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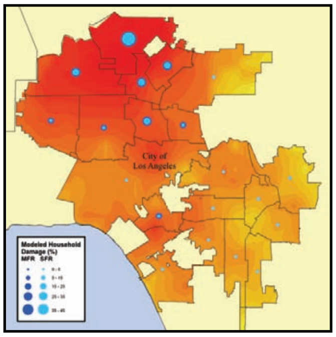
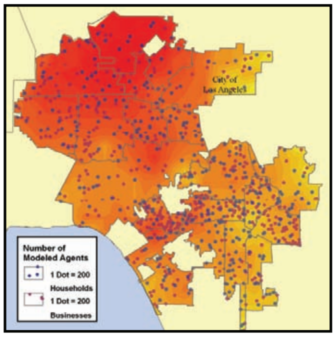
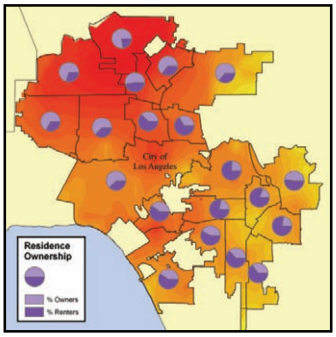
A Simulation Model of Urban Disaster Recovery and Resilience: Implementation for the 1994 Northridge Earthquake

by
Scott B. Miles and Stephanie E. Chang







Technical Report MCEER-07-0014

September 7, 2007

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A Simulation Model of Urban Disaster Recovery and Resilience: Implementation for the 1994 Northridge Earthquake

by

Scott B. Miles[1] and Stephanie E. Chang[2]

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1 Assistant Professor, Institute for Global & Community Resilience, Department of Environmental Studies, Huxley College of the Environemnt, Western Washington University
2 Associate Professor, School of Community and Regional Planning, and Institute for Resources, Environment and Sustainability, University of Brtitish Columbia

MCEER
University at Buffalo, The State University of New York
Red Jacket Quadrangle, Buffalo, NY 14261
Phone: (716) 645-3391; Fax (716) 645-3399
E-mail: *mceer@buffalo.edu*; WWW Site: *http://mceer.buffalo.edu*

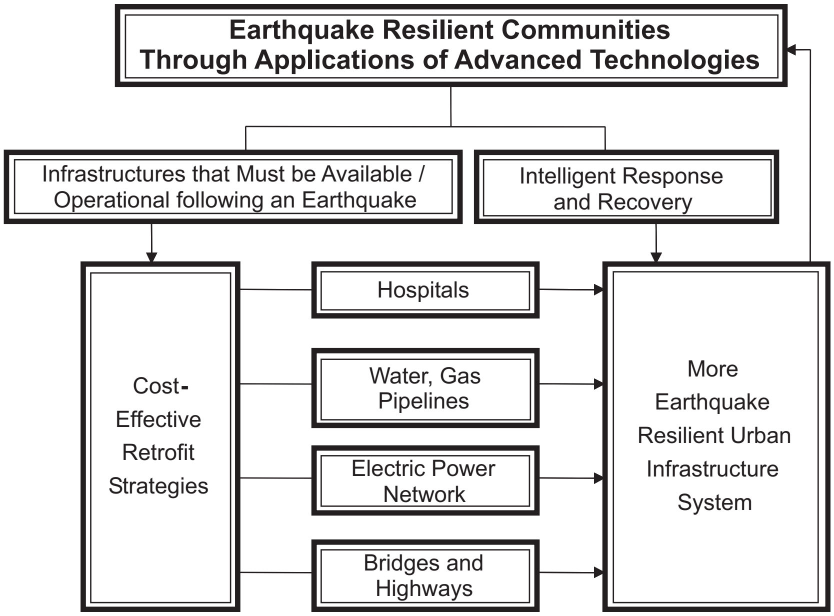
Preface

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 technical report describes a computer-based model of urban disaster recovery. The model simulates the recovery dynamics of households, businesses, neighborhoods, and the community as a whole following a disaster. The model was applied to the City of Los Angeles for the 1994 Northridge earthquake, using detailed data on the conditions and effects of the earthquake for testing and calibration purposes. Results indicated favorable performance in certain aspects of the model and identified areas where further refinements are needed. Examples of "what-if" explorations are provided to illustrate the types of analyses that can be conducted with this model. The report concludes with a discussion of potential applications, advances, limitations, and priorities for further research. The first-generation of this model was described in a previous MCEER report, "Urban Disaster Recovery: A Framework and Simulation Model," by Scott B. Miles and Stephanie E. Chang, MCEER-03-0005.

ABSTRACT

This technical report describes a computer-based model of urban disaster recovery. The model simulates the recovery dynamics of households, businesses, neighborhoods, and the community as a whole following a disaster. Building on prior work, this model represents a second-generation prototype. Like its predecessor, the model is based in the empirical literature and is distinctive in its emphasis on recovery time paths, spatial disparities, and linkages between different sectors of a community. Household recovery, for example, is influenced not only by housing damage but socio-economic attributes such as income level as well as by business recovery and the loss and restoration of critical infrastructures. Significant improvements have been made to both the underlying conceptual model and the model's implementation. A key refinement of the conceptual model pertains to the use of more meaningful indicators of recovery. With respect to implementation, the model is now fully modular in design, which provides substantially greater flexibility in implementation and testing. The model is also now scalable, allowing ready representation of any number of neighborhoods and agents within these neighborhoods. The refined model is applied to the City of Los Angeles for the 1994 Northridge earthquake. Extensive efforts were made to gather detailed data on the conditions and effects of the Northridge earthquake, and to use these data to test and calibrate the model to the extent possible. Nonetheless, available data were found to be quite limited for model calibration purposes. Results indicated favorable performance in certain aspects of the model and identified areas where further refinements are needed. Models of urban disaster recovery have several potential uses, including decision support and education. Examples of "what-if" explorations are provided to illustrate the types of analyses that can be conducted with this model. The report concludes with a discussion of potential applications, advances, limitations, and priorities for further research. One of the greatest needs is for more systematic empirical data on pre-disaster urban conditions, as well as disaster recovery.

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SECTION 1
INTRODUCTION

A community's resilience is reflected in how quickly and thoroughly it recovers from a disaster. The pace and quality of recovery are closely linked to the initial damage suffered in the disaster, the ability of the system to weather this damage, and the actions taken to respond to it. These dimensions of resilience are referred to as "rapidity," "robustness," "redundancy," and "resourcefulness" in MCEER's approach to quantifying resilience (Bruneau et al., 2003).

A community's potential to recover from a disaster is difficult to anticipate for many reasons. Recovery is both highly complex and highly uncertain. Recovery can potentially occur at different rates and ultimately attain different stable states. The resilience of a community may change over time, affecting its ability to recover from disasters. For example, with pro-active mitigation programs, the community may increase the rapidity of its recovery, perhaps reaching a higher quality stable state. If, however, vulnerability increases (e.g., urban growth continues in high-hazard areas), recovery rapidity may slow to such a degree that a lessened stable state may be obtained relative to the community's trajectory without the disaster.

One approach to developing a more systematic understanding of disaster recovery is modeling. Taking advantage of computer-based platforms for addressing computationally complex problems, recovery models can facilitate "what-if" analyses of resilience through comparison of different pre- and post-disaster scenarios. Once a basic model of community recovery is developed, it can be used to explore the effects on recovery of alterations in specific variables of interest. This can contribute insights on what variables are most influential, what types of communities are most vulnerable, and where policy interventions may be most effective. It is especially valuable to be able to characterize the effects of different policies and management plans. Such decisions range from choosing whether to retrofit a neighborhood's gas pipelines to planning to employ short-term housing instead of temporary shelters.

Miles and Chang (2003) developed a prototype model that simulates the recovery dynamics of socio-economic agents (households and businesses), neighborhoods, and communities following a disaster. This model is distinctive in its emphasis on recovery time paths, spatial disparities, and linkages between different sectors of a community. Household recovery, for example, is influenced not only by housing damage but socio-economic attributes (e.g., income level) as well as by business recovery (as businesses provide jobs) and the loss and restoration of critical infrastructures. The computer implementation of the model is based on a robust and detailed conceptual representation that facilitates application to multiple hazards, while providing significant explanatory power for interaction with decision makers and the public.

The conceptual model provides a foundation for integrating perspectives from engineering, earth science, social science, and local communities. It describes the relationships across different scales – socio-economic agent, neighborhood and community – after an earthquake occurs (Chang and Miles, 2004). The conceptual model considers attributes and behaviors of socio-economic agents and how these affect and are affected by the built environment, policy decisions, and socio-political characteristics of a community. Modeling down to the agent scale allows risk assessment to be compatible with theories of social vulnerability and risk because it facilitates questions about, for example, how disparities in household incomes within a community may affect differential experiences in damage, loss, and recovery.

Complex and meaningful simulations arise out of implementing the conceptual model to compute the socio-economic interactions over time across multiple scales. The conceptual model was initially implemented in MATLAB as a simple prototype with a restricted number of neighborhoods and agents (Miles and Chang, 2003). It was then expanded to facilitate application to the case of the catastrophic 1995 Kobe, Japan earthquake. The implementation restricted the number of neighborhoods that could be represented, but allowed for an unlimited number of agents in each neighborhood, with the limitation of requiring the number of agents to be equal in each neighborhood. The implemented model was subjected to extensive sensitivity analysis and evaluation with respect to the Kobe case study to assist in determining priorities for model improvement. To facilitate evaluation by practitioners, a graphical user interface (GUI) was developed to afford easier interaction with the computer model (as applied to the Kobe case study). The computer model and GUI was evaluated during a focus group that involved Puget Sound, Washington, area disaster planning and management professionals (Miles and Chang, 2006). The focus group was conducted to elicit practical insights about the recovery process and user needs to guide future model development efforts.

This report describes work subsequent to Miles and Chang (2006) in which many limitations or simplifications identified through sensitivity analysis, the focus group evaluation, and the authors' experience using the model have been addressed. Improvements to the model include revisions to the conceptual representation and the computer implementation. The most significant improvement to the conceptual representation of the model is revision of the recovery indicators (and dependent modeled variables) to be more relevant to planners' information needs, as suggested during the focus group evaluation. The computer implementation of the model has been extensively revised. The model has been augmented through development of spreadsheet-based input processing. The current computer model is now modular and fully scalable. Modularity means that different algorithms can be substituted easily without having to modify other aspects of the model. Scalability means that any number of socio-political jurisdictions, socio-economic agents and physical infrastructure elements can be represented (within limits of computer storage and processing capabilities). The modular implementation of the model means any technical modification of the model will be straightforward, after appropriate revision to the conceptual model. The scalability of the model allows for larger and more complex case applications of the model. The updated model was applied to simulate the 1995 Northridge earthquake, allowing the most extensive calibration and evaluation of the model to this point.

This report is comprised of seven chapters, including the introduction. Section 2 of this report describes model improvements with respect to the conceptual representation of recovery, and the computer implementation of the model. Application of the model to the Northridge earthquake disaster is described in Section 3. Section 4 addresses model calibration and evaluation of the co-event model, with post-event model calibration and results described in Section 5. Section 6 outlines preliminary experiments and sensitivity analysis run on the new model. Section 7 summarizes advances to date, areas for further research, and conclusions.

SECTION 2
MODEL DEVELOPMENT

The original design procedure for the recovery model of Miles and Chang (2003) consisted of conceptual model development followed by operationalization of the conceptual model as a prototype computer model. The conceptual model consists of the static and functional model. The former describes the structural relationships between objects, as well as the attributes and behaviors of each object. The functional model describes the relationship between inputs and outputs of specific object behaviors (or functions) independent of specific algorithms. (See Miles and Chang 2003 for a complete explanation of the process of design and the definitions of the static and functional models.) The conceptual model was first implemented in Microsoft Excel and then imported to MATLAB/Simulink, a time series simulation modeling software. Revisions to both the conceptual and computer implementation of the recovery model of Miles and Chang (2003) have been made. These are described in Sections 2.1 and 2.2, respectively. Discussions focus on refinements that have been made to the model.

2.1 Conceptual Model

The overall static model developed by Miles and Chang (2003), shown in Figure 2-1, remains the same. A community is conceptualized as consisting of a set of neighborhoods, each of which contains numerous households and businesses. Lifelines such as transportation networks are also contained in neighborhoods, although they function as systems across the community. The household and business agents are objects in this model. They are influenced by the earthquake (or other hazard agent) and interact with each other in the context of neighborhood and community conditions over the course of disaster recovery.

Changes to the static model largely consist of the removal and addition of attributes and behaviors to respective objects (e.g., households). With respect to lifelines, a significant structural change was made by representing each lifeline network as a collection of component objects. This replaces the previous concept that one object represents, for example, the entire transportation network.

Figure 2-2 shows a more detailed static model that reflects these collective changes, with new variables highlighted. Variable definitions, many of which have been revised, are given in Table 2-1. The majority of the attributes that have been removed from the conceptual model are the default driving variables, associated with an implementation technique no longer employed (described below). The model no longer employs agent variables that represent generic recovery (i.e., RECb, RECh). Instead, several more conceptually meaningful variables are used, which are described in more detail below.

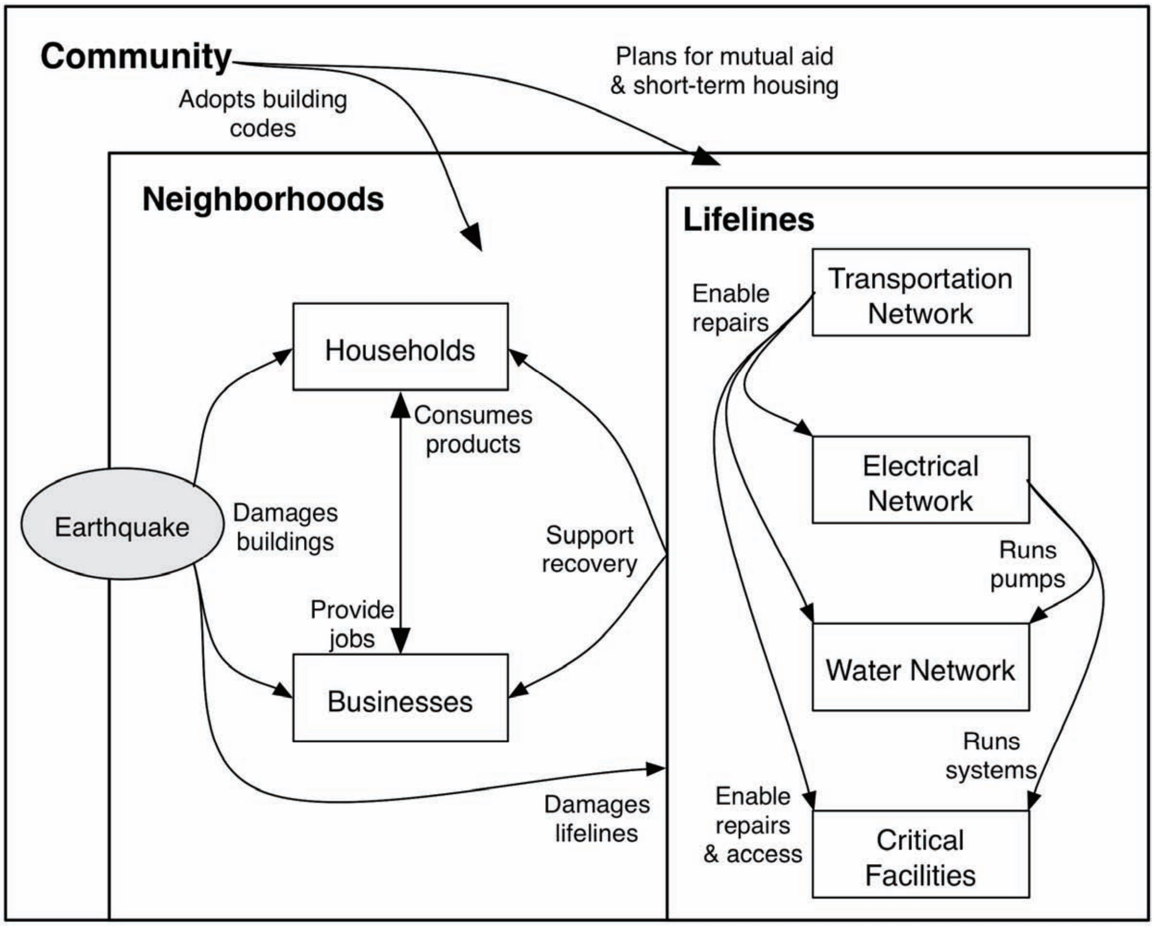

Figure 2-1 Generalized static model of community recovery from disasters

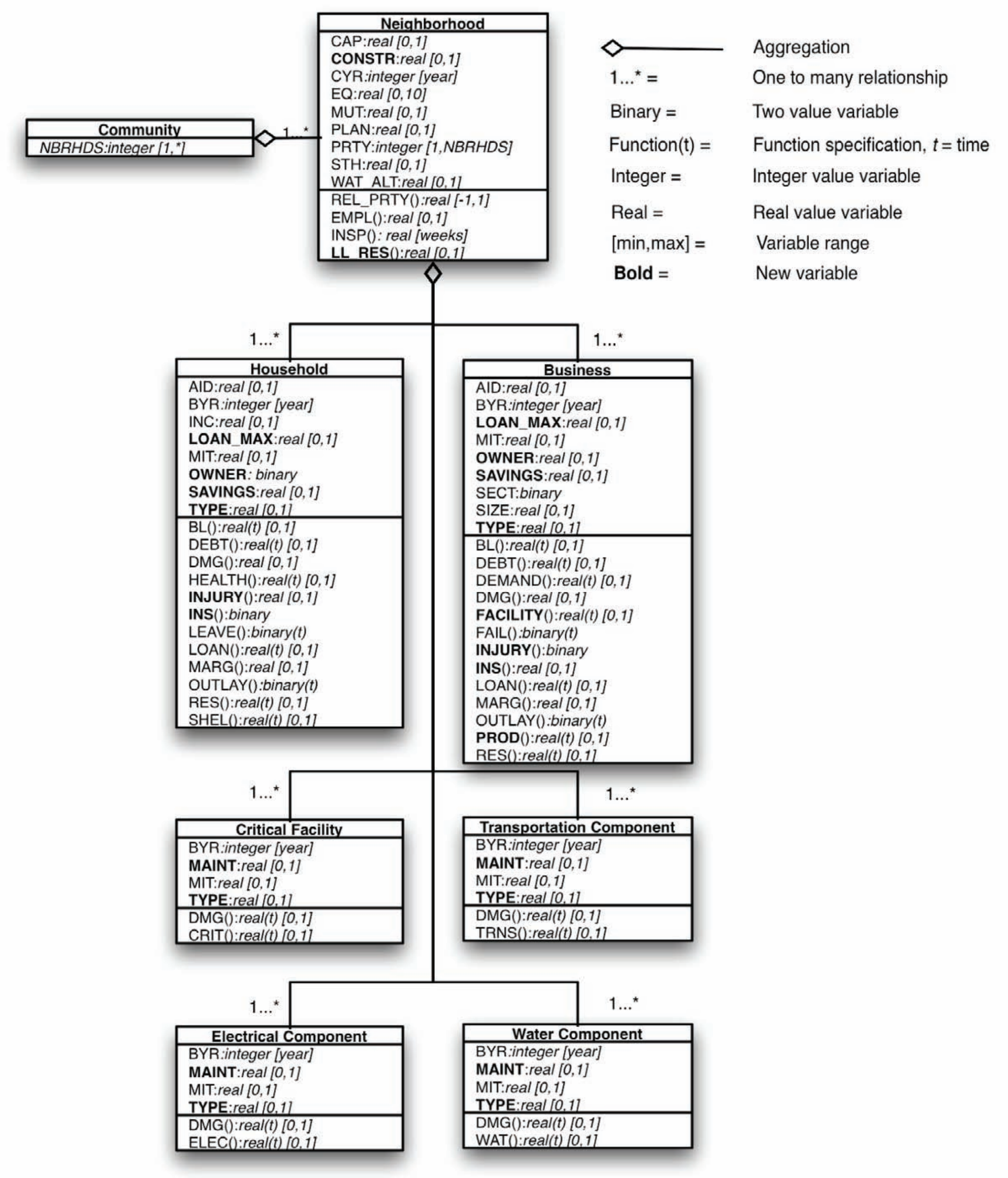

Figure 2-2 Detailed static model of community recovery from disasters.

(New variables in bold. Variable definitions given in Table 2-1)

Table 2-1 Variable definitions for recovery model

AID = Normalized post-event grant amount.
BL = Ratio of resources (materials, labor etc.) expended in reconstruction to building replacement value. Alternatively, percent to which reconstruction is complete. 0 to 1, with 1 being reconstructed.
BYR = Year building or lifeline component built.
CAP = Recovery capacity of community (proxy for integration and consensus). 0 to 1, with 1 being highest capacity.
CONSTR = construction capacity of community.
CRIT = Probability that component is fully reconstructed.
CYR = year seismic code effective
DEBT = Normalized level of debt. The inverse of LOAN.
DEMAND = Post-event demand for product. 0 to 1, with 1 indicating pre-event demand level.
DMG = Damage of building expressed as ratio of building replacement value.
ELEC = Probability that component is fully reconstructed.
EMPL = Probability that employment is available.
EQ = Severity of earthquake's physical effects. 0 to 10, Conceptually equivalent to ShakeMap intensity/MMI
FACILITY = Service level of a business's facility. 0 to 1, with 1 indicating operation at pre-event service level.
FAIL = Occurrence of business failure (Y(1)/N(0))
HEALTH = Probability that household is healthy
INC = Normalized annual income.
INJURY = Probability that household health or business demand has been injured.
INS = Whether or not an agent has insurance.
INSP = Time in weeks after event that safety inspections are completed.
LEAVE = Whether or not household has left region.
LL_RES = Overall lifeline restoration resources available in the neighborhood.
LOAN = Normalized amount of reconstruction loan taken out. Implicitly related to DMG.
LOAN_MAX = Limit on post-event loan amount.
LOAN_TIME = Time in weeks after earthquake that loan is disbursed.
MAINT = Probability that component has been well-maintained.
MARG = Pre-event financial marginality.
MIT = Pre-event structural mitigation of building or lifeline component. Currently 1 (maximum) indicates a 25% increase is fragility curve median.
MUT = Provision for mutual aid in lifeline restoration. 0 to 1, with 1 equal to maximum construction resources without mutual aid (i.e., MUT can at most double construction resources)
NBRHD = Number of neighborhoods.
OUTLAY = Whether or not an agent has received an insurance payment. 1 is implicitly defined as the replacement value of their building.
OWNER = Whether or not a household owns their residence.
PLAN = Probability of an effective restoration plan.
PROD = Probability that business is at pre-event production level.
PRTY = An absolute score given at the neighborhood level, indicating priority. The score can range from NBRHD (number of neighborhoods) to 1, with higher numbers indicating higher priority.
REL_PRTY = a relative score (-1 to 1) calculated at the neighborhood level, indicating actual inspection priority
RES = Normalized total financial resources.
SAVINGS = Normalized savings or assets.
SECT = Type of business sector (0:local or 1:export).
SHEL = Probability that household has adequate shelter and associated services.
SIZE = Normalized number of employees.
STH = Probability that short-term housing is available, Y/N.
TRNS = Probability that component is fully reconstructed.
TYPE = Type of building or lifeline component—a proxy for size and/or complexity for reconstruction. 0 to 1, with 1 indicating largest or most complex building/component type.
WAT_ALT = Provision for alternate water sources (water trucks) for neighborhood. 0 to 1, with 1 being equivalent to maximum total water service in neighborhood (WATn = 1)
WAT = Probability that component is fully reconstructed.

Notes: Object attributes (exogenous variables) in bold. Decision variables in bold underline.

Revision of model variables led to a need to revise the functional model, which describes how outputs are related to inputs. Also, to simplify interpretation and management of the model, an effort was made to reduce the number of times the same variable is a direct input to multiple functions. That is, if a variable is an input to function A and function B, and function B is also dependent on the output of function A, the variable was removed from function B unless there was a strong conceptual reason not to do this. The revised functional dependencies are given in Table 2-2.

2.1.1 Agent Recovery Concepts

The generic (aggregated) recovery variable used for agents in the previous version of the model has been dropped. Instead two indicators for business and household agents represent recovery, each having a more concrete real-world analog. The agent recovery indicators are based on general concepts: (1) ability to perform and (2) opportunity to perform. These concepts are influenced by an agent's shelter/facility service level, as well as their financial debt. In turn, the opportunity and ability to perform influence whether an agent is forced to fail/leave. The specific variables for households and businesses are described below. As part of this revision to the recovery variables, the model no longer represents recovery as four distinct stages.

2.1.2 Household Recovery

For households, the ability to perform is represented by household health (HLTH). Among other variables, health is directly influenced by availability of critical facilities (CRIT) and serviceability of shelter (SHEL, either their own residence or short-term housing). Shelter serviceability is influenced not only by residence reconstruction (BL), but availability of lifeline services (WAT and ELEC). Reconstruction time is now influenced by the size (TYPE, single-family vs. multi-family) of the respective building in addition to the construction capacity in the community (CONSTR). Reconstruction can only begin after inspections have been completed in the neighborhood (INSP), which is influenced by the quality of the preparedness plan, the recovery capacity of the community (CAP), and the neighborhood's priority (PRTY). Health influences a household's ability to pay off any incurred debt (DEBT). The current version of the model accounts for whether or not a household owns their residence (OWNER) so that if they do not, they do not incur debt with respect to any reconstruction loans. The opportunity to perform is represented by employment level in their neighborhood and broader community (EMPL). Employment influences a household's opportunity to pay off any incurred debt. Debt is one of the main influences of whether a household is forced to leave their neighborhood (LEAVE).

Table 2-2 Functional dependencies between variables of the recovery model

Community/Neighborhood
REL_PRTY = f(PRTY, NBRHDS)
INSP = f(EQ_AVG, PLAN, CAP, REL_PRTY)
LOAN_TIME = f(EQ_AVG, PLAN, CAP, REL_PRTY)
NBRHD_EMPL = f(PRODn, DEMn)

Businesses
DMG = f_{cdf}(SAVINGS, BYR, BMIT, CYR, EQ)
INJURY = f_{cdf}(SIZE, EQ)
MARG = f_{rand}(SIZE)
INS = f_{rand}(OWNER, SIZE)
OUTLAY = f(INS, INSP)
LOAN = f(OUTLAY, DMG, LOAN_TIME, MARG, LOAN_MAX, AID)
LOAN_TIME = f(INSP)
RES = f(LOAN, AID, SAVINGS, OUTLAY)
BL = f_m(INSP, RES, BTYPE, CONSTR)
FACILITY = f(ELECn, BL)
PROD = f_m(FACILITY, TRNSn, TRNSc, SIZE, HEALTHc, FAIL)
DEM = f_m(SECT, DEBTc, DEBTn, SIZE)
DEBT = f(DEM, SIZE, LOAN, PROD, LOAN_TIME, FAIL)
FAIL = f_m(FACILITY, DEM, DEBT, PROD)

Households
DMG = f_{cdf}(SAVINGS, BYR, MIT, CYR, EQ)
INJURY = f_{cdf}(INC,DMG)
MARG = f_{rand}(INC)
INS = f_{rand}(MARG, INC, OWNER)
OUTLAY = f(INS, INSP)
LOAN = f(OUTLAY, DMG, LOAN_TIME, MARG, LOAN_MAX, AID)
LOAN_TIME = f(INSP)
RES = f(LOAN, AID, SAVINGS, OUTLAY)
BL = f_m(INSP, RES, BTYPE, CONSTR)
SHEL = f(STH, ELECn, WATn, BL)
HEALTH = f_m(CRITn, RES, SHEL, LEAVE)
DEBT = f(HEALTH, INC, LOAN, NBRHD EMPL, LOAN_TIME, LEAVE)
LEAVE = f_m(SHEL, HEALTH, DEBT, NBRHD, EMPL)

Lifelines
DMG = f_{cdf}(MAINT, CRIT_BYR, CRIT_MIT, CYR, EQ)
LL_RES = f(MUT, CONST, PLAN, CAP, PRTY, NBRHDS)
CRIT = f_m(CRIT_TYPE, LL_RES)
TRNS = f_m (TRNS_TYPE, LL_RES)
ELEC = f_m(ELEC_TYPE, LL_RES, TRNSc)
WAT = f_m(WAT_TYPE, WAT_ALT, LL_RES, TRNSc, ELECn)

Notes: n — variable averaged over the neighborhood. C — variable averaged over the community. f_{cdf} - Function implemented using lognormal cumulative distribution function fragility curve(s). f_{rand} – Function implemented using uniform random number generator. f_m – Function implemented as a Markov Chain.

2.1.3 Businesses Recovery

For businesses, the ability to perform is represented by a business's capacity to be productive (not necessarily economic productivity or throughput) (PROD). The service level of a business's physical facility (FACILITY) influences this capacity, which is in turn influenced by a combination of reconstruction (BL) and lifeline service restoration (WAT and ELEC). Reconstruction time is now influenced by the complexity or size of the respective facility (BTYPE), in addition to the construction capacity in the community (CONSTR). Reconstruction can only begin after inspections have been completed in the neighborhood (INSP), which is influenced by the quality of the preparedness plan (PLAN), the recovery capacity of the community (CAP), and the neighborhood's priority (PRTY). The ability to perform is also influenced by the community-wide health level of households and by the transportation network reconstruction level (TRNS) (within the neighborhood if the business's sector (SECT) is locally oriented, or throughout the community if the sector is export-oriented). A business's ability to perform influences its ability to pay down any debt (DEBT). Similarly to households, businesses do not incur debt from reconstruction loans if they do not own their facility (OWNER). The opportunity to perform is represented by the demand for a business's product or services (DEMAND). Recovery of demand is influenced by some proportion of household debt within the respective neighborhood or the entire community, depending on the business's size (SIZE). Demand influences a business's opportunity to pay down any incurred debt, which in turn influences whether the business fails (FAIL).

2.1.4 Agent Financial Resources

The ability of an agent to reconstruct their residence or facility is influenced by their financial resources (RES). In the previous version of the model, this variable was not a simple aggregation of distinct financial resources. In the current model, however, it is the sum of insurance (INS), reconstruction loans (LOAN), disaster aid in the form of grants (AID), and pre-event savings (SAVINGS). In the previous version of the model there was no representation of grants; AID was conceptualized in the previous version as indicating the availability of loans. If the agent owns their building or facility, the maximum level of financial resources is implicitly related to the value of the building or facility. Whether or not an agent has insurance (and what amount) is now conceptually distinct from when the insurance is outlaid (OUTLAY). All elements of the financial resources are agent-specific, however a maximum value for loans (LOAN_MAX) can be specified at any resolution from agent-specific to community-wide.

2.1.5 Lifeline Restoration

To facilitate eventual representation of service outage for critical facilities, electricity, transportation, and water, all lifelines are represented as a set of components. Each component has values for attributes of construction age, maintenance level, component type, and degree of structural mitigation. In the previous version, lifelines were represented in aggregate at the neighborhood scale, having only a neighborhood-wide attribute of structure mitigation level. Currently, the model conceptually equates lifeline service restoration and lifeline component reconstruction for critical facilities, electricity, transportation, and water networks (CRIT, ELEC, TRNS, WAT). The time in which a particular lifeline component is reconstructed is influenced by new variables—the particular type of component (e.g., transformer vs. power line) (TYPE) and the overall lifeline restoration resources (LL_RES) available in the neighborhood. The neighborhood lifeline restoration resources is influenced by to the construction capacity in the community (CONSTR), the quality of the preparedness plan (PLAN) and mutual aid agreement (MUT), the recovery capacity of the community (CAP), and the neighborhood's priority (PRTY).

2.2 Improved Implementation

A majority of the work in revising the recovery model consisted of changes to the implementation of the conceptual model. Implementation refers to both the algorithms used in specifying the functional dependencies of the conceptual model and software design (in this case within MATLAB). A significant number of software design changes were made, including splitting the model into two (co-event and post-event models), making the model modular and scalable, and facilitating model inputs using Microsoft Excel files. From the standpoint of algorithm implementation, the most significant change is dropping use of several deterministic "driving variables"—simple linear equations used to create the dynamics of the simulation—thereby eliminating the majority of the arbitrarily defined multivariate polynomial equations. This change was accomplished through use of Markov chain modeling (described further below). The other significant algorithm implementation change was made in the use of fragility curves to calculate damage and injury (a new variable). The implementation improvements lead an (intended) improvement in how hazards are represented in the model. Each of these improvements is described in turn below.

2.2.1 Software Design Revisions

Both conceptually and as implemented, the model separates representation of pre-event/co-event dynamics from post-event dynamics. One advantage of this is that a series of events can be simulated by linking several co-event and post-event models. The co-event model simulates a series of variables that relate to conditions prior to and immediately following the earthquake. This includes an agent's pre-event financial marginality (MARG) and whether an agent has insurance at the time of the event. For household agents, the immediate effect of the hazard event on health (household injury) is simulated. For business agents, the immediate effect of the event on business demand is simulated. For all agents and all lifelines, damage to built infrastructure (i.e., buildings or lifeline components) is simulated. The post-event model simulates variables relating to conditions over time as the community and its constituent agents and elements recover in the weeks and months following the disaster. This includes restoration of built infrastructure with respect to agents and lifelines, as well as the various recovery indicators (and intermediate variables) described above.

All major conceptual or implementation features of the model have been encapsulated in separate Simulink models. Beforehand, the recovery model was one large Simulink model (though graphically organized by features). The model is now truly modular, meaning that the method in which a particular model is implemented can be changed without affecting compilation of the overall (co-event and post-event) model. Further, the modularity facilitates substituting a data source for a model reference. For example, rather than modeling lifeline restoration, actual lifeline restoration time-series data can be used.

The model now supports any number of neighborhoods, with each neighborhood having any number of agents. The number of neighborhoods was hard-coded in the previous version of the model. The previous version of the model also required that all neighborhoods have the same number of businesses and households (e.g., all neighborhoods had to have both 100 households and businesses). As implemented now, the number of neighborhoods and agents is determined by the input data. That is, at run-time, the model allocates arrays to match the number of neighborhoods and agents for which there is data. This revision should facilitate implementation of agent migration features into the model in future.

To facilitate the compilation of larger input data sets, a data input tool has been built to input data from Microsoft Excel for running the model. The input data can be specified as MATLAB workspace variables or can be imported (using the new tool) from a series of Excel files. Seven Excel files are required to describe, respectively, (1) community-wide and policy variables for each neighborhood, (2) households and their attributes for each neighborhood, (3) businesses and their attributes for each neighborhood, and (4~7) the components of each respective lifeline (critical facilities, electrical network, transportation network and water network) and associated attributes for each neighborhood.

2.2.2 Algorithm Implementation Revisions

For all dynamic functions (sub-models), except for the function for calculating debt, Markov chains have replaced the use of "driving variables." So rather than most variables serving to influence the default driving variable (slope value and intercept), most variables are treated as probabilities. For a particular dynamic output then, each state is calculated as a comparison between a uniform random number and the aggregation of all input variables (probabilities). Functions for which Markov chains have been implemented include building and lifeline component restoration, health recovery, business demand recovery, business production recovery, and whether an agent leaves/fails.

Currently the model is specified with a set of four fragility curves that relate MMI or the USGS TriNet ShakeMap shaking intensity scale (0 to 10) to four levels of building and lifeline component damage (25%, 50%, 75%, 100%) (DMG). Because of its role in determining loan (LOAN) amounts, DMG is implicitly the ratio of damage cost to the total replacement value. (To be consistent, damage to lifeline components can be conceptualized similarly, though there are not parallel concepts of loans and insurance for lifelines in the model.) Each fragility curve is a lognormal cumulative distribution function. The fragility curves representing the four damage levels differ by the respective median and variance. The median values for each agent are determined by their building age (CYR vs. BYR) and building/facility type for households and businesses. Currently, the median values for respective lifeline components are determined by the component's age and level of maintenance (MAINT). Modeled damage level is equal to the highest damage level in which the probability for a given shaking intensity exceeds a normally distributed random number. Structural mitigation of buildings/facilities and lifeline components is now represented as a uniform increase in the median value of each damage level's fragility curve. Currently, the maximum increase in median value is 25%.

The effects on agents' well being is also determined using fragility curves. However, in this case only one fragility curve is used (that is, not one for each level). The immediate post-event household health state is determined by the calculated injury level (INJURY). The fragility curve for household injury is a lognormal cumulative distribution function that relates building damage to injury probability. The median of the fragility curve increases with increasing household income (INC). That is, increasing income levels will result in lower probability of injury. The immediate post-event business demand level is determined as the "injury" to a business's demand (INJURY). The fragility curve for business demand reduction is a lognormal cumulative distribution function that relates shaking intensity to demand reduction probability. The median of the fragility curve increases with increasing business size. That is, increasing business size will result in lower probability of reduced demand for product/services.

In the previous version of the model, earthquake shaking intensity was represented on a scale from 0 to 1. Now the representation of generic hazard is controlled by the use of fragility curves. This means that the form of the model's fragility curves dictates the units and scale of input data describing the hazard. The hazard now can be represented at the agent and lifeline component scale. While the model still represents the location of agents at the spatial resolution of neighborhoods, representing the hazard by agents facilitates representation of a wider spectrum of hazard scenarios. For example, a terrorist attack may target all very large, export-oriented businesses or, alternatively, all major transportation network components. (Note that input data tools and input-output operations for this have not been developed, but the model implementation does currently allow for it.) Increased spatial resolution is facilitated in the current version of the model by allowing for an unlimited (within the constraints of MATLAB) number of "neighborhoods" (spatial units). With such a resolution, for example, the confined pattern of a flood can be represented.

Now multiple hazard events can be represented over time by arranging a series of Co-Event/Post-Event Model runs. For example, the effects of a main shock earthquake can be modeled, followed by recovery modeling for, say, four weeks, followed by the modeling of the effects of an aftershock and subsequent recovery. (Again, the data input tools and input-output operations have not been developed for this, but the implementation allows for it.) In this way, small intensity, long duration events can be represented the model.

SECTION 3
NORTHRIDGE APPLICATION

The previous versions of the recovery model have been applied to a fictional city (Chang and Miles, 2004) and Kobe, Japan (Miles and Chang, 2006) for the purposes of evaluating and calibrating the model. The revisions to the model make it necessary to evaluate and calibrate the model again. We chose to apply the recovery model to the 1994 M=6.7 Northridge, California earthquake, which in terms of financial losses is still one of the worst disasters in United States history (Petak and Elahi, 2001). Moreover, among U.S. earthquakes, this is probably the best-documented and most thoroughly studied. In applying the previous version of the model to Kobe, Japan, large simplifications were required in representing the disaster because of limitations of the model. However, the amount and quality of data available on the recovery of Kobe made these simplifications worthwhile. Now that the model can handle any number of neighborhoods, agents, and lifeline components, application to Northridge (and the higher volume and quality of associated data and information) makes more sense.

The model was applied to the City of Los Angeles, California, which included the areas of highest shaking intensity and greatest loss. Application of the model consists of developing datasets to parameterize each of the endogenous inputs listed in Table 2-1, as well as running the model—specifically, the co-event and post-event models. Nine neighborhood level variables had to be parameterized (CAP, CONSTR, CYR, EQ, MUT, PLAN, PRTY, STH, WAT_ALT). All but EQ was assumed to be the same value inside the Los Angeles city boundary. Based on a review of the literature, the maximum value (1) was assigned to the variables representing the recovery capacity (CAP), construction capacity resources (CONSTR), the effectiveness of mutual aid (MUT), the quality of a pre-disaster plan (PLAN), and the use of short-term housing (STH). Recovery capacity and general preparedness was high because of previous earthquakes in Southern California, such as the 1971 San Fernando earthquake. The pre-disaster plan had been adopted soon before the Northridge earthquake (Wu, 2003). For short-term housing, high apartment vacancy rates allowed effective use of rent vouchers to provide housing (Loukaitou-Sideris and Kamel, 2004; McCarty et al., 2005). Mutual aid was either in place or set in motion with respect to at least emergency management, water network repair, and building inspection (Comfort, 1994; EQE, 2001, Loukaitou-Sideris and Kamel, 2004). To our knowledge, no major alternative water source (WAT_ALT) was employed after the earthquake to aid recovery. We chose to set the building code year (CYR) as 1976, reflecting the major improvements in building standards that were in place by that time as the result of the San Fernando earthquake. Data characterizing earthquake ground shaking (instrumental intensity) for the Northridge earthquake were gathered from the USGS TriNet ShakeMap system, clipped to the boundary of Los Angeles, and averaged for each neighborhood unit (defined below).

In general, data describing agent demographics and the lifeline system had to be gathered and processed for input into the model, in addition to data describing the spatial distribution of ground shaking severity. Demographic data describing attributes of households and businesses were developed based on gathered census information and, for variables lacking adequate primary data, data simulation. The components for modeling lifeline recovery were not evaluated as part of this study. Instead, time series data describing the restoration of service for each lifeline type was developed and used directly as input to the recovery model. This facilitated focusing on the household and business aspects of the model, while demonstrating the modularity of the model—in this case, substituting data for model components. Data processing for application of the recovery model was done using geographic information systems (GIS) and spreadsheet software. An overview of data sources used for the Northridge application is given in Table 3-1. Specific data development for the agent demographics and lifeline system attributes are described in the following two sections.

Table 3-1 Overview of major data sources for Northridge application

Feature	**Data Sources**
Northridge earthquake ground motion	US Geological Survey TriNet ShakeMap, http://earthquake.usgs.gov/eqcenter/shakemap/sc/shake/Northridge/
Boundaries	
Los Angeles Community Planning Areas	Department of City Planning, City of Los Angeles (email request)
Public Use Microdata Units	University of Minnesota Population Center's Integrated Public Use Micro Data, http://usa.ipums.org/usa/
Zip Code Areas	US Census Bureau Zip Code Tabulation Areas, http://www.census.gov/geo/www/cob/z52000.html
Household demographics	University of Minnesota Population Center's Integrated Public Use Microdata Series, http://usa.ipums.org/usa/
Business demographics	U.S. Census Zip Code Business Pattern Standard Industrial Classification, http://censtats.census.gov/cbpsic/cbpsic.shtml
Lifelines	Various secondary literature sources (described below)

3.1 Agent Demographics

Demographics for both households and businesses were characterized using information from the US Census Bureau. However, the resolution, detail, and direct sources of the data differed dramatically. Household data available at the census tract level is an average of individual census survey response (to maintain anonymity). The recovery model requires data about specific households and their attributes. We chose therefore to use 1990 Public Use Microdata 5% State Sample from the University of Minnesota Population Center's Integrated Public Use Microdata Series (PUMS) (originally collected by the US Census Bureau). This data set provides individual records of households from a 1-in-20 national random sample of the census population for areas no smaller than 100,000 people. These areas are referred to as PUMAs (Public Use Microdata Areas).

There are 21 PUMAs within the City of Los Angeles. Thus, the number of neighborhoods represented in the recovery model corresponds to the 21 PUMAs in Los Angeles. A map showing the L.A. PUMAs and their relation to the L.A. Community Planning Areas (i.e., official neighborhoods) is given in Figure 3-1. The sample size across these PUMAs consisted of a total of 67,440 households (Figure 3-2).

For businesses, data readily available through the US Census is much less detailed and is provided for different spatial units than data available for households. We used 1994 Zip Code Business Patterns data for parameterizing the model. These data describe the number of different businesses by size in each Standard Industrial Classification sector. The data were aggregated within each PUMA to provide a common spatial unit of analysis with the household demographics. The total number of businesses in Los Angeles represented by this data is 102,684 (Figure 3-2). Note that unlike the household data, this data is not a sample of the population, but rather represents the entire population. However, the data may undercount the number of small businesses.

For both households and businesses, the available data did not cover all agent-attribute variables of the recovery model, requiring some data to be simulated for the purpose of parameterizing the model. Also, all demographic data required some processing—even if data existed for a particular variable—to translate the data into the units of analysis required by the model (i.e., most variables have a maximum value of 1 and a minimum of 0, requiring some normalization). The development and distribution of data describing each household and business variable within the recovery model is discussed, respectively, in the following sub-sections.

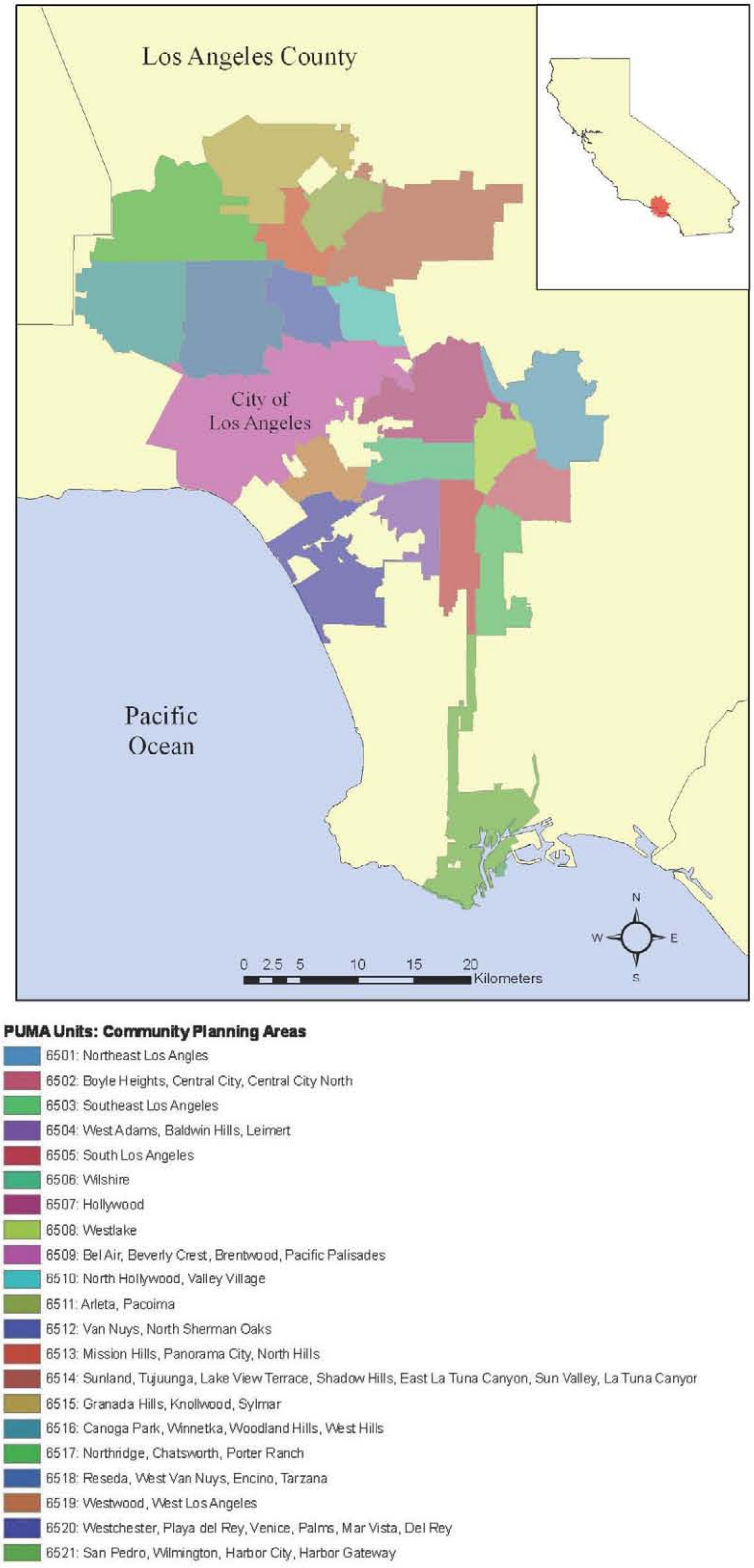

Figure 3-1 Map showing Public Use Microdata Units for the City of Los Angeles—the neighborhood unit for application of the recovery model

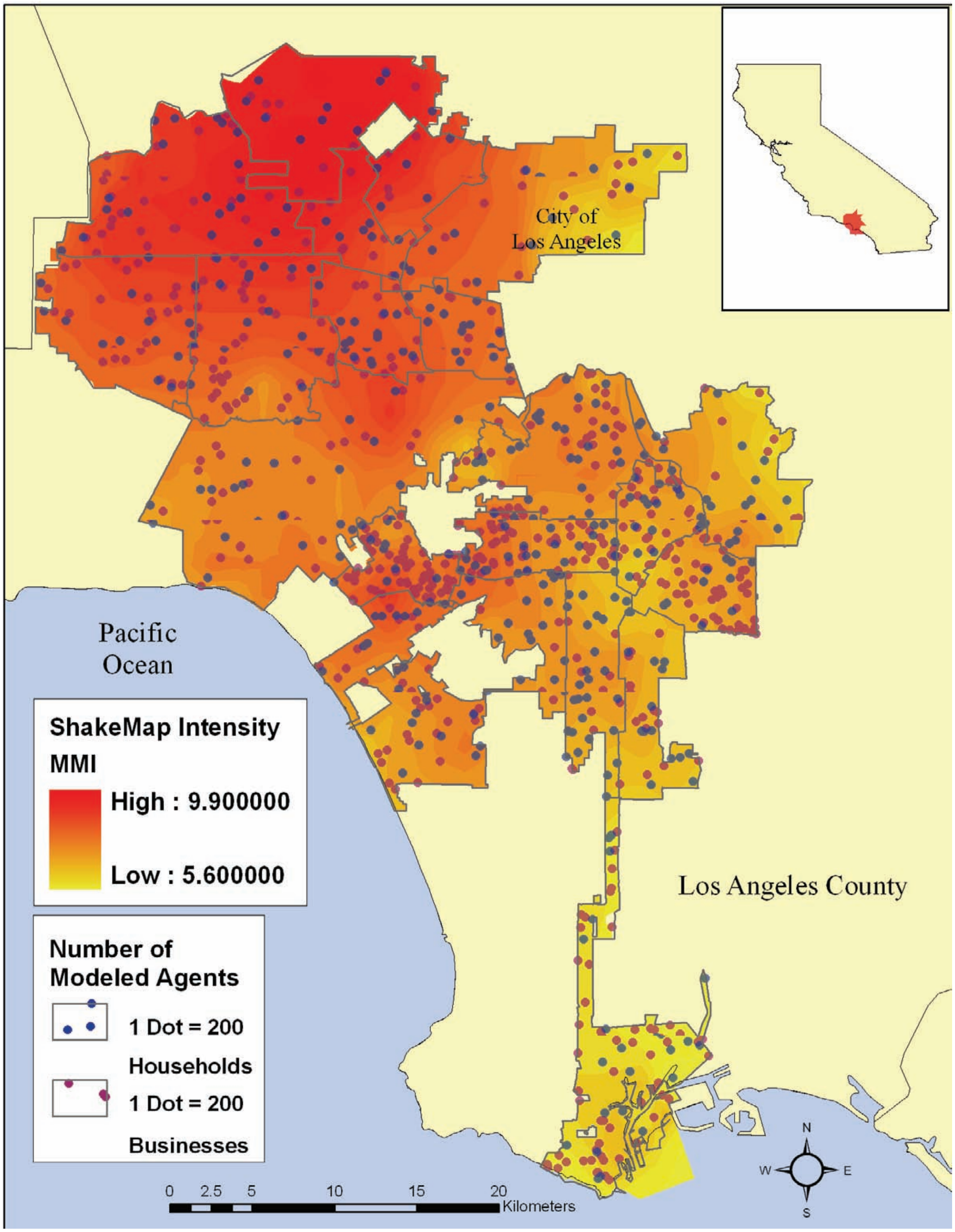

Figure 3-2 Map showing number of Los Angeles businesses and households modeled for application to the Northridge earthquake. Household data is based on the 1990 census; business data is based on the 1994 economic census

3.2 Households

From the PUMS dataset, there were data available to directly describe several attributes of households: income (INC), building year (BYR), building size (TYPE), and ownership (OWNER). For parameterizing INC, each income value (in dollars) was normalized by the 95th percentile income of the Los Angeles, which was calculated to be $125,000, to get income values that ranged from 0 to 1 (incomes greater than $125,000 were assigned a value of 1). Figure 3-3 shows a map of the distribution of high versus low incomes across Los Angeles. For the map, high income is defined as greater than half the 95th percentile income. Data describing whether the household owned their residence was translated such that a household that owned their residence had OWNER=1, while a household that didn't had OWNER=0. Spatial distribution of residence ownership is shown in Figure 3-4. Data describing the age of the building in which the household resided was available from the PUMS dataset, but the ages were given as ranges (e.g., 2 to 5 years old). To translate this data into an estimation of the year the structure was built, the minimum age value for each range was subtracted from 1990 (the census year). No residences newer than 1990 were represented in the simulation of the 1994 Northridge disaster. The lack of residences newer than 1990 has little effect because the model uses BYR to compare to see if it exceeds the code year (CYR), which for this application was set to 1976. The variable TYPE was parameterized using data on the number of units in the structure in which the particular household resides. The PUMS data describes whether a structure is a single-family house or one of six sizes of multi-family building (2, 3-4, 5-9, 10-19, 20,-49, and 50+ family units). A single-family home was assigned a TYPE=0, while multi-family buildings were assigned a value corresponding to the minimum number of units in the particular range divided by 50 (the maximum number of units). Figure 3-5 shows a map of the proportion of single- versus multi-family buildings in each LA PUMA.

The PUMS dataset did not provide data describing household savings (SAVINGS), structural mitigation (MIT), aid amount in the form of grants (AID) given to each household after the earthquake, or the post-earthquake loan amount provided to each household. Household savings was estimated by subtracting annual costs tracked by the census (e.g., rent/mortgage, utilities, etc.) from the household's annual income and divided by the value of the house. For renters, SAVINGS=0 was assigned, which is intended to represent that multi-family building residents or owners are unlikely to use personal savings to pay for reconstruction.

No data (that we're aware of) exists on the degree to which each residence had been structurally retrofitted at the time of the Northridge earthquake. Thus, we simulated this data based on data from the PUMS dataset, with the general assumption that very large residences were more likely to have been retrofitted. The simulation algorithm used a random inverse normal distribution (i.e., enter a uniform random number as the probability into a normal curve to get the simulated value). If a structure had 10 or more units, we assumed the average MIT=0.5 with a variance of (1-INC)*(1990-BYR). This reflects a decreasing chance and quality of mitigation with decreasing income, combined with an increasing chance with increasing building age. For buildings with less than 10 units, we assumed the mean MIT=0 (no retrofit) with a variance of INC*(1990-BYR). This reflects increasing likelihood and quality of mitigation with increasing income, combined with an increasing chance with increasing building age. Figure 3-6 shows the modeled proportion of households with high versus low levels of structural mitigation done to their residence.

The amount of post-earthquake grant and loan assistance available to households was estimated based on requirements set out by the Federal Emergency Management Agency (FEMA) and the Small Business Association (SBA) after the Northridge earthquake. For grant assistance, no funds were available to households that didn't own their residence. This is both due to the fact that renters would obviously not be given assistance to rebuild their residence and that, at the time, only loans were available to apartment owners for reconstruction assistance (Tierney, 1995; Johnston, 2000). For households that owned their residence, the maximum grant amount was set at \$22,200, which is the sum of available grants from FEMA's homeowner's grant programs (Loukaitou-Sideris and Kamel, 2004). For input into the model AID was set equal to this amount normalized by the value of the household's home. Within the model, the grant amount actually disbursed to households is based on the cost of damage to the house—each household is not necessarily given the maximum grant amount. The maximum available loan amount was also estimated differently for renters and owners. For renters, because the maximum amount that SBA would provide apartment owners—\$1.5 million (Johnston, 2000) —exceeded the top code of the census data on building value (\$999,999), LOAN_MAX=1 (Loukaitou-Sideris and Kamel, 2004). In reality, of course, the loan would be given to the owner of the building, not to the renter, but the recovery model does not currently represent this level of detail for rental units (including tracking what agents live in the same building). For owners, the maximum available loan was \$200,000 (Loukaitou-Sideris and Kamel, 2004), which, for input into the model, was normalized by the value of their building.

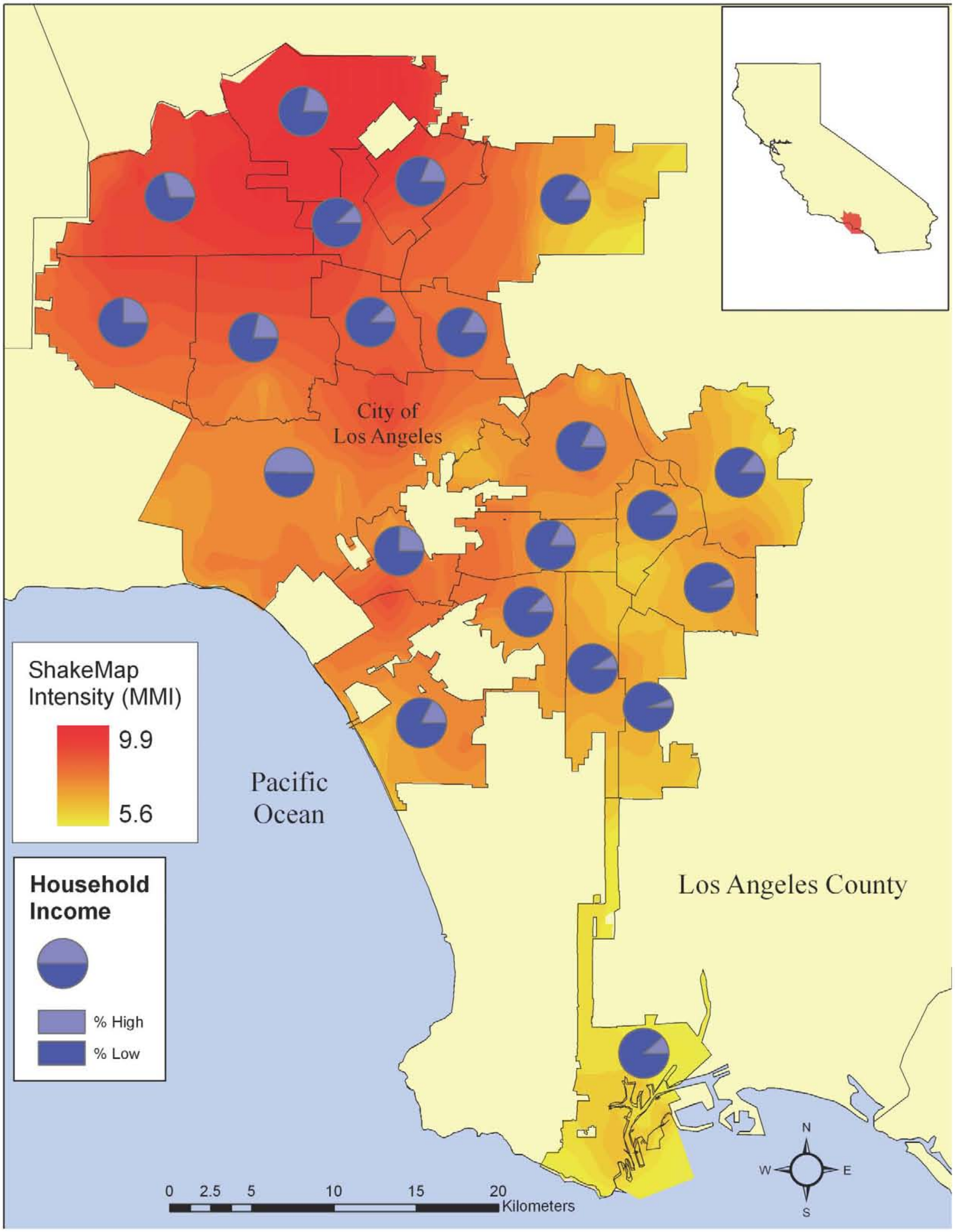

Figure 3-3 Proportion of higher and lower income households. The threshold is INC = 0.5 or $62,500 (half of the 95th percentile income of the area in 1990), based on the 1990 census

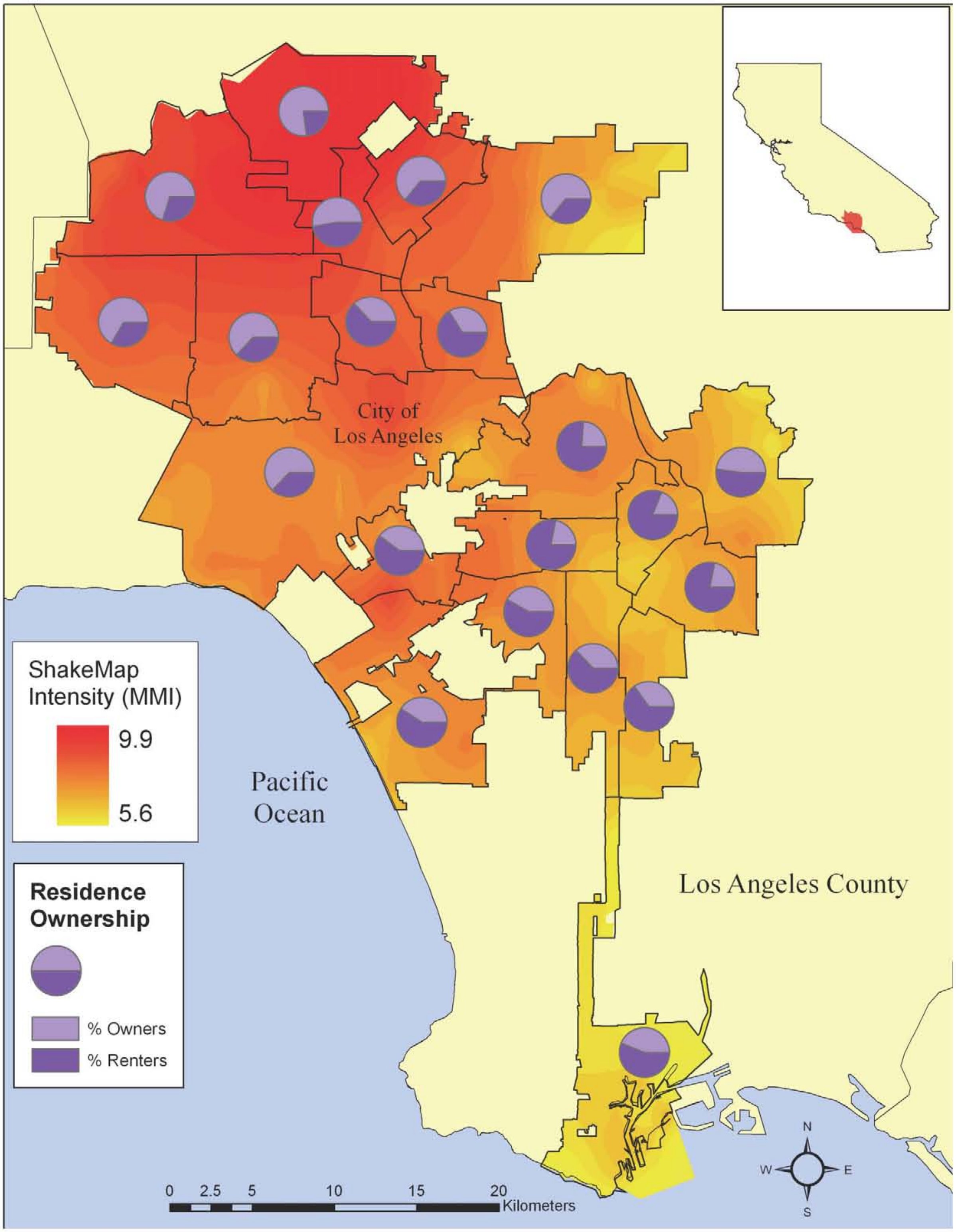

Figure 3-4 Proportion of households who own versus rent their residence, based on the 1990 census

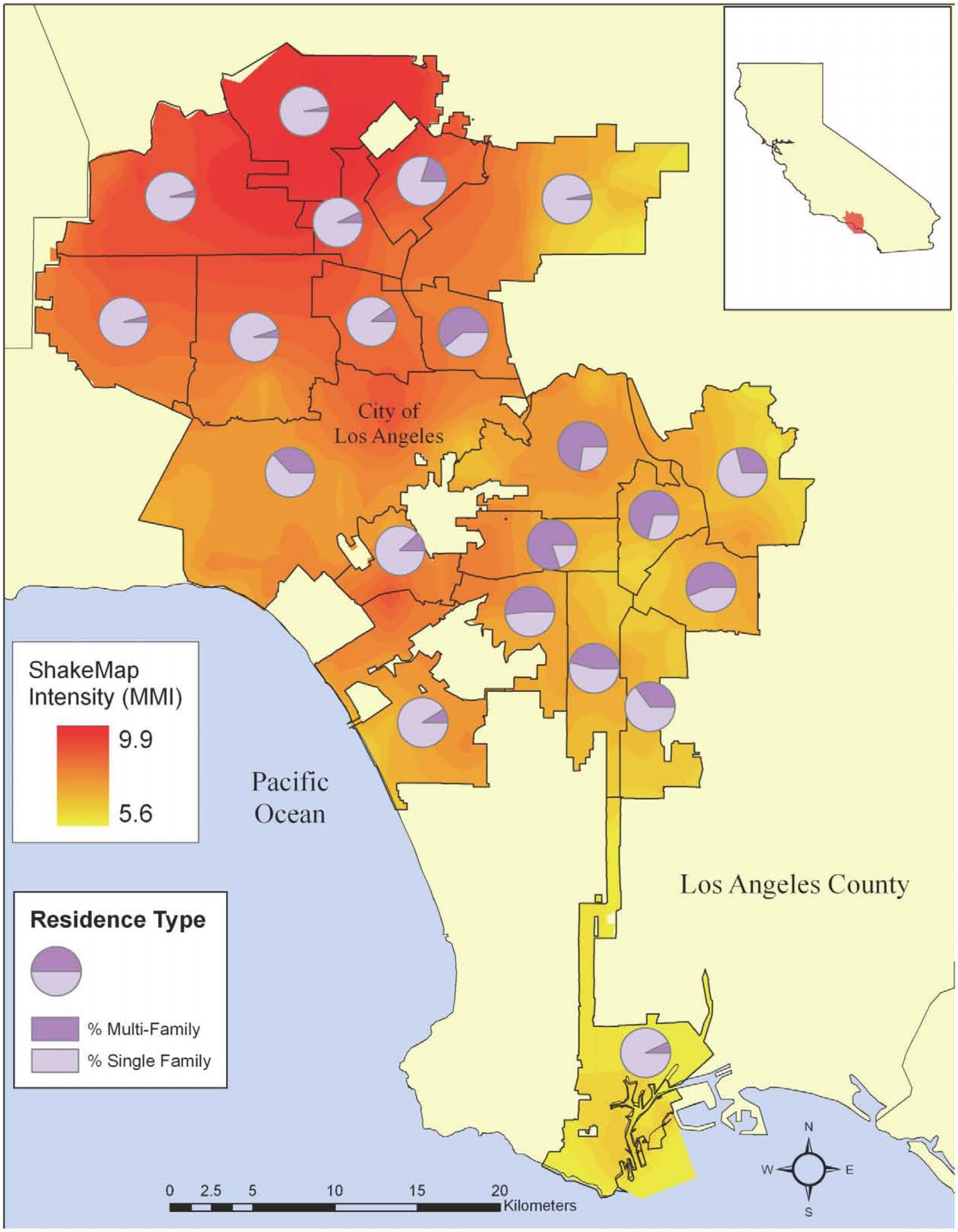

Figure 3-5 Proportion of single- versus multi-family buildings, based on the 1990 census

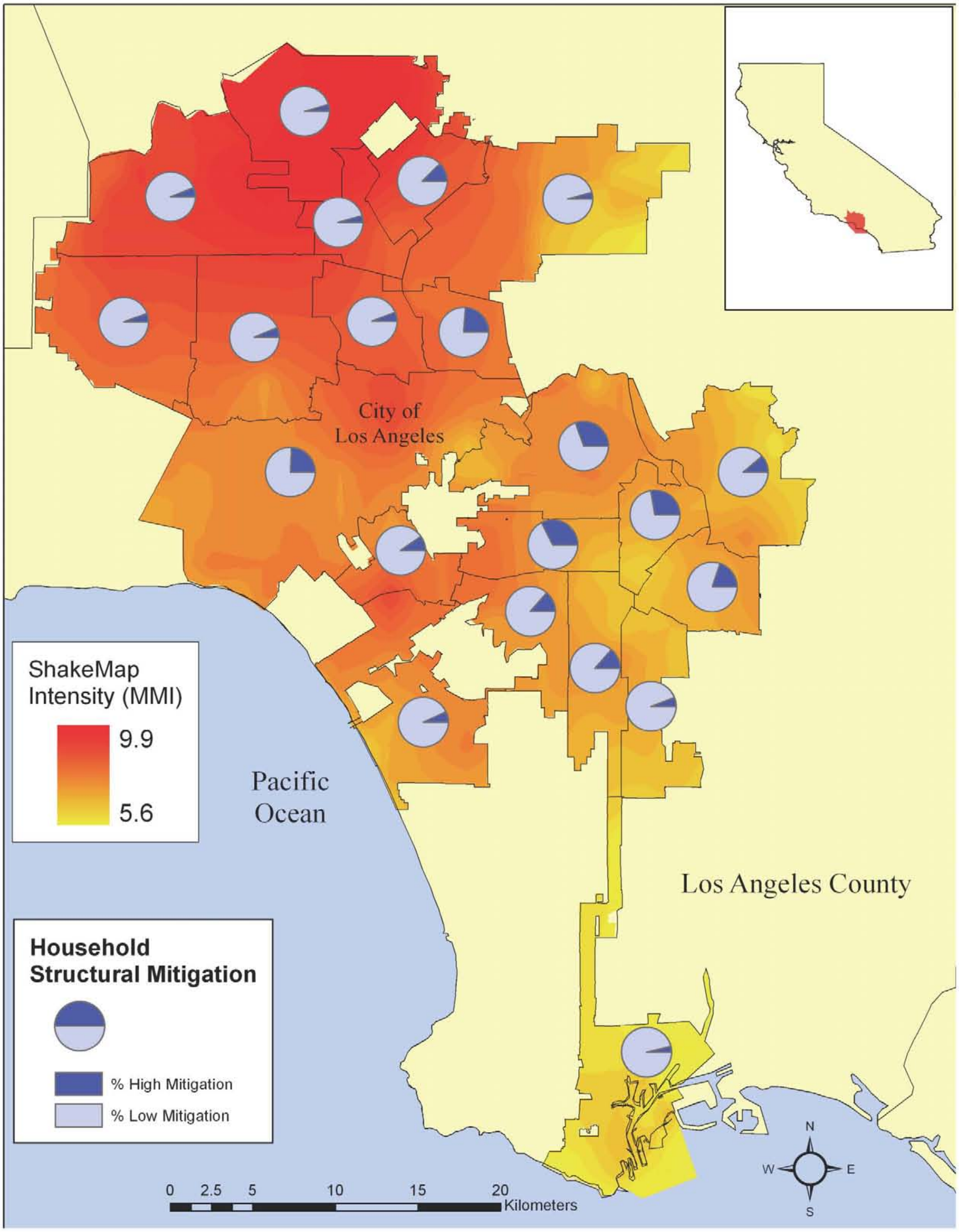

Figure 3-6 Proportion of households with high versus low level of structural mitigation done to their residence, with the threshold being BMIT = 0.5. These data were simulated, with higher incomes having a higher likelihood of having higher levels of structural mitigation

3.3 Businesses

The 1994 Zip Code Business Patterns Standard Industrial Classification (SIC) dataset includes data that can be used to parameterize the SIZE and SECT variables of the recovery model. Prior to being able to use the data, we had to map the individual SIC sector to the SECT variable values (0=locally- and 1=export-oriented businesses). The mappings between these variables are given in Table 3-2. The distribution of business types across Los Angeles is shown in the map of Figure 3-7. Within SIC, business size is defined in terms of number of employees. With the businesses sectors mapped to SECT, the number of each locally- and export-oriented businesses within each size range of the SIC dataset were summed across all the zip code areas within each of the 21 PUMAs. Summation was done by using GIS to note each zip code boundary (based on the 2000 US Census Zip Code Tabulation Areas) that fell completely or predominantly within each respective PUMA and summing the appropriate data within a spreadsheet. The value for SIZE was calculated then as the minimum value of each SIC size range, divided by 500 employees (the predominant size threshold defining large businesses for the SBA). Large businesses make up less than 1% of the total number of businesses in each Los Angeles PUMA. The only other recovery model variable for businesses that had some readily suitable information (that we're aware of) was that for availability of grants and the maximum possible post-earthquake loan amount. According to Tierney, (1995) little or no grant money was available to businesses for recovery. So for businesses, we set AID=0. For households, the maximum available loan amount was normalized by the value of the residence to calculate LOAN_MAX. This data wasn't available for businesses in a way that we could associate the values with the SIC dataset. The maximum allowed loan from the SBA was \$1.5 million for businesses. The average commercial property value in 2002 was \$1.8 million, which is about \$1.5 million in 1994 dollars. Assuming that property values increased from 1994 to 2002, this suggests that the SBA limit of \$1.5 million was a small amount above the average commercial property value in 1994. This means there were properties that were worth more that the SBA loan limit. Thus we made an assumption that larger businesses likely had properties of high value. Businesses with SIZE=1 have a LOAN_MAX=0.5 (half of their property's value), SIZE between 0.5 and 1 have a LOAN_MAX=0.85 (85% of their property's value) and for SIZE less than 0.5, LOAN_MAX=1.

Table 3-2 Mapping between Standard Industry Classification sectors and recovery model SECT variable

Standard Industry Classification (SIC) industry grouping	SECT (export=1/local=0)
Agricultural services, forestry, and fishing	Export-oriented (i.e., independent of local neighborhood recovery)
Construction	Export-oriented
Manufacturing	Export-oriented
Wholesale trade	Export-oriented
Transportation and public utilities	Locally-oriented
Finance, insurance, and real estate	Locally-oriented
Services	Locally-oriented
Unclassified establishments	Locally-oriented

The remaining attribute variables for businesses in the recovery model had to be simulated. To simulate SAVINGS, a random inverse normal distribution was used with a mean of SECT*SIZE and an assumed variance of 0.05. In other words, on average local businesses have little savings, regardless of their size, but for export-oriented businesses, savings increase with size. Without specific data, we assumed all businesses owned their buildings (OWNER=1) and hence go into debt if loans are taken out. We assumed that the age of the building (BYR) for each business was a uniformly distributed random number between 1930 and 1994. The 1930 minimum means that more pre-1976 (CYR) buildings are likely than post-1976. TYPE (facility size and complexity) was calculated with a random inverse normal distribution with a mean equal to SIZE and the variance being 0.1. Lastly, the degree to which a business mitigated its buildings against loss (MIT) was assumed to be uniformly random between 0 and 1. This means that on average half of the businesses were assumed to have MIT less than 0.5 and half greater. Originally, this variable was simulated based on SIZE and SECT, but the more complex calculation was dropped as part of model calibration (i.e. model performance was better assuming MIT was random).

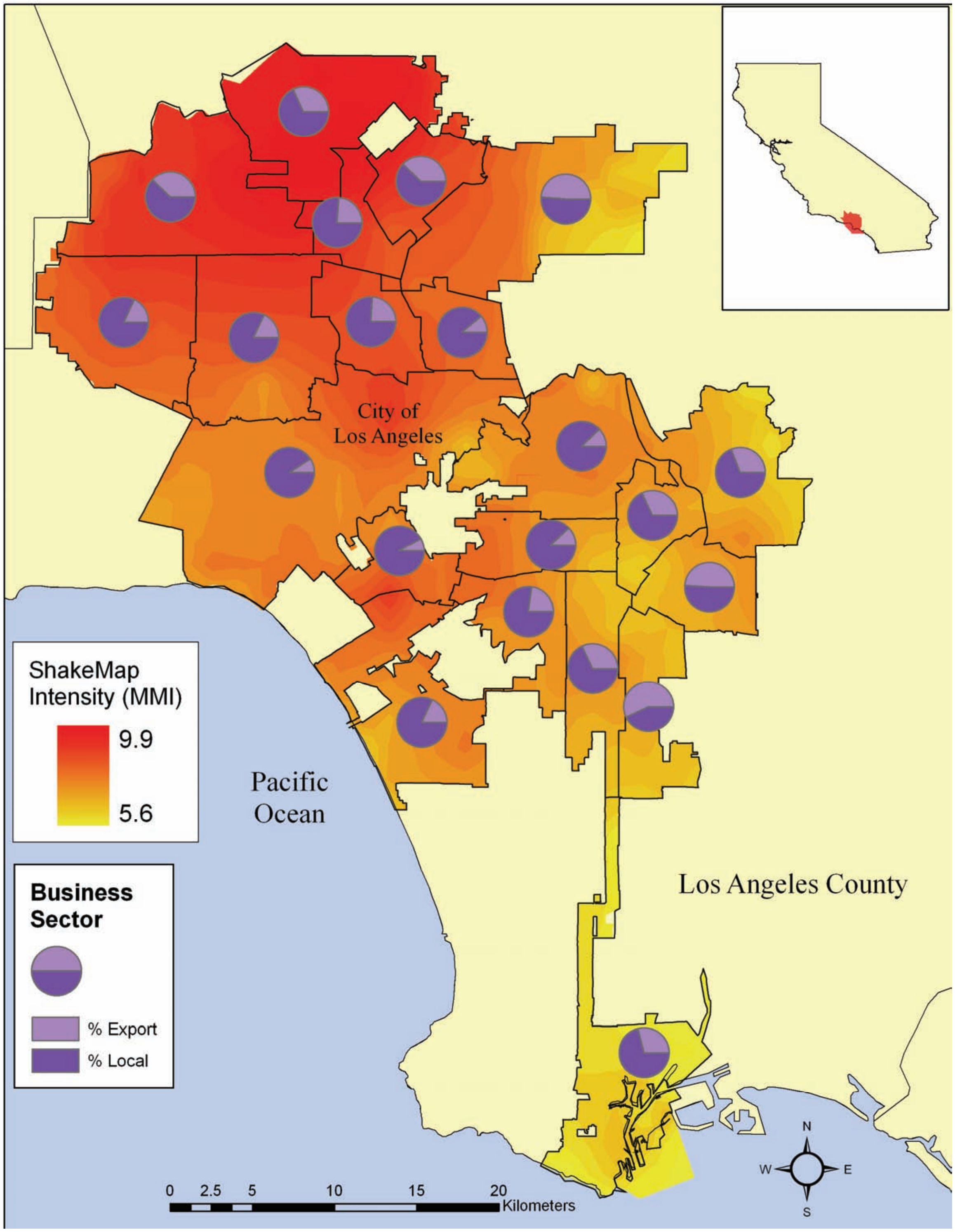

Figure 3-7 Proportion of export-oriented (SECT = 1) versus locally-oriented (SECT = 0) businesses, based on the 1994 economic census

3.4 Lifeline System

For this study, we focused primarily on the development and evaluation of the household and business components of the recovery model. Towards this end, the components for modeling the service recovery of lifelines—critical facilities, electrical network, transportation network, and water network—were replaced by time series data describing service recovery for each lifeline network. The new modularity of the recovery model made it straightforward to use lifeline-service time series data as input to the model by modifying the model to read the data rather than make calls to each lifeline sub-model. In the future, data will need to be developed describing each lifeline component variable (CONSTR, MAINT, MIT, BYR) in order to fully develop and calibrate the component models.

Inputs describing the service restoration of the transportation network in Los Angeles after the Northridge earthquake were developed based on the work of Chang and Nojima (2001). A set of post-disaster transportation network performance measures were developed and applied to earthquake disasters, including the Northridge earthquake disaster. Figure 3-8 includes a measure of traffic volume restoration of major highways in the Los Angeles area after the earthquake. This time series (denoted by 'T' in Figure) was assumed to be representative of transportation recovery for each PUMA within the City of Los Angeles study area for this project.

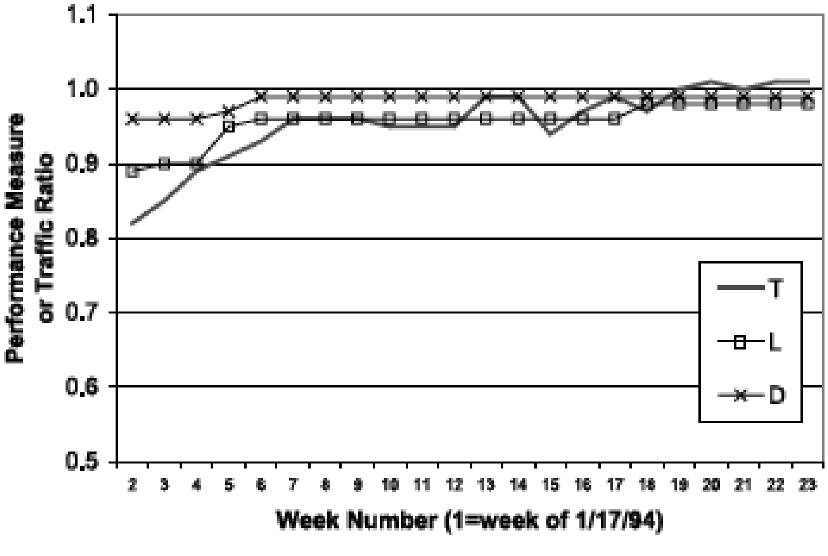

Figure 3-8 Restoration of actual traffic volumes (T) after the Northridge earthquake, and derived measures for evaluating post-disaster transportation service performance (L,D) (Chang and Nojima, 2001)

Any electrical power outages within Los Angeles were restored within the first week after the earthquake, if not within the first couple days (Chang, 2000; Davidson and Cagnan, 2005). A week is the time resolution of the recovery model and so all neighborhoods were modeled to have electricity after the first model time step. This was similarly the case for water service restoration—any outages were fixed within the first week after the earthquake (LADWP, personal communication). For critical facilities, we focused on service outages of local hospitals. Based on a survey of several references that describe hospital damage and evacuation, cross-referenced with zip codes of existing Los Angeles hospitals, a time series was created for the two PUMAs (6513 and 6517) in which we estimated there was hospital service loss (OSHPD, 2005; FEMA, 2004; Schulz et al. 2003; SSC, 1995). In the former PUMA unit, all four hospitals were damaged with three restoring service within the first four weeks after the earthquake, and one being permanently closed. For the latter PUMA, care service was restored after the first week.

SECTION 4
CO-EVENT MODEL CALIBRATION AND RESULTS

The recovery model was run to simulate the impact and recovery of the Northridge earthquake with data developed to represent the conditions of the City of Los Angeles and its lifeline networks, as well as the attributes of residing households and businesses. The developed data was organized in seven Microsoft Excel spreadsheets (one each for the neighborhood, household, business, critical facilities, transportation network, electrical network, and water network variables), with each spreadsheet, except for the neighborhood variables, having an individual worksheet corresponding to each of the 21 PUMAs. A script was run to import this data into the MATLAB workspace, prior to running the co-event model, which stores outputs in the same workspace to allow for subsequently running the post-event model. Results of both the co-event and post-event model were compared against various data gathered for evaluating the performance of each sub-model. When data was available for a particular output variable, calibration was done by either varying model parameters (not input data), revising model algorithms, or in one case (MIT for businesses) the means in which the input data was simulated. In this chapter, the calibration and final results of the co-event model are described, with the post-event model being described in the following chapter.

4.1 Household Calibration and Results

The three major sub-models that required calibration for the co-event model with respect to households were for calculating building damage (DMG), injury to building occupants (INJURY), and whether or not a household had insurance (INS). Calibration of the sub-models for DMG and INJURY was done by varying the median and variance parameters for the respective fragility curves. The parameters defining the fragility curves associated with household building damage levels for single-family residences (SFRs) and multi-family residences (MFRs) are listed in Table 4-1.

Table 4-1 Residential building damage fragility curve parameters—median and variance for lognormal cumulative distribution functions

	25% Damage Level	**50% Damage Level**	**75% Damage Level**	**100% Damage Level**
Single-family residence	median=2.253 variance=0.1	median=2.385 variance=0.15	median=2.518 variance=0.175	median=2.65 variance=0.2
Multi-family residence	median=2.142 variance=0.1	median=2.268 variance=0.15	median=2.394 variance=0.175	median=2.52 variance=0.2

Figure 4-1 shows the results of calibrating residential damage prediction, comparing the model damage estimates averaged across each neighborhood versus average shaking intensity, to observations from the Northridge earthquake (EQE, 1995). Up to MMI=8, the co-event model predicts a similar trend as measured after the Northridge earthquake, with slight under-prediction for SFRs and slight over-prediction for the MFRs. Beyond MMI=8, model predictions diverge from the data of EQE (1995), with damage for single-family buildings being over-predicted and damage for multi-family buildings being under-predicted. Model predictions for these shaking intensities however are bounded by the observed trends for two types of buildings. Figure 4-2 shows a map of the percentage of the total number of SFRs and MFRs that experience any damage computed using the calibrated damage fragility curves. Notice that in general a larger proportion of MFRs were predicted to have experienced some damage than SFRs, as was generally observed. Figure 4-3 shows a map describing the level of predicted damage for the population of damaged residences (all types). Comparing these two figures, there are some neighborhoods where a low overall percentage of damaged buildings are predicted, but of those modeled to experience some damage the level of damage is relatively high. This is due to the influence of building type (MFRs being more vulnerable) and randomness in the model.

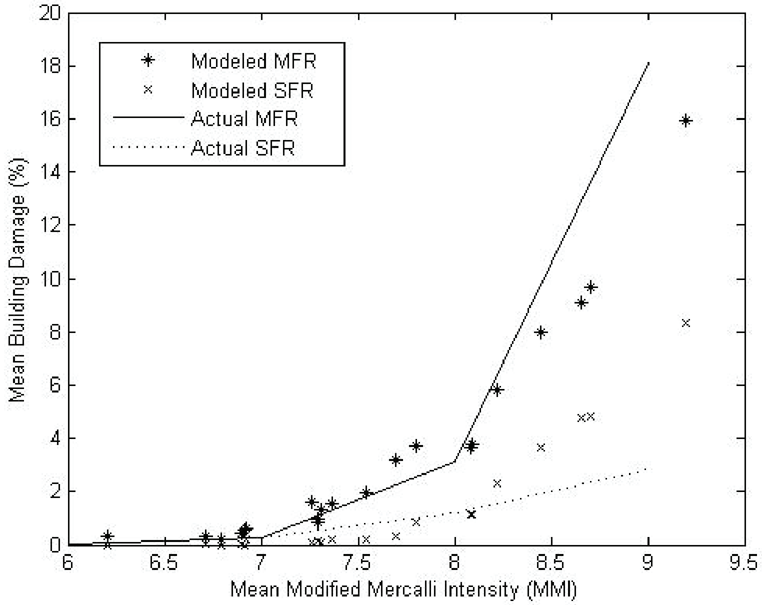

Figure 4-1 Comparison of modeled and actual relationship (from EQE, 1995) between mean building damage and mean Modified Mercalli Intensity (average across each study unit)

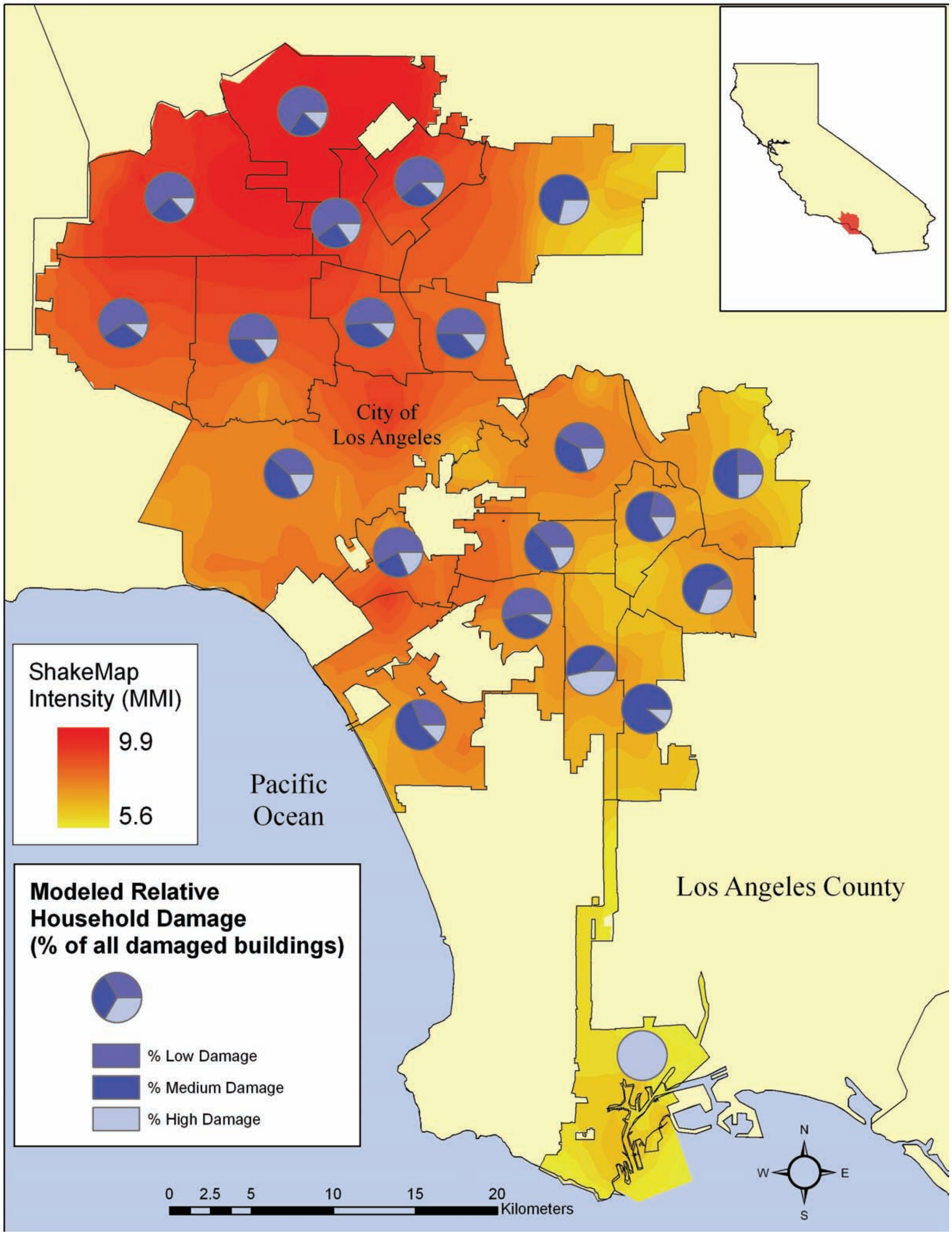

Figure 4-2 Modeled percentage of household residences damaged by Northridge ground shaking. (MFR: multi-family residence; SFR: single-family residence)

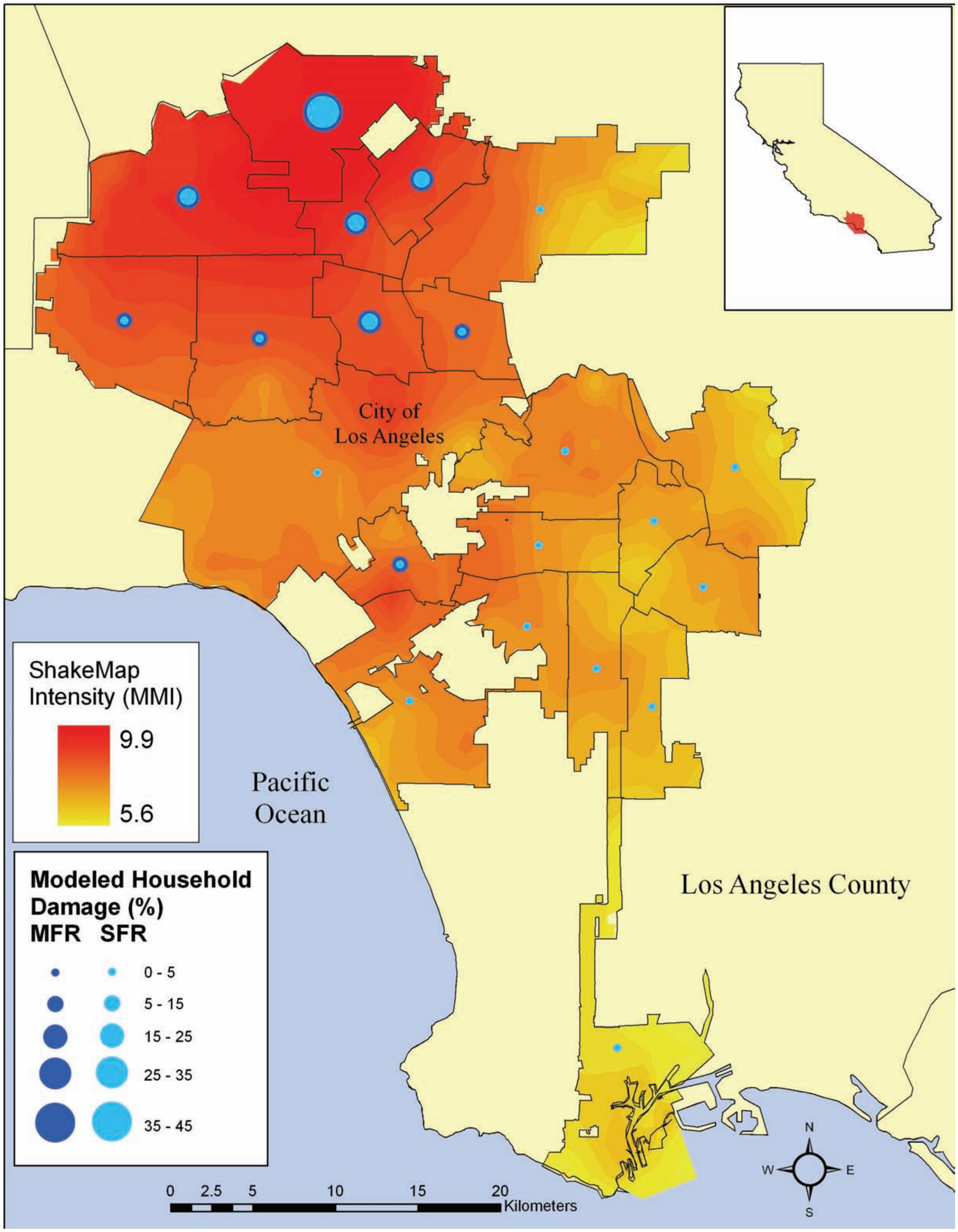

Figure 4-3 Modeled proportion of damaged residences with low, medium (yellow tag), or high damage (red tag) levels

Calibration of the sub-model for predicting household INJURY was conducted similarly to that for residential damage (by varying the median and variance of the associated fragility curve). In this case, we had two different data sources with which to calibrate the model. The final median value of the injury fragility curve is 2.275, while the variance is 0.2. Seligson et al. (2002) conducted a survey in which they found about 8% of households reporting having experienced some injury as a result of the Northridge earthquake. As calibrated, the co-event model predicted 3.76% of the total household population with some injury. Peek-Asa et al. (2000) have data describing injury rate versus average shaking intensity similar to the residential damage trends of EQE (1995) in Figure 4-1. These data are plotted in Figure 4-4 with calibrated model predictions averaged over each PUMA. Through calibration, the model is able to exhibit the bilinear trend of the Peek-Asa et al. (2000) observations, but over-predicts injury rates significantly beyond MMI=8. Further adjustments to the fragility curve parameters to decrease the predicted rate lead to predictions of no injuries. Observing that the actual injury rates are quite small, this behavior may be the result of using only 5% of the total population. Figure 4-5 shows a map of the percentage of total households predicted to have experienced some injury across each of the Los Angeles PUMAs. The predicted percentage for each PUMA is generally lower than that for residential damage shown in Figure 4-2. One of the variables having a significant influence on predicted injuries in the co-event model is a household's income. Figure and Figure 4-7 describe the predicted trend of injury rates with respect to income. Suitable data for calibrating the model with respect to income were not available, but we would expect a higher proportion of injuries to be associated with low incomes. Data are available that show a strong relationship with increasing age of residents to injury (Peek-Asa et al., 2000). However, currently the model does not account for age.

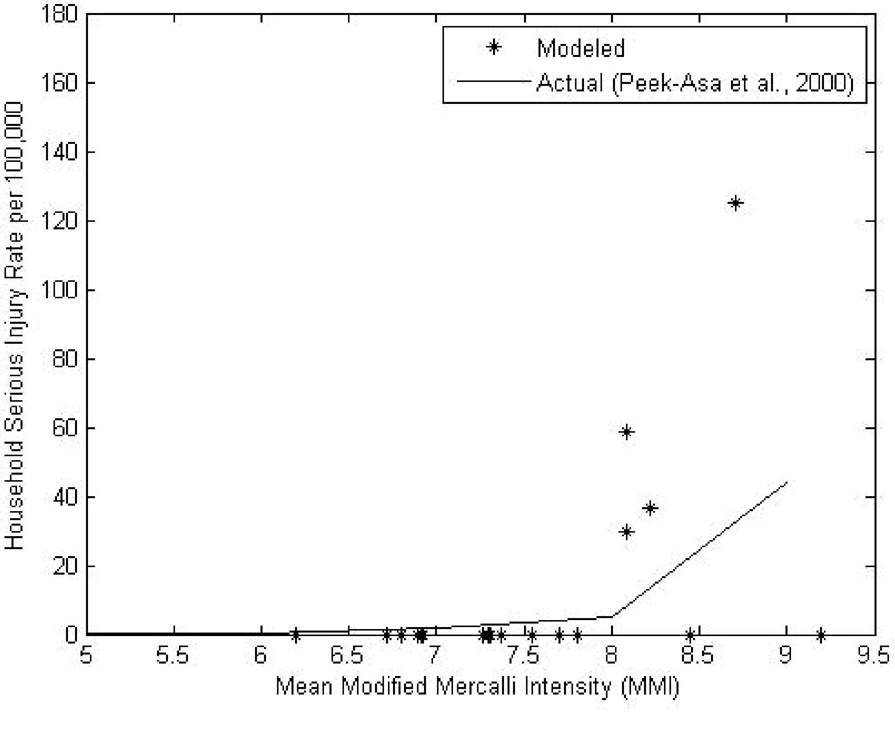

Figure 4-4 Comparison of modeled and actual relationship between household injury rate and mean Modified Mercalli Intensity (averaged over each study unit)

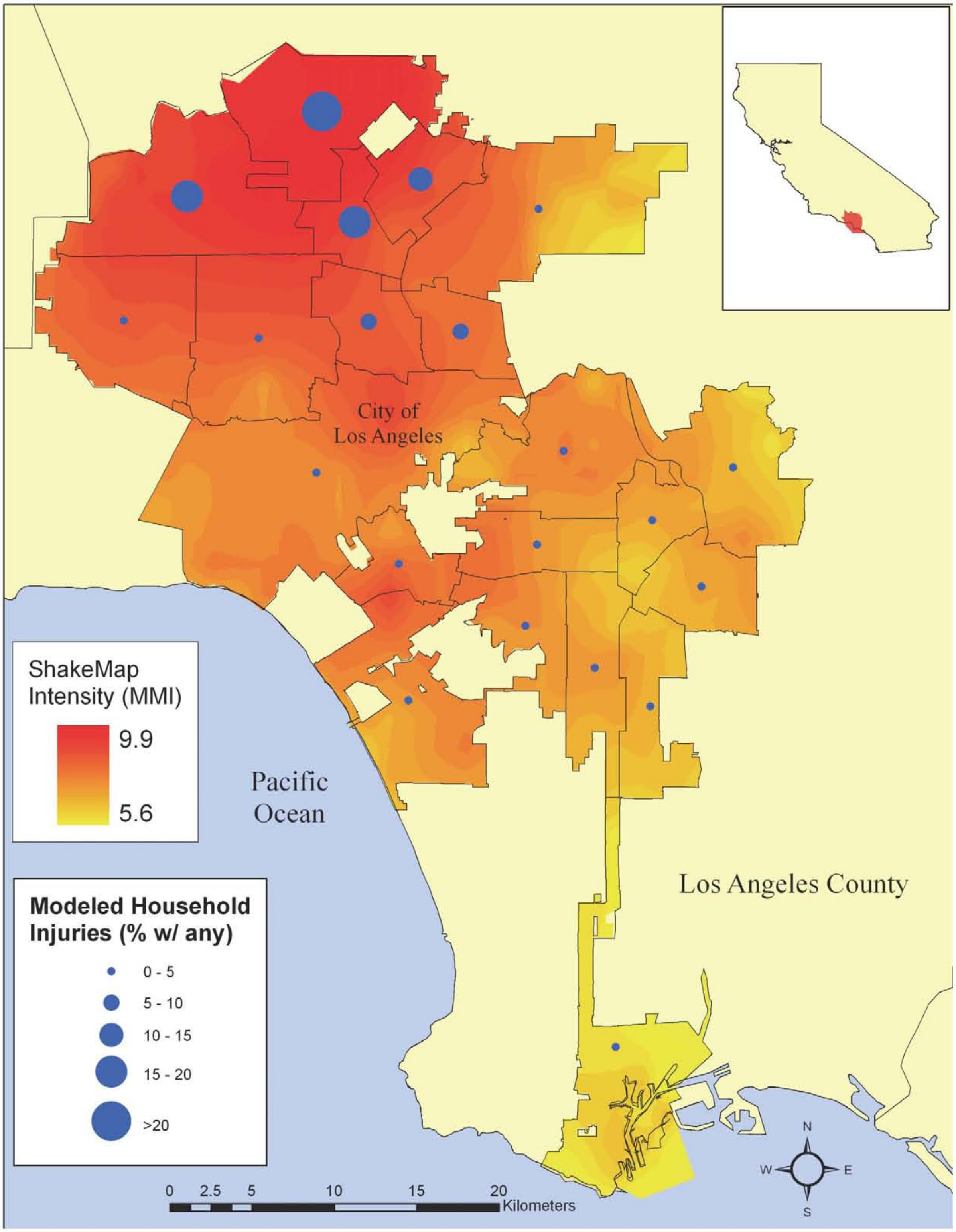

Figure 4-5 Modeled percentage of households experiencing some injury

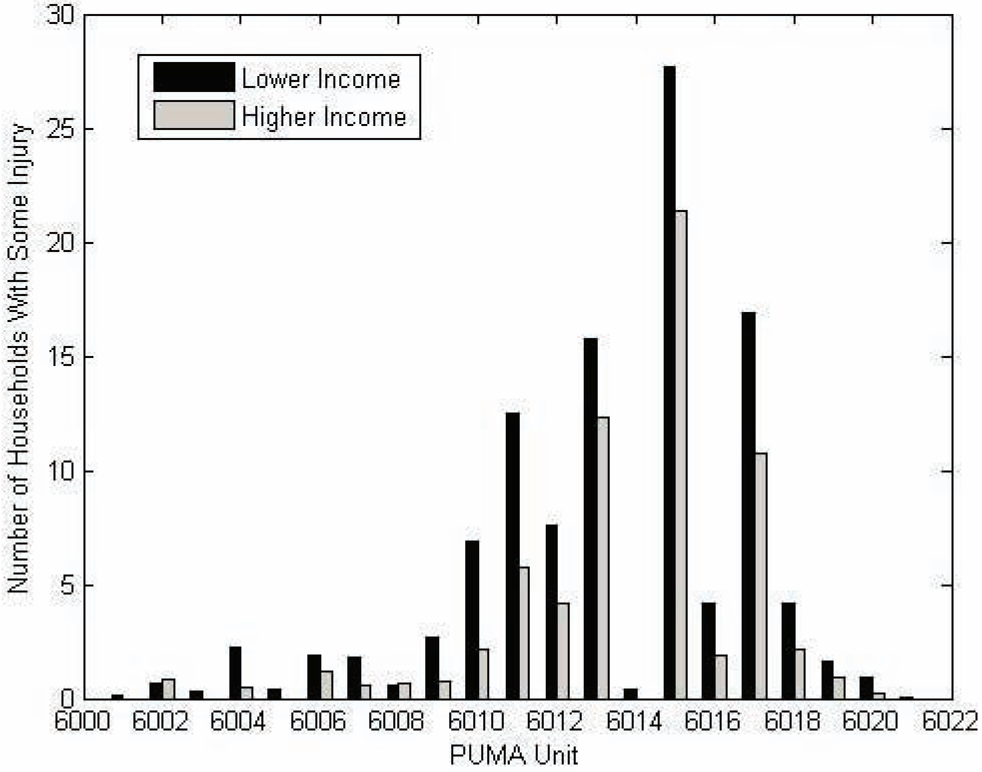

Figure 4-6 Comparison of injury rate between lower (INC<0.5) and upper income (INC>0.5) households

The final co-event sub-model associated with households was calibrated for predicting whether or not a household has insurance prior to a disaster (INS). According to Loukaitou-Sideris and Kamel (2004) about 40% of Los Angeles households had insurance, while Johnston (2000) estimated that 60% did. The percentage of households predicted to have insurance is about 34%. The sub-model for predicting INS does not have a specific parameter that can be varied in order to calibrate predictions. The algorithm treats INC, (1-MARG), and OWNER as probabilities and compares the combination of these probabilities with a uniform random number. The proximity of the predicted value to the actual percentage of households with insurance suggests that this algorithm is reasonable. Figure shows a map of the percentage of households with insurance. Note that generally the PUMAs with the highest average shaking intensities also have the highest proportion of households predicted to have insurance. This result is strongly influenced by the distribution of the proportion of homeowners (Figure 4-8).

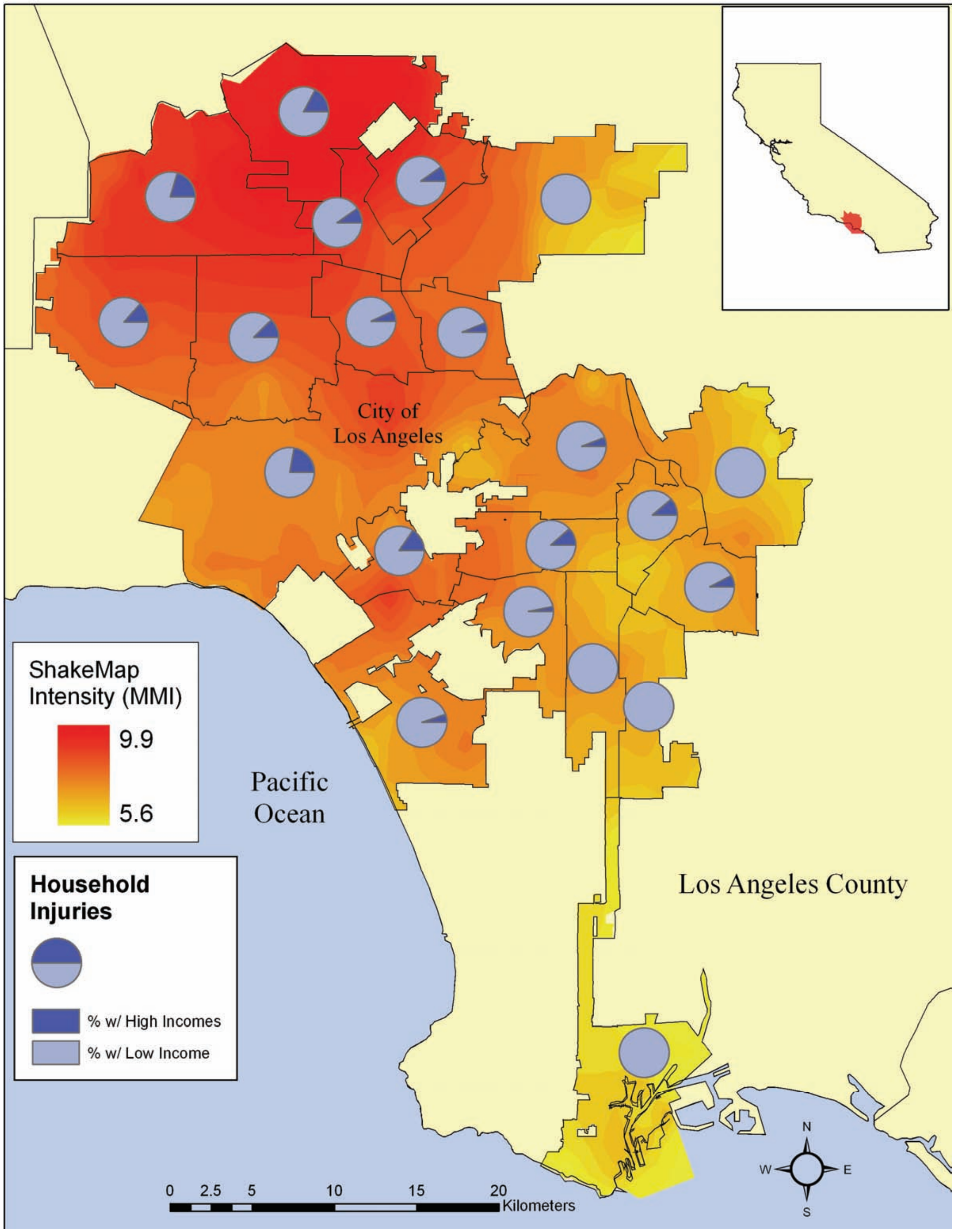

Figure 4-7 Modeled proportion of injured households with higher versus lower income, with the income threshold being INC = 0.5 (about $62,500 in 1990)

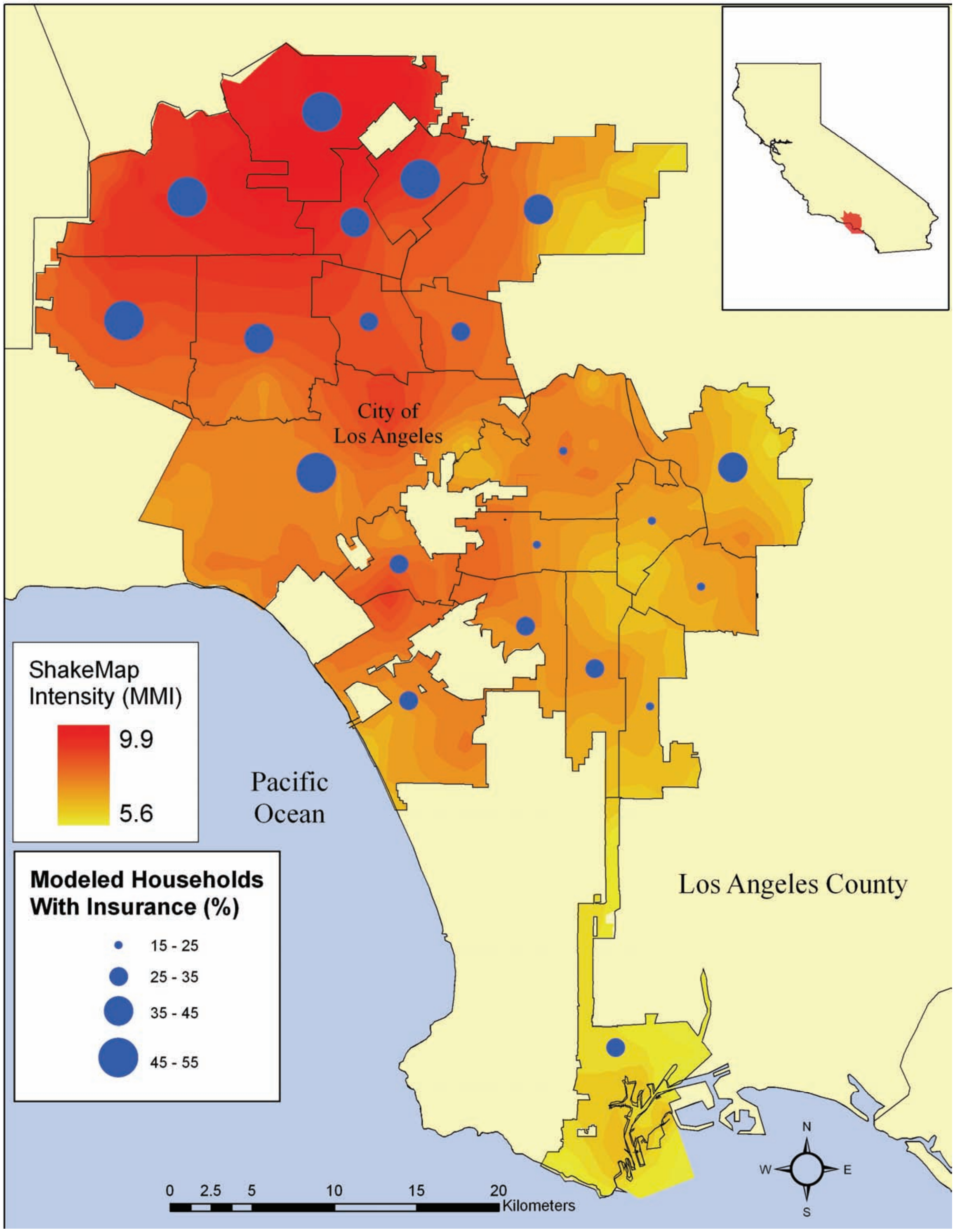

Figure 4-8 Modeled percentage of households with insurance

4.2 Business Calibration and Results

The sub-models in the co-event model associated with businesses that can be evaluated and calibrated are similar to those for households. However, the type of data that can be used in comparison to model predictions differs with respect to building damage and is not available for the immediate reduction in demand for businesses (i.e., INJURY). Data available for insurance is comparable. Data from Tierney (1995) describe the percentage of businesses across Los Angeles with some damage, as well as the percentage that were yellow and red tagged. Data also describe the percentage of small versus large businesses with some damage. These data were used to calibrate the business building damage fragility curves.

Table 4-2 Business building damage fragility curve parameters—median and variance for lognormal cumulative distribution functions

	25% Damage Level	50% Damage Level	75% Damage Level	100% Damage Level
Small buildings (TYPE=0)	median=2.01 variance=0.1	median=2.129 variance=0.15	median=2.467 variance=0.175	median=2.365 variance=0.2
Large buildings (TYPE>0)	median=2.095 variance=0.1	median=2.219 variance=0.15	median=2.342 variance=0.175	median=2.465 variance=0.2

Figure 4-9 shows the comparisons between observed and predicted damage after calibration of the business building damage fragility curves. Yellow and red-tags are associated with 33% to 66% and 66% to 100% damage, respectively. Overall, the prediction for businesses with some damage (21%) is close to the observation (22%). The model over-predicts the percentage of buildings suffering low damage (11.6% vs. 13%), while it under-predicts the percentage of red-tagged buildings (18.2% vs. 20.7%). Tierney (1995) observed that a higher percentage of small businesses suffered damage than large businesses. The model predicts a similar trend, while slightly over-predicting the absolute number of each type of businesses with some damage. Business size is not directly considered in computing building damage, but influences the result through building type (TYPE), age of occupied buildings, and the degree to which the business has taken structural mitigation measures (MIT). A map showing the predicted distribution of businesses with some structural damage across Los Angeles is given in Figure 4-10, while Figure 4-11 shows the relative percentage of damaged businesses that were yellow and red tagged. The proportion of yellow and red tagged buildings is predicted to be similar across all of Los Angeles, which probably reflects the fact that the data used in calculating damage was stochastically simulated. For comparison with Figure 4-1, the relationship of average building damage with shaking intensity is shown in Figure 4-12. The magnitude and trajectory of the trend is somewhat similar to that for damage of MFRs.

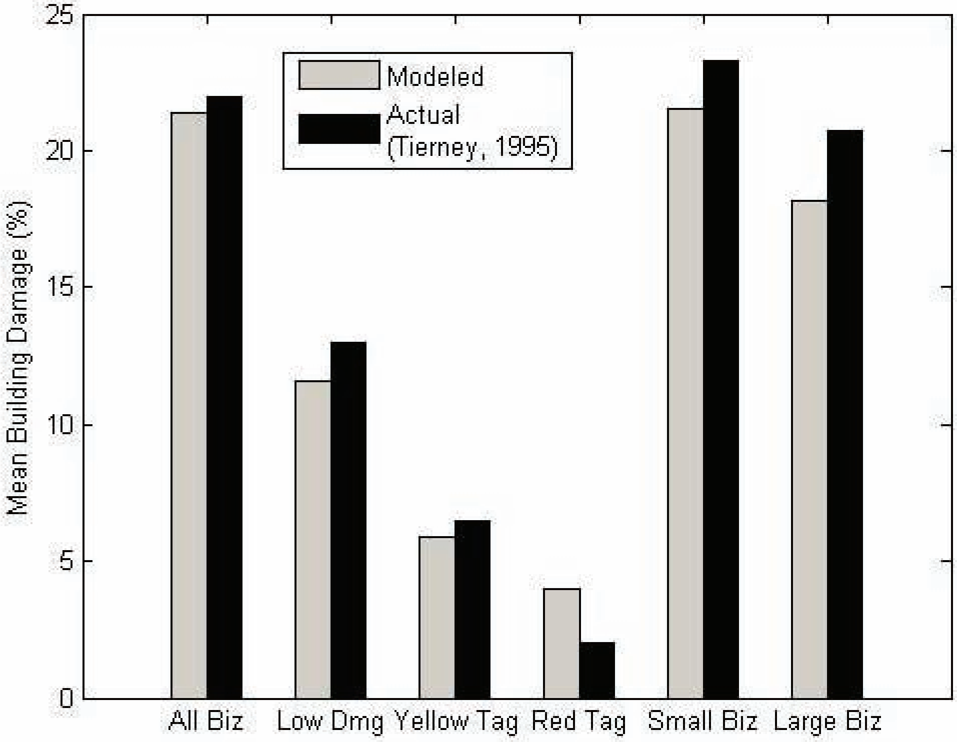

Figure 4-9 Comparison of modeled and actual building damage for businesses: All businesses with some structural damage, all businesses with low damage, all businesses with medium structural damage (yellow tag), all businesses with high structural damages (red tag), small businesses with some structural damage, and large businesses with some structural damage

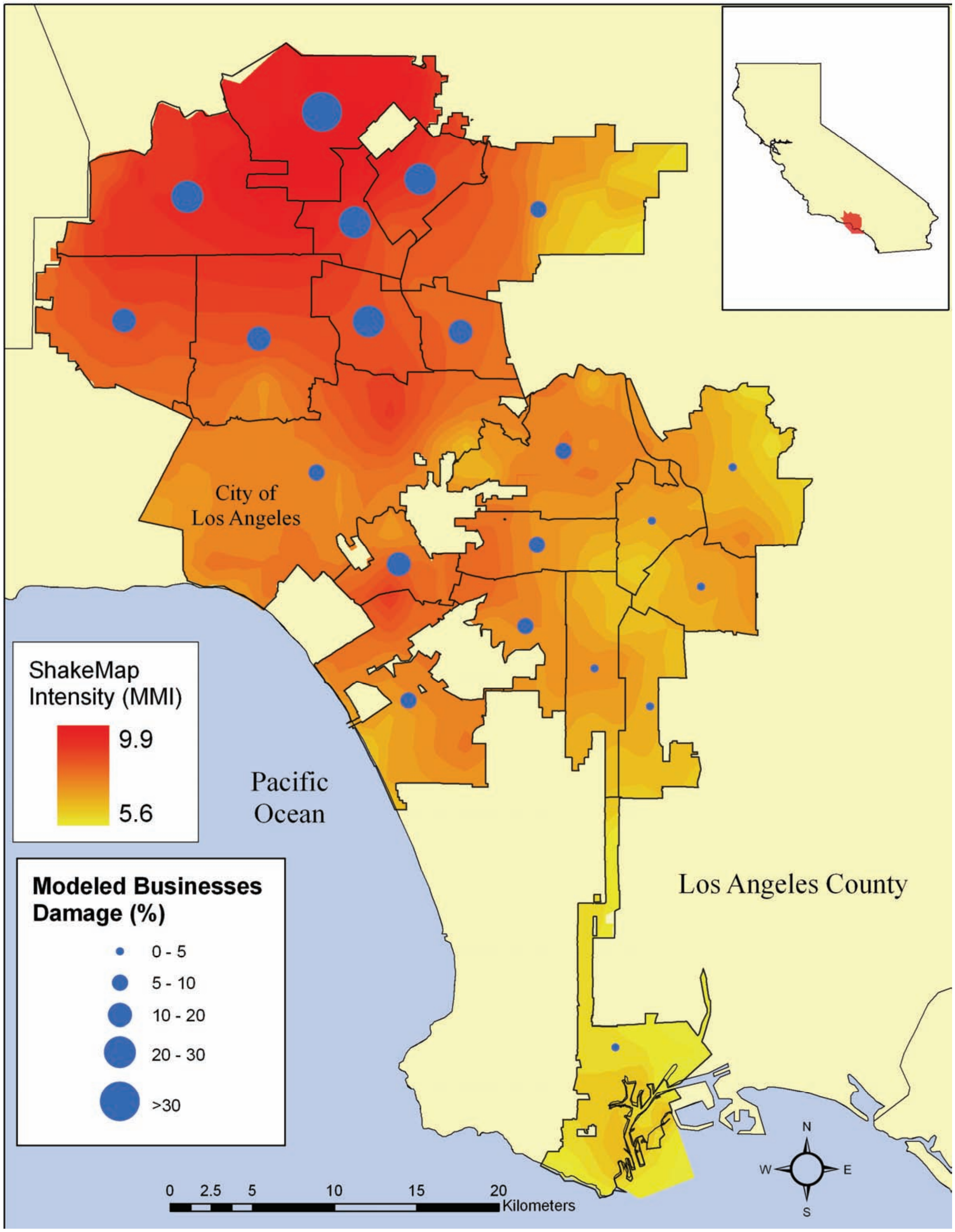

Figure 4-10 Modeled percentage of businesses with some damage

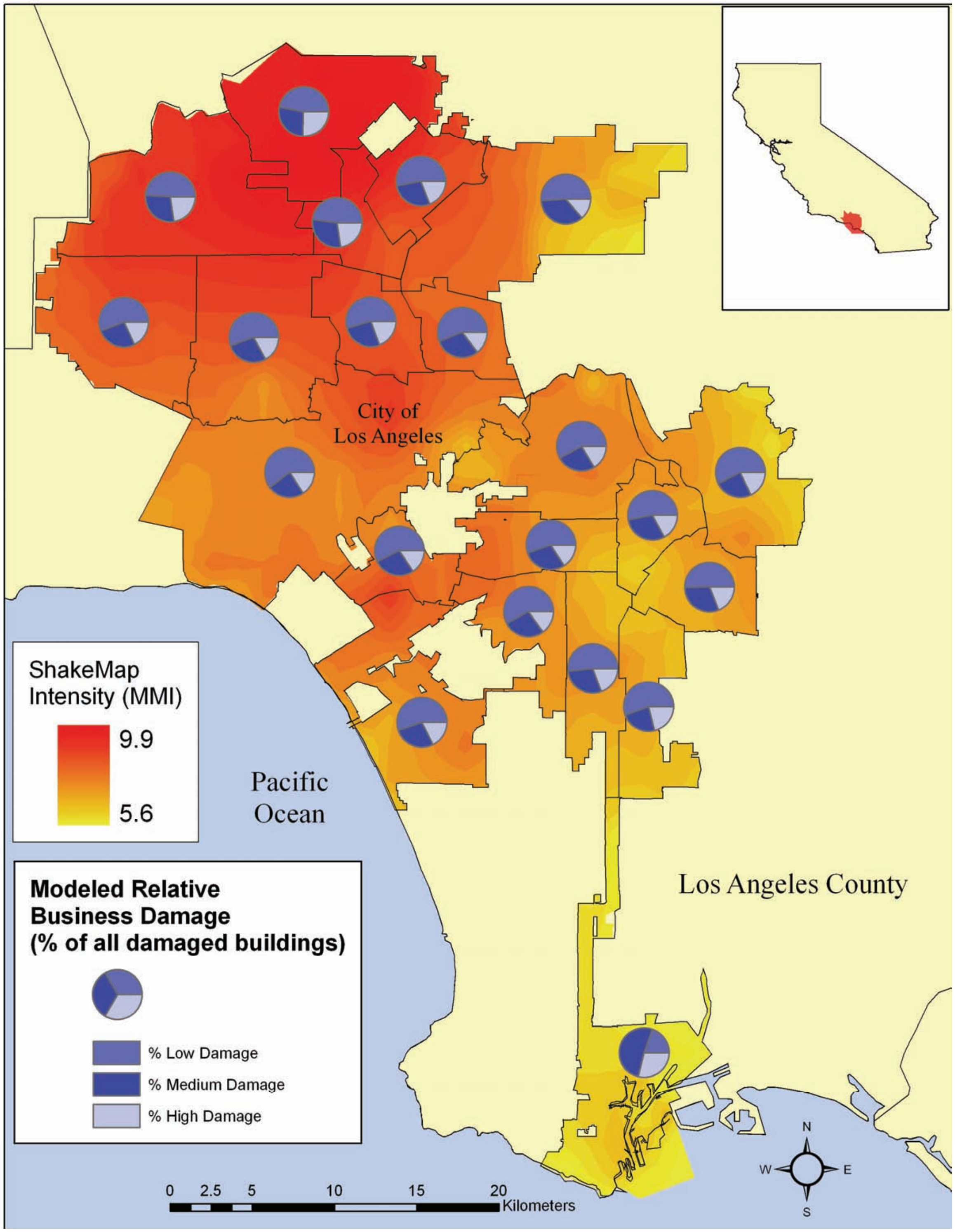

Figure 4-11 Modeled proportion of business with low, medium (yellow tag), and high (red tag) damage levels

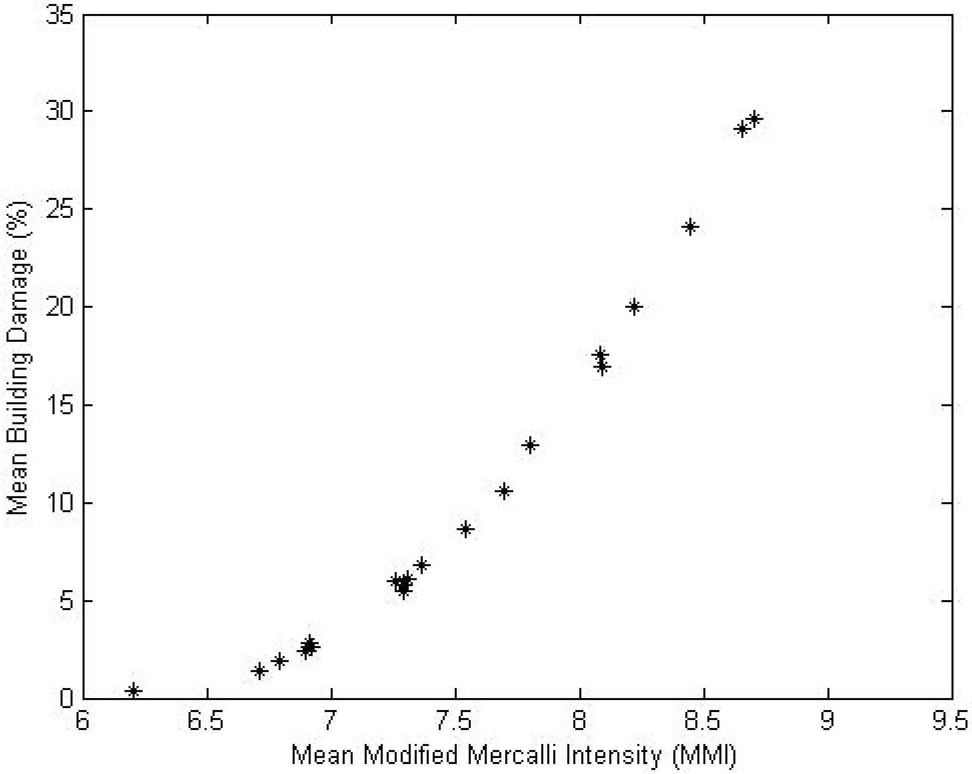

Figure 4-12 Mean building damage of businesses versus mean Modified Mercalli Intensity (MMI), averaged across each of the 21 study units in Los Angeles

The percentage of businesses in Los Angeles with insurance at the time of the Northridge earthquake was about 10% according to Alesch et al. (2004) and 20% according to Tierney (1995). The sub-model for business insurance, unlike for households, has an exponent that can be calibrated, which was varied to get a prediction of 15% modeled businesses with insurance. Figure 4-13 presents a map that shows the distribution of businesses with and without insurance across Los Angeles, which largely follows the distribution of business size.

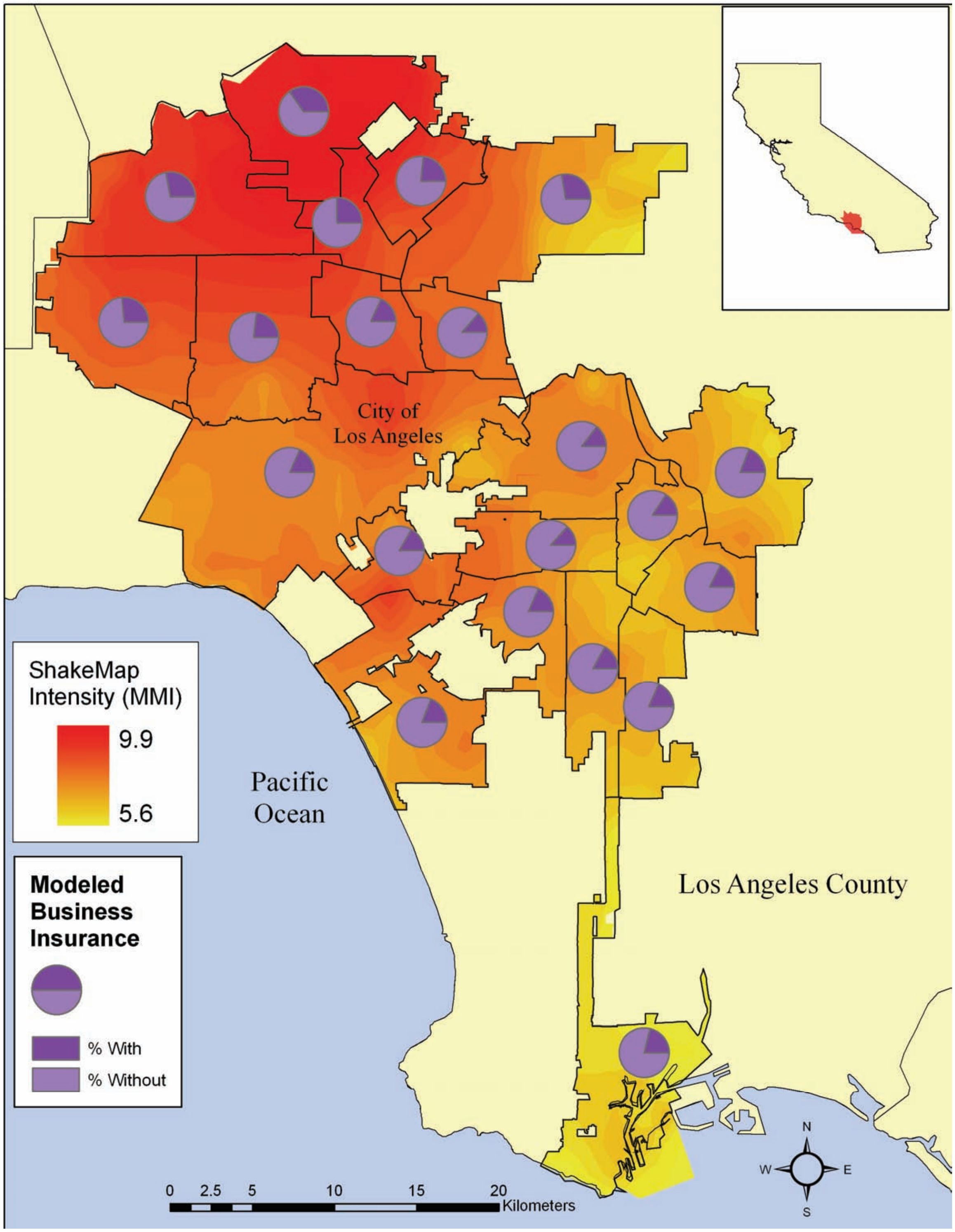

Figure 4-13 Modeled proportion of businesses with versus without insurance

No data is available that describes the immediate impact of the Northridge earthquake on demand for products and services from which to calibrate the co-event model. The median and variance of the fragility curve then were assumed such that there was a smooth transition from no effect on business demand at MMI=7 to complete disruption at MMI=10+. The median for the lognormal cumulative distribution function is 2.1, while the variance is 1. Figure 4-14 is a plot of business demand reduction versus shaking intensity; Figure 4-15 shows this information in map form.

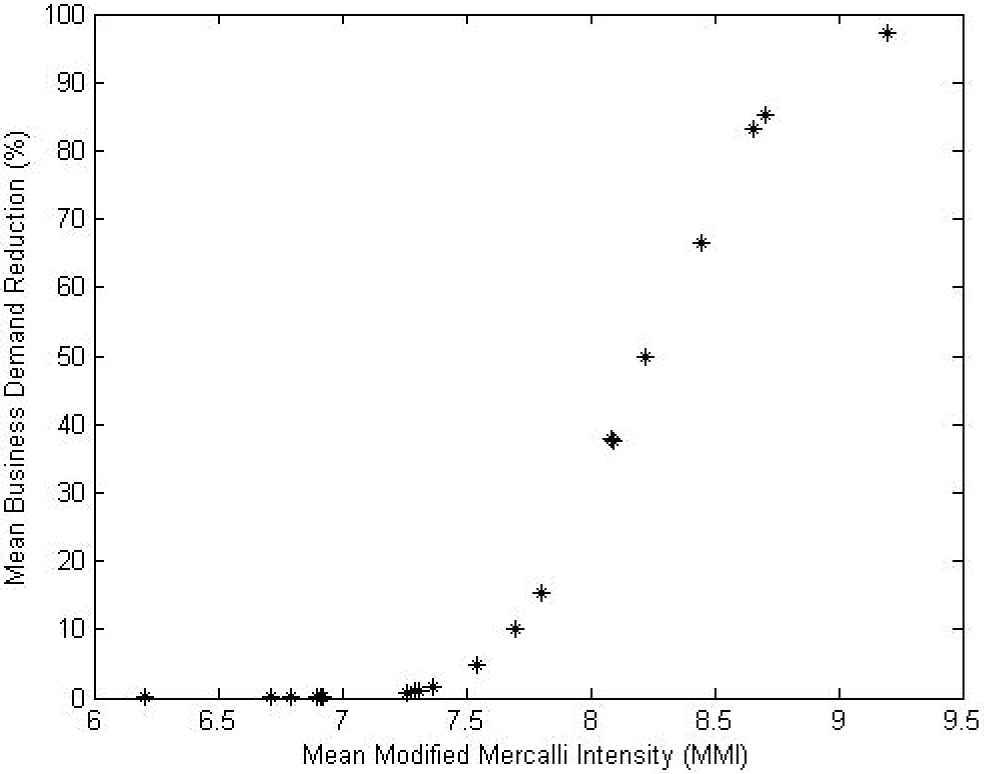

Figure 4-14 Modeled relationship between mean business demand reduction (injury) and mean Modified Mercalli Intensity (average over each study unit)

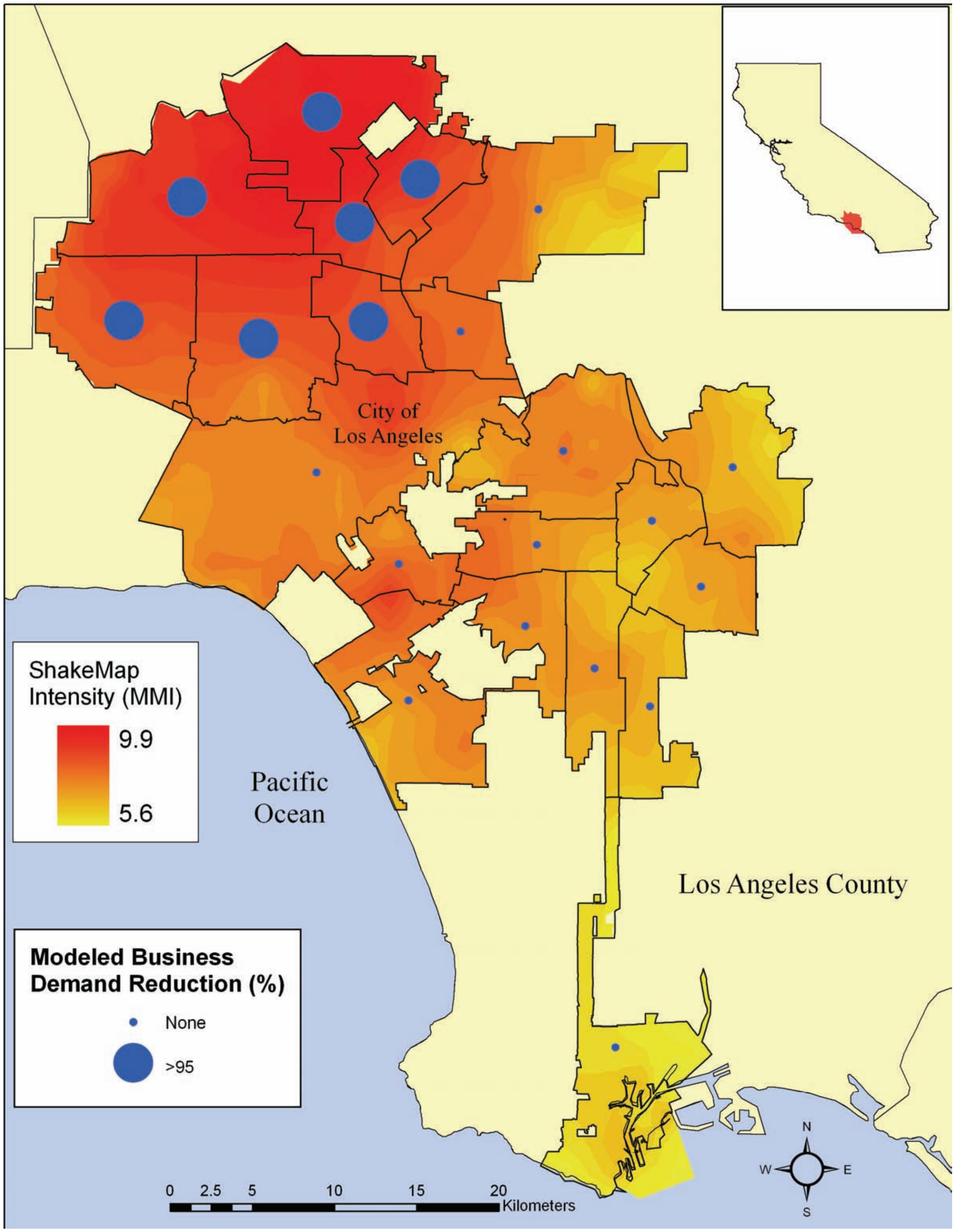

Figure 4-15 Modeled level of consumer demand reduction for businesses

SECTION 5
POST-EVENT MODEL CALIBRATION AND RESULTS

With the co-event model calibrated with respect to the Northridge disaster, the outputs were used to apply the post-event model in order to calibrate and evaluate it. Similarly to calibration of the co-event model, the components of the post-event model were calibrated if suitable secondary data sources were available. For illustrative purposes and to better understand overall behavior, outputs were generated describing recovery indicators for which calibration data wasn't developed. Because of the size and complexity of the post-event model, in comparison to the co-event model, a different overall approach was taken for calibration and evaluation. Calibration was done on a 10% random sample of the Northridge household and business data set described in Chapter 3. After calibration was completed, the post-event model was run on a non-overlapping 30% sample of the same original data set to ensure consistent performance of the model. The calibration and evaluation of the post-event model is described below for the household sector first.

5.1 Households

The only widely available data for calibrating the household components of the post-event model are associated with residential reconstruction. The results and calibration of the household reconstruction model component are described in Section 5.1.1 below. Following this, the results of the post-event model with respect to household health recovery and estimation of debt levels due to the disaster are presented. Finally, calibration of the component that models whether each household will stay or leave after the disaster is described, together with various statistics about this particular model output that help to understand the overall behavior of the model.

5.1.1 Reconstruction

The data used for calibrating the residential reconstruction component of the post-event model were compiled from several sources (Kamel and Loukaitou-Sideris, 2004; Wu and Lindell, 2004; Comerio, 1997; Comerio, 1996; Chu, 1995). Calibration was done through visual comparison of plotted calibration data with various plots of the percent of residences rebuilt with time across the entire community (Figure 5-1 through Figure 5-6). Following the findings of Comerio (1997, 1996) and the significant influence of building type and ownership status, the emphasis for the calibration was to get the best visual fit with respect to the type of residential buildings and whether or not the residence was owner-occupied or rented. To simulate the pattern of the calibration data required modifying the model to constrain the speed of reconstruction in the early weeks after the hazard event. This was done by incorporating the restoration of the transportation network (e.g., to enable the delivery of building supplies, etc.). Also added was an absolute time component where the probability of transition increases with time over the first year after the hazard event. After this modification, the calibration was done by varying the reconstruction recovery step-size of the model component's Markov chain algorithm.

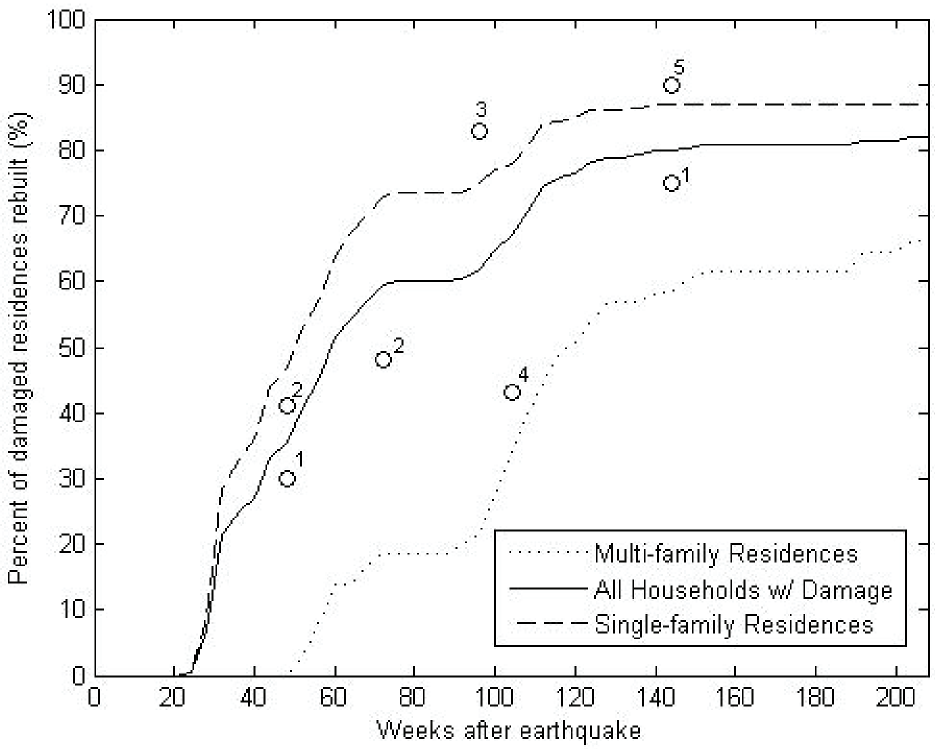

Figure 5-1 Residential reconstruction over time for all residences, multi-family, and single family, modeled using calibration input data set. Labeled circles correspond to reconstruction data from respective references. (1) Comerio (1997), (2) Chu (1995), (3) Comerio (1996), (4) Wu and Lindell (2004), (5) Kamel and Loukaitou-Sideris (2004)

The modeled reconstruction trends for MFRs and SFRs are shown in Figure 5-1. Overall, the reconstruction of the MFR stock is slower than for SFR, bounding the lower-value calibration data. While only one calibration data point (1: Comerio, 1997) is associated specifically with MFR reconstruction, post-disaster studies found a significant lag in time to repair MFR units. For example, Loukaitou-Sideris and Kamel (2004), noted that "more programs and resources were available to wealthier homeowners in neighborhoods with a larger stock of single-family housing than in poor neighborhoods with higher concentrations of rentals and multifamily apartment buildings" (p. viii). Figure 5-2 then shows the modeled trend for residential repairs with respect to higher ($INC \geq 0.5$) and lower ($INC < 0.5$) income levels. The modeled relationship between wealth and reconstruction speed is evident, exhibiting a larger positive effect than an SFR building type. The greater difference between the higher income reconstruction rate and overall trend in comparison to the lower-income trend is indicative of the fewer number of higher income households. None of the calibration data points are associated with a distinction in income. Figure 5-3 is a plot of the relative reconstruction trends associated with whether the occupant owns or rents their residence. The difference between trends is similar to that between SFR and MFR, as would be expected since MFR residents typically are renters. However, the difference in repair speed between owner-occupied and renter-occupied is modeled to be even greater than the difference between building types. Loukaitou-Sideris and Kamel (2004) found that of areas in Los Angeles with the highest damage and lowest post-disaster financial assistance there was a higher-than-average percentage of renter-occupied units.

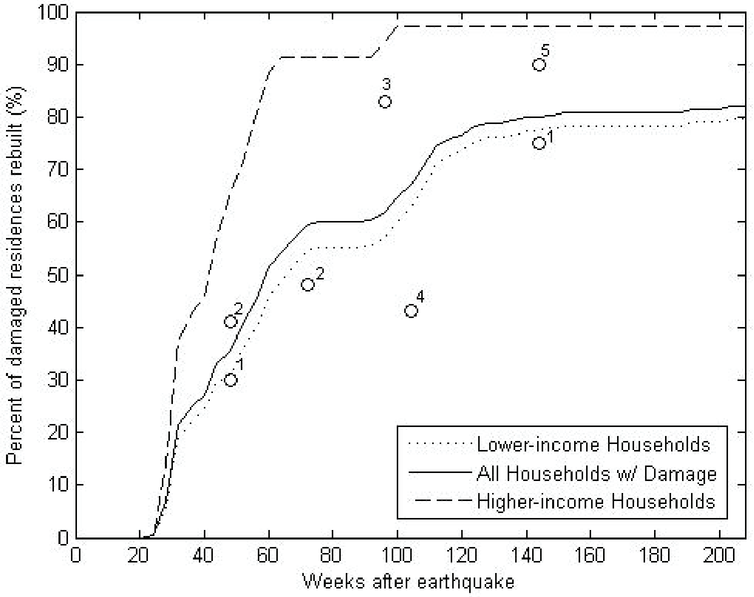

Figure 5-2 Residential reconstruction over time for all residences, residences with lower incomes (INC < 0.5), and residences with higher incomes (INC >= 0.5), modeled using calibration input data set. Labeled circles correspond to reconstruction data from respective references. (1) Comerio (1997), (2) Chu (1995), (3) Comerio (1996), (4) Wu and Lindell (2004), (5) Kamel and Loukaitou-Sideris (2004)

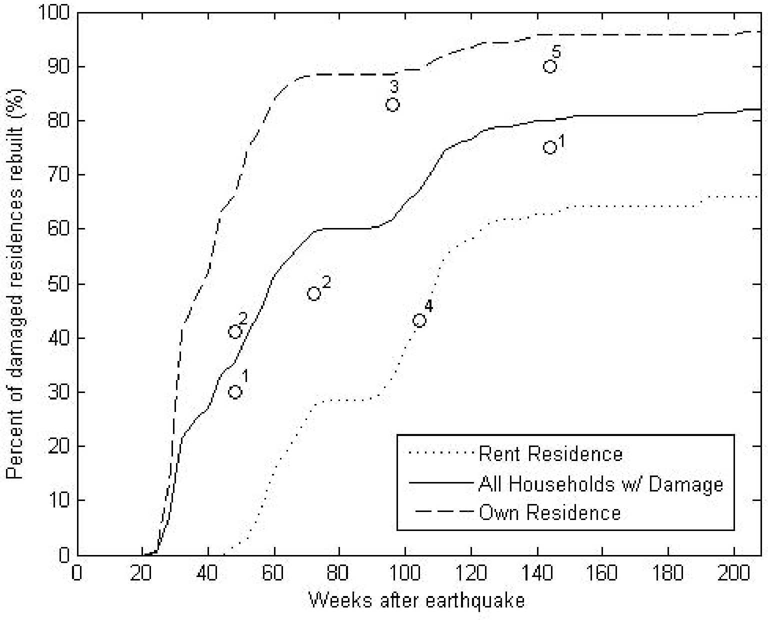

Figure 5-3 Residential reconstruction over time for all residences, households that rent, and households that own, modeled using calibration input data set. Labeled circles correspond to reconstruction data from respective references. (1) Comerio (1997), (2) Chu (1995), (3) Comerio (1996), (4) Wu and Lindell (2004), (5) Kamel and Loukaitou-Sideris (2004)

After calibrating the model on the calibration data set— a randomly chosen 10% of the data records of the full Northridge input data set—the post-event model was applied to a different set of data records from the full input data set (30% uniform random sample). Figure 5-4 through Figure 5-6 show the reconstruction trends modeled using the non-calibration data sample for building type, income, and ownership status, respectively. The modeled trends are generally similar to those computed with the calibration data set (Figure 5-1 through Figure 5-3), suggesting that the random calibration data set is representative of the full data set.

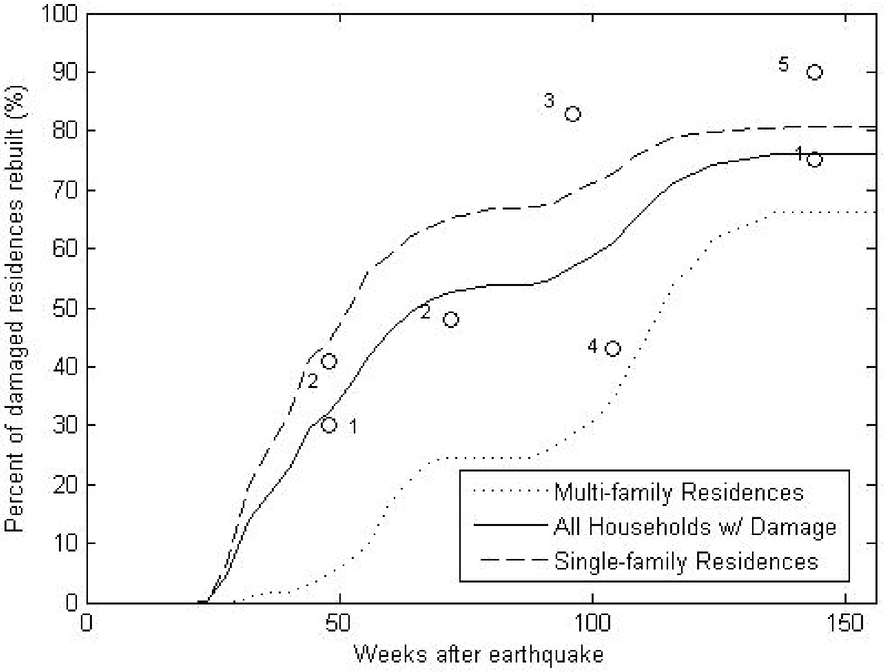

Figure 5-4 Residential reconstruction over time for all residences, multi-family, and single family, modeled using the non-calibration data set. Labeled circles correspond to reconstruction data from respective references. (1) Comerio (1997), (2) Chu (1995), (3) Comerio (1996), (4) Wu and Lindell (2004), (5) Kamel and Loukaitou-Sideris (2004)

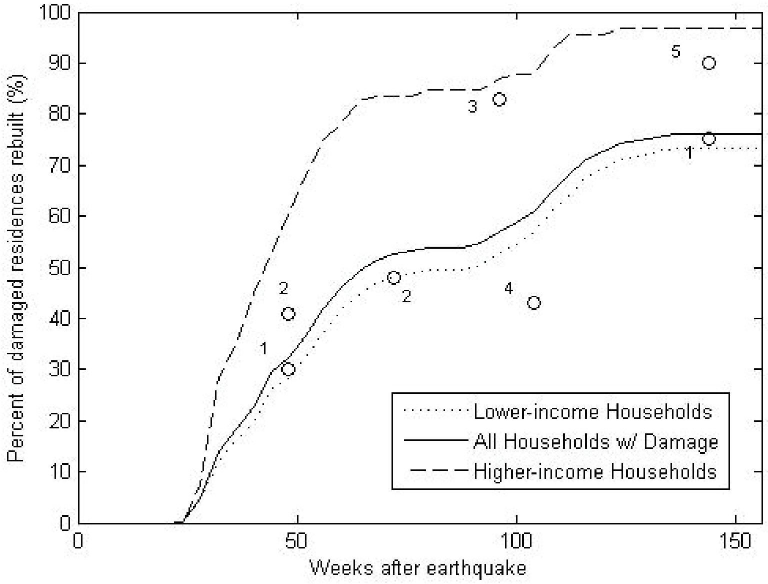

Figure 5-5 Residential reconstruction over time for all residences, households with lower incomes (INC < 0.5), and residences with higher incomes (INC >= 0.5), modeled using the non-calibration data set. Labeled circles correspond to reconstruction data from respective references. (1) Comerio (1997), (2) Chu (1995), (3) Comerio (1996), (4) Wu and Lindell (2004), (5) Kamel and Loukaitou-Sideris (2004)

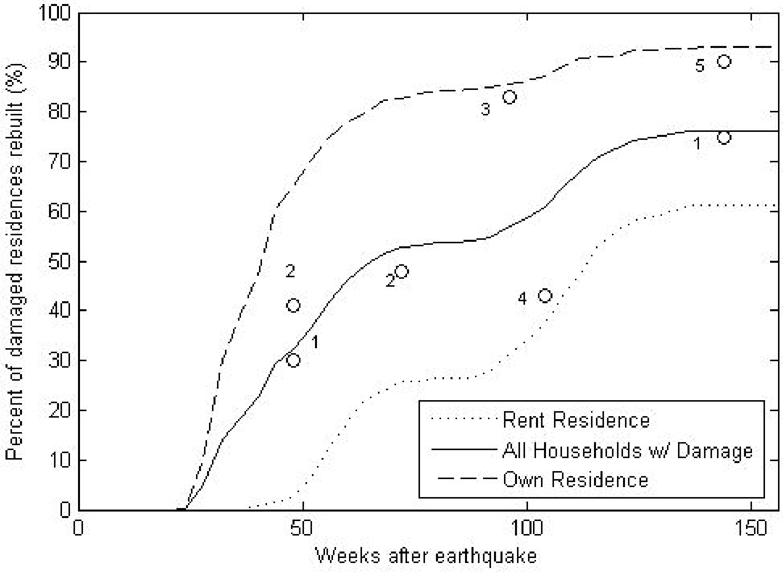

Figure 5-6 Residential reconstruction over time for all residences, households that rent, and households that own, modeled using the non-calibration data set. Labeled circles correspond to reconstruction data from respective references. (1) Comerio (1997), (2) Chu (1995), (3) Comerio (1996), (4) Wu and Lindell (2004), (5) Kamel and Loukaitou-Sideris (2004)

The results of the calibrated post-event model were analyzed and mapped across the Los Angeles PUMAs to further illustrate the behavior of the modeled reconstruction trends. The spatial distribution of PUMA-wide reconstruction time for all damaged residences is shown in Figure 5-7. There was no damage in PUMAs 6502, 6503, and 6521. The PUMAs associated with longer repair times (larger graduated symbols) correspond to areas with higher rates of lower incomes, MFRs and renter-occupied units (see Figures 3-1 and 3-3). In the north part of the study area (San Fernando Valley), there is also a relatively high proportion of lower-income residents, but a much lower rate of both MFRs (and corresponding damage) and renter-occupied units.

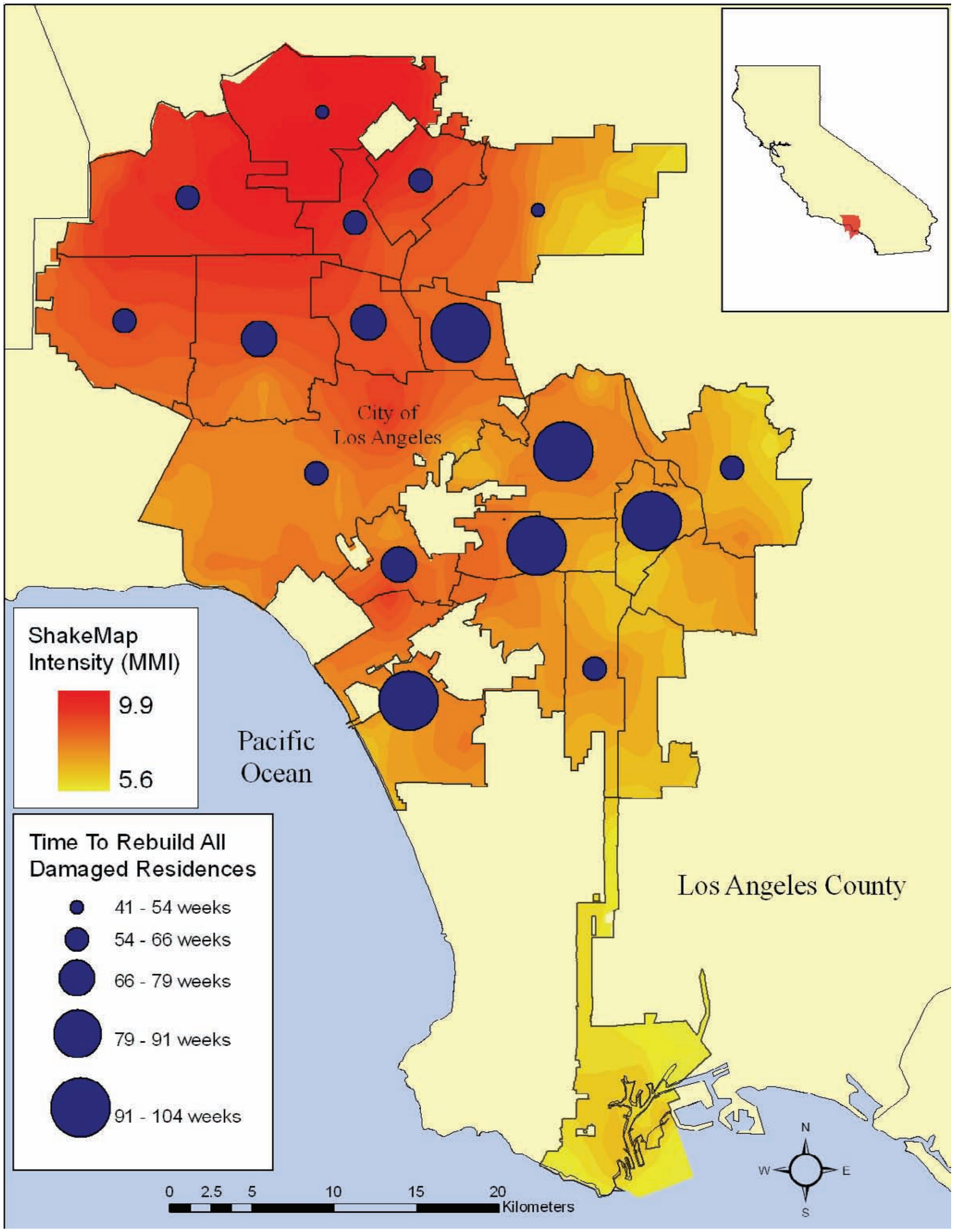

Figure 5-7 Map showing time to rebuild all damaged residential buildings within each PUMA unit. PUMAs 6502, 6503, and 6521 had no damage, other PUMAs without a graduated symbol have residences that have not been fully repaired

5.1.2 Health

The health component of the post-event model was not calibrated due to a lack of suitable data (that we are aware of) for comparison from secondary sources. The spatial distribution of modeled health recovery is shown in Figure 5-8. The differences in the time for all residences to recover their health across Los Angeles PUMAs largely correspond to the distribution of incomes. It is important to note that the modeled number and extent of injuries is quite low in all PUMAs (Figure 4-5). In the future, it is necessary to develop a health recovery dataset in order to calibrate the actual health recovery times computed by the post-event model.

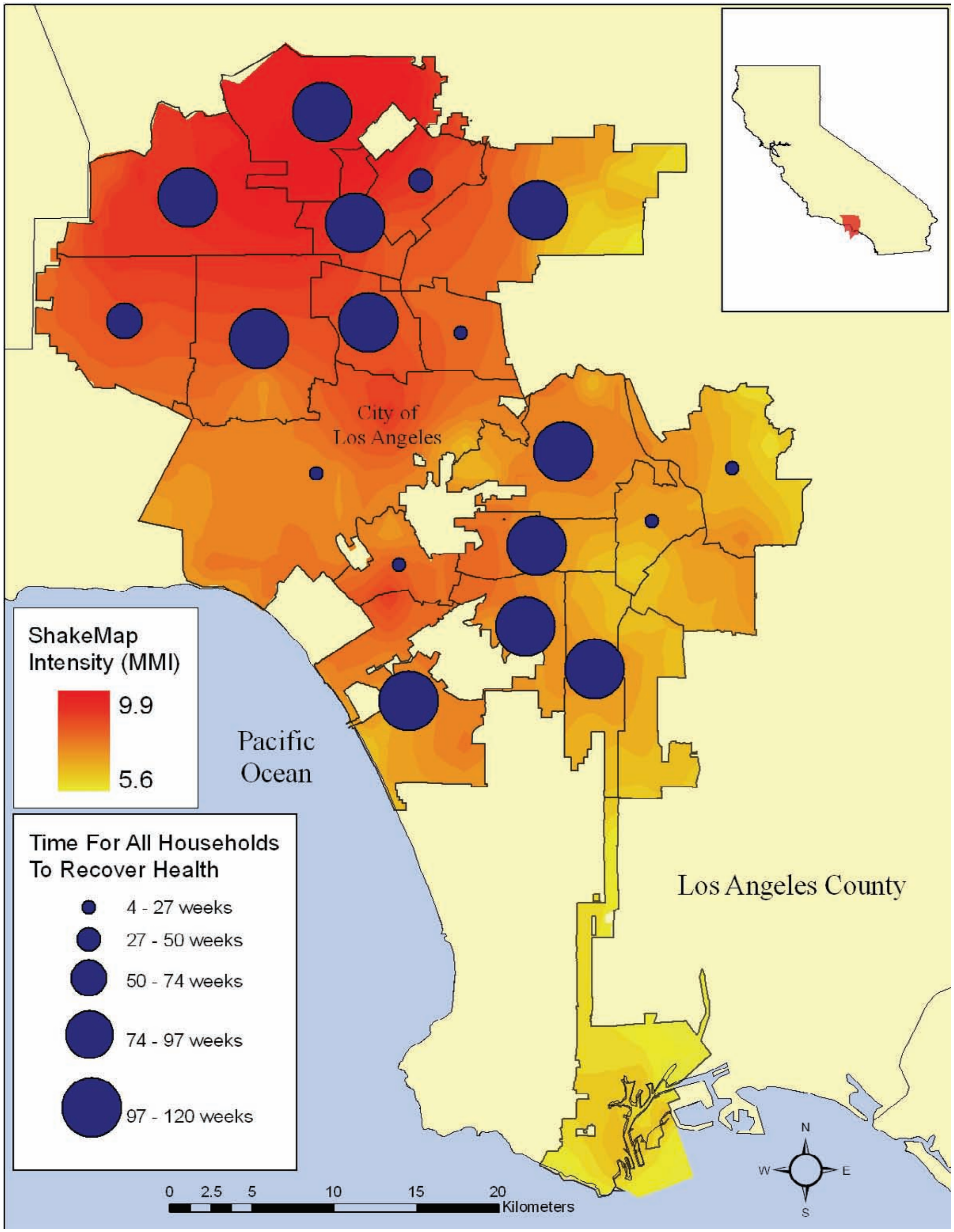

Figure 5-8 Map showing time to complete health recovery for all residents in each PUMA

5.1.3 Debt

Household debt is another component of the post-event model that has not yet been calibrated due to secondary data-source limitations. The modeled results for household debt across Los Angeles using the post-event model are shown in Figure 5-9. The model currently only represents debt specifically related to loans taken out to repair owner-occupied residences. This partly explains the modeled spatial distribution of initial debt levels. Areas with a high percentage of renters will not be modeled to incur a high rate of debt for repairing owner-occupied units. In areas where there is a predominance of owner-occupied units, the differences in average debt levels due to the earthquake are from damage (associated with shaking intensity and structural mitigation) and, to a lesser extent, income. High-income households are more likely to have insurance, obviating the need for taking out a loan, or can use their own savings, if they have any.

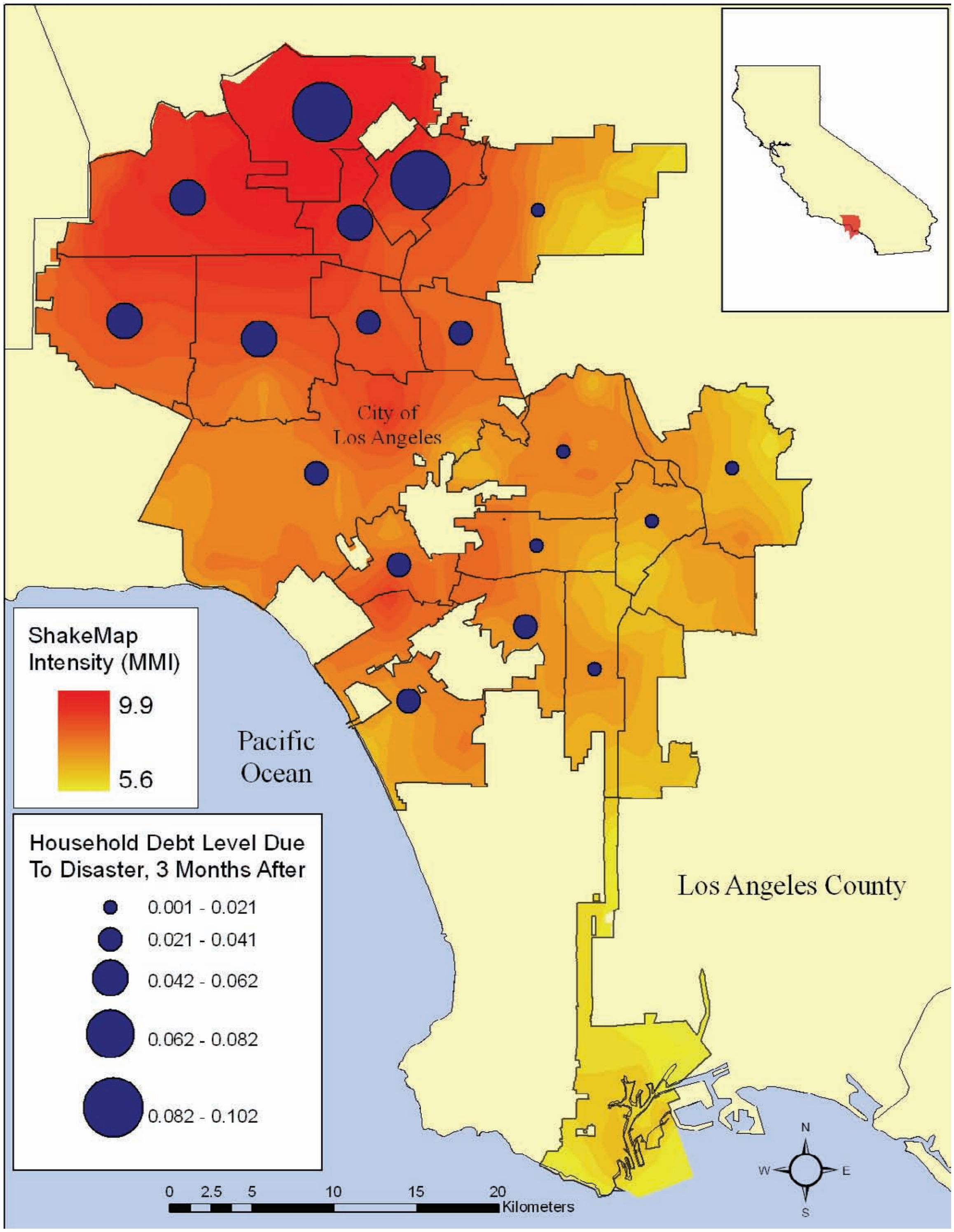

Figure 5-9 Map showing modeled initial post-disaster debt levels due to the Northridge earthquake

5.1.4 Leave

A poll conducted 18 months after the earthquake found that 91% of homeowners within the San Fernando and Santa Clarita Valleys lived in the same place as they did before the earthquake (Chu, 1995). The model was therefore calibrated so that at 18 months after the earthquake, 9.2% of all homeowners across the study area were predicted to have left their residence. Similarly, the poll found that 25% of renters in the same area had permanently moved out of their residence 18 months after the earthquake. The model was calibrated so that 25.5% of renters left their residence at the same time. Calibration of this component was done by controlling the variance of the Gaussian random number generation used for the corresponding Markov chain model. Note that the model does not currently represent where residents move to upon leaving their residences. Conceptually they could remain in the same neighborhood (PUMA), move to another neighborhood in Los Angeles, or migrate out of the area. Figure 5-10 shows the cumulative number of households in owner-occupied and renter-occupied units that were modeled to have left over time. The cumulative number of residents modeled to leave increases with time past the calibration point, but the rate at which residents leave decreases significantly at about 12 weeks after the earthquake, with the rate going to zero at about 140 weeks. Model results for this component are nearly identical for both the calibration data set and the larger non-calibration data set.

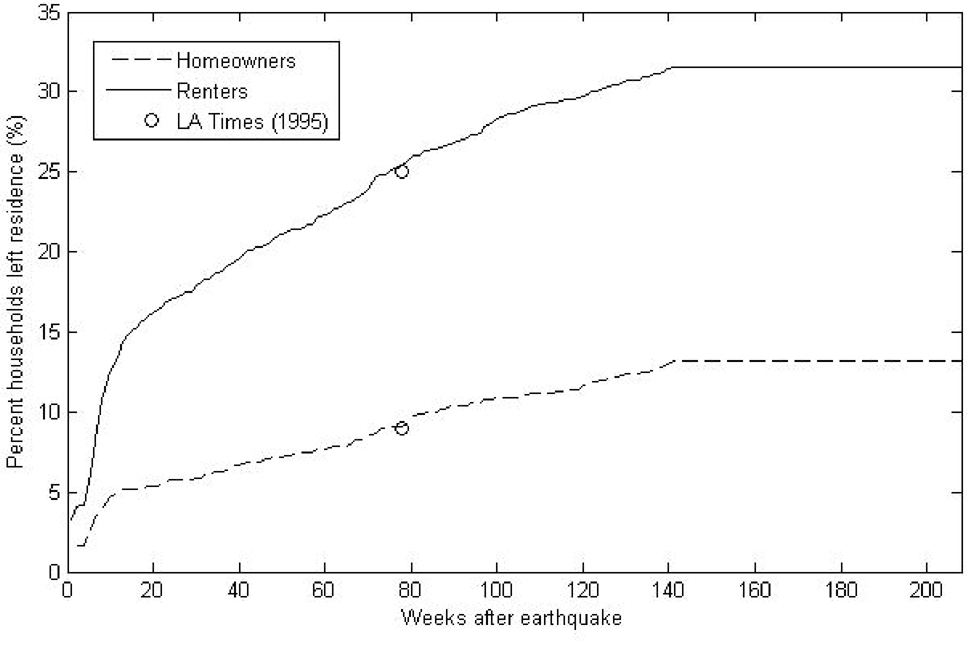

Figure 5-10 Cumulative number of homeowners and renters modeled to have left their residence over time show in comparison to data from a 1995 LA Times poll

The spatial distribution of the percentage of households leaving their residences after the earthquake is shown in Figure 5-11. The higher rate of residents leaving from the central part of Los Angeles appears largely associated with the slow rate of reconstruction. In fact Loukaitou-Sideris and Kamel (2004) found that an above-average percentage of residents, especially renters, left their residences in neighborhoods with a slow pace of reconstruction. The PUMAs with a relatively high percent of residents modeled to leave that are not in PUMAs with slow reconstruction times are associated with a slow pace of health recovery. Table 5-1 lists statistics related to those residents modeled to leave and stay, to provide insight into the relative influence of various exogenous and computed variables. The post-event component for modeling whether residents leave is the last component in the model hierarchy (for households) and thus is influenced by all other model variables. The greatest relative difference in average variable values between those residents modeled to leave and those that stay are for building type (residents of MFRs are more likely to leave), ownership (renters are more likely to leave), and having insurance (residents modeled to leave had a lower rate of insurance coverage).

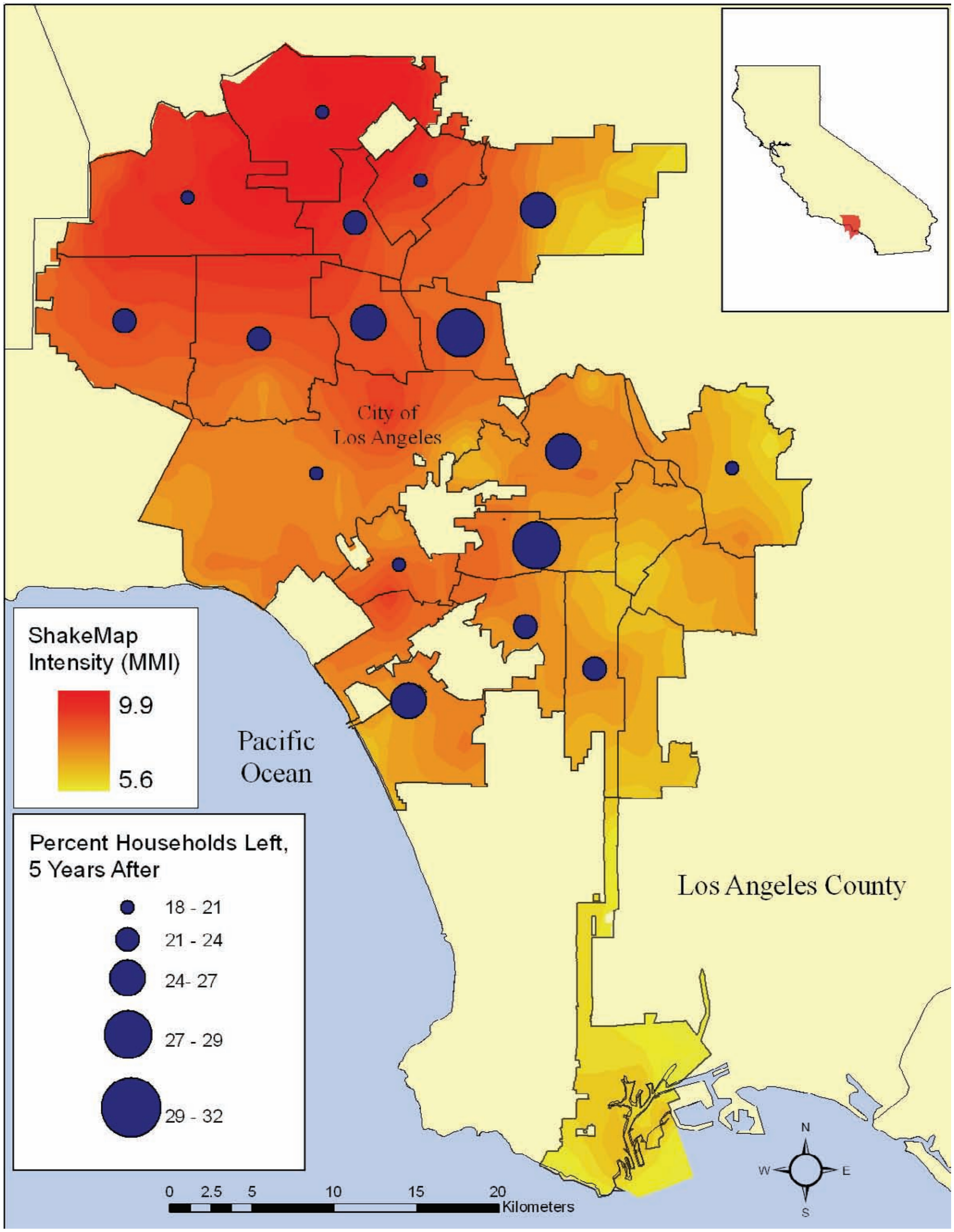

Figure 5-11 Map showing the percentage of households modeled to leave their residence as a result of the Northridge earthquake

Table 5-1 Statistics related to households modeled to leave or stay in their residence

	Left	Stayed
% Live in MFRs	62%	29%
% Renter-occupied	74%	48%
% Have insurance	6%	13%
Mean income	0.25	0.31
Mean MMI	7.4	7.5
Mean mitigation	0.21	0.19
Mean damage	0.017	0.016

5.2 Businesses

Data of varying suitability were used in calibrating three components of the post-event model with respect to business recovery. Data describing residential building reconstruction were used as a general guide for the speed of repairs for business facilities. The best available data for calibrating and evaluating the business components of the post-event model are for employment in the Los Angeles area. Data for the entire city on gross sales receipts was used to constrain the time in which business demand recovered. Components that did not have suitable secondary data-sources for calibration include business productivity level and business failure rate. Results associated with each of these components are presented after the components in which calibration was performed.

5.2.1 Reconstruction

The data used for calibrating the business-facility reconstruction component of the post-event model is the same as that used for calibrating the equivalent residential component (Kamel and Loukaitou-Sideris, 2004; Wu and Lindell, 2004; Comerio, 1997; Comerio, 1996; Chu, 1995). In fact, these data were collected for residential reconstruction, but similar secondary data-sources for commercial and industrial reconstruction were not easily available. The assumption for calibrating the business-facility reconstruction component was that the speed of repairs should be the same or slower, on average, as residential reconstruction. Calibration was done in the same way as for the residential reconstruction component, incorporating the same algorithmic modification as well.

Figure 5-12 and Figure 5-13 are plots showing the percentage of business facilities fully repaired over time for the City of Los Angeles with respect to business and facility size, respectively. Currently, the model is calibrated so that larger businesses repair their facilities much faster than smaller businesses (Figure 5-12). Notice that the reconstruction trend for small businesses is nearly identical to the trend for all businesses combined. This is because the large majority of businesses modeled within Los Angeles are small businesses. Large businesses make up less than 1% of the total number of businesses in each Los Angeles PUMA. Studies do not appear to have been done looking at the relative reconstruction speed between small and large businesses. From the standpoint of access to capital and the capacity to handle increased debt from reconstruction loans, it is logical to expect larger businesses to have an advantage over smaller ones. However, many larger businesses will also have larger or more complex facilities, which require more time for repairs. Figure 5-13 shows the modeled reconstruction trends for businesses by facility size after the Northridge earthquake. Businesses with larger facilities (TYPE ≥ 0.5) are modeled to complete repairs significantly faster than those with smaller facilities (TYPE < 0.5). Within the model, this means that the influence of financial resources (directly related to business size) is larger than the effect of facility size. The reasonableness of this is difficult to assess for two reasons. First, there does not appear to be a specific study of how quickly businesses reconstructed damaged facilities after the Northridge earthquake, with respect to business size and facility type. Second, and likely most significantly, the simulated data for TYPE resulted in only 16 modeled businesses with TYPE ≥ 0.5, making the model results very sensitive to the randomness of the Markov model.

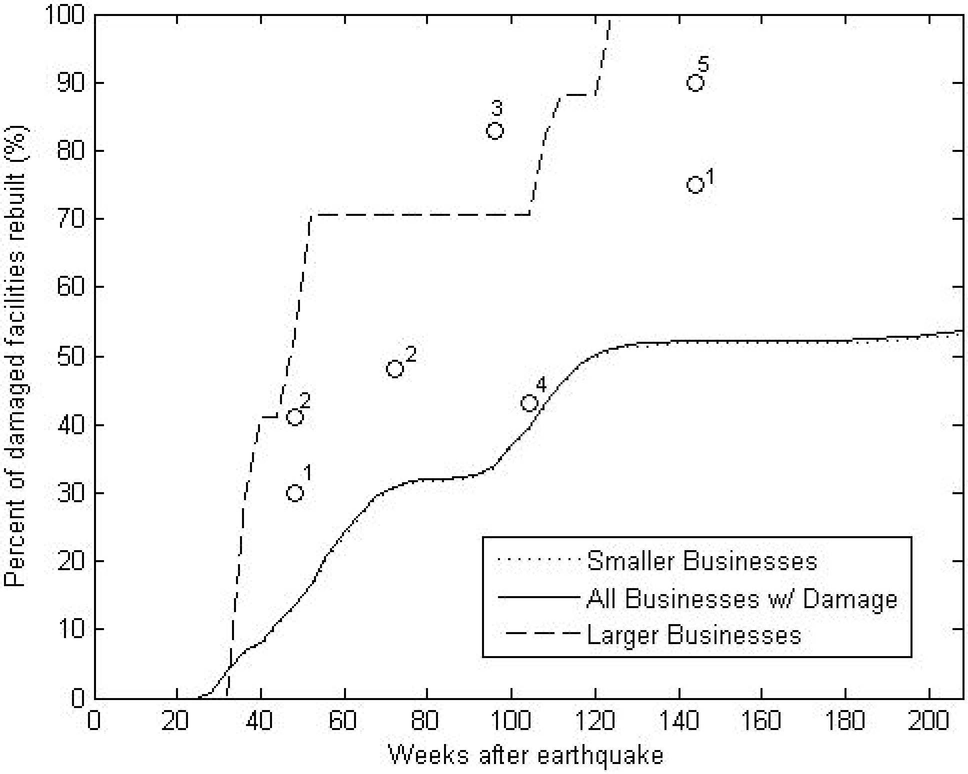

Figure 5-12 The percentage of business facilities reconstructed over time for small (SIZE < 0.5) and large (SIZE ≥ 0.5) businesses

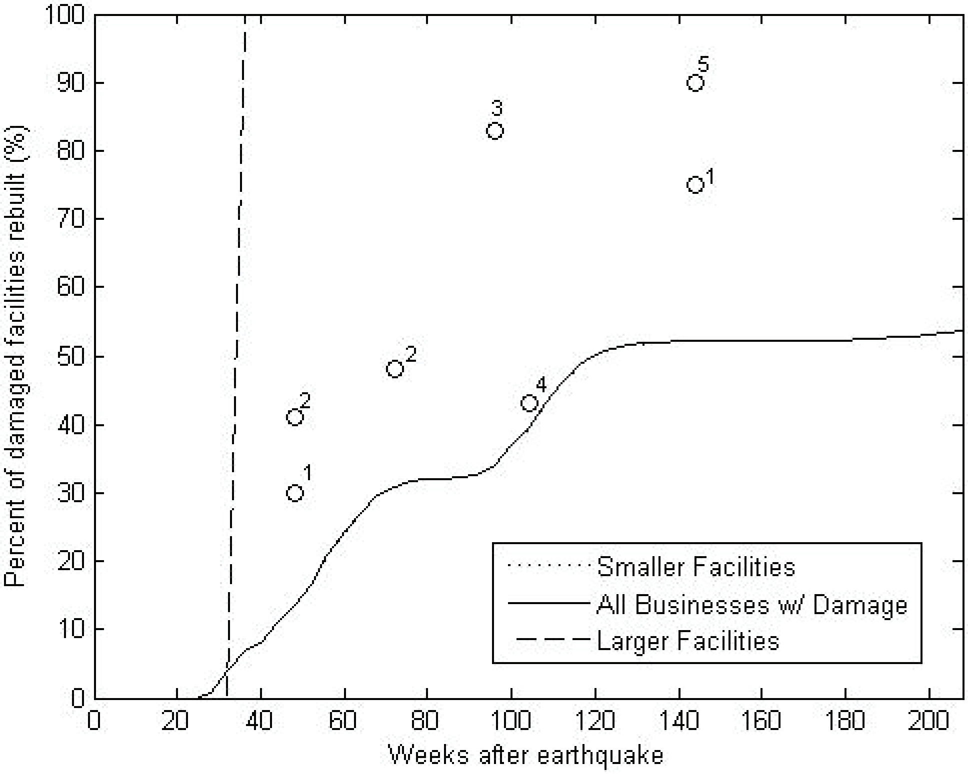

Figure 5-13 The percentage of business facilities reconstructed over time for smaller (TYPE < 0.5) and larger (TYPE ≥ 0.5) facilities

The spatial distribution of the reconstruction of business facilities is illustrated by the map in Figure 5-14. The difference between PUMAs is relatively small for most PUMAs, reflecting the large proportion of smaller locally-oriented businesses throughout the study area. The difference in the speed with which the business facilities in each PUMA were fully repaired is mostly likely associated with the number of businesses (and thus damaged facilities) within each PUMA (Figure 3-2).

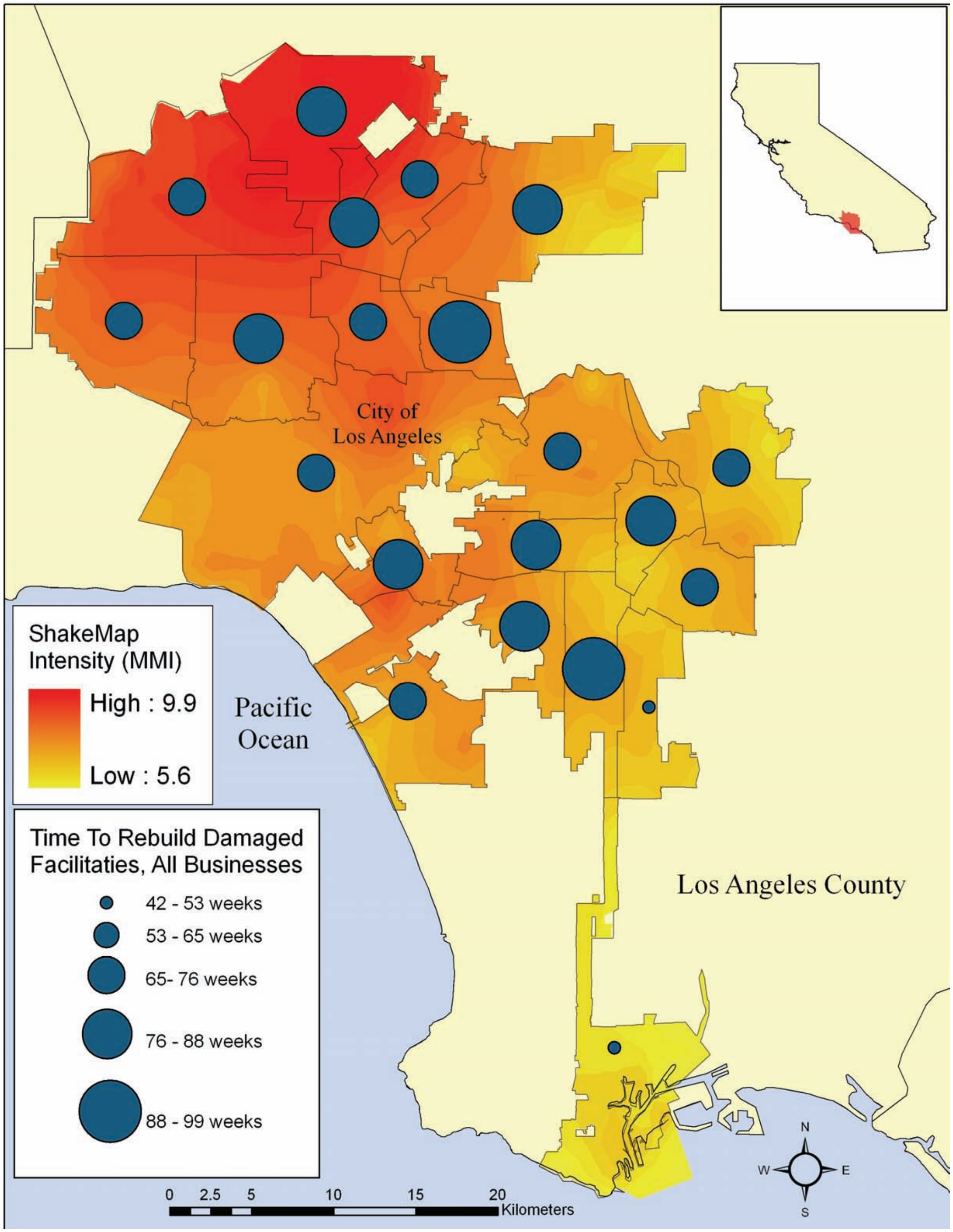

Figure 5-14 Map showing time to rebuild all damaged business facilities within each PUMA

5.2.2 Demand

No data set associated with consumer demand for businesses' products and services is readily available for calibrating the corresponding post-event component. Romero and Adams (1995) noted that total taxable sales for California dipped below pre-earthquake levels in the first quarter after the earthquake, but edged above pre-earthquake levels in the second quarter. This was used as a very general proxy for the time in which demand for businesses' products and services returned to pre-earthquake levels. This is only a fair proxy at best because taxable sales may reflect consumer purchases for an anomalous cross-section of business types, such as those associated with construction and repair. However, in lieu of better data, it provides an order of magnitude baseline for calibrating the Markov chain step-size of the demand recovery component of the model. Figure 5-15 shows a map of business demand recovery times across each PUMA. The difference in recovery times across PUMAs is likely associated with the spatial pattern of household debt level (Figure 5-9).

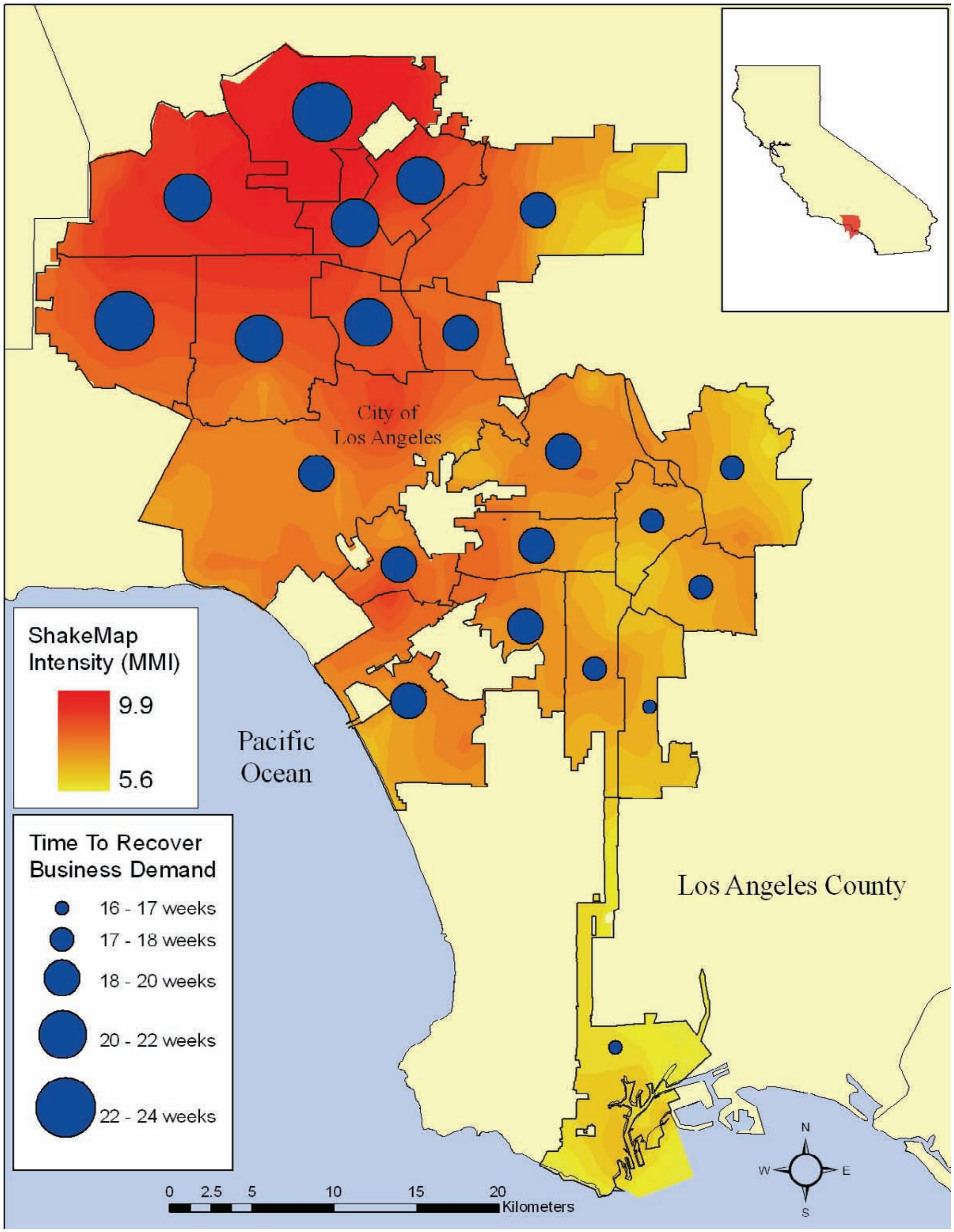

Figure 5-15 Map showing time to recover business demand for all businesses within each Los Angeles PUMA

5.2.3 Production

The map in Figure 5-16 shows a snapshot of modeled mean business production in each Los Angeles PUMA three months after the Northridge earthquake. This component of the post-event recovery model has not been calibrated against empirical data from the disaster. However, the map provides insight into the relative behavior of the productivity component, as well as influence on other post-event model components. Recovery of productivity levels lags in the northern PUMAs of Los Angeles largely due to greater overall damage in those PUMAs (Figures 4-10 and 4-11). As a general comparison, Tierney (1995) found that locally-oriented (as interpreted for this study), small businesses and those whose facilities were damaged were more likely than other businesses to report being closed for some period of time (on average 2 days) or being worse off within the first year after the earthquake. The model was run out for five years and no PUMA reached full production levels (all businesses with PROD = 1). This is likely due to households being modeled to leave their respective PUMA, which affects the household health metric and, in turn, the size and availability of the workforce.

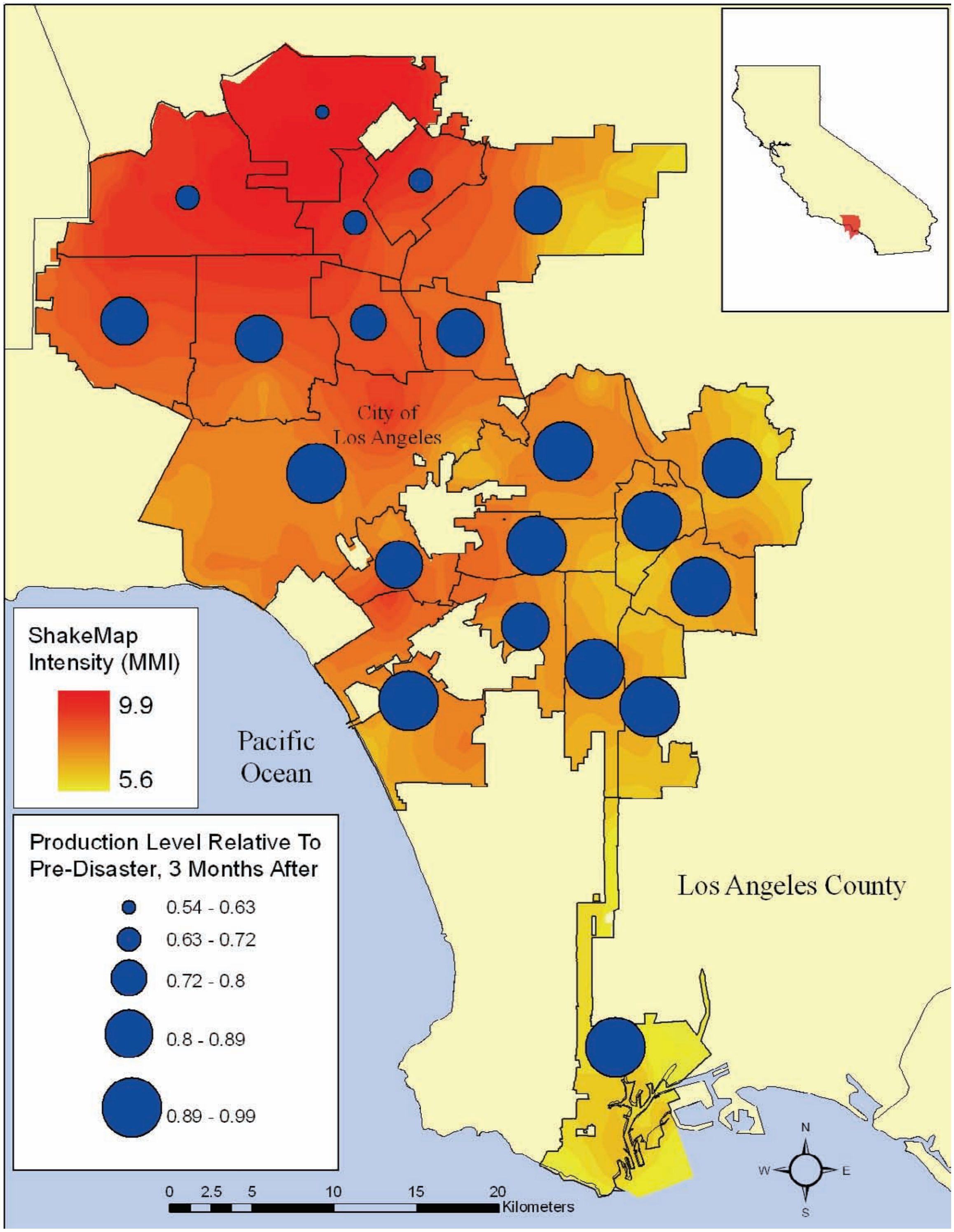

Figure 5-16 Map of relative business production levels three months after the earthquake

5.2.4 Employment

The most readily available data for evaluating the recovery model is associated with employment measures. Currently it is not possible to directly calibrate the employment component of the model, as the employment index is simply the product of the neighborhood average of demand (DEMAND) and productivity (PROD). With some difficulty, calibration can, of course, be done indirectly through those respective components. Two different data sets were available for characterizing employment after the Northridge earthquake. Gordon et al. (1995) estimated the percent of employment days lost in 1994 after the Northridge earthquake within several impact zones (SCPM zones) that coincide with the community planning areas of Los Angeles. To get a sense of the relative performance of the model across PUMAs, a comparison was made by aggregating the Gordon et al. (1995) SCPM zones to roughly correspond with one or more PUMAs—the unit of analysis for the model—resulting in six aggregate units (mapping listed in Figure). The percentages of possible employment days lost estimated by Gordon et al. (1995) were re-calculated based on aggregate counts and normalized by the mean value for the six aggregated units. If multiple PUMAs were contained in the six aggregated units of comparison, the results of the recovery model employment component (3 months after the earthquake) were averaged across the respective PUMAs. Each employment value for the six aggregated units was normalized by the mean value for the units and subtracted from 1 (to express the metric as loss). The comparison is shown in Figure 5-17. The relative employment loss across the aggregated units appears to be similar between the model results and the estimates by Gordon et al. (1995). Because the metric of the model outputs do not match the units of Gordon et al.'s (1995) estimate, the comparison is useful only to see the validity of the predictive relative geographic differences, rather than absolute employment loss.

Time series data on employment are available from the Quarterly Census of Employment and Wages or ES202 program of the Bureau of Labor Statistics. The data describe the number of covered workers who worked during, or received pay for, the pay period that includes the 12th day of the month. Historical data is provided for quarterly time intervals by zip code, based on this on-going census. The data were aggregated by PUMA and an index was calculated for four dates (April 1994, August 1994, June 1996, and December 1998) describing the ratio of the number of people employed in the particular month after the earthquake to the number of people employed that month in the year prior to the earthquake. By August 1994, all PUMAs had at least 98% of the number of workers working as were working in August 1993 (many PUMAs had more than 100%). This can be used to compare the modeled time for employment to return to pre-earthquake levels. (The recovery model does not model employment dynamics beyond reaching some pre-earthquake level.) Figure 5-18 shows the comparison between model results for 7 months after the earthquake and the ES202 data for August 1994 (approximately 7 months after the earthquake). A map of model employment levels four years after the Northridge earthquake is shown in Figure 5-19. This is output from the same model component after more time has passed, illustrating which PUMAs are lagging behind on employment recovery. The lower employment levels in the northern part of the study area (San Fernando Valley) are controlled by the modeled recovery of business productivity.

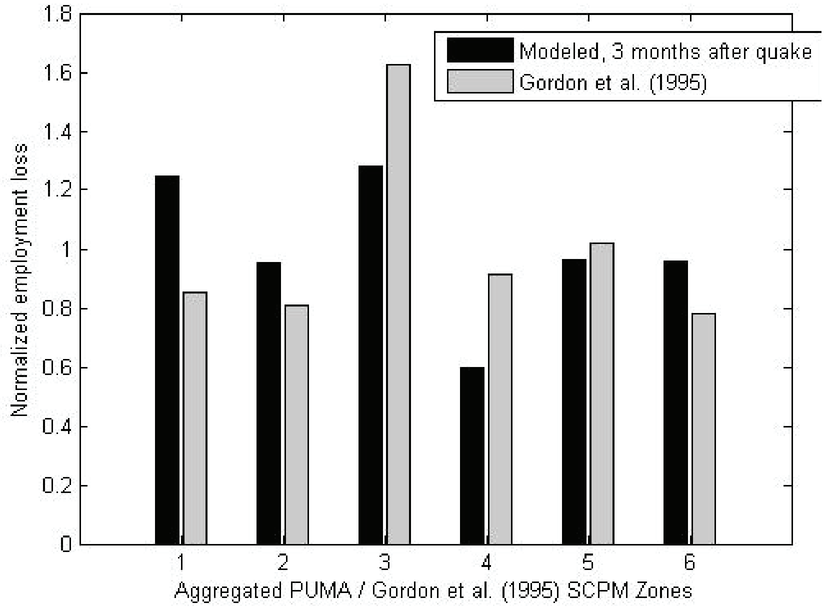

Figure 5-17 Normalized comparison of modeled reduction in employment and employment loss data from Gordon et al. (1995) for selected aggregated PUMAs. 1: PUMAs 6511, 6513, 6514, and 6515; SCPM Zones 1 and 16, 2: PUMAs 6516 and 6518; SCPM Zones 5 and 13, 3: PUMA 6517; SCPM Zone 7, 4: PUMA 6507; SCPM Zone 9, 5: PUMAs 6510 and 6512, 6: PUMAs 6504; SCPM Zone 18

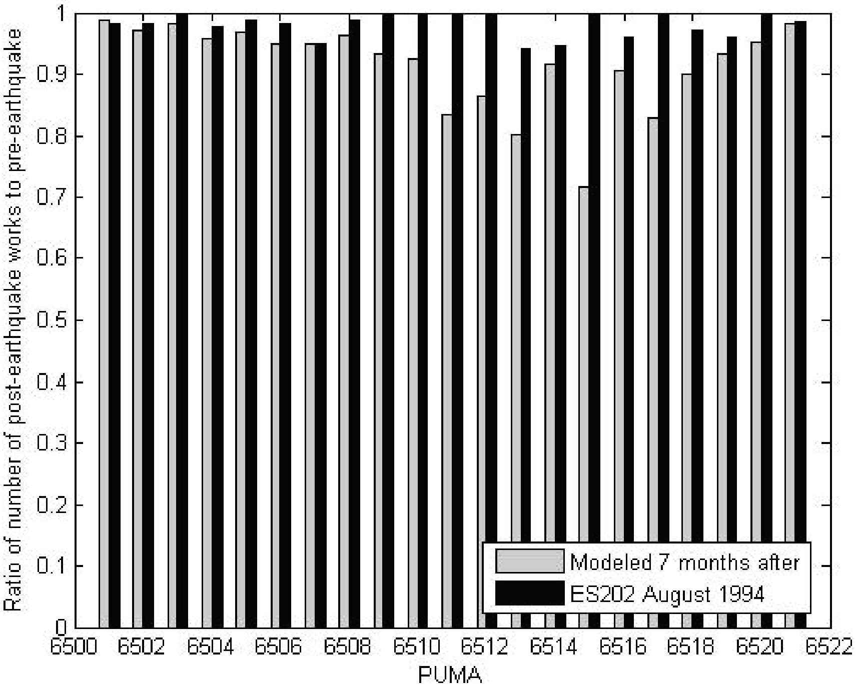

Figure 5-18 Comparison of modeled employment recovery and the ratio of the number of workers, by PUMA, in August 1994 to the number in August 1993

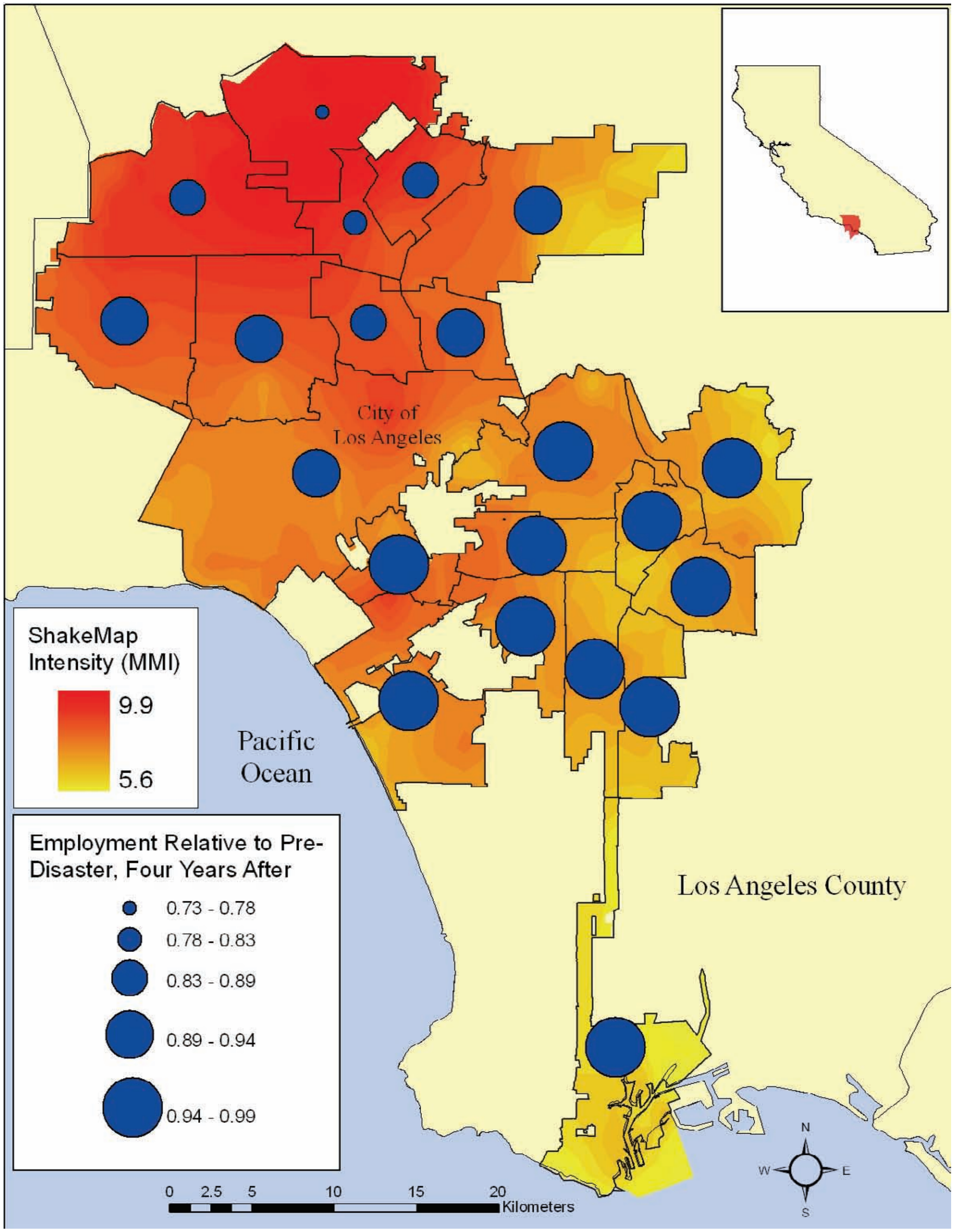

Figure 5-19 Map of modeled employment levels by PUMA four years after the Northridge earthquake relative to pre-earthquake employment

5.2.5 Debt

The post-event component for modeling business debt due to the disaster (and its elimination) is driven primarily by level of damage and the recovery levels of demand and production. For the case of the modeled Northridge application, this is illustrated by the map of average debt levels across Los Angeles (Figure 5-20). Specifically in this case, the higher damage levels and the lagging production recovery control the modeled spatial distribution of debt, where relative debt levels are higher for the PUMAs in the northern part of the study area. In other words, higher damage required larger loans for the large number of smaller businesses with fewer financial resources and the lagging production levels, partly due to a reduced workforce, resulted in less capacity to pay off the loans quickly. The business debt component of the post-event model was not calibrated because of a lack of a suitable secondary data-source. But again the observation of Tierney (1995) is relevant, that locally-oriented, small businesses and those that suffered physical damage were more likely to report being worse off a year after the earthquake.

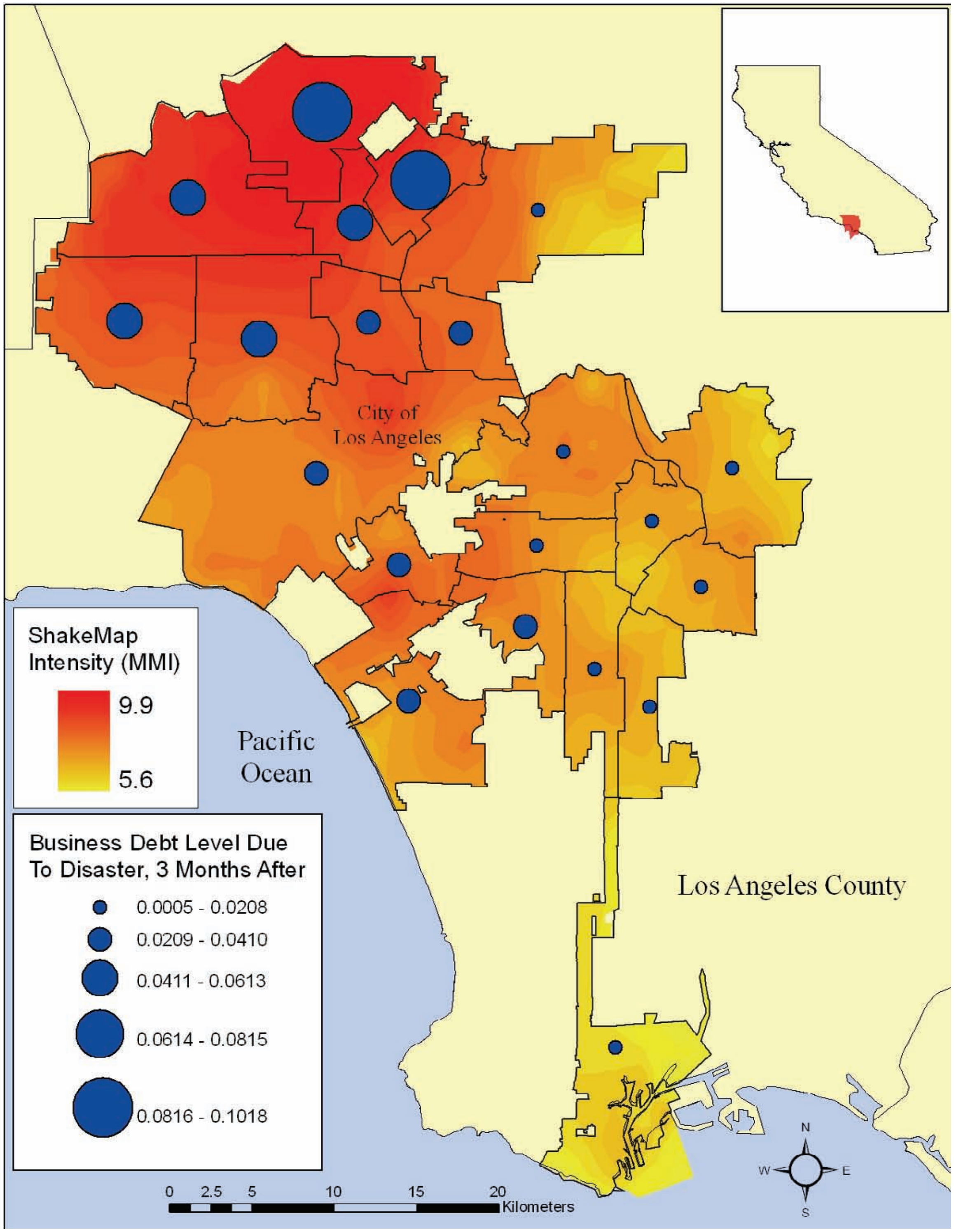

Figure 5-20 Map of average debt levels due to the Northridge earthquake disaster for each Los Angeles PUMA

5.2.6 Failure

General observations from studies about business failure resulting from the Northridge earthquake are useful to calibrate the failure component of the post-event model. Calibration was done by changing the variance value in the Gaussian random number generator of the Markov chain. Figure 5-21 shows the calibrated modeled rate of business failure due to the earthquake as a percentage of all business in Los Angeles. The rate of failure significantly drops after about 20 weeks and failures stop completely after 140 weeks (2 years, 9 months). The period of business failure is consistent with the findings of Petak and Elahi (2001), who observed that small businesses were still failing two years after the earthquake. The map in Figure 5-22 shows the spatial distribution of modeled business failures five years after the Northridge earthquake. The higher rate of failures in the San Fernando Valley PUMAs (northern PUMAs) illustrates the influence of business debt levels, and thus business production and damage levels in the respective PUMAs. While Tierney (1995) found that businesses that suffered physical damage were more likely to report being worse off after the Northridge earthquake, Petak and Elahi (2001) note in their study that damage is not a reliable predictor of business failure. The strong influence of damage on the business failure component of the post-event model is clear from the statistics listed in Table 5-2. Modeled businesses are also more likely to fail if they are locally-oriented, and if they don't have insurance or didn't structurally mitigate their facilities. Petak and Elahi (2001), in fact, found that the rate of business failure varied between locally-oriented (e.g., retail and service) and export-oriented (e.g., manufacturing) sectors, with locally-oriented businesses experiencing more failures.

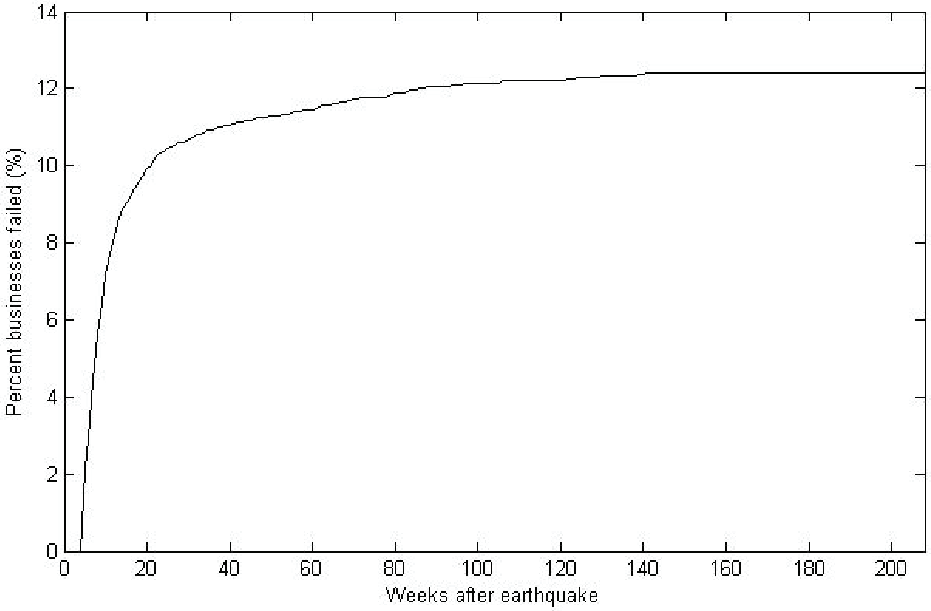

Figure 5-21 Modeled rate of business failure as a percentage of all business in Los Angeles

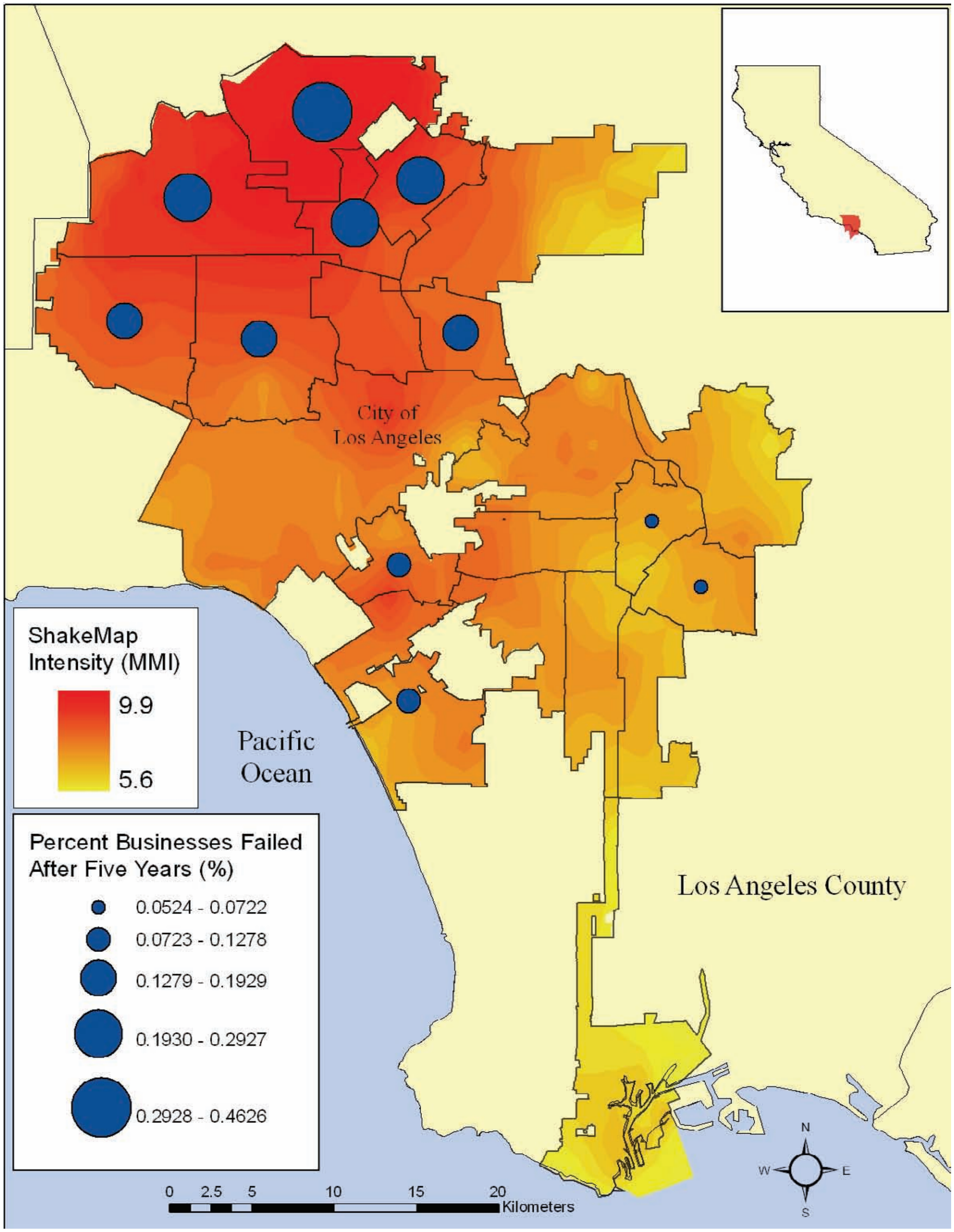

Figure 5-22 Map of business failure rates for each Los Angeles PUMA five years after the Northridge earthquake

Table 5-2 Statistics on modeled business failure due to the Northridge earthquake

	Failed	Didn't Fail
% locally-oriented	80%	74%
% with insurance	11%	15%
Mean business size	0.02	0.2
Mean building size	0.08	0.08
Mean MMI	7.8	7.4
Mean mitigation	0.42	0.52
Mean damage	0.36	0.05

SECTION 6
CONCLUSIONS

As described in Sections 2~5, numerous refinements have been made to the recovery model that was previously published in Miles and Chang (2003, 2006). Significant improvements have been made to both the underlying conceptual model and the model's implementation. The refined model has, moreover, been applied and calibrated to the 1994 Northridge earthquake. This section concludes the technical report by discussing potential applications of the model to "what-if" scenarios (Section 6.1); advances, contributions, and limitations of this study and approach (Section 6.2), and prospects and areas for further research (Section 6.3).

6.1 What-if applications: preliminary examples

A primary motivation for developing the model was to allow application to "what-if" scenarios. Because disasters are rare and complex events, empirical studies of disaster recovery have generally adopted case study approaches. Case studies provide a rich, in-depth understanding of particular communities and disaster events. They provide insights on factors and specific variables that appear to influence recovery, as well as a broad understanding of recovery processes – insights that provided the empirical foundations for the current simulation model. A more quantitative, systematic, and comparative approach is needed, however, to develop a generalized knowledge base that could be used to support decision-making. Running the simulation model for various "what-if" scenarios provides an important approach for addressing this need.

6.1.1 Types of "What-if" questions

Generally speaking, the model facilitates explore three types of "what-if" questions: (1) questions related to potential decisions and policies, (2) those related to exogenous factors such as community or hazard-event characteristics, and (3) those concerning changes over time.

Policy variables - The model currently includes several variables that represent decisions, plans, and policies that may influence recovery. These may be plans or policies implemented by the community, such as institution of seismic design codes (specifically, the variable CYR, the year that the seismic code became effective) or whether or not the community has developed an effective disaster preparedness plan (the variable PLAN). They may be policies made by lifeline or critical facilities organizations (e.g., mitigation MIT) or by higher levels of government, such as federal guidelines for disaster assistance (the variable AID). They may even be proxy variables relating to a community's "capacity" for consensus and effective decision-making (the variable CAP). Other decision, planning, and policy variables are shown (by bold font and underline) in Table 2-1.

These variables are simplified representations of actual decisions, plans, and policies. For example, the code year CYR consists of a single designated year. All buildings constructed prior to this year are considered to perform worse (as indicated by the fragility curve) than all buildings constructed after that year. A more realistic representation would be to allow for multiple code years that represent a series of code improvements and seismic design vintages over time. Fragility curves for pre- and post-code could, moreover, differ by construction type (e.g., wood-frame single-family residences v. high-rise concrete frame buildings). The structure of the model does allow for these types of refinements. But it is important to consider that these types of refinements would require not only changes in model algorithms, but associated levels of detail in input data, such as data on construction type and year. These detailed input data may not be available for many communities. In the case of the Northridge application, for Los Angeles, we were unable to obtain detailed data on nonresidential building stock.

Similarly, it should be noted that the policy variables in the model represent only a small subset of policy variables that do influence recovery and that may be of interest to users of the model. The current set of variables is based on policy-related factors that are salient in the empirical literature. Other policy variables could in principle be added to the model.

The policy variables in the model can be used to explore questions related to alternative choices that may enhance a community's ability to recover from future disasters. For example, what policy variables most influence recovery? What are the implications of policy alternative A, versus alternatives B and C? Which alternative would provide the greatest enhancement in ability to recover, and hence resilience? Within the limits of the model, how much of a change in policy variable X would be needed to attain a certain level of resilience? What are the equity implications of a given policy choice – for example, would disparities in resilience across neighborhoods increase or decrease?

Exogenous factors – A second type of question relates to variables that represent exogenous conditions rather than choices. These include inherent characteristics of the community itself that may be social, demographic, economic, geographic, or historical (e.g., income distribution, industry composition and economic structure). Other exogenous conditions refer to the hazard event itself – whether it is spatially extensive or focused (e.g., earthquake vs. terrorist bombing), the magnitude and severity of the event (e.g., ground shaking intensities for an earthquake), and whether it is a single event or a series (e.g., earthquake without or with aftershocks).

Varying these exogenous factors would allow insights into how robust the model outcomes are to different community contexts. For example, is policy alternative A always preferable to alternative B? Are there certain types of communities for which alternative B would be preferable? It would also allow insights into how resilience outcomes differ by severity and type of hazard. Are there certain thresholds of earthquake severity, for example, beyond which recovery will be particularly difficult and time-consuming? Is a given community more resilient to floods or earthquakes? Perhaps most intriguingly, when considering capacity for recovery and resilience, do characteristics of the community matter more than characteristics of the hazard itself? Are there certain types of communities that exhibit consistently low or particularly high levels of resilience?

Changes over time – A third type of "what-if" question concerns how a community's resilience may be changing over time. Projected population growth, future development in floodplains, and a shift toward a service-oriented economy are examples of changes that can be readily represented in the model (by specifying the attributes and populations of households, businesses, and neighborhoods for the community as anticipated for some future time period). How are such factors, which are independent of efforts to reduce risk, affect future risk and resilience? Similarly, what effect would policy decisions today (e.g., adoption of seismic code this year) have on community resilience in the future? "What-if" investigation that replicates actual policy decisions can help to address questions such as whether policy choices are improving resilience, and to what degree.

6.1.2 Examples of "what-if" scenarios

To illustrate how "what-if" scenarios can be applied, this section considers two cases. The first pertains to a policy variable – the year the community adopts the seismic code (variable CYR). Specifically, what if the seismic code year had been delayed by a decade, so that the effect code year were 1986 rather than 1976? Buildings built between these years would be more prone to earthquake damage than they actually are; would this have a noticeable effect on recovery and resilience? The second "what-if" scenario relates to a community characteristic, income disparity (variable INC for households). Specifically, what if there were no income disparities in Los Angeles? Clearly this case is hypothetical and not intended to represent a potential actual condition. What it does allow, however, is exploration of the question: How much does income disparity, a community characteristic, influence recovery outcomes? This case is implemented as assigning each household an income value of INC=0.5 (indicating that all Los Angeles residents have an income equal to about $62,500 or half of 1990 95th percentile income). Each of these cases is applied to a repeat of the 1994 Northridge earthquake and compared to a baseline, which consists of the model as calibrated to the Northridge event.

As indicated in Section 5 on the post-event model, numerous outputs of the model could be used to compare the various cases. For present purposes, the "what-if" scenarios are compared on the basis of structural restoration curves, as indicated in Figure 6-1 (a~c). Of all the outputs of the post-event model, restoration had the most complete and reliable empirical data for calibration. The restoration curves in Figure 6-1 are similar in form to Figures 5-1 through 5-6 and indicate the percentage of damaged residential structures rebuilt over time for all, single-family, and multi-family structures, respectively. The numbered circles in Figure 6-1 (a~c) are identical and represent the empirical calibration points from reported data, as described in Section 5. They serve as useful benchmarks for comparing the three graphs in the figure.

Comparing graphs (a) and (b) in Figure 6-1, it can be seen that the effect of delaying the code year (b) is fairly minor in terms of reconstruction. The only notable difference is that after approximately two years, reconstruction activities level off at around 65%, in comparison with the baseline case where it levels off at around 85%. This difference can be attributed to the much lower reconstruction rate for multi-family residences. Because the "what-if" scenario affects only a 10-year vintage of buildings, the similarity between the two is not surprising. Further investigation could consider whether the multi-family residences are highly represented in this 10-year vintage.

Comparing graphs (a) and (c) in Figure 6-1 reveals somewhat greater differences. In particular, after the first year, reconstruction with respect to time in the case with completely even income distribution (c) is consistently greater by about 5~10 percentage points than in the baseline (a). Reconstruction of all residences levels off at about 88% rather than 81%. Perhaps the most dramatic difference is that the complete single-family residence stock is rebuilt about 60 weeks faster in case (c). The rate of reconstruction for multi-family residences appears to be about the same in the first year, but increase in rate for case (c) during the second year. The difference in the percentage of residences rebuilt between single-family and multi-family residences is about 10% less in the case (c) than the baseline case. This illustrates that household income is, in fact, important for multi-family residence restoration, but far from sufficient. Further exploration could pursue the question of whether the effect arises more from changing incomes or from eliminating disparities, for example by comparing different neighborhoods.

6.2 Advances, contributions, and limitations

The earlier model on disaster recovery (Miles and Chang, 2003; 2006) represented, to our knowledge, the first attempt by researchers to develop a comprehensive computer-based model of urban disaster recovery. It provided an early prototype model that demonstrated the feasibility of the concept and broadly validated it for an application to the catastrophic 1995 Kobe earthquake. A series of internal and external evaluation exercises were conducted on this model. The latter included formal practitioner feedback (through focus group and survey), formal assessment from a computer programming professional, and informal peer feedback from conference presentations and seminars. Priorities for model refinements were developed from these evaluation exercises and implemented as described in this technical report.

The refined model, which can be considered a second-generation prototype, makes several important advances and contributions. First, it provides a more meaningful characterization of recovery indicators (e.g., percent of buildings rebuilt) that can be compared with data from actual disasters. Second, it is fully modular in design, with linked but separate co-event and post-event modules. The former simulates input data and impacts at the time of the disaster, and is somewhat akin to the more traditional models that estimate disaster losses in terms of human casualties and property damage ("loss estimation models"). The post-event module simulates multi-dimensional recovery over the weeks and months following the disaster. Separating the co-event and post-event modules allows for substitution of actual data or alternative simulation modules – for example, in the Northridge application, actual rather than simulated data on lifeline restoration were used. Third, the model is scalable, allowing representation of any number of neighborhoods and agents within these neighborhoods. This facilitates the incorporation of actual data on households and businesses. It also allows, in principle, for the internal migration of households and businesses within the study area, although this refinement has yet to be implemented. Finally, the model has been applied to the case of the 1994 Northridge earthquake – an event that is not only the best-documented earthquake (in English) but also one striking a major U.S. metropolitan area and, until Hurricane Katrina, the U.S.'s costliest disaster. The model has, in other words, been successfully applied to a major U.S. urban center and calibrated against the best available data for any earthquake disaster.

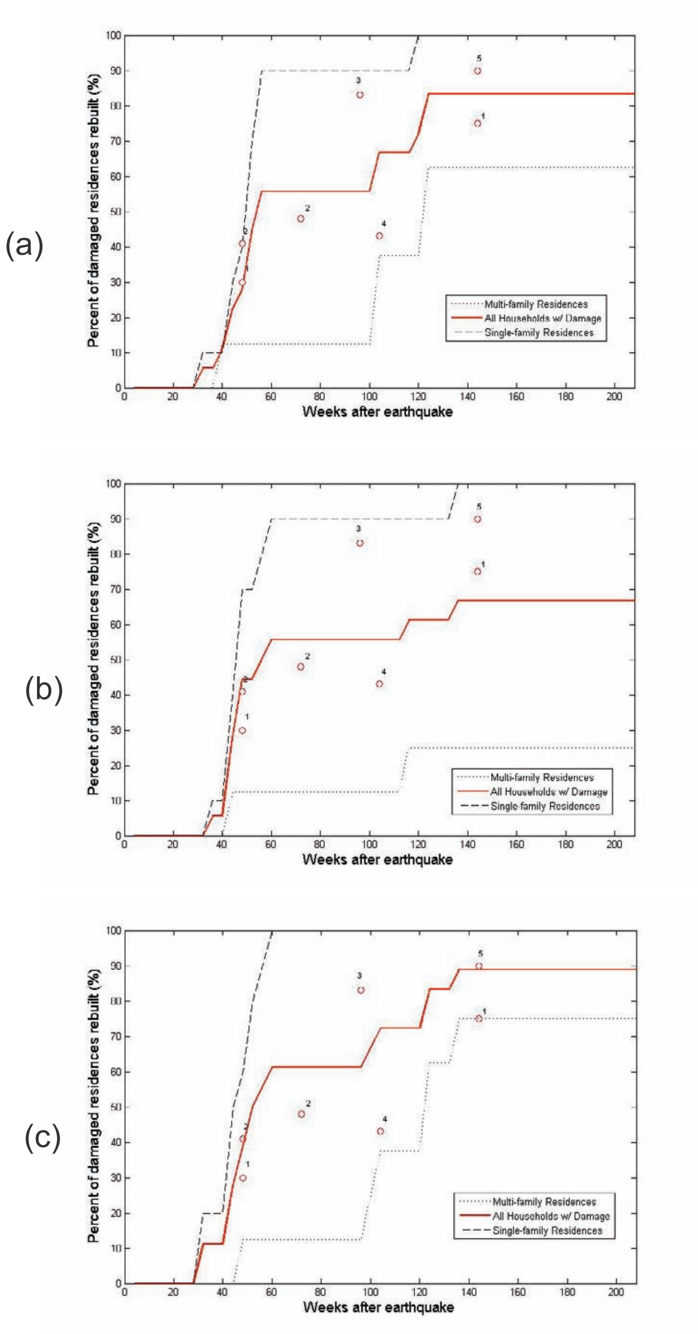

Figure 6-1. Reconstruction curves for "what-if" scenarios. (a) Baseline case, (b) Code year delayed, (c) No income disparity.

In the course of this study, several limitations became apparent, some relating to the model as currently implemented and others relating to the general approach regarding recovery simulation. Limitations of the current model include a representation of decisions and decision-making that is probably overly simplistic and limited. It is worth considering, however, the degree to which more complex representations are warranted in balance with the level of simplification in other parts of the model (see further discussion in Section 6.3 below). The lack of a capability for modeling relocation of households within the study region remains another key limitation. It should be noted, nevertheless, that very little empirical data are available on relocation in actual disasters, so that even if such a capability were to be developed, it may be impossible to calibrate.

A second general limitation derives from the model having been calibrated on a single event, the Northridge earthquake, which was a moderate-sized disaster. The performance of the model in the context of smaller, less destructive events and larger, catastrophic events is unknown. The earlier model was evaluated against the devastating Kobe earthquake, but the current model incorporates numerous substantial refinements and the exercise should be repeated. The overall reliability and performance of the model across a range of disasters is at present unknown.

Finally, a key limitation concerns the overall unevenness in reliability and performance of the model in comparison with available data for Northridge. The model performs well in simulating damage, for example, but rather poorly in simulating injuries. Some input variables in the model (e.g., household demographics) are based on reliable and complete data, while others (e.g., mitigation status of buildings) are based on rough algorithms for generating synthetic data in the absence of any real information. Some elements and outputs of the model (e.g., health recovery, debt) simply could not be verified empirically, much less calibrated, because of lack of empirical data.

6.3 Prospects and areas for further research

Models of urban disaster recovery, such as the one described in this technical report, have several potential uses, including decision support and education. They may be used by emergency managers, planners, decision-makers, and policy-makers to explore alternative approaches for reducing risk and enhancing community resilience through pre-disaster mitigations. They may also be used as one source of information to support planning for post-disaster recovery. Numerous simplifications were, however, required to render the model conceptually and computationally tractable. In this regard, this model could perhaps be more appropriately and effectively applied for educational and awareness rather than for decision-support purposes.

The comprehensive nature of the model, which is one of its key strengths, suggests that it may be especially appropriate for educational and awareness purposes. Many professionals – including emergency managers but extending also to elected officials, urban planners, and the like – make decisions that intentionally or unintentionally influence community recovery and resilience. Yet many are unfamiliar with the research literature on factors that influence recovery. In an interactive setting, where users can pose "what-if" scenarios and explore their consequences, the recovery model could be used to help educate users about empirical findings from disaster studies (e.g., what types of businesses tend to have the most difficulty recovering), to raise awareness about the interconnections between different sectors in recovery, to help visualize and develop an understanding of what to expect in the event of a future disaster, and to identify alternative approaches to enhancing recovery and resilience.

From a research standpoint, one particularly valuable prospect for the recovery model is to help develop systematic frameworks and knowledge bases regarding disaster recovery. It has already been mentioned that the model generates numerous outcomes that cannot be empirically verified at present; viewed positively, this means that the model can be used to generate hypotheses for testing in carefully designed empirical studies. For example, Table 5-1 summarized contrasted characteristics of households that left the region in the model from those that stayed (e.g., those leaving tended to have lower incomes, and lower likelihoods of being insured or living in a single-family residence). Besides pointing out the need for studies that inquire into household dislocation, this provides some starting hypotheses for such investigations. Similarly, the model generates results spatially, indicating contrasts in recovery factors and progress across neighborhoods. While many of these could not be empirically verified, they do point out the need for more spatially sensitive studies of recovery and generate hypotheses about spatial inequalities that can be pursued in other studies.

Generally speaking, the findings from this report indicate a strong need for more systematic empirical data on pre-disaster urban conditions as well as disaster recovery. It is surprising that even for one of the most highly studied earthquake-prone regions in the world, and arguably the best-documented earthquake disaster (at least in the U.S.), basic data – on such factors as prevalence of pre-disaster mitigations, insurance patterns, construction years of non-residential buildings, reconstruction timeframes for the non-residential building stock, household consumption and health recovery, and economic recovery for various neighborhoods – are unavailable or non-existent. The complexity and internal sophistication of a model must be balanced with what available data will support. While numerous advances could potentially be made in terms of model design, the need for better empirical data is probably more urgent.

In terms of model improvements, several priorities for further research can be identified. Additional variables should be included in the model to represent a wider range of resources available to agent that influence resilience and recovery. Additional agents should be included representing various levels and organizations of the governmental and non-governmental sectors. Additional types of decisions, plans, and policies, as well as more detailed representations of them (e.g., specificity with regard to type and extent of lifeline mitigations) should be incorporated. Attention should be paid to modeling systems aspects of lifeline service, damage, and restoration.

More refined treatment of agents' behaviors should be developed, particularly within the capabilities allowed by agent-based modeling. For instance, household and business agents currently have fairly static interactions with their environments and are spatially fixed in location. More refined treatment could include an explicit representation of agents' access to resources and decision-making, for example, in response to environmental conditions or behaviors of agents in their vicinity (e.g., exchange of information), in terms of migration and relocation, and on the basis of microeconomic theories of behavior and decision-making.

The conceptual framework, too, could be refined from a theoretical standpoint. One possibility would be to emphasize dynamics and ongoing forces for change, considering for example not only the current population of a neighborhood, but also how this population had been changing in the decades preceding the disaster. Another possibility would be to rebuild the model around a more theoretically sophisticated and consistent core, such as a regional economic model (e.g., a computable general equilibrium model). Clearly, such refinements would entail substantially greater data demands than what is currently required. New, alternative models of disaster recovery would provide valuable opportunities for comparative assessment.

Finally, further research should seek to apply the current model in numerous other situations – to other urban areas, types of disasters, and disaster events. The model has multi-hazard capabilities in principle. Applications to floods, hurricanes, or terrorist events could be helpful for refining the model and for developing generalized insights into resilience factors across hazards. Applications to other urban areas could begin to develop robust insights into what types of urban areas or urban conditions are most resilient (or conversely, most lacking in resilience) and ultimately, what types of policy interventions may be most effective in enhancing resilience.

SECTION 7
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University at Buffalo, The State University of New York
Red Jacket Quadrangle ▪ Buffalo, New York 14261
Phone: (716) 645-3391 ▪ Fax: (716) 645-3399
E-mail: *mceer@buffalo.edu* ▪ WWW Site *http://mceer.buffalo.edu*
University at Buffalo *The State University of New York*

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