquake performance. As well, there was a very thorough campaign to get customer input from surveys, flyers, questionnaires and fact sheets as described in the Communications Summary Report. Such efforts were made to engage stakeholders to inform them of the proposed SEP as well as to get their input on program support and financing options. The primary aim of this effort was to gauge public acceptance of increased costs on their utility bills. This summary provides an account of that process in terms of the research questions motivating this literature review.

Based on an analysis of the four CIP packages, the report recommends Package 3, costing between $162 million and $202 million (the second costliest option). It is not clear how much of an influence the participatory process had on the selection of this package, however. The extensively detailed account of this public outreach initiative is very valuable in helping to inform a strategy for the L.A. Lifelines project. Such efforts are most effective when used to reach customers of impending cost increases, but might be limited in other cases or when the participatory process is directed at a different set of goals.

4.2.4 Insights from Case Studies into the Research Questions

The overall goal of this literature review is to generate answers to the specific research questions (as listed in Section 4.2.2 above) which were thought to be crucial to developing an effective participatory process for environmental risk management decisions in the LA Lifelines project. The findings of the review are analyzed and synthesized here to provide insights into each of these research questions.

<u>1. Identification and recruitment of stakeholders</u>

Although the literature suggests that there is no widely accepted definition of stakeholders, there is a consensus that they can be defined in very general terms. Stakeholder groups are almost universally considered to be those who will be affected by an event or process. This extends beyond government and non-government associations but includes representatives from vital infrastructure organizations. (The Recommendations section below offers a list of suggestions in defining stakeholders which consists of a number of infrastructure organizations. This list was compiled from the literature but more specifically by Schiff (1995).) In a participatory process that seeks to get a community-based or public opinion, stakeholders usually encompass a very broad range of people including researchers, policy makers, government (both local and federal) officials, emergency personnel, residents and property/business owners in a specific area and industry representatives. Identification of a group of stakeholders is often dependent on the purpose of the participatory process, as well as the issue the process is meant to inform. The trend in the current literature emphasizes the benefits of diversity in stakeholder groups for two reasons in the case of hazard management. First, to ensure awareness of possible risks in as broad a section of the community as possible, and second, to avoid possible bias which ultimately undermines the participatory process and the use of its results in decision making or policy. In

Case Study 10, stakeholders were limited to customers, which make both identification and recruitment much easier and more definitive.

Few studies specifically mention how stakeholders were recruited, however two cases emphasize that the way stakeholders are recruited has an impact on how successful the subsequent participatory process will be. Recruitment efforts vary from public announcements, posters, newspaper ads and individual invitations. Case Studies 8 and 9 suggest that stakeholder recruitment must extend beyond posters or flyers advertising the opportunity to participate. Case Study 1 received the highest rate of reported acceptances, where 48 of the 93 participants who received personal invitations actually participated in the workshop. The issue of recruitment is also of significance when attempting to avoid the self-selection bias inherent in any participatory process that depends on an open invitation for participants. To avoid such bias, it is necessary to generate an outline of who the stakeholders are, what information they might need to make an informed decision, and who is best suited to delivering such information. Case Study 10 demonstrates a very effective campaign at recruitment; however such efforts benefited from a clearly defined target population (i.e., customers of EBMUD) with the added advantage of being able to reach this population through the established billing system. If possible, this is an effective way to reach and recruit a large number of people. In the case of a project using a simulation model, if the model is to be used in the participatory process, it is critical to ensure there are enough experts involved to explain how the model works and answer any questions the participants might have.

<u>2. What participatory environments (e.g. interview, focus groups, workshops etc) are most appropriate?</u>

The most common participatory methods include focus groups, workshops, surveys and public hearings. These are predominantly consensus-based forums, but as reported in Case Study 7, such approaches do not always result in effective mitigation strategies and often produce frustration and confusion for stakeholders. The most effective participatory environments include an informational session or workbook which presents relevant technical data in terms all stakeholders can understand and question. For example, in Case Study 1, a detailed workbook was provided to participants to become familiar with the technical issues before discussions took place. In other case studies (i.e. 3, 5) technical advisors or experts played integral roles in discussions where participants could receive information and get clarification. Case Study 10 demonstrates a highly effective survey and questionnaire campaign which was distributed along with the utilities' bills to its customers. The response rate of such questionnaires and surveys was high, although this could be due largely to the fact that one of the topics was of great interest to customers: rate increases. The study demonstrates that both surveys and questionnaires remain very viable sources of public engagement, however. (Ahmad et al. (forthcoming) argue that surveys are perhaps a superior form of public engagement with the proviso that they include sufficient information for the participants to make an informed decision. We have developed an online survey for just this purpose and have received both high response rates, more detailed responses when compared to focus groups, as well as the cost-effective production of data which does not require the same amount of transcription, interpretation or confusion as is sometimes the case with other participatory methods.) Environments where stakeholders and technical experts interact on equal footing and equal consideration is given to both perspectives are very effective as described in Case Study 3. Since there must be enough time allotted for stakeholders to familiarize themselves with the information and gain an adequate understanding of the issues at hand, single events are less likely to be successful (particularly single public hearings as reported in Case Study 8). It is not clear that interviews as in Case Study 3 alone are sufficiently engaging since there is little opportunity for individuals to interact with other stakeholders or experts and no opportunity for discussion which are all key features of successful participatory environments. Focus groups are more successful if they are diverse in composition, respectful of the expertise of all members and are facilitated or directed. Workshops are effective when combined with surveys or public hearings as they allow an opportunity for information exchange and learning in a variety of different modes. Public hearings are helpful in the preliminary stages of a mitigative program but provide little refinement of strategies.

3. How should the interaction between researchers and stakeholders (e.g., in a workshop setting) be structured?

Case Studies 1 and 2 show that researchers and stakeholders need to be treated as equals in any participatory environment, as both groups bring unique knowledge and skills necessary to the process of hazard mitigation. Two-way interaction between researchers and stakeholders is thought to be most effective. Researchers can be seen as authorities of their particular area but their opinions should not trump those without such specified knowledge. It is helpful when researchers can fill in any informational gaps but also request information themselves of local participants such as local geography, etc.

The often-cited problem of technical experts being intimidating for laypeople is not always the case; however, technical experts must ensure they are using a terms and explanations that are accessible. It is apparent from the review that participants expect, and perhaps depend on the information provided from technical experts but they do not want discussions dominated by such information.

4. How should the discussion be framed?

As evident in Case Study 9, the hazard mitigation process was successful when the discussion was framed in terms of the interests of local citizens. Rather than discussing geographical data or landslide effects, the discussion included the idea of keeping the Portola Valley in its natural state as much as possible. This allowed both the researchers attempting to mitigate risk from landslides, and citizens attempting to preserve their environment to reach common goals. Case Study 10 also demonstrates the effectiveness of framing discussions in terms relevant to stakeholders. In this case, the stakeholders were customers and discussions revolved largely around the issue of rate increases; however, the response rate to surveys, questionnaires and telephone responses was quite high. In other cases, when the discussion is framed in terms of its impact on the interests of the stakeholders involved, there is also a much higher rate of participation and engagement. Stakeholders need to know what is expected of them and what the expected result is intended for. This should be stated clearly at the beginning of the process. Technical discussions should similarly be framed in terms that are locally meaningful, address the specific concerns of stakeholders, or are likely to produce impacts on stakeholders' lives. Discussions of risk also benefit from being situated in reference to local interests. It is inherently difficult to talk about risks to a broad audience so grounding discussions in this way will lead to improved understanding and effective deliberations. It should also be made clear that lifeline systems are interdependent and that when one is affected, others, perhaps all, are affected. This should be included in framing the discussions.

5. How should computer-based models (i.e. MCEER's integrated lifeline model) be used in this setting?

As seen in Case Studies 5,6 and 7**,** computer-based models can greatly facilitate the incorporation of stakeholder input into the decision making process. When the models are incorporated into discussions and exercises with the stakeholders, there is a higher level of understanding and more input from the stakeholders. Facilitators are necessary to help guide stakeholders through the use of the model (if they get the opportunity for hands-on experience) but are also necessary to explain the data that the model generates. If the information from the model can be put into a visual form, this is even more useful for stakeholders. Use of the model often makes the constraints that policies are formed and decisions are made under more evident to stakeholders. Models could be effectively incorporated into two parts of the participatory process. First they could be used in the information stage where stakeholders are learning about the issues at hand. Second, they could be used in discussion stage where stakeholders could see the effect of the decisions or recommendations. In both cases, models are effective means of generating discussion, providing information, and clarifying issues.

6. How should technical information be presented?

Technical information should be presented in the most accessible and appropriate form, depending on the stakeholders involved. Every effort to explain or make the information more tangible through graphs, maps or demonstrations greatly increases the value of such information. If the information can be presented in local terms and in the context of the local setting and reflective of the needs and interests of the stakeholders, this is also very effective. Depending on the depth of the participatory process employed, technical information could be provided in two ways: first in purely informational or demonstrative terms in which participants receive the information from experts, and second in an interactive way in which participants engage in various exercises in order to understand what the information really means.

4.2.5 Recommendations

The following section outlines recommendations for conducting a participatory procedure to effectively engage stakeholders for a case study of the Los Angeles Department of Water and Power. These recommendations indicate a participatory process that LADWP itself could initiate and lead to further explore and develop specific seismic performance objectives. Based on the literature review, a single procedure is not recommended. Instead, the challenges faced in various participatory planning methods have been taken into account and, in an attempt to address these challenges; a unique, multi-faceted approach is described. The recommendations are made in terms of the research questions, and unlike much of the literature, both cost and time (but not at the expense of efficacy) are included in their consideration.

The literature review revealed the following observations which should be noted for any participatory process (adapted from Yosie and Herbst (1998) using the results of this literature review and case study analysis). Common problems found from the literature survey include:

- No clear understanding of how to define “stakeholder”
- Poor response rate to invitations to participate
- Expectations for stakeholders and goals of the participatory process often ill-defined
- Consensus-based approaches can be problematic
- Stakeholders and researchers not treated as equals
- Discussions framed in abstract terms are not effective
- Poorly supervised/explained models stymie process
- Presentation of technical information often assumes too much familiarity with issues and relevant definitions

The literature review also suggests the following useful approaches to addressing these problems:

- Stakeholders—defined according to purpose of project; inclusive of all affected representative groups and individuals via extensive recruitment efforts
- Efforts to recruit and inform stakeholders include broad advertising efforts, bill inserts, telephone contact, web pages, internet surveys, posters and informational sessions
- Clearly defined goals and expectations through recruitment, informational, and participatory sessions
- Consensus is not a requirement for success of process
- Stakeholders are *active* participants
- Discussions framed in terms relevant to stakeholder concerns (i.e. use of local examples or recent hazard events) are most effective
- Models can be beneficial in reduction of stakeholder concerns of uncertainty; require thorough explanation

- Participatory process assumes little no technical background of stakeholders and all informational material is presented in an accessible form

These approaches are elaborated upon below with greater specificity to research questions guiding this literature review for the L.A. Lifelines project.

1. Identification and recruitment of stakeholders

It is recommended here that stakeholders for this project include LADWP clients who also serve to represent groups, such as: technical and non-technical (government and non-governmental officials) experts, including researchers; emergency workers or representatives from their organizations; local and state government officials directly involved in mitigation programs; police, security and fire department representatives; community and or municipal planners and administrators; industry representatives and consumers; business owners (including both large and small businesses); commercial planners; city planners; structural and civic engineers; hospital administration and medical personnel; transportation officials; telecommunications experts or representatives; representatives from large, well-known structures that might be used as common gathering places (i.e. stadiums or convention centres); civic leaders; community representatives (includes geographic as well as cultural and socio-economic community divisions); social workers or those responsible for administering social welfare programs; and local citizens (as representative of class, gender, culture and socio-economic status as possible).

Recruitment should be considered a multi-stage endeavour in order to reach as many of the stakeholder groups as possible. It is recommended that the first stage consist of an informational campaign. This stage involves advertising in the form of brochures, newspaper/radio/television ads or posters to direct attention toward the participatory process and to begin introducing the issues at hand. Such advertisements should be targeted to reach all areas of the city to reach as many groups as possible. A telephone number should be available for further information.
If possible, sending out information sheets and/or surveys and questionnaires via billing is recommended. References made to a *recent* event are likely to generate more response. Use of an informational webpage and embedded internet survey is also an effective strategy at both recruitment and participation. Getting the issue into the consciousness of as much of the population as possible could reveal groups of stakeholders not already identified and increase the level of participation. This stage can also invite interested parties to contact the organizers if they

are interested in participating. Information can be collected in this case and representative candidates can be chosen from this pool.

The second stage would consist of individual invitations. This stage involves sending out (by letter or telephone) individualized invitations to stakeholders to become involved in the participatory event. For some groups (i.e. technical and non-technical experts, or those who can be easily identified such as health care or emergency workers) this can be done by letter or email. For local citizens, to offset the self-selection bias produced by the open call for participants in stage one, a random selection of names can be drawn up and invitations sent. This can be accomplished through an agency specializing in recruitment.

The third stage would consist of follow-up. This stage will involve following up on all the invitations sent out to confirm participation as well as to remind participants of the date, time and place of meeting. If there are insufficient participants, then a second wave of invitations should be sent out and more advertising should be done.

<u>2. Participatory Environment</u>

The most successful participatory environments are those that involve an exchange of information. However, it is not always the case that focus groups or workshops are ideal since they are time consuming, costly and fraught with potential for bias, if not carefully planned. Despite these limitations a focus group or workshop can be an effective way to generate discussion and to introduce stakeholders to the issues at hand, while also allowing them to ask questions of the experts. It must be made clear to organizers, researchers and participants that the goal is not to produce *consensus* since this is seldom a possibility, or has the unwanted effect of discouraging stakeholder participation (Gregory et al. 2001). Instead, general conclusions can be drawn from the discussions for the organizers, however, participants should be given the option to voice their dissent rather than conform to the majority. One of the goals of a focus group or workshop must be to exchange information which will subsequently help to inform decision makers. Stakeholders should also be made aware that their input will be taken as recommendations and not as definitive decisions the organizers will make, unless this will actually occur. Additionally, workshops should occur in combination with other methods to generate the most usable data (e.g. a focus group combined with a quantitative survey).

A recommended participatory environment for natural hazards could include a survey/questionnaire of key issues that both provides and collects information from stakeholders. A well-designed webpage with all relevant information as well as an embedded survey is also a good way to both provide information and to allow stakeholders to participate. This is also a recommended strategy for allowing stakeholders to self-identify. Demographics can be recorded and updates can be made easily. In cases involving direct contact with stakeholders, it is recommended that the following be included: an informational session; a hands-on or visual exercise in which participants can engage with the information they are learning about (this could include an actual tour of a relevant site, a video made in advance, use of a computer simulation model or a visual presentation); workshop/focus group held over 1 to 2 days (ideally 1 day); a clear explanation of the purpose and expected goals of the workshop at the outset; a clear set of guidelines to follow as well as a set agenda (which includes room for flexibility and accommodation of participants' questions and/or needs); structured and non-structured interaction of participants (i.e. mediated discussion and individual opportunities to voice opinion via a survey); a specific set of questions or issues to discuss and contribute opinions to; a follow-up discussion once the workshop has ended (can be in the form of an optional meeting on another day, telephone interview or internet survey); an evaluative survey allowing participants to comment further on both the effectiveness of the workshop overall as well as to make other comments or offer an elaboration of their views (important in that some participants may be reluctant to express their views or offer opinions, particularly on very technical issues); a summary report sent to all participants to demonstrate the way information was synthesized and to provide the opportunity to comment on this preliminary report.

3. Structure of researcher and stakeholder interaction

Stakeholder and researcher interaction must be well-planned to avoid the tendency of non-experts to defer to experts. It is therefore recommended that a professional mediator be hired to conduct the participatory event for two primary reasons: to minimize the bias of researchers, and to bridge the gap between researchers and stakeholders. Researchers should present their findings in plain language and make the information as accessible as possible. It should not be assumed that the stakeholders are familiar with the issues at hand. Moreover, researchers should avoid taking an authoritative voice as this is sometimes misinterpreted by non-experts as testimony or prescriptive advice and thus compromise the underlying motivation for stakeholder engagement. First names only should be used to address all participants including researchers and mediator.

It should be made clear that researchers are expecting to learn new information from non-expert stakeholders.

4. Framing the discussion

The most effective discussions are those that incorporate local references (i.e. local neighbourhoods, transportation systems, recreation sites, businesses etc). The discussion should also be framed using local knowledge and history, particularly if a significant event has occurred in the past. Part of the framing occurs in the informational and introductory sessions which explicitly outline what is expected from the stakeholders during the process. Further discussions should also be situated in this context. Stakeholders could be asked to fill out a pre-participatory event survey or information sheet which identifies areas of concern. This information could then be used to help frame the discussion. Framing should also include opportunities for open debate or input by stakeholders. The discussion should not feel as if there is only a one-way flow of information. All terms used in discussions should be clearly defined. This includes definitions of: stakeholders, hazards, mitigation, lifelines etc. Defining terms helps frame the discussion and prevent misunderstandings or lack of clarity. Risks need to be framed in understandable terms and care must be taken not to over or under-represent the risks.

5. Use of computer-based model

Models should be integrated into both the informational and decision/recommendation making aspect of the participatory process. Models are a benefit if they can reduce uncertainty. Stakeholders are concerned about the negative consequences of activities, particularly when there is imprecision in impact estimates. A model which can provide some degree of understanding about possible outcomes is thus effective at addressing this problem. If the participants are going to actually use the model, facilitators need to be readily available to help with users. If the models are used by facilitators only, they should be explained in lay-terms and demonstrations should be made of their usage. The model should also be used to demonstrate to stakeholders the outcome of their deliberations or contributions to the issues being discussed. Participants should be given an opportunity to comment on the value of the model, the data it produces and its use in discussions. It should be made clear that they are expected to use the model in their deliberations, as well as to evaluate the model for representing their interests appropriately.

6. Presentation of technical information

Technical information must be presented in an accessible and user-friendly manner. All terms should be defined and it should be assumed that participants have little to no background with such information. Various media types should be used to make the technical information more understandable. Demonstrations, where applicable, are also recommended. Technical explanations should be enhanced with written material given to all participants to refer to during the session (i.e. in the introductory material). Where possible, technical information should be presented in local terms and involve local examples.

4.3 Stakeholder participation: Los Angeles Survey

4.3.1 Overview

The recommendations noted above were intended to help LADWP design and implement, with its research partners, a multi-stakeholder participation process whereby models such as those developed in MCEER's L.A. Lifelines project could be used to help develop seismic performance goals for the utility with broad-based input from the community. It was felt that preliminary stakeholder consultation would be important in setting the stage for such a process, particularly for gathering information on perspectives from representative community groups regarding the following questions:

1. Who should be involved in defining disaster-related utility performance objectives?
2. What is an appropriate and meaningful way of framing these objectives?
3. How can information regarding objectives be best communicated?
4. What considerations are most important in disaster-related decision-making?
5. Do the views of utility providers differ from those of the community?
6. What challenges might be encountered in the process?

Preliminary information from stakeholder groups on these questions would be important for design further steps in fostering participation; for example, in designing potential workshops and in considering how to use MCEER's various L.A. Lifelines project models in such workshops. To this end, a survey was conducted of representatives of key stakeholder in the Los Angeles region, following recommendations noted above from the literature survey portion of this project.

4.3.2 Methods

Rather than a random sampling, this survey targeted key stakeholder groups who would be strongly affected by a disaster-related loss of water and/or electric power supply in the Los Angeles area. The survey sample was determined by first identifying the main stakeholder groups to be surveyed (see Section 4.2.5 above). Those selected included technical users (e.g. the utility itself [LADWP], emergency managers, emergency response organizations [police, fire], hospitals, planners, transportation officials), decision makers (e.g. utility board, politicians), and the general public (via community organizations and business associations).

Once these target stakeholder groups were identified, names of individuals that could represent these groups were solicited from two key informants. Criteria for selection included their familiarity with emergency management procedures, if possible, and their relative authority or expertise (with the aim to have higher-level managers as respondents). This initial list was then further augmented through internet research. The target sample size was 15-30.

An 8-page questionnaire was designed to solicit information regarding performance goals and information sharing. The questionnaire is included as Appendix A of this report. The survey was anonymous, but did collect background information such as professional affiliation and job title. Respondents were first asked to identify which groups they thought should participate in developing utility service goals for disasters. A list of 8 choices was provided, including: utility provider; emergency response organization (e.g., police, fire); health care provider (e.g., hospital, clinic); local government (e.g., elected official, planner); community-based organization (e.g., neighborhood council); business group (e.g., Chamber of Commerce); non-governmental organization (e.g., Red Cross); and technical expert (e.g., consultant, professional organization). An open-ended "Other" option was also provided.

Respondents were then asked a series of questions regarding the content of the performance objectives themselves, and to give comments on the appropriateness of these objectives. They were asked to indicate the maximum acceptable duration of utility outage for a series of 8 situations. Each situation referred to one of two scales of disaster ("a **moderately damaging disaster** (on the scale of the 1994 Northridge (L.A.) earthquake)" or "a **catastrophic disaster** (on the scale of Hurricane Katrina)"), one of two types of utility service (electric power or potable water), and one of two customer groups (critical facilities or 90% of the population). The following timeframe choices were provided: less than 1 hour; 12 hours; 24 hours; 72 hours; 7 days; 14 days; and an open-ended "Other" choice. Respondents were also asked to indicate whether or not they thought these types of performance goals were appropriate, and how they thought these goals might be improved.

Thirdly, to determine how information should best be communicated, several questions on information sharing were posed. Respondents were asked to indicate how helpful (on a categorical scale ranging from "not at all helpful" to "essential") each of a list of types of information would be for their organization's disaster planning efforts. The list included: maps of utility outage areas; time estimates of outage duration; number of customers without utility service; number of households displaced from their homes; number of businesses temporarily closed; loss of regional economic production; likelihood of major disruptions; and an open-ended "Other" option. This list of informational types was developed on the basis of the types of outputs that could be provided by MCEER's L.A. Lifelines project models.

Respondents were also asked to indicate the helpfulness (on the same scale) of various approaches to presenting information on the inherent uncertainty associated with such estimates. The list of approaches included: worst-case scenario ever possible; worst-case scenario likely in 50 years; worst-case scenario likely in some other timeframe (to be specified by the respondent); a few scenarios of varying likelihood; all possible scenarios together with their likelihoods of occurrence; and an open-ended "Other" response. Again, this list was developed in consideration of the types of outputs that could be provided by MCEER's L.A. Lifelines project models.

Respondents were also asked about the helpfulness (on the same scale) of various means of sharing information. The list of information-sharing means included: print information (e.g., brochures); CDs or other electronic format; interactive website; public meetings; workshops; and an open-ended "Other format" option. This list was developed on the basis of the literature review of participatory processes presented above.

Finally, a question was asked to address disaster-related decision-making priorities: "Utilities must trade off between costs and benefits when making decisions about reducing disaster damage. The following is a list of potential benefits that may be considered. How important do you think it is to consider each of the following?" Respondents were asked to reply on a categorical scale ranging from "not at all important" to "essential." The list of potential benefits included: savings in the utility's post-disaster repair and emergency response costs; reduction in post-disaster outage time; reduction in outage to critical infrastructure such as hospitals, fire stations, transportation networks, etc.; reduction in regional economic disruption; reduction in disruption to people's lives; and an open-ended "Other considerations" item. This list was again developed in consideration of the types of outputs that MCEER's L.A. Lifelines project models would be able to quantify and present.

The survey was administered via email, for expedience and ease of data collection. The questionnaire was formatted into a form-fillable MS Word document and sent electronically to the selected stakeholders, accompanied by a cover letter and email introducing the project. Follow-up phone calls were made several days later to encourage completion of the survey and respond to any questions or concerns. This telephone follow-up was continued over the summer of 2006 until a reasonable number of responses were received. As survey responses were received they were coded by number to ensure anonymity, and entered into a database for analysis.

4.3.3 Results and Analysis

The response rate was 18 out of a possible 31, for a response rate of 58%. Of the respondents, 8 were critical responders (including 4 emergency managers, 2 transportation officials, 1 health department official, and 1 fire department captain), 5 were utility providers (including 2 risk/emergency managers, an engineering director, a communications representative, and a power distributor), and 4 were community group representatives (including 2 resource group representatives, a neighborhood council representative, and a business association representative). Table 4-1 shows the response rates for these categories. Utilities had the highest response rate. But while the response rate for community groups was the lowest, it was still quite high at 45%.

Table 4-1 Response Rate by Category

	Surveys Sent	Surveys Returned	% Response Rate
Utility Providers	8	5	63%
Critical Responders	13	8	62%
Community Members	11	5	45%

4.3.3.1 Stakeholder Involvement

The survey asked respondents for their views on who should be involved in defining disaster-related performance objectives for utilities. All respondents identified the utility provider itself, and almost all also included emergency response organizations and local government. Notably, every stakeholder group (in the list provided) was identified by at least 60% of the respondents. Table 4-2 shows the number of groups selected by the respondents. Only 1 respondent (6%) thought the utility should define performance objectives alone. A full 39% of respondents thought that all the groups listed should be involved. These observations indicate support for the broad involvement of stakeholders, including both professionals and community members.

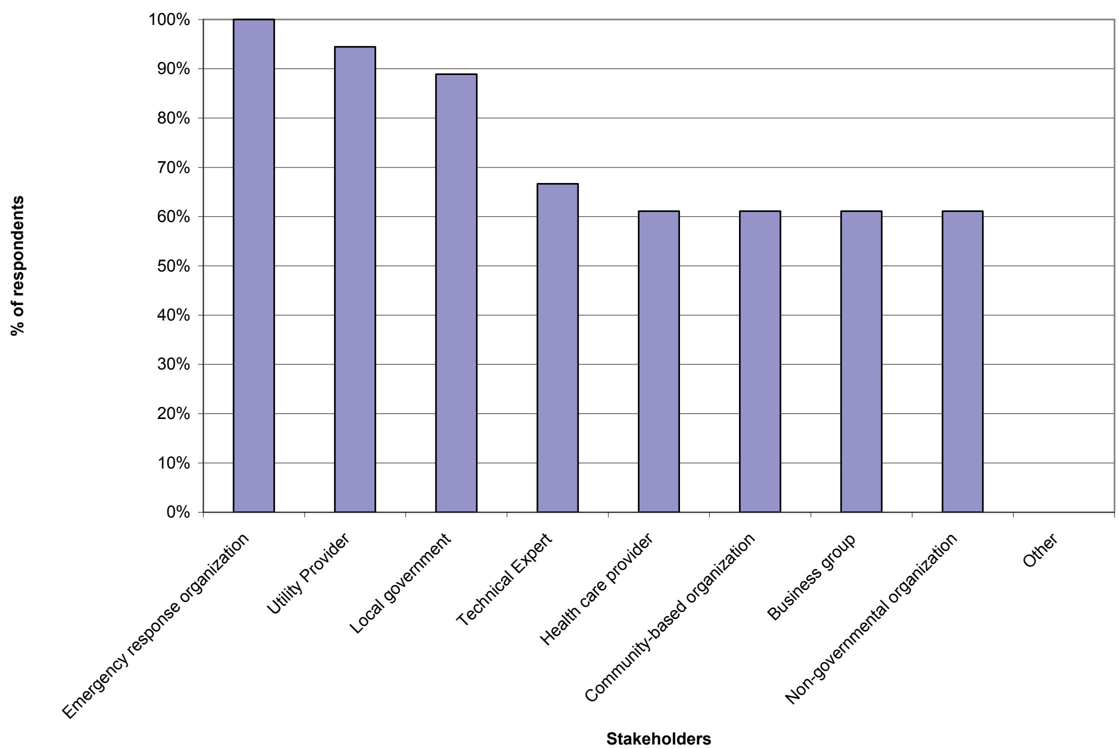

Figure 4-1 Stakeholders to Include in Development of Performance Objectives

Table 4-2 Number of Stakeholder Groups Identified by Respondents

Number of Groups Selected (*n*)	% of Respondents
1 group	6%
2 groups	6%
3 groups	6%
4 groups	11%
5 groups	6%
6 groups	17%
7 groups	11%
8 groups	39%

4.3.3.2 Performance Objectives

Information was sought regarding an appropriate and meaningful way of framing the performance objectives. The performance objectives proposed in the survey suggested that "Power [water] should be available to critical facilities [90% of the population] in (specified time period)." This phrasing is consistent with performance objectives proposed in Bruneau et al. (2003) and Chang and Shinozuka (2004). All but one respondent thought these types of performance objectives were appropriate. This respondent stated the following:

> *Our experience as a wholesaler has frequently been that we can restore service delivery before the receiving retailer can recover the capacity to take the delivery and redistribute to the end user. The foregoing performance goals do not take such realities into account.*

Further open-ended feedback from other respondents resulted in the following comments:

> *It is critical that any goals involve a back-up/alternate plan and the ability to prioritize according to the magnitude of the disaster and the resources that may be available. Flexibility needs to be added to any plan/goals.*

In addition to this flexibility, awareness of the sheer scale and diversity of the Los Angeles region could result in the need for varying objectives by geographic area, as suggested by the following comment:

The City of Los Angeles consists of 470 Square miles. Due to the vast area of the City there could quite possibly be an instance where water to critical facilities could be out for a longer period of time in certain areas.

One general comment stressed the importance of communicating individual preparedness:

Communicating the need for individual preparedness regarding water would improve response to critical areas.

In addition, challenges were encountered as a result of varying legislation outside of the City of Los Angeles. One respondent noted:

In the context of Southern California (outside of the city of Los Angeles),setting performance standards which prioritize critical facilities is not appropriate, since utilities are governed by the California Public Utilities Commission, which states that providers cannot give preferential treatment to certain users over others.

The same respondent stated that:

Question 3 has grossly oversimplified performance goals because every disaster is different and providers will obviously do their best to restore service as quickly as possible.

These comments suggest that the framing of performance objectives as proposed in this survey does not function equally well in different social or political contexts, and that utility providers might disagree as to the usefulness of performance objectives.

With respect to the content of the objectives themselves, close agreement among responses (low variation across responses for each objective) can be observed in the hypothetical case of a moderate disaster (Figure 4-2 below). In the figure, solid squares represent the modal responses for each performance goal, while the bars indicate the range of responses received. Responses in the case of a moderate disaster (on the scale of the 1994 Northridge Earthquake) are on the left of the chart, while responses with respect to a catastrophic disaster (on the scale of Hurricane Katrina) are on the right. Note that there was a greater variation in responses with respect to a catastrophic disaster. Despite this, all modal values were the same for the correlating objectives under each disaster scenario:

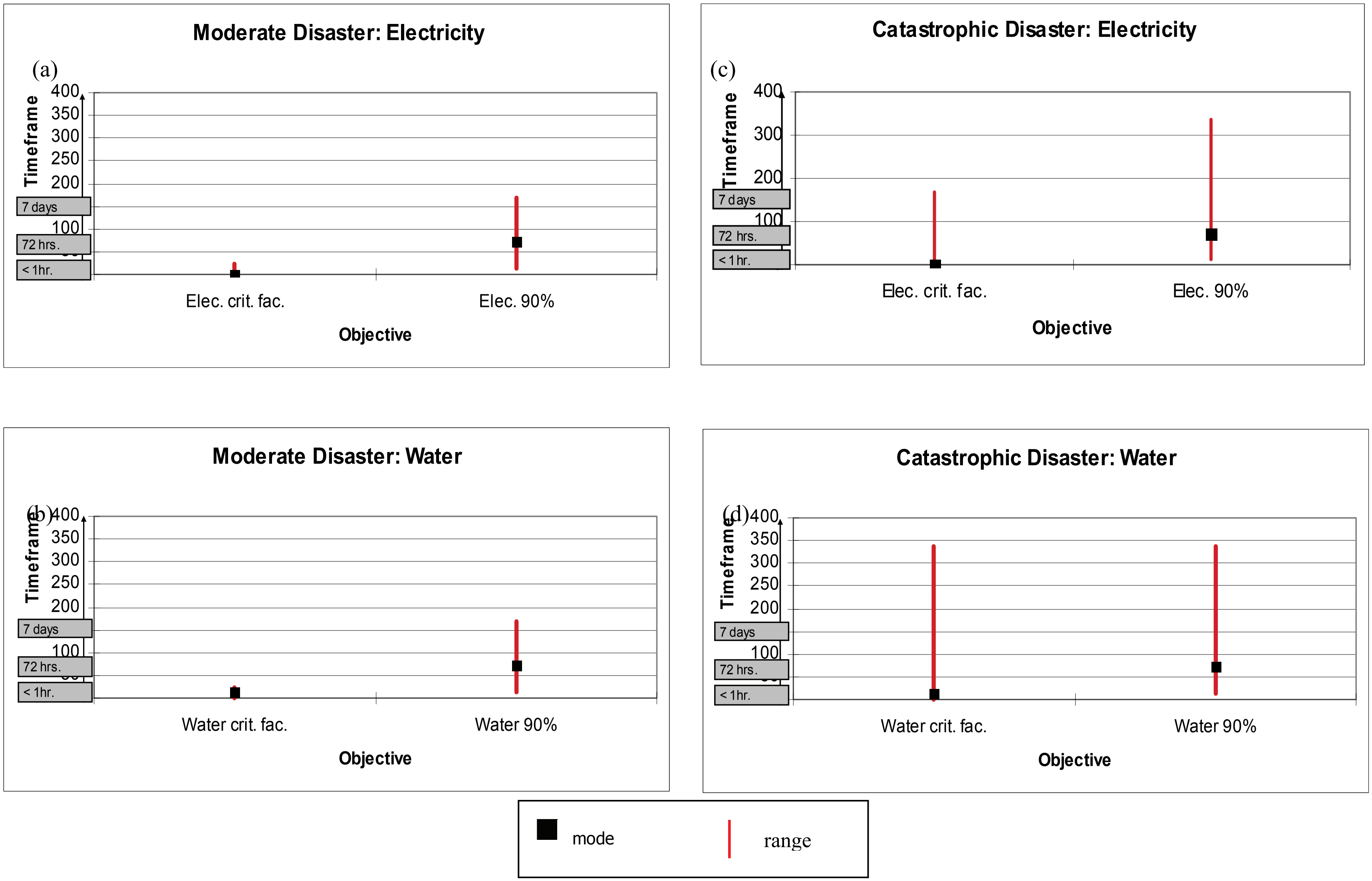

Figure 4-2 Performance Goals: Modal Response and Range of Responses

Interestingly, there appears to be little difference in terms of the modal values for the suggested performance objectives between water and power availability. In the case of a moderate disaster, the modal response for electrical restoration to critical facilities was less than one hour, while for 90% of the population it was 72 hours (Figure 4-2(a)). The modal response for the provision of water to critical facilities was 12 hours, slightly longer than that for electricity. The modal response for water to 90% of the population was 72 hours, the same as electricity (Figure 4-2(b)). Modal responses in the case of a catastrophic disaster were the same as for a moderate disaster: less than 1 hour for electricity to critical facilities, 72 hours for electricity to 90%, 12 hours for water to critical facilities, 72 hours for water to 90% (Figures 4-2(c) and (d)).

However, when comparing the situation of a moderately-damaging disaster (on the scale of the 1994 Northridge earthquake) (Figures 4-2(a) and (c)) to a catastrophic disaster (on the scale of hurricane Katrina) (Figures 4-2(b) and (d)), there is a much greater range of responses returned in the event of a catastrophic disaster (from less than one hour to 336 hours for a catastrophic disaster, versus less than one hour to 168 hours for a moderate disaster), even though the modal values are identical across scenarios. In both cases, respondents generally agree that power and water should be restored more quickly to critical facilities, whereas the greatest range of responses occurs with respect to restoration of both water and power availability to 90% of the population.

4.3.3.3 Information Sharing

The survey sought to determine how information regarding performance objectives can best be communicated. With regarding to approaches to presenting uncertainty, respondents identified the most helpful presentations to be a few scenarios of varying likelihood, and all possible scenarios together with their likelihood of occurrence. All other options were largely considered somewhat helpful, as shown in Figure 4-3. Several respondents indicated that other timeframes would be useful, with suggestions for these timeframes including the next few hours/days, within one year, budget year, 4-year electoral term, 5-10 years, 10 years, 10-20 years, and 100 years.

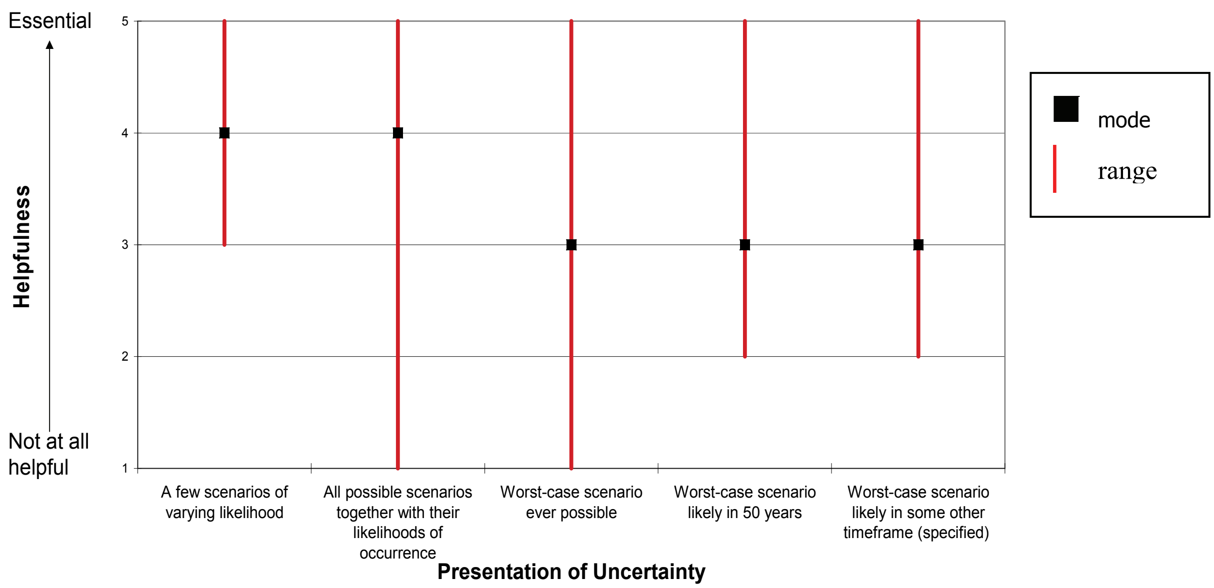

Figure 4-3 Presentation of Uncertainty: Modal Response and Range of Responses

With respect to presentations of uncertainty, one respondent expressed doubts regarding long time-frames:

> *I don't know how valuable the worst case scenario would be due to the technology available, the population, ethnic diversity, transportation modes and routes etc. To me, the worst case scenario today would be drastically different in the same cities vs. say 50 years ago.*

With regard to means of communicating information, as shown in Figure 4-4, respondents identified interactive websites and print information as the most helpful methods of communicating information. CD's, public meetings and workshops were all identified as somewhat helpful.

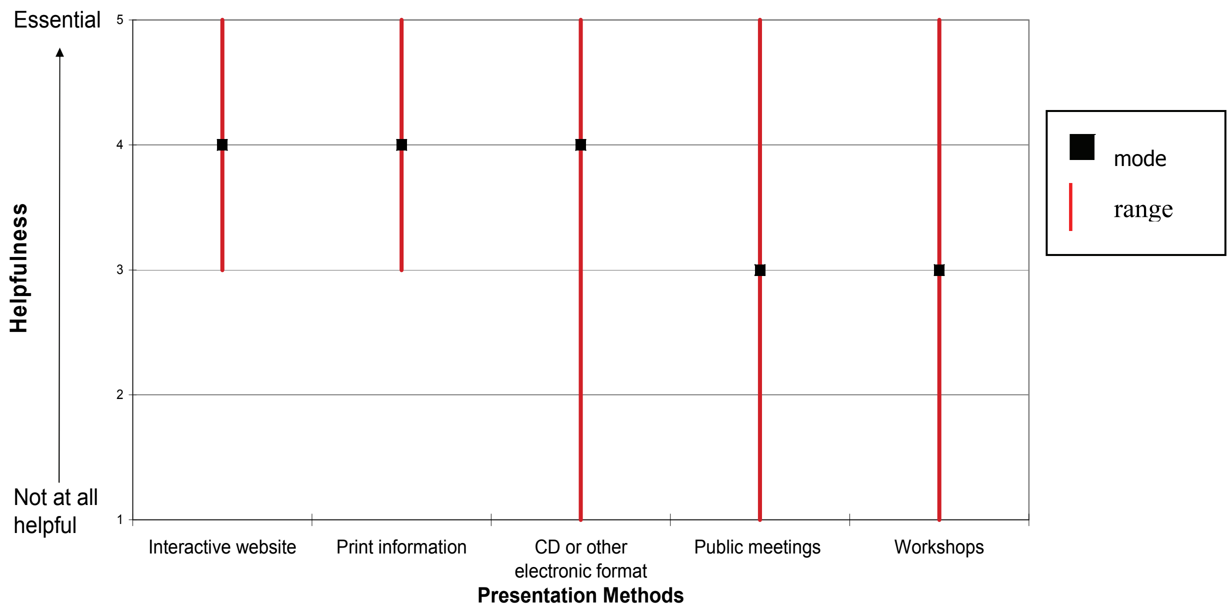

Figure 4-4 Presentation Methods: Modal Response and Range of Responses

In addition, general open-ended feedback stressed the importance of visual representations as a means of presentation:

> *Visuals indicating what areas come back first, by area, would be useful.*

This is one area where the model results could be compellingly communicated via the use of graphic tools such as map outputs from a GIS tool.

Concern was raised that sensitive information such as vulnerabilities in power and water supply systems could be exploited by terrorist groups if made widely accessible. Thus, it was suggested that

> *A dark web site activated only when needed may be a particularly useful way of disseminating the information at the right time without fear of compromising data that may reveal exploitable vulnerabilities.*

In addition, the utility of a variety of information sharing methods was stressed, so that

> *…when really needed, all information sharing methods should be used in concert.*

4.3.3.4 Decision-Making Priorities

This study is also concerned with what considerations should be most important to disaster-related decision-making. The survey asked respondents about the importance of various considerations in disaster-related decision-making by the utility. Figure 4-5 shows that most people rated a reduction in outage to critical infrastructure as an essential consideration to a utility's decision-making. Consideration of a reduction in repair or response costs was generally much less important. The other suggested considerations were all ranked as "somewhat" to "very" important:

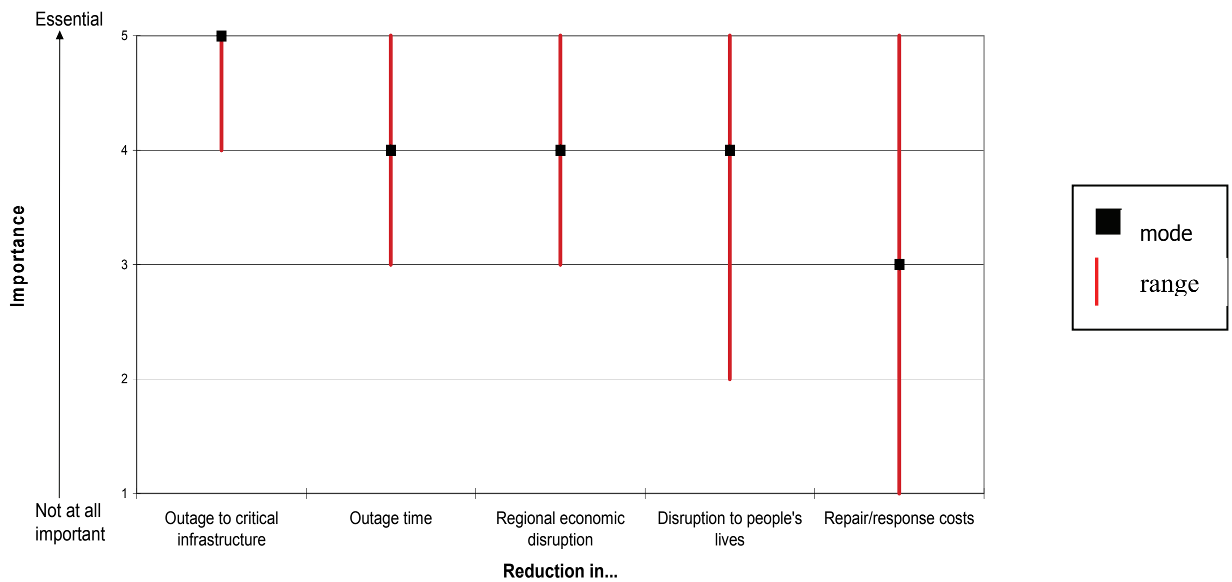

Figure 4-5 Importance of Various factors to Decision-making: Modal Response and Range of Responses

4.3.3.5 Utility Provider versus End User Responses

Analysis was conducted to determine how the utility's responses differed from those of the community. Examining the data by user type yields interesting comparisons. A comparison of the modal values of responses between utility providers and users yields few differences. A comparison of average responses, however, (Figures 4-6(a) and (b)) shows that utility providers always suggested performance standards that were temporally longer than those suggested by community groups or critical responders, particularly with respect to the case of a catastrophic disaster (Figure 4-6(b)). In many cases the provider's suggested goals are more than double those defined by the users. This may be because it is the utility providers to which the performance objectives apply, and they would therefore suggest objectives they feel it is possible to meet, with or without consideration of what they ‘ought’ to be able to provide. It is interesting to note the very high average response from utility providers for water restoration to 90% of the population in a moderate disaster (201.6 hours). Half of the utility providers stated this goal as ideal. Curiously, this response is considerably higher than in the case of a catastrophic disaster; it is not apparent from the survey results why this should be the case.

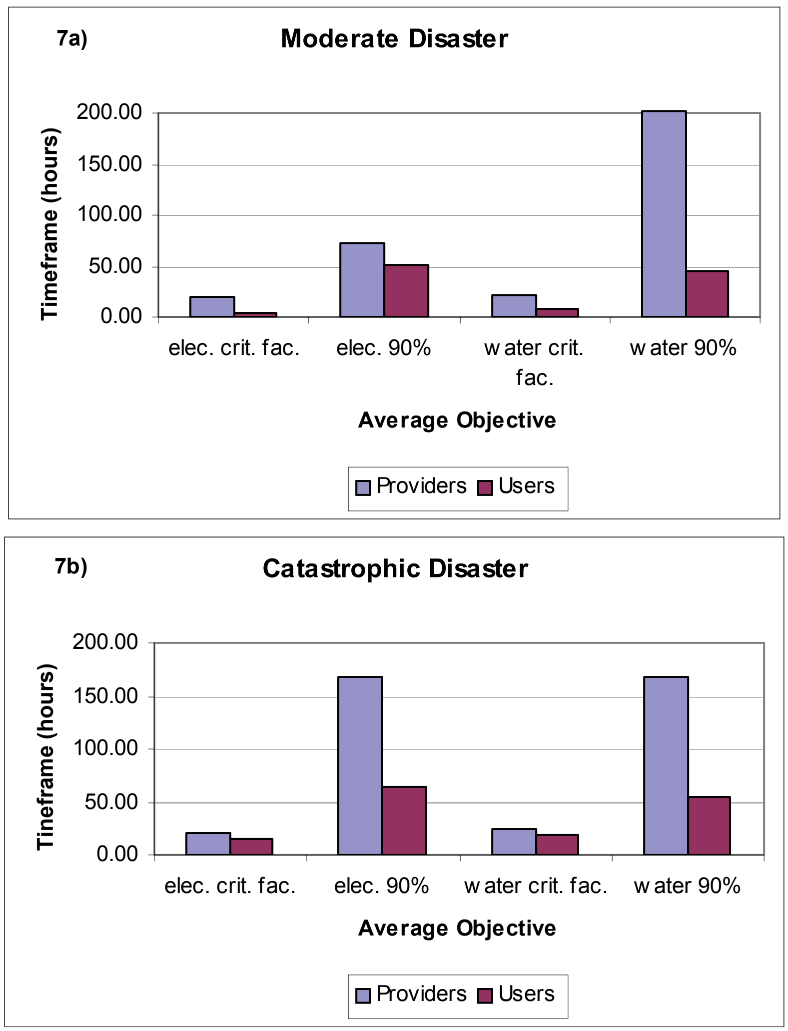

Figure 4-6 Average Performance Objectives, Utility Providers vs. Users

These comparisons suggest that with a different sample of respondents (e.g. more providers than users), the overall recommended performance objectives could change substantially. Provider and user groups alike agreed on the stakeholder groups to involve in the definition of performance objectives, however. Utility providers were only one of these stakeholder groups. Thus, based on overall modal responses from a range of stakeholders, the survey seems to have identified reasonable performance objectives which can inform further resilience modeling to aid in mitigation strategies.

There appears to be no correlation between respondent type and considerations which matter to disaster-related decision-making (Table 4-3). All respondents rated reductions in outages to critical infrastructure, and reductions in post-disaster outage time as the most important considerations, suggesting that there may be universal considerations across sectors.

Table 4-3 Decision-Making Considerations*, Utility Providers vs. Users

Reduction in…	Providers	Users
Outage to critical infrastructure	4.8	4.8
Post-disaster outage time	4.3	4.3
Disruption to people's lives	3.7	3.7
Regional economic disruption	3.5	3.3
Post-disaster repair and emergency response costs	3.3	2.7

*Average values on a scale of 1-5, where 1 = not at all important and 5 = Essential

There also appears to be no significant correlation between respondent type and the type of information sharing, methods, and presentation of uncertainty preferred; respondents across categories preferred an interactive website as a means of sharing information.

Table 4-4 Information Sharing Preferences*, Utility Providers vs. Users

Means of Information Sharing:	Providers	Users
Interactive website	3.7	4.8
Print information	3.5	3.8
CD or other electronic format	3.0	3.6
Workshops	3.2	3.3
Public meetings	3.3	3.0

*Average values on a scale of 1-5 where 1 = Not at all helpful and 5 = essential

4.3.4 Conclusions and Recommendations

Over the course of this survey, various issues arose which bear further consideration. The first of these issues is that of a survey methodology. During informal telephone conversations with respondents, much useful information was gleaned that would not have been apparent from survey responses alone. Also, the survey design used did not give room for elaboration (reasoning behind decisions, etc.), which was also revealed during follow-up. This suggests that a depth of information exists that was not captured by the survey. A combination of more open-ended survey questions and/or semi-structured interviews might help to fill this gap. In addition, some variation in responses clearly stemmed from different interpretations of certain questions. For example, it is not clear if utility respondents interpreted the performance goals as a reflection of what they felt *should* be a reasonable service goal, or whether responses were based on what they felt was *achievable under current conditions*. The 72-hour figure returned as a median response for many of the performance objectives may have been influenced by the widespread use of this timeframe in emergency preparedness guidelines, suggesting that respondents may have been responding based on what was already known, versus what they felt to be ideal. These uncertainties have not been adequately accounted for in this study. Further study would be necessary to gain a more complete and accurate understanding of performance goals.

In this context, the targeted survey of Los Angeles stakeholder groups has provided several insights into issues that should be considered in the design and implementation of a multi-stakeholder process for developing seismic performance goals for regional utilities, in particular, LADWP. It has found that widespread support exists for the inclusion of a diversity of stakeholders in the definition of performance objectives, particularly emergency managers, utility providers, and local governments. Ideally, the entire spectrum of stakeholders would be involved in the definition of objectives.

With regard to the performance objectives themselves, the survey found that context is important. Varying policy and geographic environments require different objectives. Moreover, every disaster is different, so flexibility must be incorporated into performance objectives. The suggested format of performance objectives "restoration of power [water] to critical facilities [90% of the population] within X timeframe" is broadly considered to be reasonable.

Survey respondents indicated that in the Los Angeles context, the following objectives are appropriate: In both moderate and catastrophic disaster situations, electricity should be available *to critical* *facilities* in less than one hour, and potable water within 12 hours. Both electricity and potable water should be available to 90% of the population within 72 hours. There is more consensus related to performance objective targets in moderate than in catastrophic events.

A few scenarios of varying likelihood was found to be the most helpful means of presenting uncertainty, particularly when combined with visual representations (e.g. maps). Websites and print information were considered the most useful means of sharing information. Care must be taken to ensure that sensitive information is not exploited. A combination of methods when really necessary is ideal.

A reduction in outage to critical infrastructure, as well as a reduction in overall outage time, were identified as the most important considerations for disaster-related decision-making (e.g. for mitigation).

Utility providers and user groups agreed with respect to decision-making priorities, stakeholder involvement, and information sharing. Providers, however, consistently set less stringent performance objectives than community groups, raising the issue of feasibility vs. ideal values.
Studies should be undertaken to determine the reasons for this difference and to evaluate its impact on the model, after which a decision should be made whether objectives should be based on normative circumstances or on their likelihood of being achieved. The former would result in the proposal of performance goals for utilities for the purpose of mitigation, while the latter could be used to help the public to develop realistic service expectations. If the overarching goal is the mitigation of socioeconomic impacts of disaster events, the former would seem the preferred course. However, this is a discussion which needs to occur.

There are uncertainties in the data due to methods of data collection. In order to better understand performance objectives and fill the gaps, further study should be undertaken which utilizes various methods (e.g. semi-structured interviews, focus groups). Context is important to performance objectives and needs to be taken into consideration.

The results of this survey can be used to inform modeling work with lifeline utilities in the Los Angeles region. Incorporating performance objectives into such a model will assist utilities to better respond in the event of a disaster, to minimize outage duration and extent, and to prepare for uncertain circumstances. It will also allow the modeling research to be used to quantitatively gain insights into regional disaster resilience. Data from this study can better allow LADWP and regional decision-makers to use the MCEER L.A. Lifelines project models to assist with the definition of performance objectives, and provide similar support for policy-making. Likely outcomes can be compared to desirable or acceptable outcomes based on stakeholder-defined performance objectives. This can initiate a crucial discussion regarding what level of utility disaster performance is acceptable and desirable, encouraging stakeholders and the public alike to think about disaster preparedness. Ultimately, having discussed such issues will result in a community that is better prepared to mitigate and respond to future disasters.

SECTION 5
CONCLUSIONS

Critical infrastructures such as water and electric power systems provide vital services, and their disruption in disasters undermines the resilience of the communities they serve. This study has explored the linkages between infrastructure performance and community resilience through quantitative modeling and surveys of experts and community stakeholders. Within the framework for quantifying resilience proposed by MCEER researchers (Bruneau et al. 2003; Chang and Shinozuka, 2004), in which resilience is indicated by the likelihood of a system exceeding certain thresholds of impact, it has focused on three aspects that are central to making this connection: economic impacts, social impacts, and performance goals.

New models were developed that respectively simulate the economic impacts (in terms of direct business disruption) and social impacts (in terms of populations displaced and seeking public shelter) of water and power outages in disasters. Both the economic and shelter models are innovative in being agent-based in structure, using 1% samples of actual businesses and households, respectively, as the basis for simulating impacts. A key advantage is that the models are able to account for statistical correlations and interactions between different factors that affect risk at the agent level. For example, in the case of businesses, size and sector are known to be correlated, and both affect vulnerability to loss. In the case of households, income and access to a car are correlated, for example, and both affect propensity to seek shelter.

Thus the models can be specified in a manner that is consistent with conceptual frameworks and empirical findings in the literature, as well as empirical data, which often describe and explain impacts and risk at this scale. For example, the shelter model is structured in a series of decision steps according to a household decision-making model. The economic model makes extensive use of data from surveys of businesses following the Loma Prieta and Northridge earthquakes.

The models are also distinctive in accounting for the impacts of lifeline outages in the context of other sources of disaster-related disruption, especially building damage. This is important for two reasons: first, it avoids double-counting or inflating losses, wherein losses attributed to, say, water outage could also be considered losses from building- or power outage. Second, it allows for the possibility of interaction between multiple sources of loss, which could lead to total losses that are higher than the sum from each source individually. These two effects work in opposite directions, so that the net effect cannot be determined *a priori*.

Modeling results from this study indicate that interaction effects are greater than double-counting effects. Thus multi-source loss modeling is important for model accuracy. For example, results of the shelter model for the Northridge earthquake (15,000 households) were much closer to actual reported data from the Red Cross (11,100 households) than were results from HAZUS-MH (4,100 households), in which lifeline-related disruption was not considered. Indeed, including the effects of water and power outage on households increases the number of displaced households by as much as 3 times over considering building damage alone.

While the models have been developed and implemented for the Los Angeles case with earthquake hazard in mind, they can readily be used to assess impacts from other types of hazards. The hazard-related inputs to the models consist of estimates of building damage and lifeline outages (across space and over time) due to the disaster event. These estimates may be developed from other, external models of damage, outage, and restoration. They may also consist of observational data from actual events. In applying the economic and social impact models to other types of hazards, it would be necessary to specify the associated physical damage and lifeline service disruption. A terrorism event, for example, might be targeted at the electric power system and cause widespread power outage with long restoration times; but there may be no associated damage to the general building stock. A flood event might cause extensive damage to buildings and utility service within a limited area of the city, with the remainder of the city largely unaffected.

The models developed here can be used by planners, local governments, non-governmental organizations such as the Red Cross, as well as utilities themselves for planning and decision-support purposes. They can be used to anticipate the potential economic and social impacts and needs following future disasters. For example, the shelter model can be used to help plan for the optimal number and locations of Red Cross shelters in future earthquakes, and to anticipate staffing and resource needs. In the case of the economic impact model, because simulation results are provided in terms of a loss distribution rather than a point estimate, results can also be used to explore the range of potential impacts and the likelihood of exceeding key threshold loss levels. Moreover, the models can also be used to evaluate the benefits of mitigation investments.

This project has also explored issues related to how such models can be used to support decision-making in an effective manner. The expert/practitioner and stakeholder surveys indicated that there is broad support and interest in including considerations of economic and social impacts in discussions of utility performance goals. Of the various measures of impact that models can provide, stakeholders felt that estimates of outage times would be the most useful, particular in terms of outages to critical infrastructure facilities. Model results could most effectively be communicated in terms of depicting a few disaster scenarios of varying likelihood.

The expert/practitioner and stakeholder surveys also found that there is general consensus that broad participation from the community is important for determining utility performance goals. Performance goals framed as "in a catastrophic disaster (on the scale of Hurricane Katrina), electricity should be available to critical facilities within [X timeframe]," where an example of X is 72 hours, were largely considered appropriate. Stakeholders expressed more agreement regarding what these timeframe goals should be for moderate disasters than for catastrophic events. Interestingly, responses showed considerable anchoring around a timeframe of 72 hours. Utility representatives, moreover, tended to express longer restoration timeframe goals than user group representatives. These findings suggest that many users do not have a strong basis for suggesting performance goals, beyond the widespread emergency preparedness guideline of 72 hours, and more detailed dialogue is needed between utilities and users regarding what is likely to be experienced in a disaster, as well as the costs and benefits of mitigation alternatives that can improve this performance.

A number of limitations regarding both the modeling and the survey research should be noted. In terms of modeling, while the agent-based structure provides numerous advantages as noted above, it also entails limitations in terms of data that are available to implement such a model structure. In particular, there were several types of data that were not available at the scale and specificity required, for which inferences needed to be made from aggregate data to the agent level. In terms of the stakeholder survey, it is unclear whether different stakeholders (in particular, utility representatives v. user group representatives) were interpreting the concept of "performance goals" differently; for example, as a reflection of what should be a reasonable service goal versus what was achievable under current conditions.

The outcomes of this project suggest several areas for further research. First, the models themselves can be refined. Key research needs in this regard include incorporating transportation disruption as an additional source of economic and social disruption in disasters, and gathering further empirical data on the duration of lifeline outages that households and businesses can tolerate. Second, there is a need for a participatory process (involving workshops or focus groups, for example) by which input on utility performance goals in disasters can be solicited from multiple stakeholder groups in the community, ranging from elected officials to the emergency managers to the general public. Recommendations for such a process have been made in Section 4 of this report, and preliminary information to support its implementation have been gathered in this study. Such a participatory process is important for clarifying expectations of utility performance by end users, for developing mitigation strategies that work toward resilience goals, and for garnering broad-based support from users and decision-makers for investing in these strategies. The involvement of researchers can enhance this process by providing models to help quantify and visualize disaster outcomes and mitigation benefits. Researchers can also help design a successful participatory process that avoids common pitfalls.

SECTION 6
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SECTION 7

APPENDIX A: SURVEY INSTRUMENT

UTILITY OUTAGE AND DISASTER PREPAREDNESS

PURPOSE

The purpose of this survey is to obtain feedback from selected utility users regarding potential utility outages in earthquakes and other disasters. In major disasters, some degree of outage can be expected. We are interested in your thoughts on how much outage is acceptable, and how this should be decided. Also, we would like input on how utilities might provide information that would be most helpful to you. Your responses can help utilities to invest and prepare for disasters in ways that take into account user concerns and expectations. Ultimately, this will help the L.A. region become more resilient to disasters.

This survey should take approximately 10 minutes to complete.

QUESTIONS

Background Information:

1. Which of the following best describes your professional affiliation?
Please select one:

- ☐ Utility provider
- ☐ Emergency response organization (e.g. police, fire)
- ☐ Health care provider (e.g. hospital, clinic)
- ☐ Local government (e.g. elected official, planner)
- ☐ Community-based organization (e.g. neighborhood council)
- ☐ Business group (e.g. Chamber of Commerce)
- ☐ Non-governmental organization (e.g. Red Cross)
- ☐ Technical expert (e.g. consultant, professional organization)
- ☐ Other (Please specify here)

1a. What is your job title? (Please specify here)

Performance Goals:

2. Which of the following groups do you think should participate in developing utility service goals for disasters?

Please check all that apply:

☐ Utility provider

☐ Emergency response organization (e.g. police, fire)

☐ Health care provider (e.g. hospital, clinic)

☐ Local government (e.g. elected official, planner)

☐ Community-based organization (e.g. neighborhood council)

☐ Business group (e.g. Chamber of Commerce)

☐ Non-governmental organization (e.g. Red Cross)

☐ Technical expert (e.g. consultant, professional organization)

☐ Other (Please specify here)

3. This question provides examples (3.a. ~ 3.h.) of possible performance goals for utilities in disasters. Please select one response in each example to indicate the maximum acceptable duration of utility outage.

In the case of a **moderately damaging disaster** (on the scale of the 1994 Northridge (L.A.) earthquake):

	Less than 1 hour	12 Hours	24 Hours	72 hours	7 days	14 days	Other timeframe
a. Electricity should be available to critical facilities (e.g. police, fire, hospitals) within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)
b. Electricity should be available to 90% of the population within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)
c. Potable water should be available to critical facilities (e.g. police, fire, hospitals) within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)
d. Potable water should be available to 90% of the population within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)

In the case of a **catastrophic disaster** (on the scale of Hurricane Katrina):

	Less than 1 hour	12 hours	24 hours	72 hours	7 days	14 days	Other timeframe
e. Electricity should be available to critical facilities (e.g. police, fire, hospitals) within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)
f. Electricity should be available to 90% of the population within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)
g. Potable water should be available to critical facilities (e.g. police, fire, hospitals) within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)
h. Potable water should be available to 90% of the population within:	☐	☐	☐	☐	☐	☐	☐ (Please specify here)

4. Do you think the types of performance goals in Question 3 above are appropriate?

☐ Yes ☐ No

5. How might these goals be improved?

(Provide suggestions here)

6. Utilities must trade off between costs and benefits when making decisions about reducing disaster damage. The following is a list of potential benefits that may be considered. How important do you think it is to consider each of the following? Please select one response for each potential benefit:

	not at all important	not very important	somewhat important	very important	essential
a. Savings in the utility's post-disaster repair and emergency response costs	☐	☐	☐	☐	☐
b. Reduction in post-disaster outage time	☐	☐	☐	☐	☐
c. Reduction in outage to critical infrastructure such as hospitals, fire stations, transportation networks, etc.	☐	☐	☐	☐	☐
d. Reduction in regional economic disruption	☐	☐	☐	☐	☐
e. Reduction in disruption to people's lives	☐	☐	☐	☐	☐

f. ☐ Other consideration(s) (Please specify here)

Information Sharing:

We are interested in how utilities can best provide information to their users about potential outages in future disasters.

7. Type of Information
How helpful would each of the following types of information be for your organization's disaster planning efforts?
Please select one response for each type of information:

	not at all helpful	not very helpful	somewhat helpful	very helpful	essential
a. Maps of utility outage areas	☐	☐	☐	☐	☐
b. Time estimates of outage duration	☐	☐	☐	☐	☐
c. Number of customers without utility service	☐	☐	☐	☐	☐
d. Number of households displaced from their homes	☐	☐	☐	☐	☐
e. Number of businesses temporarily closed	☐	☐	☐	☐	☐
f. Loss of regional economic production	☐	☐	☐	☐	☐
g. Likelihood of major disruptions	☐	☐	☐	☐	☐

h. ☐ Other (Please specify here)

8. Forms of presenting uncertainty
The uncertainty associated with future disasters can be presented in different ways. How helpful would each of the following forms of presentation be for your organization's disaster planning efforts?
Please select one response for each form of presentation:

	not at all helpful	not very helpful	somewhat helpful	very helpful	essential
a. Worst-case scenario ever possible	☐	☐	☐	☐	☐
b. Worst-case scenario likely in 50 years	☐	☐	☐	☐	☐
c. Worst-case scenario likely in some other timeframe (Please specify here)	☐	☐	☐	☐	☐
d. A few scenarios of varying likelihood	☐	☐	☐	☐	☐
e. All possible scenarios together with their likelihoods of occurrence	☐	☐	☐	☐	☐

f. ☐ Other (Please specify here)

9. Means of sharing information

Information on potential outages can be presented different ways. How helpful would each of the following means be to your organization's disaster planning efforts? Please select one response for each means:

	not at all helpful	not very helpful	somewhat helpful	very helpful	Essential
a. Print information (e.g., brochures)	☐	☐	☐	☐	☐
b. CD or other electronic format	☐	☐	☐	☐	☐
c. Interactive website	☐	☐	☐	☐	☐
d. Public meetings	☐	☐	☐	☐	☐
e. Workshops	☐	☐	☐	☐	☐

f. ☐ Other format (Please specify here)

Thank you for your time in completing this questionnaire. If you have any questions or comments, please direct them along with the completed questionnaire to Kristi Tatebe, Research Assistant at ktatebe@gmail.com.

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