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An Urban Earthquake Disaster Risk Index

by

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Abstract

The Earthquake Disaster Risk Index (EDRI) is a composite index that allows direct comparison of the relative overall earthquake disaster risk of cities worldwide, and describes the relative contributions of various factors to that overall risk. The development of the EDRI brings together a body of knowledge about earthquake disasters from a wide range of disciplines to provide three principal benefits.

First, the direct comparison of overall earthquake disaster risk provides a useful tool for inter-city allocation of mitigation resources and effort. Most previous work in earthquake risk assessment has focused on a single component of the risk, and/or on a single region. The EDRI provides a systematic way to directly compare the overall earthquake disaster risk across a large number of cities or regions. Second, the disaggregated EDRI will increase awareness of the wide range of factors on which a city's earthquake disaster risk depends, from the expected magnitude of ground shaking, to the number of structures, to a city's current economic situation. A comprehensive EDRI will highlight the fact that even in urban regions with low seismicity, an earthquake may occur, and if it does, the other characteristics of the city could turn that single event into a major disaster. Third, by reevaluating the index periodically, the EDRI may be used to monitor trends in earthquake disaster risk over time.

The EDRI has been developed using the following six-step procedure: (1) create a conceptual framework of all the factors that contribute to earthquake disaster risk—geological, engineering, economic, social, political, and cultural factors; (2) identify simple, measurable indicators to represent each of the factors in the framework (e.g., population, per capita Gross

Domestic Product, percentage of the urbanized area that is soft soil); (3) combine the indicators mathematically into the composite EDRI; (4) gather data and evaluate the EDRI for each of the world's major cities, (5) perform a sensitivity analysis to determine the robustness of the results, (6) interpret the numerical findings to assess their reasonableness and implications, and present the results in a variety of easily understandable graphical forms. A ten-city sample analysis was conducted to explore the challenges associated with this process, and to illustrate its feasibility and the usefulness of the results.

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Chapter One
Introduction

1. Introduction

Imagine a landscape without people, buildings, or any human influence. Suppose an earthquake occurs in that setting. The geology of the area will determine the characteristics of the ground shaking. Now imagine a city, with all its infrastructure and residents, is superimposed on the same landscape, and the same earthquake occurs. The characteristics of the city will determine the sequence of events that follow the ground shaking. Finally, if that city is removed and replaced with another, the same earthquake will precipitate a different sequence of events because the second city exhibits a different set of characteristics.

This study aims to identify and understand the factors (i.e., city characteristics) that together determine the sequence of events surrounding an urban earthquake, and to represent those factors and the overall risk in an easily accessible way, so that the earthquake disaster risk of two cities, like those described above, can be compared directly. These objectives are pursued through the development of a comprehensive urban Earthquake Disaster Risk Index (EDRI). The EDRI is a composite index that allows direct comparison of the relative overall earthquake disaster risk of cities worldwide, and describes the relative contributions of various factors to that overall risk. The index demonstrates that the risk in Jakarta is about the same as the risk in San Francisco, but significantly less than the risk in Tokyo. Examining the components of the EDRI indicates that while the risk in Jakarta is mostly the result of the high vulnerability and insufficient emergency response and recovery capability, the risk in San Francisco is due primarily to the high frequency of earthquakes, and the risk in Tokyo is driven by the incredible number of people and structures exposed.

The EDRI represents a novel approach to earthquake risk assessment. It is more comprehensive than traditional earthquake loss estimation models in that it aims to measure not the risk of a certain amount of physical damage or economic loss, but the risk of an earthquake *disaster*. Assessing the risk of a disaster requires that the implications of the expected impact be interpreted in the economic, political, and social context in which that impact will occur. The EDRI directly assesses risk for a city as whole, not for a specific site. By using the composite index as a means to synthesize the many determinants of risk, the EDRI enables comparative analyses that are more succinct and easily understandable than earthquake damage scenarios can offer. Finally, the EDRI data requirements are far less restrictive than those for either loss estimation models or earthquake damage scenarios. (See Table 2.1 for a summary comparison of these three methods).

1.1. Anticipated benefits of the EDRI

The development of the Earthquake Disaster Risk Index brings together a body of knowledge about earthquake disasters from a wide range of disciplines to provide three principal benefits. First, the EDRI allows direct comparison of the relative overall earthquake disaster risk of different cities throughout the world. Many factors (e.g., frequency of earthquakes, structural vulnerability, quality of emergency response and recovery planning) contribute to a city's overall risk. A city may have a relatively high risk with respect to certain factors, and low with respect to others. By creating a composite index that combines all the pertinent factors, the overall disaster risk of different cities can be compared directly. Such a comparison could be useful for governments and international aid organizations as they allocate resources among various cities. Multinational companies will be able to refer to the index in locating manufacturing facilities. Insurance and reinsurance companies could employ it as they plan their portfolio diversification and establish premiums for earthquake insurance policies. Any interested person will be able to use the EDRI to improve his or her understanding of the risk in different cities worldwide by comparing those cities to ones for which he has an intuitive feel. While risk assessment studies have been performed for many regions around the world, for the most part, each project focuses on a single component of the risk, and/or on a single region. Relatively little work has been done in systematically comparing the overall risk across a large number of cities or regions. The EDRI aims to provide this service.

There have been many appeals to create a method for interregional comparison of the risk of earthquake disasters (or more generally, the risk due to all natural disasters). Throughout *Urban Scale Vulnerability: Proceedings of the U.S.-Italy Colloquium on Urban Design and Earthquake Hazard Mitigation* (Heikkala 1982), there are repeated calls for the development of a holistic, multidisciplinary method to compare the vulnerability of different urban regions to earthquake disasters. The Editor's Overview of *Environmental Management and Urban Vulnerability* (Kreimer and Munasinghe 1992) lists among the important topics for future research the development of an "index of vulnerability" to measure a city's vulnerability to natural catastrophes. In fact, the need to create a method of interregional comparison is not just an academic notion. The United States Federal Emergency Management Agency currently is developing a method to compare the multi-hazard natural disaster risk of each state in the country. The agency hopes to use the resulting technique to help determine the most effective and efficient way to allocate its mitigation resources (Nishenko 1997).

Second, closer examination of the disaggregated EDRI conveys information about the various factors that comprise the overall risk. One can focus on a single factor, and explore how the values of that factor vary among cities. For example, a structural engineer interested primarily in the vulnerability of the infrastructure could see that the Physical Infrastructure Vulnerability in Boston is about 1½ times that in Tokyo and two-thirds that in Manila. Alternatively, one could focus on one city at a time, and determine the relative contributions of different factors to the overall risk within each. The analysis might show, for example, that in

Lima, Hazard contributes twice as much to the overall risk as Exposure does; while in Mexico City, the reverse is true, i.e., Hazard is about half as important as Exposure. Understanding the causal factors of earthquake disaster risk constitutes the first step in designing the most effective and efficient strategies to mitigate that risk. In a given city, those factors that are contributing most substantially to the risk, and that are most easily "controlled" through structural or non-structural means will emerge as the most promising targets for mitigation efforts in that city. Since every city is unique—in its natural setting, its infrastructure, the activities it supports, and its relationships with other regions, the relative contributions of these causal factors will not be the same in every city, and therefore, the optimal mitigation strategy will not be the same across cities either. Looking at the components of the EDRI will help to illustrate, at the broadest level, which factors are the most important in each city.

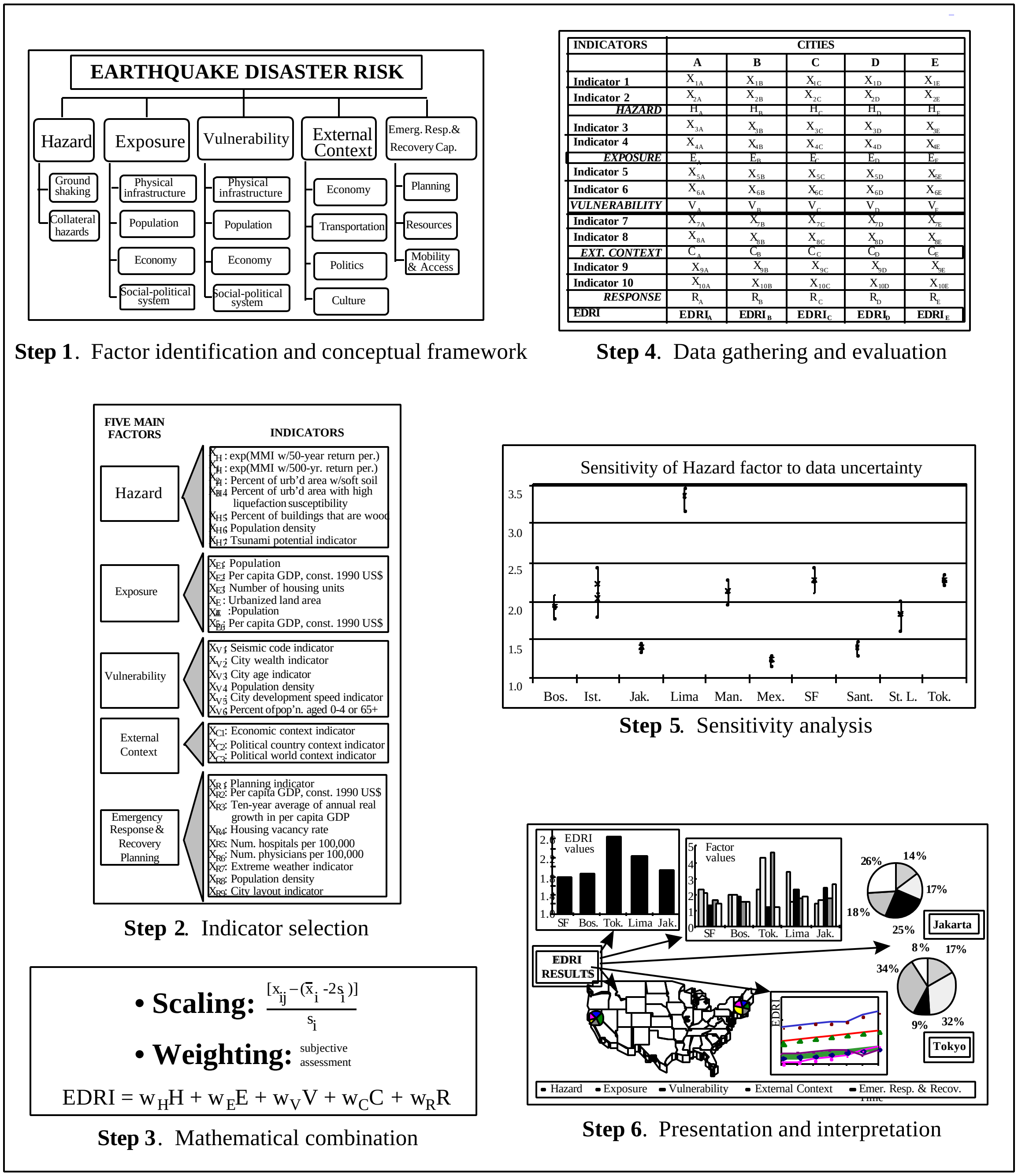
The disaggregated EDRI also should increase awareness of the wide range of factors on which a city's earthquake disaster risk depends, from the expected magnitude of ground shaking, to the number of structures, to the current economic situation in the city. The frequency of historical earthquakes is not the only determinant of a city's earthquake disaster risk, and a comprehensive EDRI will highlight that important point. This contribution will be particularly valuable in urban regions with infrequent earthquakes and negligible awareness. The EDRI will convey the critical message that although they are rare in those cities, an earthquake may occur, and if it does, the other characteristics of the city could turn that single event into a major disaster. Further, the index can serve as a vehicle to help change the way in which earthquake disasters are commonly conceived—from events due only to uncontrollable natural forces, to events whose severity are determined in large part by the economic, social, and political characteristics of the city on which those natural forces are unleashed. While people may not be able to stop the occurrence of *earthquakes*, they will be able to affect some of the other contributing factors (e.g., resources available for emergency response and recovery, vulnerability of the infrastructure), thereby reducing the frequency and severity of *earthquake disasters*.

Third, by reevaluating the index periodically, trends in earthquake disaster risk over time could be monitored with the EDRI. The predominant feeling among earthquake professionals today suggests that worldwide earthquake disaster risk has grown significantly over the past several decades due to exploding populations in seismic regions, unimpeded urbanization, and the increasingly interconnected and internally complex nature of cities. Currently, however, this is little more than a feeling. There exists no systematic way to track the earthquake disaster risk over time. The EDRI can fill this gap and demonstrate, not only if the risk is growing as believed, but also by how much each year, and why. It may indicate that the risk is increasing over time because the population is growing, because the infrastructure is becoming more vulnerable as it ages, or due to some other reason.

1.2. Six-step development procedure

Outlining the basic six-step procedure used to create the Earthquake Disaster Risk Index should help both to describe the index further and to provide an outline for the remainder of the dissertation. The following is a brief introduction to the approach (Fig. 1.1). Each of the steps will be elaborated on at length in the chapters that follow.

1. **Factor identification and conceptual framework development**
   A systematic investigation identifies all the factors—geological, engineering, social, economic, political, and cultural—that contribute to a city's earthquake disaster risk, and a conceptual framework is created to organize these factors and facilitate understanding of how they relate to each other and to the overall disaster risk. A contributing factor can be any characteristic of a city's physical makeup, location, residents, or activities that can significantly affect the expected impact from future earthquakes.



Step 1. Factor identification and conceptual framework

Step 4. Data gathering and evaluation

Step 2. Indicator selection

Step 5. Sensitivity analysis

Step 3. Mathematical combination

Step 6. Presentation and interpretation

Figure 1.1. Six-step EDRI development procedure

2. **Indicator selection**

One or more simple, measurable indicators (e.g., population, per capita gross domestic product, number of hospitals) are selected to represent each of the broad, abstract factors in the framework. Operationalizing the factors, and thus the concept of earthquake disaster risk that they collectively define, enables the performance of objective, quantitative analysis.

3. **Mathematical combination**

   A mathematical model is developed to combine the indicators into the composite EDRI that best represents the concept of earthquake disaster risk.

4. **Data gathering and evaluation**

   Data is gathered for each indicator and each of the world's major cities. The values of the main contributing factors and of the EDRI are evaluated for each city using the mathematical model developed in Step 3.

5. **Sensitivity analysis**

   A sensitivity analysis is performed to determine the robustness of the results, given the many uncertainties involved in the analysis.

6. **Presentation and interpretation**

   The results are presented using a variety of graphical forms (e.g., charts, maps) to make them as easily accessible as possible, and the numerical findings are interpreted to assess their reasonableness and their implications.

The EDRI development begins theoretically and gradually incorporates the restrictions associated with gathering and comparing international data. The conceptual framework constructed at the outset provides a solid foundation and rationale for the choice of indicators that are included in the EDRI and the way in which they are combined. Operationalizing the framework's ideas moves the framework from theory to practice, transforming it into a working model that can produce objective, directly usable results. As a final note, the EDRI development process is not actually as linear as this six-step method suggests. Rather, it is an iterative process in which the steps often cannot be performed strictly independently of each other.

1.3. Organization of the dissertation

In this first chapter, after motivating the development of the EDRI through a discussion of its anticipated benefits, the basic six-step approach used to create the EDRI was outlined. Chapter 2 explicitly highlights a few key features of the EDRI to distinguish it from traditional probabilistic earthquake loss estimation models and earthquake damage scenarios, and to clarify what the EDRI aims to achieve and how. Proceeding sequentially, each of the Chapters 3 to 8 expounds on one of the steps in the six-step procedure outlined above: *Factor identification and conceptual framework development* (Chap. 3), *Indicator selection* (Chap. 4), *Mathematical combination* (Chap. 5), *Data gathering and evaluation* (Chap. 6), *Sensitivity analysis* (Chap. 7), and *Presentation and interpretation* (Chap. 8). In the course of this project, a sample analysis was conducted both to produce the EDRI proposed herein, and to illustrate the EDRI development process so that future researchers could repeat the process, altering it as they see fit. Each of the Chapters 3 to 8 describes the basic procedure necessary to complete the associated step, discusses the issues and challenges that arise in doing so, and presents the results of the sample analysis for that step. Chapter 9 concludes by suggesting future work to improve and build on the EDRI.

Chapter Two
Key Features of the Earthquake Disaster Risk Index

2. Introduction

Earthquake risk assessment efforts to date generally have taken one of two forms—loss estimation models or earthquake damage scenarios. The Earthquake Disaster Risk Index is fundamentally different from both. The remainder of this chapter highlights a few key features of the EDRI to distinguish it from the more familiar types of earthquake risk assessment, and to elucidate and elaborate on what the EDRI aims to achieve and how. First, since the concepts that the three techniques assess are somewhat different, Section 2.1 discusses at length the definition of earthquake disaster risk, the idea which the EDRI aims to describe. The objectives of the index are laid out explicitly in Section 2.2. Section 2.3 describes the holistic, multidisciplinary approach that has been adopted in creating the EDRI. Section 2.4 discusses the EDRI's use of the greater metropolitan area as a unit of study, and Section 2.5 explains why the composite index form was selected as a means of presenting the risk assessment findings. Table 2.1 offers a summary comparison of the EDRI, loss estimation, and earthquake damage scenario methods.

2.1. Definition of earthquake disaster risk

While loss estimation models estimate the expected *impact* of future earthquakes (e.g., deaths, injuries, damaged buildings, economic loss), the EDRI aims to assess the risk of *earthquake disaster*. The economic, social, political, and cultural context of the

Table 2.1. Comparison of three earthquake risk assessment methods

	EDRI	Loss Estimation Models	Earthquake Damage Scenarios
Input	Simple, measurable, scalar indicators	Detailed technical information	Detailed qualitative and quantitative info.
Output	Composite index. Relative EDRI values of cities. Relative contributions of factors to EDRI.	Expected structural damage and economic loss in absolute terms	Qualitative description of expected series of events following an earthquake
Unit of study	Greater metropolitan area	Specific site (aggregate to region or portfolio)	Greater metropolitan area
Data needs	Low	High	High

earthquake hazard, therefore, plays a critical role. As it is considered here, disaster is a function of not only the physical impact of an earthquake, but also the capacity of the affected city to sustain that impact, and the implications of the impact to the city and to world affairs.

Many attempts have been made to define the term *earthquake disaster* by setting forth the set of conditions that must be satisfied to make an event a disaster (Appendix A). These past efforts can be divided into two groups. In the first, the conditions are quantitative and relate to the resulting number of deaths and injuries, economic loss, and/or duration of functionality loss of various services. For example, *World Disasters Report 1994* defined as a disaster any event that caused ten deaths, and/or affected one hundred people, and/or led to an appeal for international assistance (International Federation of Red Cross and Red Crescent Societies, and the Centre for Research on the Epidemiology of Disasters 1994).

In the second camp, the conditions are more qualitative and incorporate the importance of the context in which the damage and losses occur. Wenger, for example, asserts that a disaster is an “event that creates demands upon the community system that cannot be met by its traditional, institutional structure” (Wenger 1978). A tradeoff exists between the quantitative and qualitative types of conditions. The former neglect the importance of the context in which the damage occurs and involve somewhat arbitrarilydefined cutoff values, but are objective and operational; the latter are more comprehensive and do not include arbitrary threshold values, but are subjective and require judgment to apply. Ideally, a definition of *earthquake disaster* could be both operational and comprehensive.

While most people have some intuition about what constitutes a disaster, the plethora of definitions of disaster that have been proposed demonstrates that "there cannot be one all-purpose term with a single referent which can meet all needs—legal, operational, or scientific—and be equally useful to all users. What is important is not consensus on one definition—an impossible goal—but clarity of the term and its referent on the part of various users" (Quarantelli 1987). With that understanding, it is clear that the treatment of the term *earthquake disaster risk* suggested here will not be satisfactory to all users any more than those presented previously. The following approach to earthquake disaster risk has been tailored to the issues of earthquake-related risk assessment and the EDRI project in particular. It aims to be both operational, like the quantitative definitions, and comprehensive, like the qualitative ones.

In the development of the EDRI, earthquake disaster risk is explored, not by directly examining the *expected consequences* of earthquake disaster risk (e.g., deaths, economic loss), but by considering the *factors that contribute* to earthquake disaster risk (e.g., frequent earthquakes, vulnerable structures). In the first approach, loss estimation studies could be conducted in every city, and the cities with higher expected losses would be considered to have higher risk. In the EDRI approach, a city is considered to have a relatively high risk if it exhibits a lot of characteristics that typically cause more severe or more frequent earthquake losses. This latter approach requires identifying the factors that contribute to earthquake disaster risk and assuming either a direct or inverse relation between each factor and the risk. If a factor has a *direct* relationship with risk and the factor value is higher in City A than City B, then the earthquake disaster risk in City A will be higher too. If the same factor had an *inverse* relationship with risk, the earthquake disaster risk will be lower in City A than in City B. Once it is decided how Cities A and B compare with respect to each contributing factor, that information can be integrated to determine how they compare with respect to the overall risk.

In this project, the main factors that have been identified as contributing to a city's earthquake disaster risk are:

- **Hazard**
  Severity, extent, and frequency of the geological trigger phenomena to which the city may be subjected.
- **Exposure**
  Size of the city. Quantity of people and physical objects, and the amount and type of activities they support.
- **Vulnerability**
  How easily the exposed people, physical objects, and activities may be affected in the short- or long-term.
- **External Context**
  How impact within a city affects people and activities outside the city.
- **Emergency Response and Recovery Capability**
  How effectively and efficiently a city can reduce the impact of an earthquake through formal, organized efforts made specifically for that purpose.

Evaluating a city with respect to all these contributing factors and combining the resulting information provides a portrait of the city's earthquake disaster risk. This new approach circumvents many of the difficulties associated with consequence-based disaster definitions. The particular types of consequences, or impact parameters (Fig. 2.1) are not addressed individually, because the definition of earthquake disaster risk proposed here does not rely on enumerating the expected consequences of risk. Instead, they are all

I. Type of losses

In physical terms:

- Damaged buildings and infrastructure facilities
- Destroyed buildings and infrastructure facilities

In economic terms:

- Direct economic loss
- Indirect economic loss

In human terms:

- Deaths
- Injuries
- Homelessness

In terms of disruption:

- Disruption to lifeline services
- Disruption to political processes
- Disruption to social processes

II. Terms of assessment

- Total for the city overall
- Total for the city as a percentage
- Distribution within city
- Degree to which it is felt outside city

III. Examples of impact parameters

An impact parameter is a unit of measure that could be used to assess the severity of earthquake impact. Impact parameters can be formed by choosing one item from each of boxes I and II. The following are some examples of possible impact parameters:

- Total number of damaged or destroyed structures in the city
- Direct economic loss as a percentage of the city's total wealth
- Percentage of people homeless in the most severely impacted group
- Degree to which political disruption is felt outside the city

Figure 2.1. Impact parameters

included by defining a contributing factor as any characteristic of the city that increases or reduces the consequences of an earthquake, as measured by *any* one or more types of losses (Fig. 2.1; Box I), using any of the four terms of assessment (Fig. 2.1; Box II). With the proposed definition, it is not necessary to decide which of the impact parameters should be combined and how (Should the definition depend only on the expected number of deaths? Is economic loss important too? Are they equally important?); what threshold values should be used for each parameter (Do ten deaths constitute a disaster? One hundred?); or if the definition should focus on the city as a whole, on its most severely impacted neighborhoods, and/or on the extent to which the impact is felt outside the city. Unfortunately, the problem of weighing the relative importance of different impact parameters (e.g., number of deaths versus dollars of economic loss) is not entirely avoided, but rather replaced by the task of weighing the relative importance of the factors that contribute to earthquake (e.g., Hazard versus Exposure; see Section 5.3). The latter approach does not require "value of life" judgments, or the estimation of the expected number of deaths, economic loss, and other impact parameters in absolute terms. The EDRI approach is also more amenable to assessment of a comprehensive concept earthquake disaster risk that addresses all impact parameters, rather than one focused on the more quantitative aspects of earthquake impact.

In the EDRI approach, disaster risk is viewed from a global perspective. An observer may consider a specified impact level to be more or less serious depending on his point-of-view. For example, if the impact level is considered from the perspective of an individual, a single fatality would be a disaster if it was the individual's parent who died, but fifty deaths may not be a disaster *for that individual* if he had no personal connection to any of those killed. Similarly, an earthquake might be a disaster for the Japanese government, but not for the Cuban government. Therefore, to interpret the impact level from a global perspective implies not that the impact must shake the entire global civilization, but that all the effects of an earthquake must be considered, whether they occur within the area of ground shaking or elsewhere in the world. This global point-of-view gives significance to a city's prominence on the world stage, and is represented by the inclusion of the External Context factor.

The EDRI considers *relative* risk only, not absolute risk. Definitions that propose an absolute scale with which to measure earthquake disaster risk (e.g., number of deaths, injuries, buildings damaged, economic loss, or some combination thereof) neglect part of what it takes to have a disaster. Since no units exist with which to measure the broad concept of earthquake disaster risk used in the EDRI, the index presents a relative measure of risk, which is entirely adequate for comparing the risk in different cities. The level of earthquake disaster risk is conceived of as a continuous, unitless, open-ended scale, not a binary categorization of events with only two possible values: *Disaster* or *Not a disaster*.

The EDRI addresses *disaster risk* directly; no definition of a *disaster* is provided. To make the transition from a definition of *disaster* to *disaster risk*, the concept of probability must be incorporated. With a definition of *disaster* in hand, *disaster risk* can be defined simply as the probability that a disaster will occur in a specified future time period. In this project, with no definition of exactly which events are classified as disasters and which are not, that approach is not possible. Instead, probability is incorporated in the Hazard factor, which includes the probabilistically expected levels of ground shaking for two different time periods. The choice of time period implicitly defines a time horizon for the EDRI. If the level of ground shaking with a one-year return period was used in the Hazard factor, for example, the hazard for many cities would be zero. However, there is an enormous difference between a small chance of an earthquake and no chance. By using the levels of ground shaking with fifty-year and five-hundred-year return periods, the EDRI addresses the small, but real hazard in areas of low seismicity. Return periods of fifty and five hundred years correspond to shaking with a ten percent chance of being exceeded in five and fifty years, respectively. These are reasonable time horizons for planners and individual citizens.

2.2. Objectives of the EDRI

It is useful to set forth the EDRI's objectives up front so that they may guide the decisions encountered during the index's development, and so that they may provide a basis for assessing the success of the final index in achieving its aims. The broad goal of the EDRI is similar to that of the Consumer Price Index or the Physical Quality of Life Index, but instead of rating the relative levels of prices in different years, or the relative quality of life in various countries, the EDRI rates the relative levels of earthquake disaster risk in different cities. Like the other composite indexes, the EDRI aims to establish a yardstick with which to measure an unobservable concept, in this case, earthquake disaster risk. Specifically, the EDRI is intended to:

1. Convey the relative overall earthquake disaster risk (as defined in Section 2.1) at a point in time for each major city in the world.
2. Convey the relative contribution[1] of each component factor to a city's overall earthquake disaster risk.
3. Convey the change in a city's relative overall earthquake disaster risk over time.
4. Be straightforward to develop, evaluate, and interpret so that the information it conveys is easily accessible to the general public.

The EDRI does *not* attempt to measure the earthquake disaster risk on any absolute scale (see Section 2.1). While that goal is appealing, as yet no units exist to measure earthquake disaster risk as it is defined in this study. Instead, a city's earthquake disaster risk is assessed only relative to that of other cities. The EDRI also does not attempt to provide information about the distribution of risk within a city. While this would be another worthwhile goal, it is not one that the EDRI endeavors to achieve. The EDRI is oriented toward providing inter-city, not intra-city comparisons of risk. Finally, the EDRI is fundamentally concerned with providing information about the factors that come together to create earthquake risk (see Objective 2), not only in providing a way to describe the varying degrees of expected impact.

2.3. Holistic, multidisciplinary approach

The development of the EDRI represents a holistic, multidisciplinary approach to earthquake risk assessment. Taking a fresh look at urban earthquake risk, the process begins by asking, without bias to any single discipline, "What characteristics of a city help determine the impact that an earthquake will have?" A characteristic could be of any type—geological, structural, economic, social, political, cultural, or anything else. As long as it contributes to earthquake disaster risk (as defined in Section 2.1), the characteristic should be considered a factor.

To get a handle on the expansiveness of the problem, the challenges of earthquake risk assessment have been divided into smaller, focused tasks, and groups from each discipline have undertaken to address the tasks that relate to their area of expertise. Geologists study the characteristics of fault rupture. Structural engineers explore the vulnerability of the built environment. Emergency response planners investigate the requirements of an effective response effort. Economists try to understand how damage to the physical infrastructure translates into disruption in a region's economy. Each group has delved deeply into the details of their task, and the understanding of what happens following an earthquake has improved markedly. As a holistic, multidisciplinary effort, the EDRI aims to put the pieces of the puzzle back together; to integrate the findings of the detailed studies in every field, and to interpret their implications for the 'big picture.'

The EDRI is, of course, not the first study to exhibit a holistic orientation. The following brief literature survey will offer some background on the history of holistic, multidisciplinary earthquake risk assessment work, and will demonstrate how the EDRI aims to contribute something new and valuable to the collection. The surveyed work can be separated into the engineering and social science camps.

The efforts of the engineering community to put the pieces together are primarily centered on earthquake loss estimation modeling. The development of probabilistic seismic hazard analysis (PSHA) in the 1960s (Cornell 1968) provided a methodology for mapping the probabilistically expected levels of earthquake ground shaking for a region. In determining the expected magnitude of ground motion for a specified site and future time period, the framework integrates data about earthquake sources (e.g., locations, recurrence relationships, and maximum possible magnitudes), the attenuation of ground motion as it travels from the source to the site, and the ability of the soil at the site to amplify or reduce the ground motion. Typically, the hazard is presented in terms of the probability of exceedence of a certain peak ground

[1] Refers to the *city-specific* relative contribution (Section 5.1.4).

acceleration in a specified time period. Other local site effects, like liquefaction, landslides, and surface fault rupture are portrayed on separate maps.

In probabilistic earthquake loss estimation modeling, engineers combine the hazard information that is the output of the PSHA with information about the quantity, value, location, and vulnerability of the exposed infrastructure to determine quantitative estimates of the potential damage and economic losses that a region will suffer in a specified future time period. Figure 2.2, reprinted from King and Kiremidjian (1994), shows the basic steps in regional seismic hazard and risk analysis. Other models have been developed to estimate economic losses arising from business interruption and damage to non-structural components and contents; and non-monetary losses, including casualties, injuries, unemployment, and homelessness. King and Kiremidjian (1994) provides a clear overview of the seismic hazard and risk analysis methodology.

Recently, this holistic engineering work has consisted primarily of automating the loss estimation methodology, applying it to an increasing number of geographical regions and hazard types, and refining the modules that comprise it. Earthquake loss estimation software has been developed using expert systems and Geographic Information Systems (GIS) technologies (Shah, Boyle, and Dong 1991). The software extends the possibilities of this methodology enormously by enabling the maintenance of the large databases required, increasing the speed of analyses, and providing user-friendly spatial representation of the data and analysis results with GIS. Mention of a few studies will suffice to illustrate the variety of projects that explore specific components of loss estimation modeling. Coburn, Spence, and Pomonis (1992) estimate levels of human life loss due to building collapse in earthquakes. Scawthorn (1986) estimates losses from fire following an earthquake. Cret and Katayama (1992) estimate damage to lifeline systems during earthquakes. *Assessment of the State-of-the-Art Earthquake Loss Estimation Methodologies* (RMS and CUREe 1994), which provides an extensive review and comparison of available earthquake loss estimation studies, offers a helpful summary of recent developments in this area.

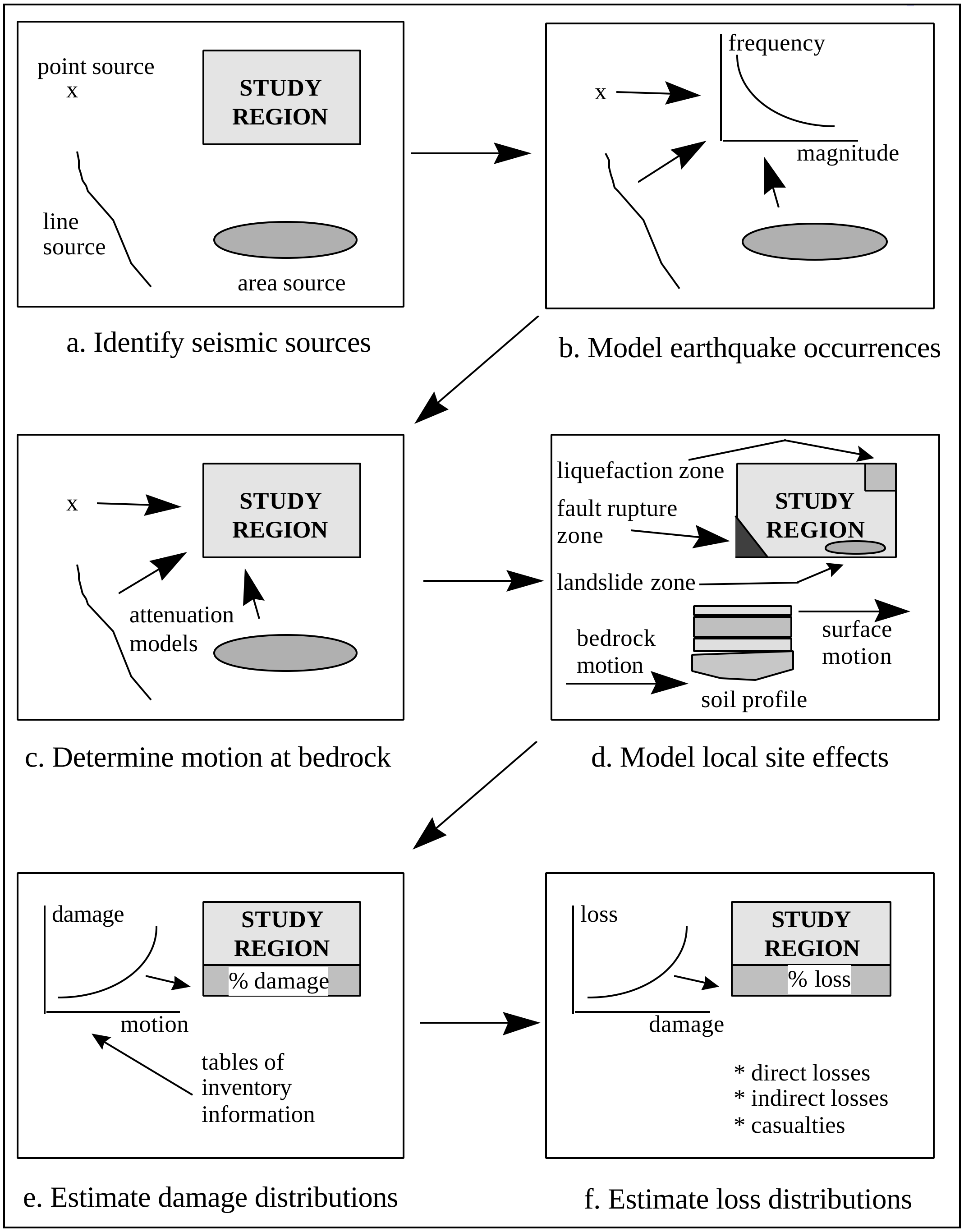


Figure 2.2. Basic steps of regional seismic hazard and risk analysis
Reprinted from King and Kiremidjian (1994)

Working from an entirely different perspective and knowledge base, geographers and other social scientists in disaster studies also have endeavored to put the pieces of earthquake risk together. The body of mostly conceptual work they have produced over the past twenty years chronicles the evolution of the way in which they conceive of disasters. At least until the 1970s, the prevailing view described natural disasters as being entirely the result of the externallyimposed extremes of natural processes. Accordingly, research traditionally has focused on understanding the geophysical or climatic mechanisms of different hazards, and on the development of technical methods to reduce their impact on society. The traditional view also tries to encapsulate natural disasters as a special problem distinct from “ordinary” life, completely separate from the rest of society’s relationship with the environment. This “extreme narrowing of the range of interpretation and acceptable evidence” (Hewitt 1983) makes the complex problem of natural disaster mitigation more manageable, but neglects the interconnectedness of everyday life and disasters.

The new paradigm that has been evolving over the past twenty years highlights the relevance of the societal context in determining an event’s impact. A geophysical event alone cannot create a disaster. Disasters occur only when a natural phenomenon intersects in space and time with a vulnerable population. There is a new awareness of the interaction between nature and society. Cities are no longer only at the receiving end of the disaster, innocently suffering the damage nature inflicts. In the new paradigm, a city’s vulnerability and capacity to handle impact are causal factors as significant as the earthquake itself. As part of this emerging viewpoint, a broader concept of vulnerability has appeared that goes beyond the engineering notion of structural vulnerability. Social, political, economic, and cultural characteristics of a city are also important ingredients of the city’s vulnerability. For more discussion of this broad view of natural disasters, see the following: Albala-Bertrand (1993); Blaikie et al. (1994); Burton, Kates, and White (1993); Hewitt (1983); Kreimer and Munasinghe (1992); and Varley (1994).

The earthquake loss estimation modeling of the engineering community offers a quantitative, objective approach to holistic work in earthquake risk assessment. It is focused on delivering a product to its users, usually an estimate of the expected damage and economic loss as it is distributed throughout a region. The engineering work is increasingly incorporating social, economic, and political considerations, but mostly in the types of impacts that are estimated (the output), not in the factors that create those impacts (the input). Engineering work continues to exhibit a bias toward the technical and quantitative, largely ignoring the contextual factors that contribute to earthquake risk. The social science community, on the other hand, has taken a much more comprehensive approach to putting the pieces of earthquake risk together, including all types of factors that contribute to the risk—geological, engineering, social, economic, political, cultural—on equal footing. Nevertheless, its work has been mostly conceptual, often remaining unknown, or at least unusable, to the decision-makers charged with mitigating the assessed risk.

The EDRI aims to bring together the parallel research paths laid down by the engineering and social science communities. The project to create the EDRI has been designed to merge the comprehensiveness and broad perspective of the social sciences with the engineering emphasis on remaining objective and quantitative, operationalizing, and delivering a helpful product to those involved in managing earthquake risk.

2.4. Urban risk

The EDRI assesses a single value of earthquake disaster risk for each greater metropolitan area (hereafter referred to as a city), providing no direct information about the distribution of risk within that area. The index uses the city as the unit of study for a few reasons. First, focusing on urban risk reflects the author's recognition of the growing concern among earthquake professionals about the potential impact of earthquakes in the world's largest urban areas. Recent efforts by two leading voices in earthquake risk assessment and management illustrates the existence of this emerging consensus. In 1996, a consortium of nine western U.S. universities defined the focus of the proposed Pacific Earthquake Engineering Research Center (PEERC) to be the development of *urban* earthquake risk reduction technologies. The Secretariat for the International Decade for Natural Disaster Reduction (IDNDR) recently proposed the "Disaster Reduction for Sustainable Development" project, which includes *urban vulnerability reduction* as one of the three thematic areas on which it will concentrate (UN Secretariat for the IDNDR 1996). Second, by the year 2005, fifty percent of the world's population will be gathered in urban areas, and by 2025, more than sixty percent will be (United Nations. Dept. for Economic and Social Information and Policy Analysis. Population Division 1995b), so by addressing only urban areas, most of the world's population is still considered.

Third, earthquakes primarily affect people and the components of their built physical environment, both of which are concentrated in urban areas. Furthermore, the unprecedented size, complexity, and interconnectedness of today's megacities have created situations unlike any that existed in the past. Smaller cities may expect to experience events similar to those that occurred historically. There have been few large earthquakes that directly impacted a megacity, however, so the potential implications of the new nature of cities on earthquake risk are unclear, and pre-earthquake risk assessment takes on added importance for major urban conglomerations. Fourth, the impact area of a single earthquake is of the same order as a greater metropolitan area. Impact generally will not be contained within legal city limits; nor will it extend over an entire country. Since many lifeline networks, economic, social, and political functions are defined for or roughly uniform over greater metropolitan areas, that unit of area provides the best common ground for assessing expected physical impact, emergency response and recovery capability, and context of the impact.

It is generally understood that a greater metropolitan area is a large, continuous urbanized area composed of many smaller cities or other administrative units whose economic and social lives are interdependent. Nevertheless, no precise, universally applicable definition exists. In the United States, the Bureau of the Census established the following definitions of a Metropolitan Statistical Area (MSA) and a Consolidated Metropolitan Statistical Area (CMSA):

> "An MSA must include at least: (a) one city with 50,000 or more inhabitants, or (b) a Census Bureau-defined urbanized area[2] (of at least 50,000 inhabitants) and a total metropolitan population of at least 100,000 (75,000 in New England)." "An area that meets these requirements for recognition as an MSA and also has a population of one million or more may be recognized as a CMSA if: 1) separate component areas can be identified within the entire area by meeting statistical criteria specified in the standards, and 2) local opinion indicates there is support for the component areas" (U.S. Bureau of the Census 1995).

The Bureau of the Census also publishes lists of all MSA's, CMSA's, and the cities and counties that are included in each.

The United Nations Population Fund says that a metropolitan area "includes the central city, the suburbs and satellite communities whose economic and social life are tied to the city in such a way that both the central city and its zone of influence form an indissoluble functional whole" (Institut d'Estudis Metropolitans de Barcelona 1988). The determination of what areas to include in a greater metropolitan area should be made for each urban center individually by local authorities familiar with the area. To ensure consistency among indicators and among cities, it is critical to establish at the outset exactly what areas are included in each greater metropolitan area (city) in the analysis. For each city, the values for every indicator should refer to the same area. It does not make sense to count the "number of hospitals" in Tokyo prefecture, but determine the "number of housing units" from the entire five-prefecture Tokyo metropolitan area. Similarly, comparing Boston as defined by its legal city limits, to the CMSA of Los Angeles, which includes five counties would produce meaningless results. For the EDRI sample analysis, the U.S. cities were defined as the appropriate CMSA, and the international cities were defined using either the UN Population Fund guidelines, or definitions set forth by the

[2] A census bureau-defined urbanized area "comprises one or more places ("central place") and the adjacent densely settled surrounding territory ("urban fringe") that together have a minimum of 50,000 persons. The urban fringe generally consists of contiguous territory having a density of at least 1,000 persons per square mile. The urban fringe also includes outlying territory of such density if it was connected to the core of the contiguous area by road and is within 1½ road miles of that core, or within 5 road miles of the core but separated by water or other undevelopable territory. Other territory with a population density of fewer than 1,000 people per square mile may be included in the urban fringe if it eliminates an enclave or closes an indentation in the boundary of the urbanized area" (U.S. Bureau of the Census 1993b).

local statistical agency. Appendix B describes which areas (e.g., counties, cities) are included in each of the ten sample analysis cities.

2.5. Composite index form

Composite indexes have been used for a long time in a wide variety of disciplines to measure complex, multi-dimensional concepts that cannot be observed or measured directly. Their power lies in their ability to synthesize a vast amount of diverse information into a simple, easily usable form. In the case of the EDRI, there are volumes available on the seismicity, structural types, economic and political conditions of different cities. All of that material would be helpful in understanding the relative earthquake disaster risk of those cities, but the amount of information could be overwhelming. It is difficult to see the forest when lost among so many trees. The EDRI offers a unique way to bring the many components of earthquake risk together to reveal the big picture. Furthermore, the straightforwardness of the development, evaluation, and interpretation of the EDRI makes the information easily accessible to the general public, government agencies, insurance companies, and other potential users.

While the EDRI can provide a concise tool for measuring earthquake disaster risk that currently is not available from any other source, clearly it cannot profess to provide all the insight that the volumes of theory and data on seismicity, geology, structural engineering, economic modeling, and other relevant topics would. For detailed understanding of each individual component of earthquake disaster risk, the focused studies that address those topics are the best sources. To understand the sum effect of all those components, the EDRI should prove useful.

One drawback of the composite index form should be noted here. Since earthquake disaster risk cannot be measured directly (in fact, the purpose of creating the EDRI is to provide a way to do so), there is no satisfactory way to validate the EDRI. In the chapters that follow, many aspects of the EDRI are validated to the extent possible. This includes, among other things, demonstrating that the factors that are said to contribute to earthquake disaster risk do, establishing that the indicators represent the concepts that they purport to represent, justifying the proposed values of the weights, and verifying the reasonableness of the final results of the sample analysis. Most often these efforts at validation fall short of scientific proof, and instead rely on imperfect empirical evidence or even intuition. A sensitivity analysis was performed to determine the robustness of the results in the face of the uncertainties in the EDRI development and evaluation.

Nevertheless, the fact that scientific validation is impossible is not cause to discard the idea of a composite index. The Consumer Price Index is just one reasonable representation of the general level of prices. It is derived from the prices of a certain group of goods and the quantity of each that were sold at those prices in a given year. While one could argue that a better representation of the general level of prices would rely on a different set of goods, the fact that the current derivation of the CPI has been accepted as a reasonable one, and that the index has been tracked for many countries and many years, has endowed the CPI with a substantial degree of meaning and usefulness. The EDRI has the potential to serve an analogous role in the area of earthquake risk assessment.

The plethora of existing indexes are evidence of the usefulness of the composite index form. The Consumer Price Index, Dow Jones Industrial Average, Economic Freedom Index (Johnson and Sheehy 1996), Human Development Index (UNDP 1990-95), Physical Quality of Life Index (Morris 1979), and World Competitiveness Index (IMD International and WEF 1992) are but a few examples of composite indexes successfully measuring that which previously could not be measured.

Chapter Three
Factor Identification and Conceptual Framework

3. Introduction

The conceptual framework that describes the components of earthquake disaster risk provides the foundation on which the Earthquake Disaster Risk Index rests. To determine which indicators to include in the EDRI, the factors that they aim to represent must be well-defined. Any errors or omissions in the framework will be perpetuated through the subsequent steps of the project, resulting in an EDRI that does not represent earthquake disaster risk as well as it could. This chapter presents the construction of the conceptual framework of earthquake disaster risk. Section 3.1 describes the basic approach taken to complete this task, and Section 3.2 discusses the challenges that arise in the process. Section 3.3 presents the results of this first step from the sample analysis. It first reveals the conceptual framework that was developed, then elaborates on each of the factors that comprise it. The discussion of each factor includes a definition, a discussion of how it contributes to a city's earthquake disaster risk, and an explanation of the variables on which it depends.

3.1. Approach

The strategy for identifying the factors that contribute to earthquake disaster risk involves starting with the most general concept—earthquake disaster risk, decomposing it into the factors that together describe it, then decomposing each of those factors into sub-factors, and so forth. For example, a thorough understanding of a city's earthquake disaster risk requires knowing something about the hazard to which the city is subjected. To be able to assess a city's hazard, one must know about the ground shaking hazard as well as the collateral hazards, such as liquefaction, landslides, and tsunami. The process continues until all of the factors and sub-factors have been identified. The development of the framework is an entirely conceptual undertaking that should be performed without regard for issues of measurability or data availability. The final conceptual framework should be as comprehensive as possible, even if measurability and data constraints prevent some of its components from being included in the final EDRI.

3.2. Challenges

The search for factors that contribute to earthquake disaster risk is complicated for a few reasons. With earthquake disaster risk defined as broadly as it is, it becomes clear that the contributing factors span an extremely wide range of disciplines. Furthermore, the factors are not well-defined, distinct entities that exist a priori. The index developer must define them into existence. Geological, economic, social, and political activities overlap and interact in the complex web that forms the life of a city. The factors must be extracted from that web and defined so that they are mutually exclusive and collectively exhaustive. Aspects of the city that affect its earthquake disaster risk should not be double counted or omitted. For example, since Economic External Context includes the economic effects of impact to a city that will be felt by those outside the city, the Economic Vulnerability factor should refer only to the ease with which activities *within* the city may be disrupted.

Factors should be defined so that they are neither too specific nor too general. They should be disaggregated to the point that is most natural for their assessment. Factors only need to be as specific as necessary to convey the concept of earthquake disaster risk clearly. Making them more specific than required will succeed only in complicating the framework. If the factors are defined to be too general, it may be difficult to hone in on the way in which they affect earthquake disaster risk. For example, suppose the factor "Economic Wealth" was proposed. It could be argued that risk both increases and decreases with Economic Wealth. Cities with greater wealth generally have better enforcement of building codes, which would indicate a lower risk; but they also produce more goods and services, so damage in wealthy cities would create more indirect economic losses, thereby increasing the risk. A better alternative would be to consider building code enforcement and the amount of production as two separate factors, rather than considering the broader "Economic Wealth" factor.[1] Whenever possible, a factor should be important to earthquake disaster risk in itself, not because it affects something else that, in turn, is important to earthquake disaster risk. "Enforcement of Building Codes" would be an example of the first case, a directly relevant factor, while "Economic Wealth" could be an example of the second, a factor that is relevant only indirectly.

However carefully the factors are defined, the innumerable interactions that exist among the factors make it possible to argue that almost every factor both increases and decreases earthquake disaster risk, at least indirectly. A large proportion of wood-frame structures, for example, could be considered to increase the vulnerability to fire damage, and therefore to increase the risk; or one could argue that wood-frame structures generally exhibit excellent resistance to ground shaking damage, so a high proportion of them would indicate lower risk. Following are other examples of interactions among factors:

- The components of the Exposure factor are related to each other, e.g., cities with more people will have more physical infrastructure as well.
- The soft soil, liquefaction, and landslide components of Hazard are all related to a city's soil conditions.

[1] Note that because of data constraints, there is often less freedom in the selection of indicators for the EDRI than in the definition of conceptual factors. There may be cases in which an indicator is used more than once to represent more than one concept. For example, if it was impossible to find appropriate alternative indicators for enforcement of building codes and amount of economic production, the per capita Gross Domestic Product could be used to represent both. A different weight could be associated with each use. This topic is discussed more thoroughly in Section 4.2.

- Economy Exposure, Economy Vulnerability, Economic External Context, and the financial resources component of Emergency Response and Recovery are all related to the structure and size of a city's economy, and therefore, they are related to each other.
- Physical Infrastructure Vulnerability and Mobility and Access are related because the former helps determine the amount of debris and the condition of the transportation network following an earthquake, two conditions that, in turn, help determine the latter.
- The Planning component of the Emergency Response and Recovery factor may be related to the Hazard if cities with a history of earthquakes have been convinced by their experience to plan for future events.

Given the complexity of the interactions among factors, the best that can be done is to acknowledge this difficulty, define the factors in a way that avoids this problem as much as possible, focus on the *principal* effect that each factor has on earthquake disaster risk, and determine weights that reflect only that principal effect on risk. To continue the previous example, if the proportion of structures that have a wood-frame is included as an indicator to represent the city's vulnerability to fire hazard, then the weight associated with that indicator should be determined based only on the relative importance of the proportion of wood-frame structures as it affects vulnerability to fire hazard, with no regard to what it indicates about the vulnerability to ground shaking.

Due to the many interactions among factors, almost any aspect of a city's makeup could be considered to affect the city's earthquake risk in some way. To be included in the final framework then, factors must contribute *significantly* to the risk and must have values that potentially vary from city to city, so that they may affect the relative rankings of different cities.

3.3. Sample analysis solution

Figure 3.1 illustrates the conceptual framework of earthquake disaster risk that was developed in this work. It is hypothesized that the five main factors contribute to a city's earthquake disaster risk: Hazard, Exposure, Vulnerability, External Context, and Emergency Response and Recovery Capability. Each of these five main factors is disaggregated into the more specific factors that comprise it. For simplicity, the framework does not portray interactions among the factors.

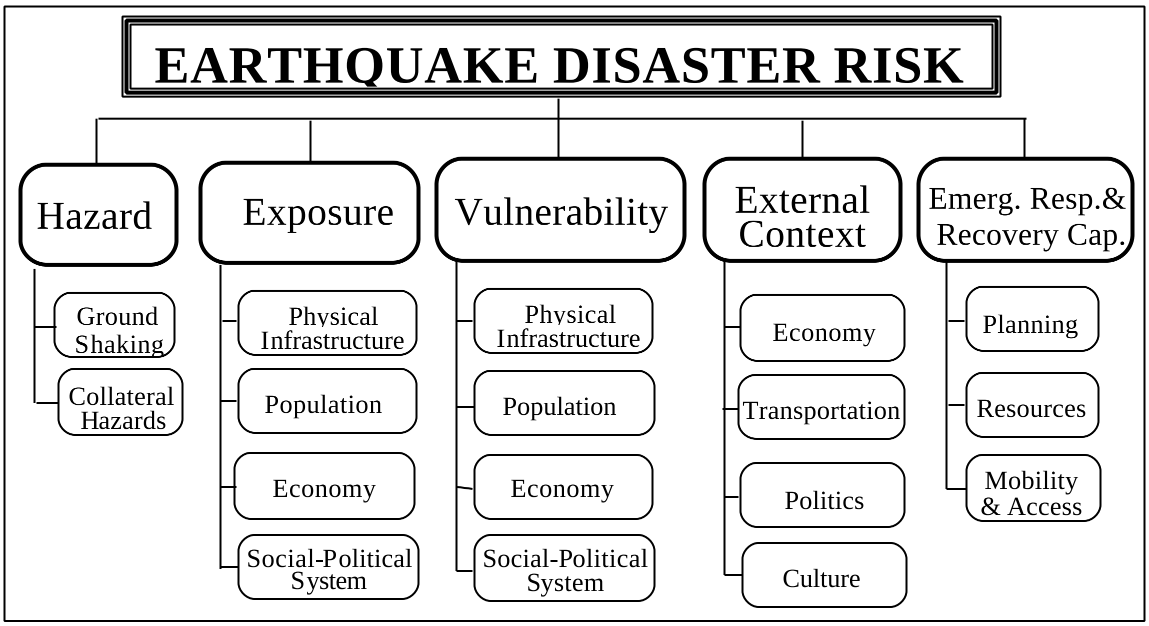


Figure 3.1. Conceptual framework of earthquake disaster risk

3.3.1. Hazard factor

Hazard represents the geophysical phenomena that serve as initiating events of earthquake disaster, the demand to which a city will be subjected. This factor describes, for both ground shaking and collateral hazards (i.e., fire following, liquefaction, landslide, and tsunami and seiche), the frequency of each possible severity level as it is distributed throughout the city.

3.3.1.1. Ground Shaking

Ground Shaking is the most important component of Hazard because it is usually directly responsible for the majority of damage suffered in an earthquake, and because most other hazard types (i.e., liquefaction, landslide, fire) require a sufficient level of ground shaking to trigger them. The characteristics of ground shaking that may be of interest include the amplitude, frequency content, and duration. Amplitude is typically assessed in terms of acceleration (e.g., peak ground acceleration, PGA, or spectral acceleration, S_a) or intensity (e.g., Modified Mercalli Intensity, MMI, or Japan Meteorological Agency, JMA).

Given the occurrence of a particular earthquake, the amplitude of the resulting ground shaking can be determined at every location throughout a city. In assessing the city's overall earthquake risk, however, it is important to know not only the amplitude of ground shaking that will be caused by each conceivable earthquake, but also the probability that each of those earthquakes will occur. By using Probabilistic Seismic Hazard Analysis (PSHA), these two equally important quantities can be integrated into a single parameter, the expected value of the magnitude of ground shaking for a specified future time period. Employing a short time period shows how frequently ground shaking occurs, while using a longer time period conveys how strong the ground shaking potentially can be. The probabilistically expected severity of ground shaking at a given site depends on (1) the locations, recurrence relationships, and maximum possible magnitudes of the faults and area sources that might produce the ground shaking; (2) on the attenuation relationships that are associated with soil and topography and describe the way in which ground motion changes in magnitude and frequency content as it travels from the source to the site; and (3) on the ability of the soil at the site to amplify or reduce the ground shaking. Topography and directivity of fault rupture have been identified as additional determinants of the severity of ground shaking at some sites, but they have not been incorporated into the PSHA yet.

3.3.1.2. Liquefaction

Liquefaction is a phenomenon in which soil "changes from a firm material into a viscous semi-liquid material" (Gere and Shah 1984). "If a saturated sand is subjected to ground vibrations, it tends to compact and decrease in volume; if drainage is unable to occur, the tendency to decrease in volume results in an increase in pore water pressure, and if the pore water pressure builds up to the point at which it is equal to the overburden pressure, the effective stress becomes zero, the sand loses its strength completely, and it develops a liquefied state" (Seed and Idriss 1983).

Liquefaction can cause structural damage to buildings and lifelines. When soil liquefies, it loses its bearing strength, causing any buildings or other structures that rest on it to settle. Structures may remain essentially intact, but tilted. In that case, the structure must be rebuilt, but little loss of life results. Liquefaction can damage underground infrastructure, like pipelines and septic tanks, by causing them to float up towards the surface of the ground. Roads and railroad tracks can also be damaged when a portion of the road or track sits on soil that liquefies and settles, while an adjacent portion does not. Liquefaction became widely recognized as a significant collateral hazard after causing extensive damage in the Niigata, Japan and Alaskan earthquakes of 1964. In the more recent Great Hanshin earthquake of 1995, the lateral spreading of the ground associated with liquefaction, caused extensive damage.

Rather than measure degrees of liquefaction, it usually suffices to make a binary assessment of whether liquefaction occurred or not, and refer instead to the area over which liquefaction takes place. The liquefaction potential of an area (the probability that liquefaction will occur) equals the convolution of the liquefaction opportunity (a function of the ground shaking demand on the soil) and the liquefaction susceptibility (the probability that liquefaction will occur given sufficient ground shaking). Liquefaction susceptibility is determined by the type and relative density of the soil, and the water table depth. Liquefaction can occur only in cohesionless, sandy soil that is saturated with water (RMS 1997).

3.3.1.3. Fire Following Earthquake

Fires that break out following earthquakes can be extremely destructive because there may be many simultaneous ignitions, and because the fire suppression capability may be impaired by damaged water supply systems, the unavailability of personnel, and restricted mobility due to debris-filled, damaged roads. The severity of the fire following earthquake hazard is often described in terms of the percentage of the city area that is expected to be burned.

Three main components govern the fire hazard: the number and locations of potential ignition sources, the ease with which fire will spread in the city, and the ease with which fire can be suppressed. Potential post-earthquake ignition sources include gas line breaks, overturned water heaters, electrical shorts, and flammable liquid spills. The fire spread depends on the distribution of fuel (e.g., wooden structures, building contents) and the weather conditions (e.g., humidity, temperature, wind speed, and wind direction). Fire suppression depends on the characteristics of the region’s fire suppression agencies—their management, fire-fighting personnel, emergency water supply, and equipment (e.g., fire trucks, stations, and hydrants). Conceptually, fire suppression could be considered either as part of the Hazard factor, as discussed here, or as part of the Emergency Response and Recovery Capability factor, as discussed below. To avoid double counting, it should be included in one but not both factors. Since fire suppression is an activity that is carried out to reduce impact and not a characteristic of the natural setting, it is considered to be a component of the Emergency Response and Recovery Capability factor.

3.3.1.4. Landslide

Landslides can be triggered by the ground shaking associated with earthquakes. Besides damaging buildings and other structures, landslides can increase the impact of an earthquake by blocking and destabilizing roads, and by blocking rivers and lakes, and thus inducing flooding. Like liquefaction, landslide hazard is discussed in terms of susceptibility, opportunity, and potential. Landslide susceptibility depends on soil cohesion, water level, and slope steepness. Landslide opportunity depends on ground shaking demand, precipitation, and distance to the earthquake source.

3.3.1.5. Tsunami and Seiche

Tsunamis are "long period sea waves produced by uplifts or downdrops of the sea floor during an earthquake. Once generated, a tsunami can travel thousands of miles, propagating at speeds as high as five hundred miles per hour. Although virtually undetectable at sea, the incident waves interact with shallow sea floor topography upon nearing a landmass, causing the characteristic increase in wave height, or run-up (defined as the maximum elevation reached by the wave about the initial water level)" (RMS and CUREe 1994). When a tsunami runs up on land, everything in its path will be inundated with water, and often will be dragged out to sea by the wave as it ebbs. Because they can occur quickly and without warning, and because they will indiscriminately destroy everything in their paths, tsunamis can cause severe loss of property and life. A seiche is a major water wave that occurs in a lake, bay, or other inland body of water because of large uplifts or downdrops of land, e.g., in the 1959 Hebgen Lake, Montana earthquake (RMS and CUREe 1994).

The severity of a tsunami, described in terms of its run-up height and the area that it inundates, depends on three conditions: (1) the seismic source mechanism, i.e., the magnitude and type of earthquake faulting that generates the tsunami; (2) the distance and seafloor topography over which the tsunami travels as it propagates from the source to the site of interest, and (3) the topography of the coast at the run-up site (RMS and CUREe 1994).

3.3.2. Exposure factor

Exposure describes the size of a city; a list of everything that is subject to the physical demands imposed by the hazard. It includes the quantity and distribution of people and physical objects, and the number and type of activities they support. Exposure is a necessary component of risk. No matter how severe the hazard, without an exposed population and infrastructure, there would be nothing to be damaged or disrupted, and therefore, there would be no risk. The larger the exposure then, the greater the risk. Exposure can be addressed with respect to the following components of a city: its physical infrastructure, population, economy, and social-political system.

3.3.2.1. Physical Infrastructure Exposure

The physical infrastructure can be divided into several components, so that the exposure and vulnerability of each can be assessed separately. Several schemes exist to categorize the built physical environment into components with similar risk characteristics (i.e., vulnerability to damage, value, occupancy patterns, functions, potential consequences of damage). RMS and CUREe (1994) provides a good survey of the many available classification schemes. While all the systems are somewhat similar, they vary depending on their intended uses, and the techniques and resources that will be available to assess the exposure in each category. As an example, the NIBS standardized loss estimation methodology (RMS and CUREe 1994, RMS 1997) refers to the basic components in Table 3.1.

In a general sense, the physical infrastructure exposure relates to the circumstances of a city's development—when, where, how, how fast, and why structures have been built to serve society's needs. Physical Infrastructure Exposure may be assessed in terms of the number, size (e.g., square footage, height), geographical distribution, and monetary value of each infrastructure component. The monetary value (value per square foot) depends on the cost of labor and materials for construction and the

Table 3.1. Physical infrastructure components

Infrastructure component		Sub-components
Buildings	General building stock	Residential, commercial, industrial, agriculture, religion/non-profit, government, education buildings
	Essential facilities	Hospitals, health care facilities, police and fire stations, emergency operations centers, communication centers, planned shelters
	High potential loss facilities	Nuclear power plants, dams, military installations, industrial facilities
Transportation systems	Highway systems	Roads, bridges, tunnels
	Railways	Rail track, rail bridges, rail tunnels, rail stations, rail fuel facilities, rail dispatch facilities, rail maintenance facilities
	Light rail	Light rail track, light rail bridges, light rail tunnels, light rail substations, light rail dispatch facilities, light rail maintenance facilities
	Bus	Bus stations, bus fuel facilities, bus dispatch facilities, bus maintenance facilities
	Ports and harbors	Port waterfront structures, port handling equipment, port warehouses, port fuel facilities
	Ferry	Ferry waterfront structures, ferry passenger terminals, ferry fuel facilities, ferry dispatch facilities, ferry maintenance facilities
	Airports	Airport control towers, airport runways, airport terminal buildings, airport parking structures, airport fuel facilities, airport maintenance and hanger facilities
Utilities	Potable water supply	Pipes, water treatment plants, wells, tanks, pumping plants
	Waste water	Pipes, waste water treatment plants, lift stations
	Oil systems	Pipes, refineries, pumping plants, tank farms
	Natural gas systems	Pipes, compressor stations
	Electric power	Substations, distribution circuits, power plants
	Communications	Central office

Source: RMS and CUREe (1994), and RMS (1997).

lifestyle of the buildings' users. The infrastructure will be more expensive in cities that give more weight to its appearance, and the comfort and amenities it offers. A city’s physical infrastructure exposure may be determined through a labor-intensive brute force count; by extrapolating from censuses, tax assessors’ files, and other available databases; or by using indirect estimation methods (Jones 1994).

3.3.2.2. Population Exposure

Population Exposure conveys the number and geographical distribution of the set of all city residents, and of the socio-economic and other groups that exist within the city. It is only necessary to consider separate groups of people if they exhibit different risk characteristics. It is possible that all groups of people within a city could be equally vulnerable to earthquake losses and equal recipients of emergency response and recovery efforts, regardless of their economic class, ethnicity, religious affiliation, or other characteristics. Often that is not the case, however, as the poor, ethnic minorities, the homeless, and other marginalized groups are frequently forced to live in more hazardous areas and in more vulnerable structures, and reap a disproportionately small share of the benefits of emergency response and recovery efforts. The elderly and the very young can also be considered a group with distinct vulnerability characteristics, as they are likely to be physically less resilient and less able to survive in a post-earthquake atmosphere of hardship than others.

To assess the vulnerability of these groups separately, it is necessary to assess their exposure separately as well. Population Exposure may also include an understanding of how these quantities vary with the time of the day, the day of the week, and season of the year. This factor is generally assessed by a straightforward count of the individuals in each group and in the city as a whole, as reported in population censuses.

3.3.2.3. Economy Exposure

The economic circuit is the "continuous and timely flow of production, services, and money between productive units (i.e., intermediate flows) and between these units and households (i.e., final flows) within a framework of technical and economic interdependence"[2] (Albala-Bertrand 1993). Economy Exposure describes the economic flow that takes place within a city—the volume, type, origins, and destinations of goods, services, and money that are transacted. Flow into and out of the city are considered in the Economic External Context factor (see Section 3.3.4.1). The volume and types of economic flow within a city typically are assessed by dividing an economy into its principal sectors (e.g., agriculture; mining; construction; manufacturing; transportation; trade; finance, insurance, and real estate; service; and government), and determining the total value of production in each sector and in the economy as a whole. The sectors should be specific enough so that all the units and activity within each exhibit similar economic vulnerability (see Section 3.3.3.3.). Input-output models describe the interactions among sectors (see RMS 1997 for an overview). Those interactions are critical in determining the extent and severity of economic disruption that will result from physical damage.

3.3.2.4. Social-Political System Exposure

Every city has an infrastructure of interconnected political and social institutions. Those institutions carry out organized political, policy-making, bureaucratic, and administrative activities related to government functions or social sectors. Government functions can be executive, legislative, judicial, coercive, and informational. A social sector is a group of people with some common cohesive characteristic (e.g., ethnicity, religion, social status, regional identification) that defines the group and differentiates it from others (Albala-Bertrand 1993).

[2] "Technical interdependence refers to the level of output that each of the industries of an economy should produce to satisfy all input requirements as well as the final demands of that economy, so that no bottlenecks will arise anywhere." "Economic interdependence, in turn, refers to the circular flow of income and their leakages, i.e., the flow of payments and receipts between firms and households as well as public finance and foreign payments" (Albala-Bertrand 1993).

The Social-Political System Exposure describes the number and types of those institutions, the activities they engage in, and the complexity of the connections among them. The less formal aspect of this factor may be described as a city's social capital. Social capital is "the set of human ties that a community's members find in that place" (Kling 1992). Those ties may be friendships, professional relationships, or an internal sense of stability or home. They provide psychic income that is nontransferable (unlike job satisfaction) because it is attached to specific people and is developed over time.

To clarify the difference between the two factors, Population Exposure refers to the actual people who live in a city, while Social-Political System Exposure refers to the activities and ties that exist among those people, and to the social and political institutions that support those activities and ties. Social-Political System Exposure is directly proportional to the size of the population.

3.3.3. Vulnerability factor

Vulnerability describes how easily and how severely a city's exposed entities can be affected given a specified level of hazard. Vulnerability refers to the potential for the physical infrastructure to be damaged or destroyed; members of the population to be injured, killed, or left homeless, or to have their daily lives disrupted; and the economic and social-political systems to be disrupted. Everything that is exposed must have an associated vulnerability, so the same categories exist for the two factors.

3.3.3.1. Physical Infrastructure Vulnerability

The Physical Infrastructure Vulnerability describes the expected degree of direct damage to the physical infrastructure, given a specified level of hazard demand. In general, the severity of structural damage is assessed as a damage ratio, i.e., the repair cost divided by the replacement cost, and structural vulnerability is portrayed using a damage curve, or fragility curves. A damage curve (Fig. 3.2) depicts the expected severity of damage associated with each level of hazard. Fragility curves (Fig. 3.3) come as a set, one curve for each damage state. Each fragility curve shows how the probability that that damage state will occur increases with the level of hazard.

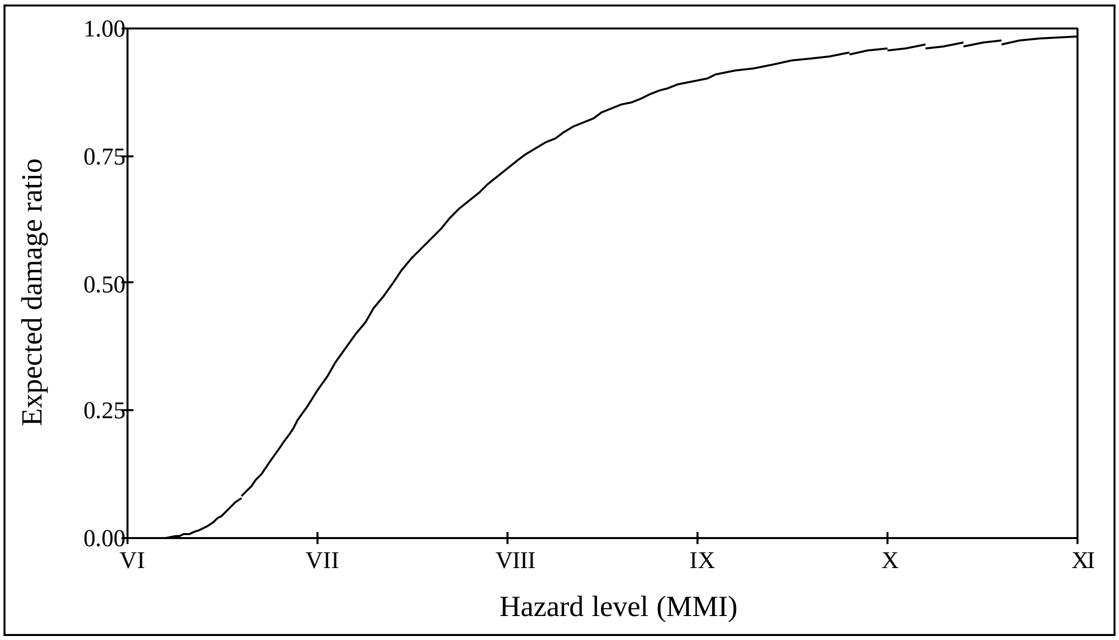


Figure 3.2. Schematic example of a damage curve. Based on RMS (1997).

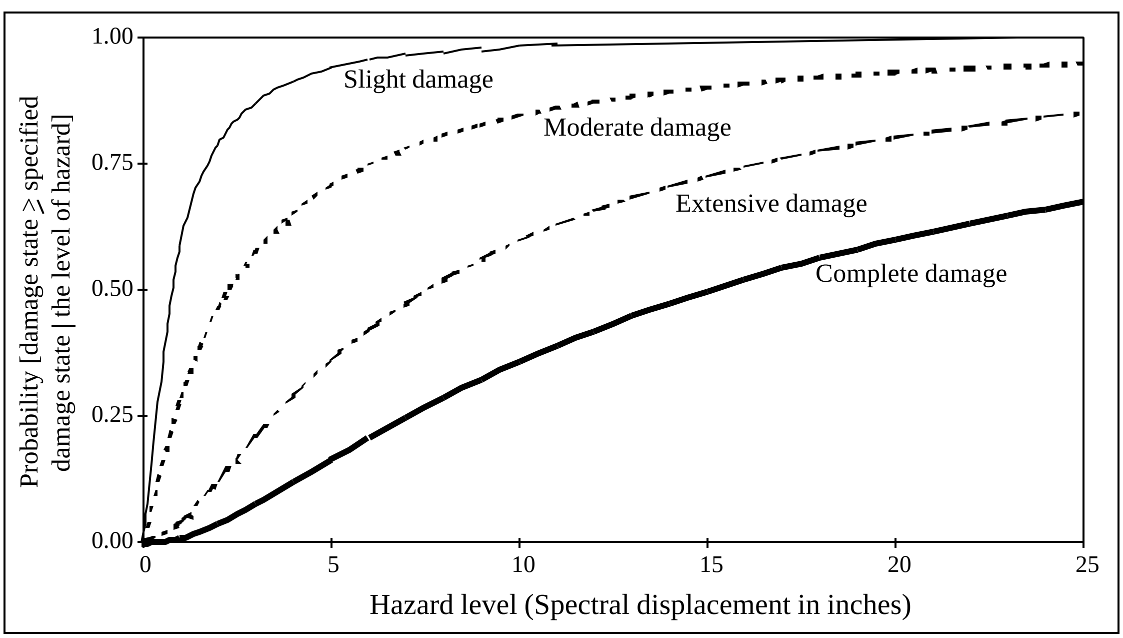


Figure 3.3. Schematic example of a set of fragility curves. Based on RMS (1997).

Two features make Physical Infrastructure Vulnerability a critical factor. First, it determines the extent of physical damage a city will suffer, and physical damage indirectly affects many other post-earthquake events. For example, the ability to carry out an effective emergency response effort depends greatly on the degree of physical damage to the transportation network, and the severity of business interruption losses can depend on the degree of physical damage to all the lifeline networks. Second, the Physical Infrastructure Vulnerability is one of the factors over which society has a relatively significant amount of control. Some of the most effective mitigation strategies that have been implemented to date are those aimed at reducing physical infrastructure vulnerability, e.g., the design and enforcement of seismic building codes, and land use zoning.

In a general sense, the Physical Infrastructure Vulnerability depends on the circumstances of the city's development—when, where, how, how fast, and why structures have been built to serve society's needs, and how they have been maintained since their construction. Although every city is unique, and the process of urban development is complex, some general observations about the relationship between a city's vulnerability and the history of its development may be made. A city can develop an infrastructure with low vulnerability to earthquake damage by chance (if the traditional construction styles happen to exhibit earthquake-resistant characteristics), by deliberate effort, or by some combination of the two. In the absence of good luck, a city must have the motive, means, and opportunity to create an infrastructure with low vulnerability. That is, the city must have:

1. **Motive**
   - Awareness of the problem of earthquake risk at the time the infrastructure is built.
   - Desire to address the problem, i.e., a perception that the risk is unacceptably severe in the context of the other problems the city faces.

2. **Means**
    - Knowledge of how to reduce the vulnerability. Organizations and individuals to create, enact, and enforce effective seismic codes.
    - Financial resources to pay for the code development, implementation, and enforcement.
3. **Opportunity**
    - Good timing. The need to construct the infrastructure must occur at a time when the motive and means exist. The more recent the construction, the less the deteriorating effects of aging.
    - Ample physical space to accommodate the population growth so that the infrastructure is not too dense, and there is room for lifeline redundancy.
    - Ample time to construct the infrastructure in a quality-controlled way.

At a micro level, the vulnerability of the individual structures that make up a city can be assessed by applying the principles of structural analysis. A city's vulnerability could then be considered the aggregation of the vulnerability of all the structures it contains. The ability of a structure to resist earthquake forces depends on the following characteristics:

1. **Structural system and construction material**

    The structure should be able to "undergo long-duration horizontal and vertical shaking without excessive loss of stiffness or strength" (Rojahn 1994). For example, in California, single-story wood-frame houses and ductile reinforced concrete frames generally resist earthquake forces effectively. Unreinforced masonry buildings and non-ductile concrete frames do not.
2. **Configuration**

    The plan shape should be regular and symmetrical to minimize torsional response, and the elevation should have no great discontinuities in stiffness, strength, or mass.
3. **Structural continuity**

Structural elements should be tied together well so that they remain as a unit during shaking.

4. **Changes in structural condition since construction**

   The effects of aging, maintenance (or lack thereof), damage in previous earthquakes, and retrofitting can significantly diminish or improve a structure's original performance.

5. **Proximity to other structures**

   A sufficient space should separate adjacent structures so that they do not pound against one another during shaking.

6. **Network redundancy**

   The more redundancy in lifeline infrastructure components the lesser the consequences of physical damage to any one component of the lifeline network, and therefore, the less the vulnerability.

The first approach addresses the city as a whole, and bases its assessment on the processes that generally lead to lower vulnerability. It is an indirect, macro technique. Since more is known about the general development of the city than about each structure it contains, this first approach lends itself to relatively easy evaluation. Its main disadvantage is that shared by all indirect, overly general measures. The occurrence of the processes described cannot fully determine a city's level of vulnerability. There surely will be cases in which other processes interfere to create outcomes entirely different from those expected. The second approach examines each structure individually as it appears, without regard for how it came to exhibit or not exhibit the various earthquake resistant properties (by chance or by design). It is a direct, micro technique. If all else is equal, direct approaches are always more desirable than indirect ones, because it is more certain that they actually will represent the quantities that they intend to represent. Often this directness comes at the price of an enormous increase in assessment difficulty. It would be impossible to conduct a full structural analysis of every individual structure in a city, and in its purest form, that is what the second approach demands.

The approach that loss estimation models use to assess the physical vulnerability of a city combines aspects of each of the two methods. It finds a middle ground in resolution by dividing the entire stock of infrastructure into components that exhibit similar levels of earthquake resistance (see Section 3.3.2.1.), and assessing the vulnerability of each component separately (i.e., creating damage or fragility curves for each). Although loss estimation models aim to determine the vulnerability of areas smaller than an entire city, they could be used to assess a city's vulnerability by aggregating the results of each infrastructure component analysis, weighing the vulnerability of each component by the proportion of the infrastructure that it represents. Loss estimation models also lie somewhere between the extreme directness and indirectness of the two approaches described above. They identify the typical characteristics of each infrastructure component, and begin to apply the principles of structural analysis to determine its vulnerability. When a relevant structural characteristic is unknown, the models look to the processes that may have helped determine that characteristic. For example, if it is not clear how well a particular type of building in a certain city will endure shaking, the models instead would rely on information about the year in which seismic codes were adopted relative to the average age of the building type, and about the degree to which those codes are enforced in the city under consideration.

3.3.3.2. Population Vulnerability

Population Vulnerability describes the characteristics of individuals that make them more or less likely to be injured, killed, displaced, or to have their daily lives disrupted as the result of an earthquake. It also includes their ability to recover from any impact they do experience. There can be considerable variation in the vulnerability of residents within a city, due, for example, to their age, ethnic group, or economic status. An earthquake's expected impact on a city may be spread evenly over a city's entire population, or may be concentrated on a small number of highly vulnerable people. All else being equal, a city exhibiting the latter situation would have a higher earthquake disaster risk. This factor attempts to include the concept of internal heterogeneity of the population. It contributes to a city's earthquake disaster risk by altering the distribution of risk so that certain highly vulnerable groups within a city experience an especially great level of risk. Population Vulnerability can exist in three different forms: physical, economic, and social.

Physical Population Vulnerability describes the physical characteristics of the city's residents that make them more or less vulnerable. Groups that might be more vulnerable are those who are young (less than five years old), old (sixty-five years old or older), sick, disabled, or pregnant. These characteristics can be important due to their potential effect on a person's ability to escape from a collapsing structure, recover from an injury, or survive in a post-earthquake atmosphere of hardship. As noted in Blaikie et al. (1994), "studies of disaster casualties have indicated that the young and the old are often most at risk. They are, for example, less mobile (capable of evacuation), more dependent, have less resistance to disease, and often command fewer resources."

Economic Population Vulnerability highlights the fact that for residents who are struggling financially before an earthquake, the poor or unemployed, it may be especially difficult to recover from losses. They may be unable to afford the health care costs associated with earthquake injuries. The financial loss they suffer will make up a greater percentage of their income than it would for wealthier residents. The poor will have to rely more heavily on aid because they do not have a buffer of personal savings or good credit.

Social Population Vulnerability accounts for the fact that individuals who are members of certain marginalized groups often suffer a disproportionate share of the impact. Non-native speakers, the homeless, certain ethnic groups, and other minorities often have limited access to resources and political power. That limited access may translate into increased vulnerability if those groups are relegated to more hazardous locations in a city, are left out of pre-earthquake mitigation efforts, or receive a disproportionately small amount of emergency response and recovery services (Blaikie et al. 1994).

3.3.3.3. Economy Vulnerability

The vulnerability of a city's economy describes the expected severity and distribution of the disruption in economic flows that will occur given a specified level of hazard. Economy vulnerability relates to indirect losses, i.e., losses that arise in economic sectors not because of direct physical damage they sustain, but because they are either forward-linked (rely on obtaining supplies from) or backward-linked (rely on selling their output to) to sectors that do experience direct physical damage, or because of a reduction in government, investment, or export demands for goods and services (Cochrane 1996). While exposure and vulnerability of the physical infrastructure largely determine the amount of direct economic losses, exposure and vulnerability of the economy largely determine the extent of indirect economic losses. West (1996) discusses the many types of indirect effects that may result from an earthquake.

The calculated indirect economic effects will depend on the perspective that is adopted in conducting the analysis. First, the gains and losses that are included in the analysis will vary. If a local government provides aid to a household, the amount constitutes a gain from the perspective of the household. However, from a regional point-of-view, it is neither a gain or a loss, but a redistribution of funds within the region. Second, the loss as a percentage of total value will vary depending on the viewpoint of the analysis because each unit has a different total wealth. A nation is much wealthier than a region, which is much wealthier than an individual household.

Consider three possible perspectives on the indirect economic losses due to earthquakes: (1) city (greater metropolitan area), (2) nation, and (3) individual households, companies, sectors, or neighborhoods. Experience suggests that, from the standpoint of a greater metropolitan area, the indirect losses following earthquakes are negligible (RMS 1997, Munroe 1992). Earthquakes generally do not result in a significant, long-lasting effect on the performance of the economy of a greater metropolitan area as a whole (i.e., its total output) (Albala-Bertrand 1993). The outside assistance that enters a region following an earthquake seems to offset the indirect losses that the region suffers. While there are several examples of a regional or national economic depression following a natural disaster (e.g., Managua, Nicaragua earthquake of 1972), Cochrane (1992) argues that if one compares the losses *with and without* the earthquake, rather than *before and after* the earthquake, it can be seen that "disasters tend to accelerate ongoing economic and social processes that were working prior to the event." They do not cause robust economies to collapse.

If economic effects are considered from a national perspective, then the negative national implications of the federal assistance that comes into the affected city must be considered. The cost of providing federal disaster relief is passed on either to another region of the country or to a future generation by cutting lower priority programs, raising taxes, or increasing the federal debt. RMS (1997) suggests that the negative effects of federal assistance on other regions or generations roughly balance the positive effects for the recipient city. In that case, the absolute value of indirect losses would be greater when viewed from a national rather than a regional standpoint, because outside aid cannot be considered as a component that offsets the indirect losses. Still, the total indirect losses would be a much smaller percentage of the national economy than of the regional economy.

From the perspective of individual households, companies, sectors, and local geographical areas, there will be winners and losers. Suppose a store is damaged and therefore is unable to sell its product for six months, that store will suffer serious economic losses, but an undamaged store down the street may experience economic gains by taking over business that previously belonged to the damaged store. The vulnerability of a productive unit is determined by the unit's profits, solvency, liquidity, stocks, client power, market access, business connections, and political influence (Albala-Bertrand 1993). In general, size is a good indicator of the vulnerability of a productive unit with larger units being less vulnerable.

Since the EDRI is focused on the greater metropolitan area as a unit of study, the Economy Vulnerability factor should adopt the same perspective. It considers the potential for disruption to the economic flows within the metropolitan area, including aid that comes into the area as an mitigating factor. The Economic External Context factor considers any indirect economic losses that are suffered outside the metropolitan area, including the negative effect of offering federal assistance on other regions of the country. Even if the economic effects seem negligible for the metropolitan area as a whole, however, an earthquake may cause devastating indirect economic losses to individual households, companies, sectors, and neighborhoods. Since the EDRI acknowledges not only the total economic losses in the metropolitan area, but also the distribution of those losses within the area (see Fig. 2.1), a city in which certain individual units (i.e., households, companies, sectors, or neighborhoods) suffer severe economic losses would be considered to have a higher risk than one suffering the same amount of loss, but evenly distributed among units.

Direct effects on labor and capital stock (i.e., inventories and fixed assets) can initiate disruptions in local economic flows and impairment of productive processes. A disrupted labor force and damaged production facilities or inventories can cause a loss of sectoral function (i.e., a reduction in the output of a sector). Loss of sectoral function can, in turn, lead to a shortage of supplies for all forward-linked sectors, a reduction in demand for inputs from all backward-linked sectors, and/or a reduction in government, investment, or export demands for goods and services (Cochrane 1996). The vulnerability of a city's economy depends on (1) the pattern of direct physical damage in the city, (2) the internal and external capacity of its component sectors, (3) the structure of the economy, and (4) the amount of outside aid that will be available for emergency response, recovery, and reconstruction. The remainder of the section presents a discussion of each of these four items in turn.

The Physical Infrastructure Vulnerability and Exposure factors determine the expected severity and distribution of physical damage to inventories, facilities, and lifelines in the city. That damage pattern, in turn, determines the amount of money necessary to repair the damage, and the degree and duration of reduction in the output of each sector. West (1996) refers to studies by Brady and Perkins (1991) and Cochrane (1995) in arguing that, for indirect losses, "*what* is damaged is more important than *how much* is damaged." If the damage is evenly distributed among sectors, indirect effects will be less than if one or two sectors suffer a disproportionate amount. According to Cochrane (1996), a uniform damage pattern (i.e., when each sector suffers an equal damage ratio) causes the economy to shrink proportionately, so that forward- and backward-linked sector losses disappear, and the economy remains balanced. Damage to the city's lifeline infrastructure (e.g., transportation, communications) can disrupt economic flows and affect the productivity of many sectors simultaneously.

Economic disruptions take place within the context of a dynamic economic system. Indirect effects do not propagate through the economy unchecked. As soon as the physical damage occurs, each sector will begin trying to restore the economy's equilibrium by utilizing available excess capacity. The amount of capacity in a sector describes the ability of that sector to absorb the direct effects of an earthquake, thereby minimizing indirect losses to forward- and backward-linked sectors. Capacity may be internal (i.e., originating within the city) or external (i.e., originating outside the city). If direct damage to facilities and inventories causes a shortage of supplies to forward-linked sectors, forms of capacity that might help reduce the indirect losses to those forward-linked sectors include unemployed labor, idle inventory within the region, and supplemental import sources. If direct damage causes a reduction in demand for inputs from backward-linked sectors, forms of capacity that might help reduce the indirect losses to those backward-linked sectors include the ability to accumulate inventory for future sale (requiring that the goods be non-perishable, and that storage space exists), and new export markets. The degree of capacity may depend on post-event household spending patterns, the mobility of the workforce, the elasticity of supplies from the construction industry, and the potential for product substitutions due to relative price changes (RMS 1997).

Given a certain level of disruption within each economic sector, the network of flows of money, services, and goods among sectors will cause the effects of that disruption to propagate through the economy. The economic structure, i.e., the nature of inter-industry flows and the relative importance of the sectors, will determine the magnitude and distribution of indirect effects within the economy. According to Jones (1992), some sectors of the economy are more vulnerable to disruption than others, and if the more vulnerable sectors control a larger proportion of the economic flows, the economy as a whole is more vulnerable. Specifically, Jones (1992) argues that while "extractive industries are little dependent on linkages and interaction at low levels of development," "fabricative sectors are fairly robust and show remarkable ability to recover. Distributive sectors are heavily dependent on lifelines and infrastructure and are likely to be heavily impacted. Services are highly dependent on transportation and communication and are perhaps the most vulnerable of all" (Jones 1992). Since economies with a high per capita Gross Domestic Product (GDP) are dominated by the service and distribution industries, they are more vulnerable to natural disasters than economies with a low per capita GDP, in which the extractive and fabricative sectors have larger shares.

There is disagreement about how the complexity of a city's economic network affects the severity and distribution of losses it will suffer. A more extensive, interconnected network might allow the losses to spread further, affecting more people and increasing the risk, as Jones (1992) suggests, but it also might indicate more capacity for substitution of suppliers and buyers, thereby reducing the vulnerability of the economy. As Cheng notes, "to ignore the benefits provided by the economic linkages, including a greater capacity to deal with disasters, and to view them primarily as the nodes of a network by which diseases are spread would be theoretically wrong and very misleading." (Cheng 1992).

Finally, considering economic vulnerability from the perspective of a city, the amount of indirect losses depends on the percentage of spending on recovery and reconstruction that come from outside aid and payments on insurance claims. Those outside sources can significantly offset any indirect losses that are incurred.

3.3.3.4. Social-Political System Vulnerability

An earthquake disaster may disrupt individual institutions and organizations within a city's social and political structure, and/or the connections among them. Institutions may experience (1) functional deficiencies due to the damaged physical infrastructure and disrupted work force, and (2) new demands that emerge as part of the response, recovery, and reconstruction efforts (Albala-Bertrand 1993). The infrastructure that connects the many social and political institutions may experience instability or sectoralization. This factor captures the characteristics of a city's social-political infrastructure that determine the likelihood, severity, and extent of disruption that will occur given a specified level of hazard. The Nicaragua earthquake of 1972 provides a well-known example of the way in which the social-political situation can affect the earthquake impact, and vice versa (Albala-Bertrand 1993). In general, the social-political vulnerability depends on the type of political system, the strength and complexity of linkages among local institutions and organizations, the tendency of groups to act centrifugally, and the ability of in-built mechanisms (e.g., self-help, family-centered activities) to counteract deficiencies in the infrastructure by relieving stress on formal institutions (Albala-Bertrand 1993).

3.3.4. External Context factor

In today's global community, major cities are increasingly interconnected. No city is an island. Neither the factors that contribute to a city's risk, nor the consequences of an earthquake disaster are confined within a city's borders. External Context is included to describe how damage to a city affects those outside the city. It incorporates the reality that, depending on a city's prominence with respect to economics, transportation, politics, and culture, damage to certain cities may have more far-reaching effects than damage to others. A city's External Context rating indicates the degree to which economic losses, and disruption to transportation networks, political processes, and social lives will extend beyond its borders. The ripple effect may both (1) increase the total impact by creating additional economic losses or disruption that would not occur if the city was completely isolated, and (2) redistribute any impact that may otherwise have been confined within the city to regions outside the city. Increasing the total impact would increase the overall risk, but spreading out losses that otherwise would be concentrated within the city, may reduce the overall risk.

This factor may be divided into the external context that depicts the city's relationship to its country, and the external context that depicts the city's relationship to the world. The two do not necessarily convey the same information. A city may be important to its country, but not very important to world affairs, relative to other cities worldwide. Santiago, Chile, for example, is home to one-third of Chile's population, and serves as the country's political, economic, and cultural center, but relative to Tokyo, New York, Paris, London, and other megacities, it does not play a large role in global affairs. External context as it relates to both city-country relationships and city-world relationships, consists of four main components: economics, transportation, politics, and culture.

3.3.4.1. Economic External Context

Economic External Context describes the economic ripple effect of an earthquake disaster. It depends on the number and strength of economic linkages between the city and those outside city. This factor is related to, but not the same as total wealth. A city could be extremely wealthy, but isolationist, so damage to it would not affect outsiders significantly. The Economic External Context can be conceived as similar to a balance of payments account for a city, i.e., a record of all transactions between a city's residents and the rest of the world. For a more detailed understanding, consider the transactions included in a balance of payments: merchandise trade, transportation service, tourist services, business, and professional services, unilateral transfers (donations), direct investment, long-term portfolio investment, and short-term capital flows. The need for and existence of alternatives for the particular types of imports and exports concerned are also important.

3.3.4.2. Transportation External Context

Transportation External Context considers how many people travel to, from, and through the city. Transportation might include the transport of goods as well as people, but the movement of goods is accounted for already through the Economic External Context factor, so only passengers are included in this component. All forms of transport should be considered: road, railroad, air, and water. For the last three, the factor could focus on the rail terminals, airports, and ports, assuming that all inter-city travelers would pass through the main facility. For roads, there is no central facility that all travelers must use, so the amount of inter-city traffic might be conceived of as the passenger-miles of trips that originate or end in the city.

3.3.4.3. Political External Context

Political External Context conveys the degree to which people outside a damaged city are affected politically. As Albala-Bertrand (1993) notes, "disaster impacts on capital cities (i.e., where both the central administration is located and a high proportion of the population live, like Managua or Guatemala City) are institutionally more disruptive and pressing than events in the countryside or secondary towns." The factor depends on how many people are affected and how significantly (i.e., how soon and in what way). Political functions are generally concentrated in the capital of each province (or state) and country. A disruption in performance of those political functions could affect people outside the city in two ways:

1. **Domestic political functions**

All the people governed by a particular capital could be affected by damage to the capital city if government officials are disrupted in performance of their jobs. The effects on constituents would vary between countries, depending on the form of the government. In the U.S., for example, citizens could be affected, especially in the long-term, through a slowing or temporary halt in program funding, tax collection, and provision of public services. The extent of impact would depend on the population of the country (or province) of which the city is capital, and the degree of control and centralization of the government.

2. **Foreign political functions**

   Other cities and countries could be affected by the disruption of their relations with the impacted city's government. The extent of impact would depend on the degree of political relations between the country of the impacted city and others, and how much power the country has in those relations.

Note that the nominal political capital does not always retain all of a country's political power. Another city that was the country's capital in previous years, or a city that serves as the country's economic and cultural center may hold some political power as well, either because political functions are physically located there, or because it sets the political agenda. For example, Ankara is currently the capital of Turkey, but because Istanbul was the capital of the region until 1923 and still is the economic and cultural center of the country, it retains a degree of the country's political power as well.

3.3.4.4. Cultural External Context

A city's Cultural External Context describes the degree to which people outside the city rely on the city's cultural resources. The cultural resources includes the stock of historic and cultural assets (monuments, human artifacts, art) that "are important in providing identity and continuity to a society's culture," and the social capital, i.e., intangible assets like human relationship networks and individual's sense of place (Kling 1992). The value of historic and cultural assets lies in their ability "(1) to give a sense of place in history and an identity shared by other people, times, and places, or (2) to provide examples of great aesthetic traditions." They are unique, irreplaceable, and enjoyed jointly and freely (Kling 1992). As discussed in Section 3.3.2.4., social capital is "the set of human ties that a community's members find in that place" (Kling 1992). Those ties may be friendships, professional relationships, or an internal sense of stability or home. They provide psychic income that is nontransferable (unlike job satisfaction) because it is attached to specific people and is developed over time.

Clearly every city has cultural significance, and it would be impossible to rank the relative amount in different cities. This factor is included for completeness, to recognize that cities are not only economic and political machines. They also have significance in other less tangible, but equally important ways.

3.3.5. Emergency Response and Recovery Capability factor

Emergency Response and Recovery Capability describes how effectively and efficiently a city can respond to and recover from short- and long-term impact through formal, organized activities that are performed either after the earthquake, or before the earthquake, but with the primary purpose of improving post-earthquake activities (e.g., planning). It is assumed that any other actions taken before the earthquake (e.g., retrofitting) are significant only if they changed the current snapshot of the city, in which case they are accounted for in other factors. Note also that the Emergency Response and Recovery Capability factor does not include some less visible response activities that happen after an earthquake, e.g., the in-built mechanisms that counteract economic effects, like utilizing excess capacity (see Section 3.3.3.3.). Although those activities help the city reduce and recover from impact, they occur without a deliberate, formal, organized effort. They are so automatic and integrated into the economic, social, and political systems that they are considered to be characteristics of those systems, and therefore, are included in the various components of the Vulnerability factor. Following are twelve aspects of an effective emergency response and recovery effort that are included in this factor. Appendix C describes each in more detail.

1. **Emergency management system**

   There must be an emergency management system to coordinate the response effort. The system must manage problems associated with convergence, disputes over access to the disaster site, and disputes over authority. It must also determine what aid is needed, channel requests upward, and distribute assistance when it arrives.

2. **Communications**

   The procedures and physical equipment must be ready for inter-organizational communication (e.g., among government agencies, relief organizations, and utility companies), inter-jurisdictional communication, and communication between the public and officials. Each party should know who to talk to, what information to convey and to receive, and what form of communication to use.

3. **Financial arrangements**

   The financial arrangements should be in place to facilitate timely assistance to households, businesses, and local governments for relief and reconstruction.

4. **Legislation**

   Pre-disaster legislation should establish channels to request and receive assistance efficiently so that emergency response and recovery efforts are not hindered by legal delays.

5. **Damage assessment**

The procedures and equipment should be available to determine, in almost real time, the type, severity, and location of damage and human losses, and to use that information to identify and prioritize the emergency response and recovery tasks.

6. **Search-and-rescue**

   The effort should be able to locate and rescue survivors trapped in collapsed structures.

7. **Secondary hazard control**

   The procedures and equipment should be available to control secondary hazards. This may include fire prevention and suppression, removal of hazardous debris, sanitation control, and security from looting.

8. **Health care**

   Health care teams must be provide on-site first aid, transport the injured to health care facilities as necessary, and treat patients at those facilities with the greatest speed and highest quality possible.

9. **Mass care**

   The effort must identify the type and quantity of basic needs required, determine where they are needed, and provide them as necessary. Basic needs include emergency food and water, water containers, blankets, cooking utensils, and clothes.

10. **Shelter**

The effort should determine how many people need shelter and for how long, what kind of shelter is appropriate for them, and how to provide it.

11. **Clean-up**

    Undamaged items must be returned to their correct positions, damaged items should be repaired, and destroyed items must be removed. Clean-up includes the task of locating and burying the dead.

12. **Restoration of services**

    Interrupted utility service must be restored, and damaged or blocked transportation routes must be reopened.

Experience has demonstrated that certain aspects of a response and recovery effort are important to its overall effectiveness. To estimate the effectiveness of a city's response and recovery then, one can determine how well the effort achieves those important elements relative to other cities. A city's Emergency Response and Recovery Capability depend on:

1. **Pre-earthquake organizational and operational planning**
2. **Resources available post-earthquake**: Financial, equipment and facilities, and trained manpower.
3. **Mobility and access post-earthquake**

Each of the three components should be measured with respect to the twelve main aspects of the Emergency Response and Recovery Capability factor (see above). Following are discussions of each of these three components.

3.3.5.1. Planning

The planning factor describes the number and quality of plans and procedures developed before the earthquake to guide the twelve main aspects of emergency response and recovery. Plans should be organizational, establishing the roles and responsibilities of each involved party, and operational, creating the procedures that explain what should be done, how, and when. A city's historical experience with earthquakes (or lack thereof), as well as its general cultural and economic setting may influence the degree of planning since a society must have both the desire and the means to plan.

3.3.5.2. Resources Available Post-earthquake

Resources come in the form of money, equipment and facilities, and trained manpower. The term *available* means that the city either has the resources on hand or can obtain them from another source for use immediately following an event. The availability will depend on what is available before the earthquake and the probability that it still will be available after the earthquake, which in turn is a function of the level and geographical extent of physical damage. The resources themselves may be damaged, or the ability to bring them to those in need may be hindered because of damage to the transportation network. In identifying resources, it is helpful to think of all the possible suppliers of the resources, and each of the twelve main response tasks.

Money available for recovery and relief may come from local, state, or national governments, insurance coverage for individual homeowners or businesses, residents' personal savings, businesses, relief organizations like the Red Cross, or foreign sources (bilateral aid, multilateral aid, or non-governmental organizations). Albala-Bertrand (1993) estimates that domestic disaster assistance (especially local) is generally about twice as much foreign disaster assistance, but the ratio may vary from region to region. Equipment and facilities necessary for response includes equipment for emergency communications (e.g., emergency generators), damage assessment (e.g., loss estimation computer models), search and rescue (e.g., the "jaws of life"), secondary hazard control (e.g., fire trucks), health care (e.g., hospital beds), mass care (e.g., food, water, blankets), temporary shelter (e.g., mobile homes), and clean-up (e.g., earth-moving trucks). Possible trained manpower resources also can be identified through their role in each of the twelve main aspects of response. For example, manpower resources could include search-and-rescue teams, physicians, firefighters, public volunteers, and military personnel from a nearby base.

3.3.5.3. Mobility and Access Post-earthquake

The ability to maneuver within and gain access to a city after an earthquake depend on the condition of the post-earthquake transportation system, amount of debris, city layout, city topography, remoteness, and weather conditions. The condition of the transportation system, and the amount of debris are both determined by the severity of direct physical damage, and are already incorporated into the EDRI through the Physical Infrastructure Vulnerability and Exposure factors.

Chapter Four
Indicator Selection

4. Introduction

Once the factors have been identified, a set of simple, measurable, scalar indicators must be selected to represent each in the Earthquake Disaster Risk Index. The meaningfulness of the EDRI hinges on the ability of the indicators to represent the ideas of the conceptual framework. Clearly there are no simple indicators that can convey the ideas of the framework completely. Information necessarily will be lost in the move from complex, conceptual factors to simple, measurable indicators. It is the unavoidable price of operationalization, but a price that is willingly paid to enable the quantitative comparison that the EDRI aims to provide. The process of indicator selection therefore, is an exercise in making tradeoffs between comprehensiveness and simplicity. The challenge is to minimize the loss of information so that together the indicators provide a meaningful measure of earthquake disaster risk.

This chapter begins with a list of the criteria that guide the selection of indicators. Section 4.2 discusses the strategy adopted in the indicator selection process. Sections 4.3.1 to 4.3.5 describe the execution of the process for each of the five main factors. Each section presents the indicators selected in the sample analysis to represent the associated factor, explains why those indicators were chosen, discusses alternative indicators that were considered and the reasons that they were not selected, and lists the aspects of the factor that the indicators fail to represent.

4.1 Criteria for indicator selection

The tasks of defining the factors and creating the conceptual framework are carried out as if the framework is the ultimate goal, without concern for the issues of measurability and data availability. These constraints enter the analysis as indicators are chosen to represent the framework factors. Since there are no indicators that can be proven to be the “correct” ones, it is helpful to list the criteria that an ideal indicator would satisfy, then judge the possible indicators on the basis of their ability to meet them. Rossi and Gilmartin (1980) discuss many qualities with which to assess and compare social indicators. Based on their ideas and the particular needs of the EDRI, the criteria that should guide the indicator selection process are:

1. **Validity**

   The indicators should represent the concepts they purport to represent. Unless a convincing argument demonstrates that the proposed indicators accurately represent the factors for which they are proxies, the EDRI will not be meaningful or useful.

2. **Data availability and quality**

   The indicators should be measured by data that is reliable, available in a consistent form for all the world's major cities, and relatively easy to collect. This criterion is difficult to satisfy. The availability and quality of data vary significantly from city to city, indicator to indicator, and year to year. Data for many indicators that might be included in the EDRI have not been compiled into a consistent form from local sources, or have not been collected at all. Most international comparative data is available only for countries, not for metropolitan areas.

3. **Quantitativeness and objectivity**

The EDRI aims to be transparent and replicable to earn greater credibility and to provide greater insight into the composition of risk. By making the indicators that comprise the EDRI quantitative and objective whenever possible, the EDRI can be more easily evaluated and understood. If all else is equal then, indicators that are evaluated with directly available quantitative data are preferable to those that rely on subjective assessments.

4. **Understandability**

   Indicators should be intuitively understandable, using familiar concepts and quantities when possible.

5. **Directness**

   An indicator is direct if it measures the concept of interest itself, indirect if it measures "some other variable that is assumed (based on experience or theory) to be closely related to the variable of interest." "Direct and indirect indicators differ in the extent to which a change in the indicator matches a corresponding change in the aspect of society being considered. A direct indicator will tend to vary more sensitively, changing its value to reflect changes in the value of the variable being measured. An indirect indicator, on the other hand, can change without the occurrence of corresponding change in the variable of concern (and vice versa)." "Because of other possible influences, an indirect indicator will not be as valid and accurate as a direct one. Thus, direct indicators are always preferable if they are available" (Rossi and Gilmartin 1980). Unfortunately, data are often more easily available for indirect indicators than for direct ones.

4.2. Strategy

The indicator selection process originates with the conceptually complete framework factors. As the constraints of quantitativeness, objectivity, measurability, and data availability are incorporated, the list of possible indicators gradually shrinks until the final set that will be used in the EDRI is determined. Proceeding gradually from the framework factors to the indicators that are the best possible under the true conditions of the current time offers two benefits. First, the process clarifies the conceptual rationale that supports the indicator selection. Second, it suggests ways in which the data availability and quality should be improved, and ways in which an EDRI might be developed if more data gathering resources or better access to data were available.

Indicators may be identified using a microscopic approach or a macroscopic approach. For example, in identifying indicators to represent the physical infrastructure vulnerability, the former would rely on assessing the vulnerability of each type of infrastructure component separately and aggregating the results, while the latter would look to the general trends of the city's development and what they indicate about the vulnerability of the infrastructure for the city as a whole. The microscopic approach, involves disaggregating a factor into its smallest components, attempting to represent each with separate indicator, and combining the many indicators to represent the entire factor. Compared to the macro approach, it generally uses more direct indicators and focuses on precisely the specific concepts that the factor intends to represent, but it requires more detailed analysis and data that is more difficult, if not impossible to obtain. The macroscopic approach, which identifies indicators that represent the factor as a whole, generally has less demanding data requirements, but often results in an indirect measure that suffers from the associated disadvantages of indirect measurement (see Section 4.1, Criterion 5).

The number of indicators that should be used to represent a factor is not predetermined, nor is it necessarily the same for every factor. There are advantages and disadvantages associated with using more or fewer indicators to represent a factor. Using more indicators provides a more complete representation of the factor and makes the composite EDRI less sensitive to any one indicator, but it requires more data and complicates the index. While the Competitiveness Index includes over 330 indicators, the Human Development Index includes only three. A balance must be found between completeness and simplicity so that a sufficient number of indicators are included to represent the factor meaningfully, but no more.

Note that some indicators in the sample analysis are used more than once, to represent more than one concept. For example, "per capita GDP" helps to represent three different factors—economic exposure, physical infrastructure exposure, and financial resources available for emergency response and recovery. In fact, an indicator may increase the earthquake disaster risk in one use and decrease the risk in another. A higher "per capita GDP" indicates a larger exposure, and therefore a higher risk; but it also indicates more financial resources for recovery, and therefore a lower risk. Although multiple uses suggests that an indicator is broader or more inclusive than would be ideal, it is not incorrect to use an indicator more than once. Care must be taken, however, to ensure that the weight associated with the indicator reflects only the relative importance of the concept it represents in the associated use. That is, the weight associated with "per capita GDP" in the Exposure factor should reflect only the effect that the "per capita GDP" has on the exposure, without taking into account its affect on the recovery at all.

4.3. Sample analysis solution

Figure 4.1 presents the indicators that were selected in the sample analysis. The indicators are listed in the rightmost column, the five main factors they represent in the leftmost column, and the factor components in the middle. The following five subsections (4.3.1 to 4.3.5) discuss the indicator selection process as it applies to the five main factors. For each of these subsections, the discussion presents a list of the indicators selected to represent the associated factor, and describes the rationale behind their selection, the assumptions on which they rest, the procedure to calculate them, alternative indicators that were considered, and the aspects of the factor that are omitted from the indicator set. The sensitivity of the results to the indicator selection and definition is discussed in Chapter 7.

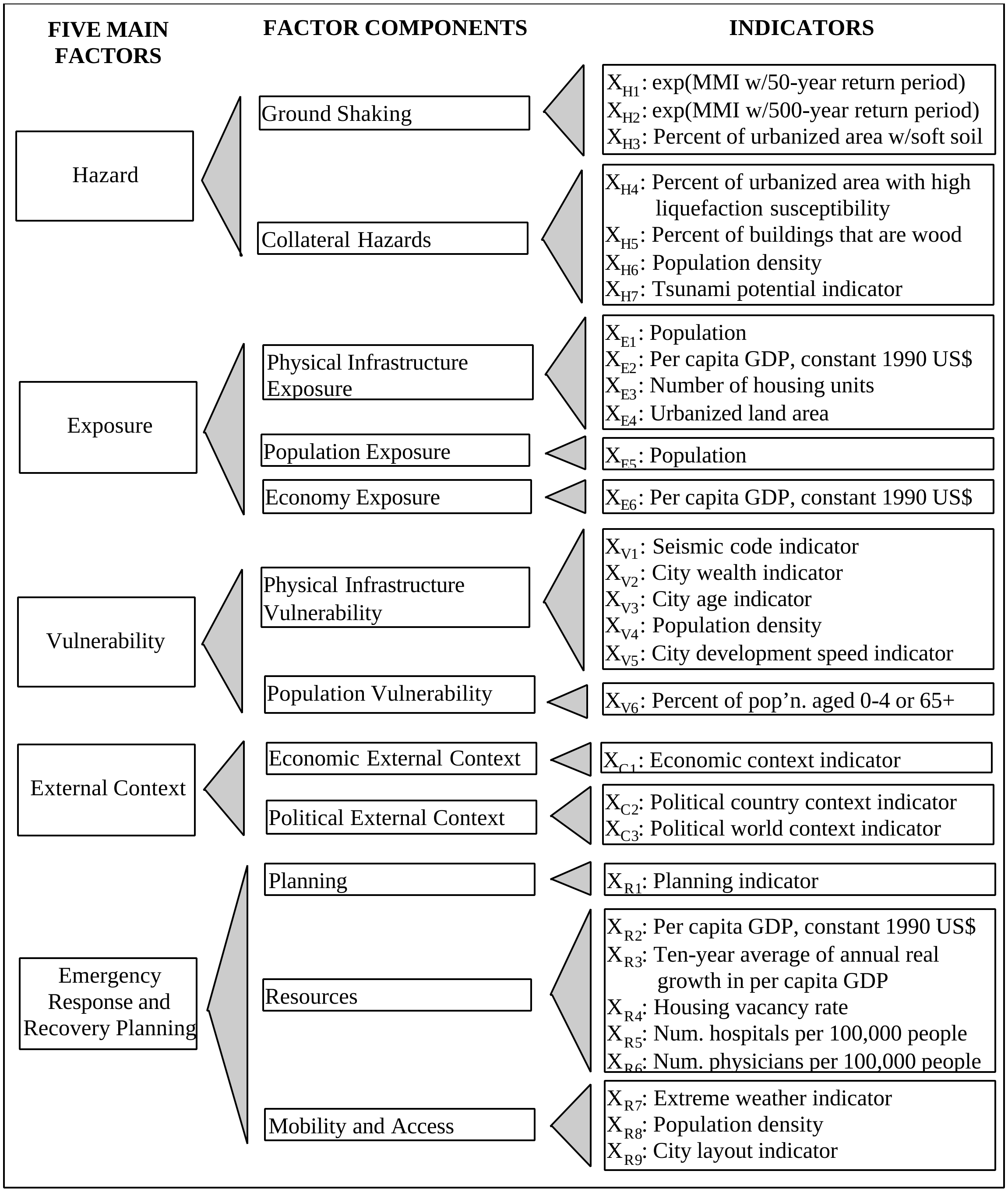


Figure 4.1. Sample analysis indicators

4.3.1. Hazard factor

The seven indicators listed below are used to represent the Hazard factor. The first three represent the ground shaking hazard, and the last four represent the collateral hazards of liquefaction, fire following earthquake, and tsunami:

1. $\mathbf{X_{H1}}$: $e^{(\text{MMI with a fifty-year return period})}$
2. $\mathbf{X_{H2}}$: $e^{(\text{MMI with a fi ve-hundred-year return period})}$
3. $\mathbf{X_{H3}}$: Percentage of urbanized area with soft soil
4. $\mathbf{X_{H4}}$: Percentage of urbanized area with high liquefaction susceptibility
5. $\mathbf{X_{H5}}$: Percentage of buildings that are wood
6. $\mathbf{X_{H6}}$: Population density (people per square kilometer)
7. $\mathbf{X_{H7}}$: Tsunami potential indicator

Just as the Hazard factor was defined in Chapter 3 by considering ground shaking, then each of the collateral hazards in turn, so will the discussion of the indicator selection be divided into the same subsections—ground shaking, liquefaction, fire following earthquake, and tsunami. The landslide hazard is not included in the sample analysis indicator set because no appropriate indicators could be identified to represent it. One possible measurable landslide indicator might be "percentage of urbanized area with high landslide potential (i.e., slopes steeper than a certain grade and made of soil without adeqeuate cohesiveness)." Another might be derived from the number and size of historical landslides. The data are not available for either of these possibilities, however, so no landslide indicators are included.

4.3.1.1. Ground Shaking

As discussed in Section 3.3.1.1, the ground shaking hazard depends on (1) the locations, recurrence relationships, and maximum possible magnitudes associated with the faults and areas sources that might produce the ground shaking; (2) the attenuation relationships that are associated with soil and topography and describe the way in which ground motion changes in amplitude and frequency content as it travels from the source to the site; and (3) the ability of the soil at the site to amplify or reduce the ground shaking. Not only do all of these characteristics need to be included to create a complete representation of ground shaking hazard, but their interactions must be acknowledged too.

Probabilistic Seismic Hazard Analysis (PSHA) is a technique that integrates these components to produce a summary expression of the level of bedrock ground shaking hazard, i.e., the probabilistically expected magnitude of ground shaking at a given site, in a specified future time period. Using the output of the PSHA ensures that ground shaking is represented as completely as possible. Since the typical PSHA output is a map showing contours of equal hazard with a hazard curve of return period versus ground shaking for each (Fig. 4.2), one or more scalar quantities must be derived from that output to serve as indicators in the EDRI. Two points are selected from the hazard curve to capture the influence of both events with a high rate of occurrence and small magnitude, and events with a low frequency and large magnitude. According to the Poisson model of earthquake occurrence, these two points—the MMI with a fifty-year return period, and the MMI with a five-hundred-year return period—correspond to the levels of ground shaking with a ten percent chance of being exceeded in five and fifty years, respectively.[1]

Because earthquake magnitudes are defined as logarithmic functions (e.g., Richter magnitude = logA- logA_o, where A is the maximum amplitude of a seismogram measured in micrometers, and A_o is the zero amplitude), roughly speaking, the amplitude of ground shaking varies as $e^{(\text{earthquake magnitude})}$. The difference in ground shaking between earthquakes of magnitudes eight and nine is much more severe than the difference between earthquakes of magnitudes two and three. Therefore, $e^{(\text{MMI with a fifty-year return period})}$

[1] According to the Poisson model, P = [probability of occurrence of ground shaking at least as severe as the specified level, within t years] = 1 - $e^{-(t/RP)}$, where RP is the return period associated with the specified level of ground shaking. Therefore, if P=0.1 and t=5 years, then RP≈50 years; and if P=0.1 and t=50 years, then RP≈500 years.

and $e^{(\text{MMI with a five-hundred-year return period})}$ (X_{H1} and X_{H2}) are better indicators of the amplitude of ground shaking than the MMI values themselves. To evaluate $e^{(\text{MMI with a fifty-year return period})}$, a single, average value is estimated for the entire city from available, published PSHA results; likewise for $e^{(\text{MMI with a five-hundred-year return period})}$.

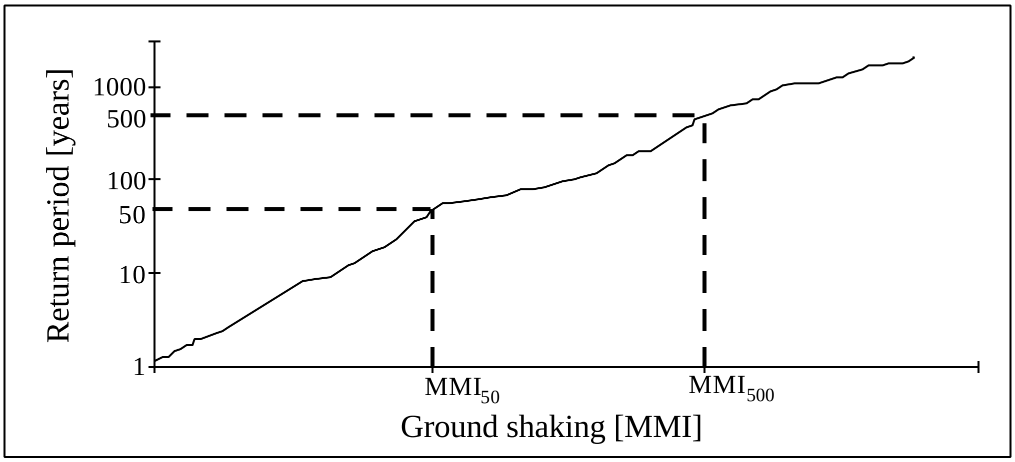


Figure 4.2. Schematic example of a hazard curve

By building on PSHA, the two bedrock ground shaking indicators provide a relatively complete representation of a city's bedrock ground shaking hazard. The cost of directly using the output of PSHA studies to evaluate the indicators is that the results then depend on the quality and consistency of those studies. If the MMI values are taken from analyses conducted by different researchers, the methods and data may not be consistent across studies. It can also be argued that PSHA is too complicated for use in the EDRI, which aims to be simple to evaluate and interpret. However, the relative sophistication of X_{H1} and X_{H2} can be justified because it is far easier to find the results of a PSHA for every major city, than to determine all the pieces of the analysis (e.g., recurrence and attenuation relationships) from scratch, and the representation of ground shaking hazard would be incomplete if some aspects of the PSHA were omitted.

The indicator "percentage of urbanized area with soft soil" (X_{H3}) represents the extent to which soil conditions are likely to increase the expected bedrock ground shaking in the city.

While it would be useful to know the distribution of each soil type with respect to the infrastructure and the expected bedrock ground shaking throughout a city, that information is too unwieldy for direct inclusion in the EDRI. Instead, the "percentage of urbanized area with soft soil" conveys only the information that is most critical in comparing the soil conditions of different cities. "Soft soil" includes soils of type E or F (Table 4.1), as used in *Hazus97*, the NIBS standardized earthquake loss estimation methodology (RMS 1997). It refers to those soils that will amplify the ground shaking most severely. The indicator X_{H3} considers only the "urbanized area," i.e., the built-up area within the city's boundaries, because soft soil will only increase the city's earthquake disaster risk if it supports a structure.

Table 4.1. Soil classifications (from the 1997 NEHRP Provisions)

Name	General description	Shear wave velocity (m/s)	
		Minimum	Maximum
A	HARD ROCK Eastern United States sites only.	1500	
B	ROCK	760	1500
C	VERY DENSE SOIL AND SOFT ROCK Undrained shear strength $u_s \geq 2000$ psf ($u_s \geq 100$ kPa) or N ≥ 50 blows/ft.	360	760
D	STIFF SOILS Stiff soil with undrained shear strength 1000 psf $\leq u_s \leq 2000$ psf (50 kPa $\leq u_s \leq 100$ kPa) or $15 \leq N \leq$ blows/ft.	180	360
E	SOFT SOILS Profile with more than 10 ft. (3 m.) of soft clay defined as soil with plasticity index PI > 20, moisture content w > 40% and undrained shear strength $u_s < 1000$ psf (50 kPa) (N < 15 blows/ft.)		180
F	SOILS REQUIRING SITE SPECIFIC EVALUATIONS 1. Soils vulnerable to potential failure or collapse under seismic loading, e.g., liquefiable soils, quick & highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays (10 ft. (3 m.) or thicker layer). 3. Very high plasticity clays (25 ft. (8 m.) or thicker layer with plasticity index > 75). 4. Very thick soft/medium stiff clays (120 ft. (36 m.) or		

	thicker layer).		

Source: Reprinted from RMS (1997).

For a given city, the value of "percentage of urbanized area with soft soil" can be estimated by superimposing the boundaries of the city's urbanized area onto a map that depicts the distribution of soft soil throughout the city, perhaps using Geographic Information Systems (GIS) software. If a soil map portraying areas of soft soil (as it is defined in Table 4.1) is not available, it may be necessary to determine the soft soil areas directly from a geological map of the city, which should almost always be available.

The EDRI ground shaking hazard indicators do not convey any information about topographic or directivity effects, or about the relative distributions of soft soil and bedrock ground shaking throughout a city. Although MMI values were used in the sample analysis, it would be better to use spectral acceleration or peak ground acceleration values if the PSHA results were available for all cities.

4.3.1.2. Liquefaction

The liquefaction indicator (X_{H4}) represents an approach similar to that of the soft soil indicator. Considering the percentage of the city's urbanized area that exhibits the characteristics associated with the highest risk (i.e., soft soil or high liquefaction susceptibility) conveys the most critical information in a single, simple value. "High liquefaction susceptibility" refers to the soil deposits that would be classified as having either high or very high liquefaction susceptibility in the NIBS standardized loss estimation methodology (according to Youd and Perkins 1978; and Liao, Veneziano, and Whitman 1988). Table 4.2 indicates the Youd and Perkins liquefaction susceptibility classifications for a variety of soil types. Table 4.3 defines each liquefaction susceptibility category in terms of the associated probability of liquefaction given a certain peak ground acceleration. As with the soft soil indicator, the liquefaction indicator considers only the "urbanized area," i.e., the built-up area within the city's boundaries, because liquefiable soil will only increase the city's earthquake disaster risk if it supports a structure or lifeline.

Table 4.2. Liquefaction susceptibility of sedimentary deposits
(from Youd and Perkins 1978)

Type of deposit	Distribution of cohesionless sediments in deposits	Likelihood that cohesionless sediments when saturated would be susceptible to liquefaction (by age of deposit)			
		<500 yr. Modern	Holocene <11 ka	Pleistocene 11 ka-2 Ma	Pre-Pleistocene > 2Ma
(a) Continental deposits					
River channel	Locally variable	Very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very low
Marine terraces and plains	Widespread	---	Low	Very low	Very low
Delta & fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine, playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very low	Very low
Sebka	Locally variable	High	Moderate	Low	Very low
(b) Coastal zone					
Delta	Widespread	Very high	High	Low	Very low
Esturine	Locally variable	High	Moderate	Low	Very low
Beach: High wave energy	Widespread	Moderate	Low	Very low	Very low
Beach: Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low
(c) Artificial					
Uncompacted fill	Variable	Very high	---	---	---
Compacted fill	Variable	Low	---	---	---

Source: Reprinted from RMS (1997).

Table 4.3. Conditional probability relationship for liquefaction susceptibility categories (from Liao, Veneziano, and Whitman 1988)

Susceptibility category	P[Liquefaction|PGA=a]
Very high	9.09a-0.82
High	7.67a-0.92
Moderate	6.67a-1.00
Low	5.57a-1.18
Very low	4.16a-1.08
None	0.00

Source: Reprinted from RMS (1997).

For a given city, the value of "percentage of urbanized area with high liquefaction susceptibility" can be estimated by superimposing the boundaries of the city's urbanized area onto a map that depicts the distribution of high liquefaction susceptibility soil (as it is defined in Tables 4.2 and 4.3) throughout the city, perhaps using GIS software. If no such liquefaction susceptibility map is available, it may be necessary to estimate the value of X_{H4} directly from a geological map of the city.

4.3.1.3. Fire Following Earthquake

Two indicators—"percentage of buildings that are wood" and "population density" (X_{H5} and X_{H6})—represent the fire hazard. The first conveys information about the amount of fuel available to feed post-earthquake fires, and the second refers to the ease with which post-earthquake fires can spread and be suppressed. Planners in Kobe, Japan used the same two indicators to estimate the hazard of fire following earthquake before the Great Hanshin earthquake of 1995 (Bauman 1997). Although the indicator X_{H5} refers to all buildings whose primary construction material is wood, the value may be estimated from residential building stock, for which data are generally available from housing censuses.

While fire spread is more directly related to infrastructure density than population density, population data is more easily available than infrastructure data, so it is assumed that infrastructure density and population density are proportional, and population density is used instead. In the indicator X_{H6}, population density is defined as the weighted average of the densities of the counties (or smaller cities, neighborhoods, or other administrative units) that make up the greater metropolitan area, where the weights are the populations of those counties:

$$X_{H6} = (\Sigma_i d_i p_i) / \Sigma_i p_i, \tag{4.1}$$

where d_i is the density of county i, p_i is the population of county i, and the summation is over all counties i that comprise the greater metropolitan area. The weighted average provides a more accurate representation of the city's density than a simple ratio of total population divided by total land area would, because some greater metropolitan areas are defined to include large, sparsely populated surrounding areas that would make the densities of those cities appear smaller than they are. Still, the population density calculation can be problematic because the results will depend on how many counties (or administrative units) there are within the metropolitan area, and on how their boundaries are defined. The sensitivity analysis compares the two possible definitions of population density (Section 7.1).

The set of hazard indicators omit several important aspects of the fire hazard factor. No information is included about the location and number of potential ignition sources, the distribution of fuel, the existence of other types of fuel besides wood buildings, or the typical weather conditions (e.g., precipitation, wind speed and direction) that may influence the fire spread. Since fire suppression capability is accounted for within the Emergency Response and Recovery Capability factor, no attempt is made to represent it with the Hazard indicators.

4.3.1.4. Tsunami and Seiche

The "tsunami potential indicator," X_{H7}, is defined as a three-level classification system to rate a city's susceptibility to tsunami damage. The indicator has three possible values (Table 4.4):

Table 4.4. "Tsunami potential indicator" definition

Tsunami potential X_{H7}	Category description
0	None. No historical tsunamis. Physically impossible because city is not adjacent to a body of water that contains an earthquake source capable of generating a tsunami.
1	Low. Physically possible, but unlikely (i.e., tsunami has occurred less than twenty times in historical record)
2	High. Physically possible, and not unlikely (i.e., tsunami has occurred twenty or more times in historical record)

The value of X_{H7} for a given city can be assessed by examining the worldwide historical database of tsunamis (NGDC 1997), and the city's geographical location relative to possible tsunami-generating sources. The indicator does not take into account a city's coastal topography, which can influence the run-up height and the extent of inundation should a tsunami occur.

4.3.2. Exposure factor

The following six indicators represent the Exposure factor. The first four describe the Physical Infrastructure Exposure, the fifth represents the Population Exposure, and the sixth refers to the Economy Exposure. Note that two of the indicators are listed twice because they are each used in two different capacities, as discussed below. For a given city, X_{E1} and X_{E5} will always have the same value, as will X_{E2} and X_{E6}. The indicators are separated for conceptual clarity, so that, for example, the weight assigned to X_{E1} relates to the population as it conveys information about the Physical Infrastructure Exposure, and the weight assigned to X_{E5} relates to the population as it conveys information about the Population Exposure.

1. $\mathbf{X_{E1}}$: Population
2. $\mathbf{X_{E2}}$: Per capita Gross Domestic Product, in constant 1990 US dollars[2]
3. $\mathbf{X_{E3}}$: Number of housing units[3]
4. $\mathbf{X_{E4}}$: Urbanized land area (square kilometers)
5. $\mathbf{X_{E5}}$: Population
6. $\mathbf{X_{E6}}$: Per capita Gross Domestic Product, in constant 1990 US dollars

The Social-Political System Exposure is not represented explicitly by the set of Exposure indicators, but it seems reasonable to assume that cities with relatively high Physical Infrastructure, Population, and Economy Exposure, would have a relatively high Social-Political System Exposure as well.

4.3.2.1. Physical Infrastructure Exposure

Jones (1994) proposes that "there are strong regularities in human behavior in constructing elements to shelter people and their activities and to facilitate movement of people, goods, and information, and that there will be strong patterns in the ways in which populations occupy space and locate structures to accommodate their needs (Isard, 1956)." Based on these assumptions, he and his colleagues have developed a methodology for making indirect estimates of a city's physical infrastructure—the amount (in terms of number, square footage, and replacement value) and distribution (i.e., distance from the center of gravity of population of the city) of each type of infrastructure component (e.g., residential buildings, commercial buildings, roads). The model that he and his colleagues developed was calibrated and verified with extremely labor-intensive, direct count inventories of all infrastructure components for a few case study cities (Wichita, Kansas; Ithaca, New York; Kyoto, Japan). The studies that produced this model and inventory data aimed to estimate the physical infrastructure in absolute

[2] See Section 4.3.2.3. for a description of the difference between Gross Domestic Product and Gross National Product.

terms, but for the purposes of the EDRI, which aspires to assess only the relative physical infrastructure exposure of different cities, the most important findings are the following:

1. At the scale of a greater metropolitan area, the physical infrastructure exposure depends primarily on the population, and the level of technological development and income. "More developed and elaborately organized societies use time in more specialized ways and have greater variety in structures to accommodate uses that fulfill needs. Within a given culture at a level of technological development resulting in a level of income, there should be little variation from place to place, and differences should reflect particular geographical characteristics of places. Strong regularities will exist, but the parameters [e.g., number of buildings per capita, square footage per capita, and replacement cost per capita, for each building use category] will differ with culture and over time with income" (Jones 1994).

2. The indirect, macroscopic approach to estimating a city's physical infrastructure exposure is reasonable, supported by theoretical assumptions and by empirical evidence.

Based on these findings, an indirect, macroscopic approach was used to determine the Physical Infrastructure Exposure indicators for the EDRI. Four simple indicators were identified to represent the factor—"population" (X_{E1}), "per capita Gross Domestic Product, in constant 1990 US dollars" (X_{E2}), "number of housing units" (X_{E3}), and "urbanized land area" (X_{E4}). Inclusion of the first two follow the arguments put forth by Jones et al., with "per capita GDP" representing the city's level of technological development and income. The third is added as a direct measure to support the population. The fourth, "urbanized land area," was included on the hypothesis that it indicates the length roads and other lifelines in a city, because a larger area of urbanization requires more extensive lifeline systems to service it.

[3] The term "housing unit" is defined in Section 4.3.2.1.

Recognizing that many indicators of physical infrastructure exposure are well-correlated, and that therefore a principal components analysis might be possible, an analysis was performed to further verify the selection of the four Physical Infrastructure Exposure indicators (see Section 5.3.2 for more about principal components analysis). The analysis was conducted with two separate databases of physical infrastructure information for cities worldwide. The first includes data on ten indicators, for 160 cities[4] in forty-five countries; the second includes data on six indicators, for 76 cities[5] in forty-six countries[6] (Table 4.5). The complete data sets are presented in Appendix D.

Table 4.5. Indicators in the two physical infrastructure exposure data sets

Data Set One *Statistics of World Large Cities* [160 cities in forty-five countries]	Data Set Two *Human Settlements Statistics* [76 cities in forty-six countries]
1. Per capita real Gross Domestic Product of country in which the city is located (PPP$)	1. Per capita real Gross Domestic Product of country in which the city is located (PPP$)
2. Population	2. Population
3. Number of housing units[7]	3. Number of housing units[8]
4. Land area (sq. km.)	4. Total electricity consumption per day (1000 kwh)
5. Total (domestic & industrial) consumption of electric light & power (1000 kwh)	5. Total annual water consumption (1000 m^3)
6. Total (domestic and industrial) gas consumption (1 million kcal)	6. Number of motor vehicles
7. Total (domestic and industrial) water supply (1000 m^3)	

[4] All cities with population over one million people are included in the database.
[5] For each country, the capital city and up to three of the other largest cities were included in the database.
[6] The data are not complete for all cities and indicators, so each regression analysis reported in Tables 4.6 and 4.7 includes only those cities with data for every indicator in that particular regression model. The number of cities used in each regression is listed in the final column of Tables 4.6 and 4.7. All cities are used in the principal components analysis described in Section 5.3.4.1.
[7] The indicator is actually "number of dwellings," but for these purposes, it can be taken as equivalent to the value of the "number of housing units" indicator.
[8] The indicator is actually "number of occupied housing units," but for these purposes, it can taken as equivalent to the value of the "number of housing units" indicator.

8. Length of roads (km)
9. Number of telephone subscriptions
10. Number of establishments

In both data sets, the per capita GDP data is taken from the *Human Development Report 1995* (UNDP 1990-95). Data for the last nine indicators in Data Set One are from *Statistics of World Large Cities 1991* (TMG 1991) published by the Statistical Division of the Tokyo Metropolitan Government; data for the last five indicators in Data Set Two are from the United Nations' *Compendium of Human Settlements Statistics 1995* (UN Centre for Human Settlements 1995). Note that Data Set Two does not contain data for the land area, so the analysis is performed only for the other three indicators (X_{E1}, X_{E2}, X_{E3}) in that case.

Both of the data sets contain a great deal of uncertainty, and the data for different indicators and cities relate to roughly, but not exactly, the same year. Nevertheless, they are the best available data on physical infrastructure exposure *for cities*, and they should suffice to suggest if the four proposed indicators provide a reasonable representation of a city's physical infrastructure exposure. Furthermore, duplicating the analysis with the two, presumably independent data sets, provides additional support for the results of each.

Using these two data sets, an analysis was conducted to determine if the four selected indicators (X_{E1}, X_{E2}, X_{E3}, X_{E4}) do in fact provide a reasonable representation of a city's physical infrastructure exposure. The analysis first assumes that the complete set of indicators (ten for Data Set One; six for Data Set Two) together represent a city's physical infrastructure. Intuitively, each indicator in Table 4.5 should relate to the physical infrastructure. For example, to support a greater level of water, gas, or electricity consumption, there must be more infrastructure to deliver each of those services. Second, the efficiency of the proposed indicators (four for Data Set One; three for Data Set Two) in representing the complete sets of indicators is evaluated by determining the percentage of the total variation of the complete set that the proposed indicators explain. Let the proposed indicators be called the "retained" indicators, and the other indicators (six for Data Set One; three for Data Set Two) be the "discarded" indicators. To carry out this second step, each of the discarded indicators is regressed on the retained indicators, in turn. The percentage of variation of the complete set that is explained by the retained indicators equals:

$$(n_r + \Sigma_i R^2_{i,r})/N, \qquad (4.2)$$

where n_r is the number of retained indicators, $R^2_{i,r}$ is the squared multiple correlation of the *i*th discarded indicator with the r retained indicators, and N is the total number of discarded and retained indicators in the complete set (Dunteman 1989).

Table 4.6. Results of principal components analysis for Data Set One
(*Statistics of World Large Cities*)

	P-values of retained indicators					R^2	Signif-icance F	No. obs.
Discarded indicators	Popu-lation	No. of housing units	Per cap. GDP	Land area	Inter-cept			
Elec. consum.	0.5341	0.0013	0.0044	0.9784	0.8479	0.497	3.43e-08	63
Gas consum.	0.9345	0.5274	0.5912	0.6830	0.0023	0.021	0.9052	52
Water supply	0.5900	0.2609	0.4450	0.6749	0.0012	0.028	0.7971	63
Roads length	0.0098	0.2663	4.01e-05	1.2e-14	7.57e-65	0.804	8.97e-18	57
No. phones	0.6545	0.7170	0.0551	0.5728	0.0568	0.104	0.1336	68
No. establish.	0.0056	6.2e-06	0.9726	0.0462	1.36e-05	0.695	7.28e-11	49
Sum of R^2 values + n_r =						6.149		
Total amount of variation explained by four proposed indicators =						**62%**		

Table 4.7. Results of principal components analysis for Data Set Two
(*Human Settlements Statistics*)

	P-values of retained indicators				R^2	Signif-icance F	No. obs.
Discarded indicators	Popu-lation.	No. hous-ing units	Per capita GDP	Inter-cept			
Elec. consumption	0.0012	4.94e-06	0.4989	0.0008	0.904	6.73e-06	15
Water consump.	0.3858	0.5586	0.9976	0.2524	0.140	0.7353	12
No. motor vehicles	0.0765	0.8757	0.0273	0.2513	0.593	0.0013	21
Sum of R^2 values + n_r =					4.637		
Total amount of variation explained by three proposed indicators =					**77%**		

Tables 4.6 and 4.7 display the results of the analyses conducted for the two data sets. The four proposed indicators (population, number of housing units, per capita GDP, and land

area) explain 62% of the total variation of the complete set of indicators in Data Set One, and the three proposed indicators (population, number of housing units, and per capita GDP) explain 77% of the total variation of the complete set of indicators in Data Set Two. Since the complete sets of indicators are not perfect representations of the physical infrastructure exposure, it is not important that the proposed indicators represent all of the variation in the complete set. In both cases, however, the proposed indicators explain a large enough proportion of the total variation to suggest that they could reasonably represent the complete set of indicators, and therefore, that they could reasonably represent a city's physical infrastructure exposure.

Finally, the P-values indicate which of the retained indicators help explain the variation in each discarded indicator. For each retained indicator, the P-value, or observed significance level, measures the extent to which the data disagrees with the null hypothesis that the β value (weight) associated with that retained indicator should equal zero. The P-value is the probability of observing results that are at least as contradictory of the null hypothesis as those computed from the sample data (McClave and Dietrich 1988). The results in Tables 4.6 and 4.7 suggest that in Data Set One, the retained indicator "population" helps predict "length of roads" and "number of establishments"; "number of housing units" helps predict "electricity consumption" and "number of establishments"; "per capita GDP" helps predict "electricity consumption," "length of roads," and "number of phones"; and "land area" helps predict "length of roads" and "number of establishments." In Data Set Two, "population" helps predict "electricity consumption" and "number of motor vehicles"; "number of housing units" helps predict "electricity consumption"; and "per capita GDP" helps predict "number of motor vehicles." Each of the proposed indicators then is helpful in predicting at least one of the discarded indicators. The results of the two data sets match in that in both cases, the number of housing units relates to electricity consumption, and both population and per capita GDP relate to the transportation network (number of motor vehicles or length of roads). They are inconsistent in that per capita GDP helps predict electricity consumption in Data Set One, but not Data Set

Two; and population helps predict electricity consumption in Data Set Two, but not Data Set One.

Despite the uncertainty associated with each data set in this analysis, the fact that they both independently suggest that the proposed indicators may reasonably represent the physical infrastructure, makes the analyses worthwhile. While the four proposed indicators will not be perfect replacements for doing direct counts of the inventories of every city, the findings of the Jones et al. studies and these principal component analyses suggest that the four proposed indicators do convey roughly the same information as direct counts would, and much more simply.

The "population" and "number of housing units" data for a city will be available from censuses. The EDRI adopts the U.S. Bureau of the Census definition that a "housing unit is a house, an apartment, a mobile home or trailer, a group of rooms or a single room occupied as a separate living quarters or, if vacant, intended for occupancy as separate living quarters"[9] (U.S. Bureau of the Census 1993b). If it is unavailable directly, the "urbanized land area" can be evaluated by estimating the percentage of the total area that is urbanized from a map showing the urbanized area, and multiplying that percentage by the total land area, which is reported in most country censuses and statistical yearbooks.

Finally, a couple of points regarding the indicator "per capita Gross Domestic Product, in constant 1990 US dollars" deserve note. First, taking the USA as an example, Gross Domestic Product (GDP) is defined as the "market value of the final goods and services produced by resources located in the United States" (Johnson 1993). GDP data for a specified country and year is generally reported in terms of the national currency, at the prices corresponding to the specified year. To enable GDP comparison across countries, the values

[9] "Separate living quarters are those in which the occupants live and eat separately from any other persons in the building and which have direct access from outside the building or through a common hall. The occupants may be a single family, one person living along, two or more families living together, or any other group of related or unrelated persons who share living arrangements" (U.S. Bureau of the Census 1993b).

must all be converted to the same currency units using exchange rates or purchasing power parity; and to enable comparisons across years, the values must be converted to constant dollars using GDP deflators. So that comparisons of GDP among countries and over time reflect only the change in volume of output (and not differences in currency or price inflation), the GDP data used in the EDRI is measured in terms of constant 1990 US dollars.[10]

Second, GDP data is almost always calculated only for countries. To find the equivalent of GDP for a city for use in the EDRI, it is assumed that GDP is distributed throughout a country according to population distribution, i.e., that GDP per capita is constant throughout a country and equal to the country GDP divided by the country population. Using GDP and population data collected for regions within several countries, the veracity of this assumption was tested. Figure 4.3 shows the GDP versus population for five countries—China, France, India, Indonesia, and USA. As the figure demonstrates, the assumption seems to hold fairly well, with the notable exception that in some cases the largest cities are responsible for a disproportionate amount of the GDP. For those largest cities then, using the country per capita GDP underestimates the city's per capita GDP. Future refinements of the EDRI may take this observation into account in evaluating the "per capita GDP" indicator.

[10] Several sources exist that should be equally suitable for determining the per capita GDP. However, because of subtle differences in the various sources of GDP data, it is best to calculate the per capita GDP for each city in a consistent way, using data from a single source.

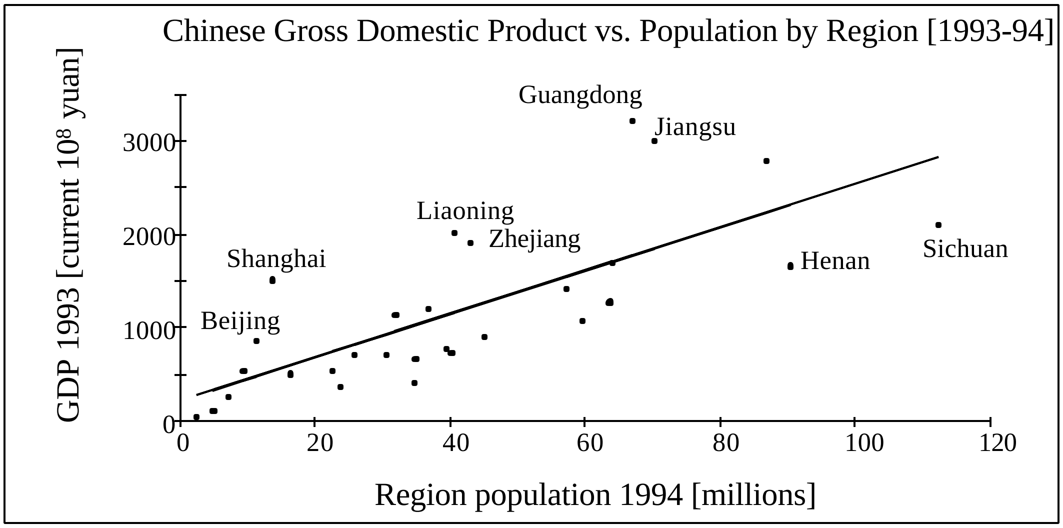


Figure 4.3a. Distribution of GDP in China. Source: People's Republic of China (1995).

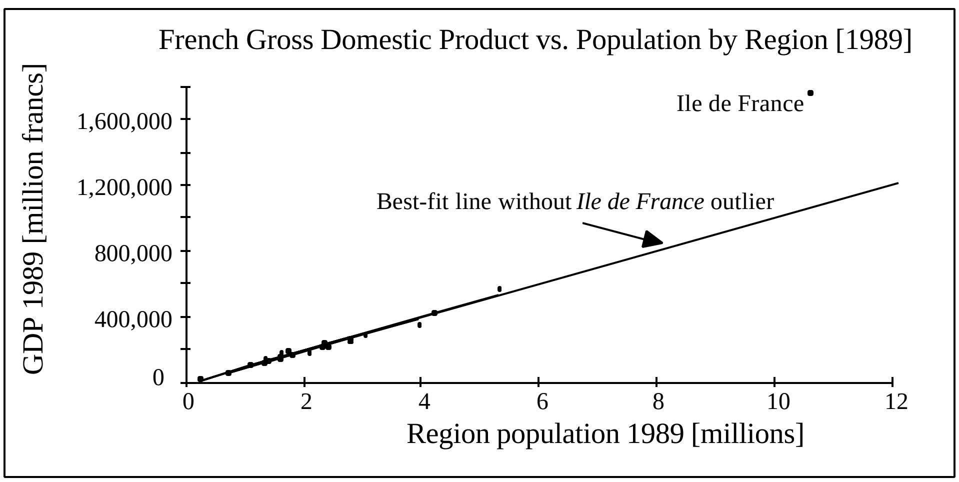


Figure 4.3b. Distribution of GDP in France. Source: INSEE (1990).

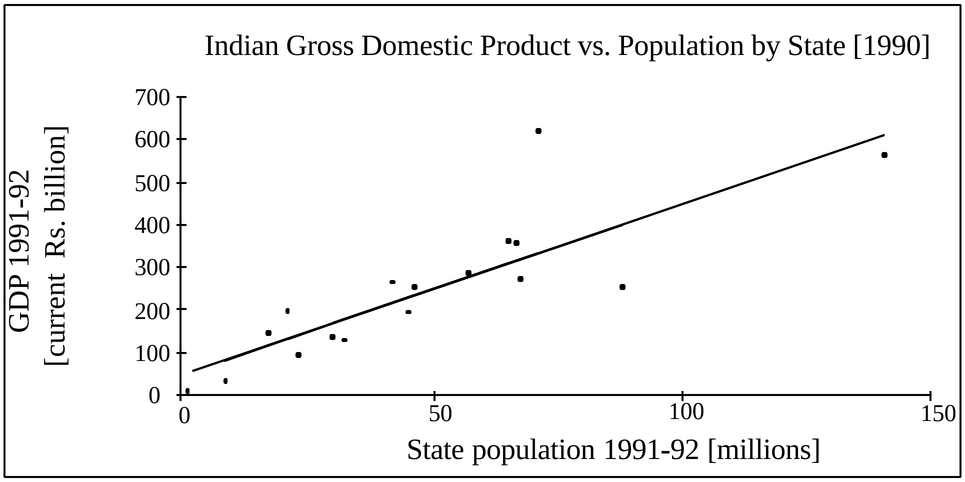


Figure 4.3c. Distribution of GDP in India. Source: EIU (1995).

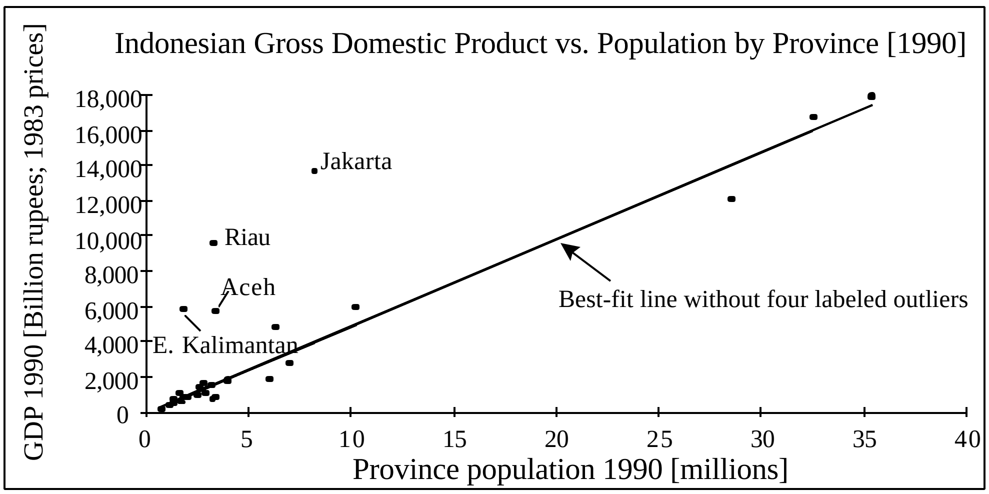


Figure 4.3d. Distribution of GDP in Indonesia. Source: EIU (1996).

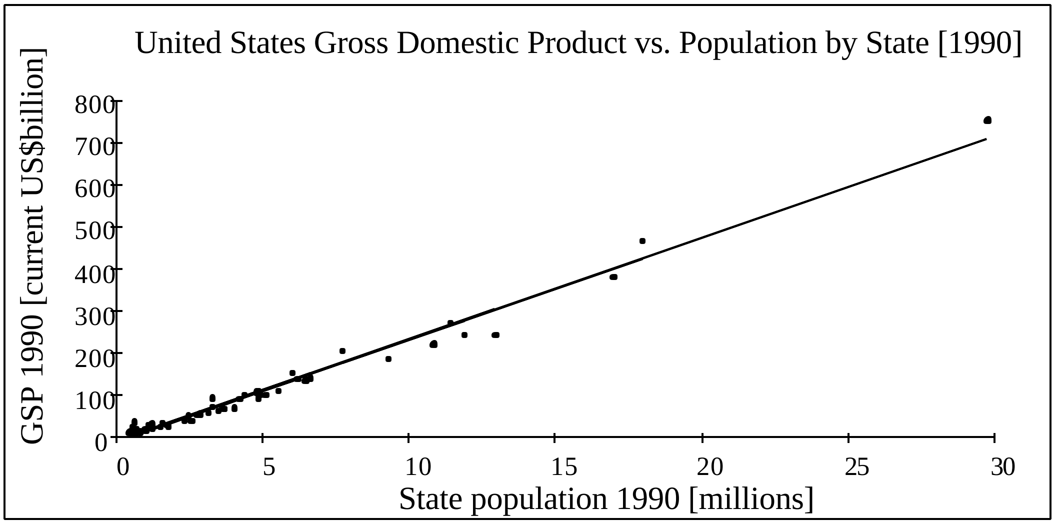


Figure 4.3e. Distribution of GDP in the USA. Source: U.S. Bureau of the Census (1995).

The Physical Infrastructure Exposure indicators do not convey any information about the within-city geographical distribution or volume of use of the various infrastructure components.

4.3.2.2. Population Exposure

Population Exposure is the most straightforward factor to represent in the EDRI. The ideal, direct measure of population exposure, i.e., "population" (X_{E5}), is readily available in censuses, so the indicator selection requires no simplification or justification. Using only "population" to represent Population Exposure, however, does not convey any information about the distribution of the population within the city, or the breakdown of different, particularly vulnerable groups within the city. The percentage of the population that belongs to each group is included instead in the Vulnerability section (see Section 4.3.3.2).

4.3.2.3. Economy Exposure

In Section 3.3.2.3., Economy Exposure was defined as the volume of the economic flow of goods, services, and money that are transacted within a city. The indicator "per capita Gross Domestic Product, in constant 1990 US dollars" (X_{E6}) provides the best representation of the volume of that economic flow. Another economic indicator that could be considered is "per capita Gross National Product." The difference between the two is explained as follows, considering the USA as an example. GNP "relates to production by labor and other factor supplied by residents of the United States. Thus, the income earned by American residents on their investments in other countries is included in the gross national product." GDP relates to "production by factors physically located in the United States, no matter who owns them" (Johnson 1993). Since the EDRI is concerned with the economic flows that could be disrupted by direct physical damage, GDP seems the more appropriate quantity. Furthermore, the Bureau of Economic Analysis has been changing the emphasis from GNP to GDP since 1991 (Johnson 1993). Of course, the discussion in Section 4.3.2.1 about calculating "per capita Gross Domestic Product, in constant 1990 US dollars" holds for X_{E6} too.

4.3.3. Vulnerability factor

The Physical Infrastructure Vulnerability factor is represented by the first five indicators listed below; Population Vulnerability by the last indicator.

1. $\mathbf{X_{V1}}$: Seismic code indicator
2. $\mathbf{X_{V2}}$: City wealth indicator
3. $\mathbf{X_{V3}}$: City age indicator
4. $\mathbf{X_{V4}}$: Population density (people per square kilometer)
5. $\mathbf{X_{V5}}$: City development speed indicator
6. $\mathbf{X_{V6}}$: Percentage of population aged 0-4 or 65+

Economy and Social-Political Vulnerability are not represented because indicators that reflect those concepts could not be identified. If Jones' assessments of the relative vulnerability of the extractive, fabricative, distributive, and service sectors of the economy are assumed to be correct (see Section 3.3.3.3), a possible method for representing Economy Vulnerability would be to determine the percentage of each city's GDP associated with each of those four sectors, and conclude that those cities with a larger share of the economy in more vulnerable sectors have a more vulnerable economy. Unfortunately, while GDP data are often reported by sector share, those data are available only for countries, not metropolitan areas, and it would be inappropriate to assume that the structure of a city's economy would be the same as that of the country in which it is located. In general, indirect economic losses are difficult to assess even after an earthquake occurs (much less to estimate before an earthquake) because the indirect effects are often shifted to other regions or generations, because the in-built mechanisms that immediately go to work to reestablish equilibrium in the economy hide the indirect effects, and because it is impossible to know how the economy would behave without the occurrence of the disaster, and assessment of indirect effects requires a comparison of the economy with and without (not before and after) the earthquake.

4.3.3.1. Physical Infrastructure Vulnerability

Section 3.3.3.1. discusses two methods by which the Physical Infrastructure Vulnerability factor could be assessed—an indirect, macroscopic approach based on the circumstances of a city's development, and a direct, microscopic one based on structural analysis principles. The Physical Infrastructure Vulnerability indicators in the sample analysis were selected using the former method because of its simplicity. The characteristics of a city's development that generally influence the vulnerability of the infrastructure were identified, and an indicator was derived to represent each. They are discussed in turn below. The characteristics include knowledge of how to reduce vulnerability (X_{V1}), financial resources to reduce vulnerability (X_{V2}), recentness of development to reduce effects of aging (X_{V3}), ample space to accommodate population growth so that the infrastructure is not too dense, and there is room for lifeline redundancy (X_{V4}), and ample time to construct the infrastructure in a quality-controlled way (X_{V5}). Although the infrastructure is the real quantity of interest, since population data are more easily available, all five Physical Infrastructure Vulnerability indicators use population data instead of physical infrastructure data, relying on the assumption that infrastructure construction coincides with population growth.

The "seismic code indicator" (X_{V1}) conveys an awareness of the problem of earthquake risk at the time the infrastructure is built, a desire to address the problem (i.e., a perception that the risk is unacceptably severe in the context of the other challenges the city faces), and the existence of the knowledge of how to reduce the vulnerability. It demonstrates if a city has the organizations and individuals to create, enact, and enforce effective seismic codes, and when the codes were developed in relation to the development of the city.

The "seismic code indicator" can be calculated following a five-step process. First, identify the benchmark years in which significant changes in the quality of the city's seismic code took place. Second, assess the sophistication of the seismic code during each inter-benchmark period according to the Sophistication Rating Scale in Table 4.8. Third, determine the percentage of the current city population that arrived in each inter-benchmark period. Fourth, rate the quality of code enforcement in the city using the Enforcement Rating Scale in Table 4.9. Fifth, evaluate the seismic code indicator using the following expression:

$$X_{V1} = e*[\Sigma_k(s_k)*(p_k)], \qquad (4.4)$$

where e is the enforcement rating, s_k is the sophistication rating for inter-benchmark period k, p_k is the percentage of the current population that arrived in inter-benchmark period k, and the summation is over all inter-benchmark periods k. The summation is essentially a weighted average of the sophistication of each inter-benchmark period, where the weights are the percentages of the current infrastructure built (or population arrived) during each period.

Table 4.8. Seismic code sophistication rating scale

Sophistication level s_k	Category description
0.1	No regulations.
0.3	Only requirement is to limit the base shear to an arbitrary constant

	percentage of building weight. Not based on theory.
0.5	Includes a base shear equation with coefficients to account for some, but not all of the following: soil type, building period, seismic zone, importance of the structure, and ductility of the structural type.
0.8	Includes some, but not all of the basic components* of a seismic code.
0.9	Includes all of the basic components of a seismic code.
1.0	Refined version of a seismic code with all the basic components.

* Basic components include: (1) provisions for static and dynamic design methods; (2) an equation to calculate the base shear; (3) coefficients in the base shear equation to account for soil type, building period, seismic zone, importance of the structure, and ductility of the structural type; (4) a method to distribute forces along the height of structure; (5) provisions for addressing torsion; (6) provisions for addressing irregularities in plan or elevation; (7) method to address inter-story and total drift; (8) special provisions for essential facilities; and (9) provisions for detailing.

Table 4.9. Seismic code enforcement rating scale

Enforcement level e	Category description
0.2	Poor
0.4	Below average
0.6	Average
0.8	Above average
1.0	Excellent

The seismic code indicator evaluation includes a great deal of subjective assessment because there is no purely quantitative, objective way available to include this essential information about the seismic code development. Because the subjective enforcement rating value will control the seismic code indicator values, it may seem unnecessary to require so much detail in calculating the benchmark periods, and the values of s_k and p_k. Nevertheless, the formulation is defined as it is for conceptual completeness, addressing the timing and quality of the development of seismic codes, as well as the degree of their enforcement. The specific values in the Sophistication and Enforcement Rating Scales were determined by calibrating the final seismic code indicator values for the ten sample analysis cities so that the results appear reasonable. Appendix E illustrates the calculation of the "seismic code indicator" for the sample analysis.

The "city wealth indicator" (X_{V2}) conveys the availability of resources in the city to develop, implement, and enforce both a general building code and a seismic code. It relates to a city's general quality of design and construction. The "city wealth indicator" equals the average gross domestic investment (GDI) per capita per year in constant 1987 US dollars. GDI is one of the four main components of GDP (along with personal consumption expenditures, net exports, and government purchases). Also known as gross fixed capital formation (GFCF), GDI "measures the outlays for the addition of reproducible capital goods to the fixed assets of private and public enterprises, private nonprofit institutions, and general government (reduced by their net sales of used or scrapped capital goods) and the value of the net increase or decrease in inventories" (World Bank 1980). Since there is no exact year in which a city begins, and data certainly would not be available for so long ago anyway, a historical time period had to be established over which the average would be taken. Using the time period from the present back to the year in which the city had one-half of its current population makes the number of years averaged different for each city, but makes the percentage of the total existing infrastructure built with that GDI consistent among cities.

The "city age indicator" (X_{V3}) represents the extent to which the effects of aging have increased the vulnerability of the physical infrastructure. It is defined as a weighted average of the age of the population:

$$X_{V3} = \Sigma_i(p_i)*(a_i), \tag{4.5}$$

where p_i is the percentage of the current population that arrived in year i, a_i is the age of the population that arrived in year i (i.e., current year - year i), and the summation is over all the years from the year in which the population was one-half of its current level to the current year.

Cities require ample physical space to accommodate population growth so that the infrastructure is not too dense, and so that there is room for lifeline redundancy. When a city's development becomes too dense, more vulnerable areas (e.g., those with steep slopes or artificial fill) are more likely to be occupied. The "population density" indicator (X_{V4}) represents the extent to which a city has had adequate space to develop. It is exactly the same quantity as X_{H6}, and is evaluated in the same way.

In many rapidly expanding cities in developing countries, the population growth is occurring so quickly that a quality, low vulnerability infrastructure cannot be developed fast enough to support the new residents. The "city development speed indicator" (X_{V5}) conveys whether or not the city has been developed with ample time to construct the infrastructure in a quality-controlled way. It is defined as the number of years that have passed since the city population was one-half of its current level.

Collectively, the five indicators (X_{V1} to X_{V5}) offer an assessment of the Physical Infrastructure Vulnerability factor. These assessments were validated using results obtained with the loss estimation modeling approach to physical infrastructure vulnerability assessment. Risk Management Solutions, Inc. developed aggregate damage curves for many regions throughout the world (RMS 1996-97). Each curve is a weighted average of the damage curves for the individual infrastructure components, with the weights equal to the proportion of the total infrastructure in the region that is composed of the corresponding type of infrastructure component. The curves are expressed as the mean damage ratio (MDR) versus MMI. To compare the damage curves to the five-indicator EDRI assessments, two points were selected from each curve—MDRs corresponding to MMI values of VII and XI (Fig. 4.4), the two MDRs were scaled[11], and the average of the scaled values were taken as the loss estimation modeling assessment of physical infrastructure vulnerability. As shown in Fig. 4.5 and Table 4.10, the two methods—EDRI and loss estimation modeling—produce reasonably similar results for a sample of seven cities. The Spearman rank correlation coefficient[12] for the two

[11] The MDR values were scaled in the same way as the EDRI indicators (see Section 5.2.7).
[12] Spearman's rank correlation coefficient (r_s) measures the correlation between two sets of ranks. The following formula is used to evaluate the Spearman coefficient when there are no ties in the ranks:

$$r_s = 1 - \left[\frac{6\sum_i (u_i - v_i)^2}{n(n^2-1)} \right]$$

methods is 0.75, suggesting reasonable, but not perfect correlation between the results of the two methods for this small sample.

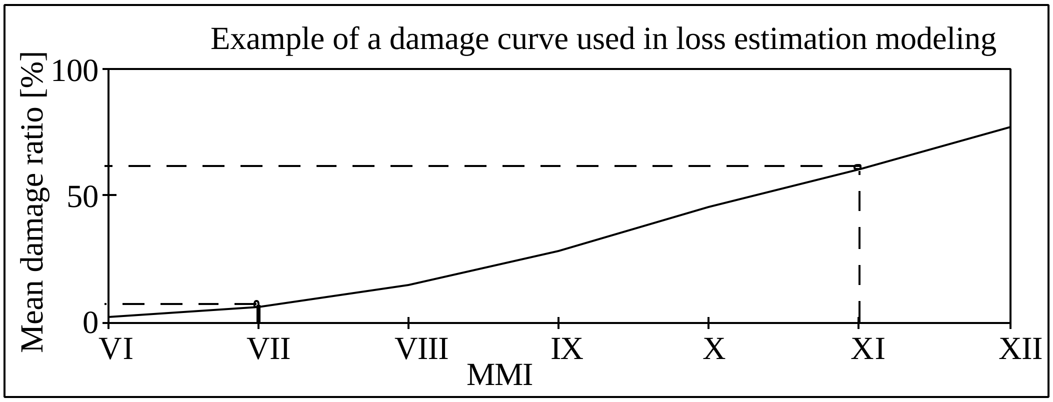


Figure 4.4. Example of a loss estimation model damage curve

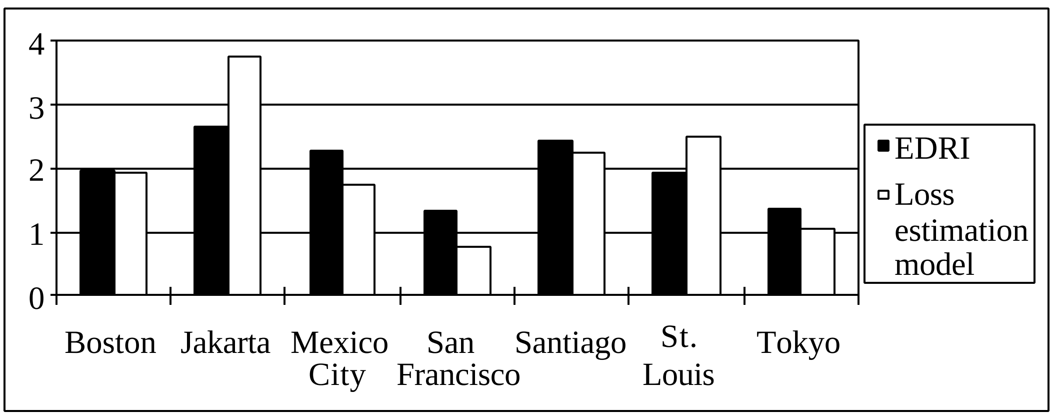


Figure 4.5. Comparison of the Physical Infrastructure Vulnerability factor assessment using EDRI and loss estimation models

Table 4.10. Comparison of two methods for Physical Infrastructure Vulnerability factor assessment

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where u_i and v_i are the ranks of the *i*th observation in samples 1 and 2, respectively, and n is the number of pairs of observations (number of observations in each sample).

	Scaled values		Ranks		Squared differences
City	EDRI	Loss estimation model	EDRI	Loss estimation	
Boston	1.97	1.94	4	4	0
Jakarta	2.66	3.76	1	1	0
Mexico City	2.28	1.75	3	5	4
San Francisco	1.34	0.77	7	7	0
Santiago	2.44	2.24	2	3	1
St. Louis	1.94	2.48	5	2	9
Tokyo	1.37	1.06	6	6	0

Spearman rank correlation coefficient = 0.75

The five physical infrastructure vulnerability indicators (X_{V1} to X_{V5}) together represent the key characteristics of a city's development that affect the vulnerability of its infrastructure. Because each characteristic is explicit and separate, each component easily could be improved as further study supports or contradicts the assumptions on which these sample analysis indicators are based. The representation of Physical Infrastructure Vulnerability embodied by these indicators has the advantage of relatively simple data requirements, compared to the alternative loss estimation modeling approach that relies on assessing the exposure and developing fragility curves for each component of the infrastructure individually.

The approach does suffer from a few disadvantages. The indicators are not as objective as would be ideal. The indirect approach is based on the assumption that the identified characteristics of a city's development do in fact determine the vulnerability of the city's physical infrastructure. Ideally, the vulnerability indicators would depend on a city's hazard. The structural requirements should not necessarily be the same in different cities, but they should be consistent with the city's level of hazard. It is inappropriate for a city with low hazard to have a seismic code as strict as that for a city with high hazard.

Finally, there are a few aspects of the Vulnerability factor that are not represented by the sample analysis vulnerability indicators. Maintenance, previous damage, and retrofitting can affect the vulnerability of the physical infrastructure, but because there are no good indicators available to represent them, and they are probably relatively insignificant compared to the other determinants, they are not included. Vulnerability to nonstructural and content damage are not represented, because there is little data or theory to determine how these ideas could be included, or if they would vary significantly from city to city. No indication of the redundancy of the city's lifeline networks is included either, because no consistent, city-level data is available on the length of pipelines or other lifelines.

4.3.3.2. Population Vulnerability

Population vulnerability can exist in three forms: physical, economic, and social. The "percentage of population aged 0-4 or 65+" indicator (X_{V6}) is a direct measure of one type of physical Population Vulnerability. It conveys the number of residents who may be less able to escape from a collapsing structure, recover from an injury, or survive in a post-earthquake atmosphere of hardship because they are very young or very old. The threshold ages of five-years-old and sixty-five-years-old were chosen both because they are reasonable estimates of the ages at which people become more vulnerable, and because census data is generally reported for the age groups defined by those cutoffs.[13] Theoretically, similar indicators could be used to capture other types of population vulnerability, e.g., percentage of the population that is sick, disabled, poor, homeless, or disenfranchised. Those indicators were not included in the sample analysis because of the difficulty in defining and obtaining data for the other potentially vulnerable groups. A value judgment is required to determine which, if any, minority groups are more vulnerable, and the groups will not be the same from city to city.

4.3.4. External Context factor

[13] The age thresholds appropriate for this indicator may vary regionally, because life expectancies are not uniform across cultures and regions. Sixty-five may be too young for industrialized cities.

Three indicators convey the External Context factor in the sample analysis. The first represents the Economic External Context; the last two represent the Political External Context. They are:

1. $\mathbf{X_{C1}}$: Economic external context indicator
2. $\mathbf{X_{C2}}$: Political country external context indicator
3. $\mathbf{X_{C3}}$: Political world external context indicator

Transportation and Cultural External Context are not included explicitly because of the difficulty in finding appropriate indicators. An accurate measure of transportation external context would have to include all modes of transportation, because the relative predominance of different modes varies considerably from city to city. One city may be a major port, but have little rail traffic, while another might be a rail hub, but have no port. To compare the transportation external context of these two cities, both rail and water would have to be assessed. Although some transportation data exist, particularly for travel through airports and ports, it would be difficult to address all modes consistently. Nevertheless, the information conveyed in the three indicators listed above should be sufficient to convey the relative external context ratings of different cities because in general, any major transportation hub or cultural center will exhibit a high economic and/or political external context rating also. Appendix F shows the values for the external context indicators (X_{C1}, X_{C2}, and X_{C3}) for a set of 319 cities.

4.3.4.1. Economic External Context

The "economic external context indicator" (X_{C1}) is calculated according to the following equation:

$$X_{C1} = (TFT) * (Pop_{country}) * (\frac{Pop_{city}}{Pop_{country}}) * (\frac{Pop_{city}}{Pop_{largest\ city}}) \qquad (4.6)$$

where TFT is the total foreign trade between the country in which the city is located and other countries, Pop_{city}, $Pop_{country}$, and $Pop_{largest\ city}$ are the population of the city of interest, of the country in which the city is located, and of the largest city in that country, respectively. TFT is the sum of the absolute values of a country's current account credits and debits, capital account credits and debits, and financial accounts assets and liabilities in US$millions (see IMF 1995 for more information). The first two terms of the expression for X_{C1} convey the economic importance of the country to the world—a function of the amount of economic exchange between the country and others, and of the size of the country, measured in terms of population. The last two terms convey the importance of the city to its country. Assuming a constant economic importance per capita throughout the country, the first two terms must be multiplied by the ratio of $Pop_{city}/Pop_{country}$ to determine the economic external context associated with the city alone. Finally, since the economic importance per capita will probably be higher in the largest cities in the country, particularly if there are only one or two principal cities (see Fig. 4.3), the final factor is included to increase the relative X_{C1} value for a country's primary cities. The reason for adopting this country-to-world, and city-to-country approach is that economic exchange data is widely available for exchange between countries, but virtually nonexistent for inter-city exchange.

4.3.4.2. Political External Context

The "political country external context indicator" (X_{C2}) represents the political power of the city in its country. Assuming that quantity depends largely on how many people are governed by the city, X_{C2} is defined as:

$$X_{C2} = \left(\frac{Pop_{political\ region}}{Pop_{country}}\right) \qquad (4.7)$$

where $Pop_{political\ region}$ and $Pop_{country}$ are the population of the largest region of which the city is a political capital, and the population of the country in which the city is located, respectively. $Pop_{political\ region}$ is defined so that $Pop_{city} \leq Pop_{political\ region} \leq Pop_{country}$. Note that X_{C2} equals one for all country capitals, because, without exploring the differences due to the type of government, all country capitals are equally important *to the people in their country*. That is, San Jose is as important to the people of Costa Rica as Washington D.C. is to the people of the USA. If the city is not a capital of any state or country, $X_{C2} = Pop_{city}/Pop_{country}$.

To distinguish among the country capitals, the indicator "political world external context indicator" (X_{C3}) is included, conveying the relative political power of cities on the world stage. Assuming that wealthier country capitals will control more political power than poorer ones, X_{C3} is defined as:

$$X_{C3} = (\text{per capita GDP})*(Pop_{\text{political region}}), \qquad (4.8)$$

where per capita GDP is the "per capita Gross Domestic Product, in constant 1990 US dollars," the same quantity as indicators X_{E2} and X_{E6}, and $Pop_{\text{political region}}$ is defined as above. Equivalently, X_{C3} equals the GDP associated with the largest region of which the city is the political capital.

The political external context indicators do not convey any information about the type of government, and they assume that the nominal political capital controls all the political power. As mentioned in Section 3.3.4.3, this is not always the case.

4.3.5. Emergency Response and Recovery Capability factor

The sample analysis uses the following nine indicators to capture a city's Emergency Response and Recovery Capability:

1. $\mathbf{X_{R1}}$: Planning indicator
2. $\mathbf{X_{R2}}$: Per capita Gross Domestic Product, in constant 1990 US dollars
3. $\mathbf{X_{R3}}$: Average annual real growth in per capita GDP during previous ten years
4. $\mathbf{X_{R4}}$: Housing vacancy rate
5. $\mathbf{X_{R5}}$: Number of hospitals per 100,000 residents
6. $\mathbf{X_{R6}}$: Number of physicians per 100,000 residents

7. $\mathbf{X_{R7}}$: Extreme weather indicator
8. $\mathbf{X_{R8}}$: Population density (people per square kilometer)
9. $\mathbf{X_{R9}}$: City layout indicator

The first one represents the planning component of Emergency Response and Recovery Capability; the next five, the resources component; and the last three, the mobility and access.

4.3.5.1. Planning

"Years since the first emergency response plan was developed" or "number of revisions to the emergency plan" are possible quantitative indicators of planning. Neither, however, convey any of the crucial information about how comprehensive the plan is and how effectively it will be used in the event of an earthquake. The "planning indicator" (X_{R1}) was developed to provide a more comprehensive representation of emergency response and recovery planning. The three values of the "planning indicator" are defined in Table 4.11.

Table 4.11. Planning indicator definition

Planning level X_{R1}	Category description
1	Minimal. Planning is inadequate AND inactive.
3	Good. Planning is inadequate OR inactive.
4	Excellent. Planning is adequate AND active.

In Table 4.11, "adequate" means that the city's planning situation meets six or more of the following criteria: (1) is organizational, i.e., establishes the roles and responsibilities of all involved parties;, (2) is operational, i.e., includes procedures to explain what to do, how, and when; (3) addresses all main aspects of emergency response and recovery, i.e., emergency management system, communications, financial arrangements, legislation, damage assessment, search-and-rescue, secondary hazard control, health care, mass care, shelter, clean-up, restoration of services (see Section 3.3.5); (4) exists for the region as a whole, for local governments, and/or for specific organizations and institutions;

(5) includes a revision completed within the last ten years; (6) addresses earthquake hazard specifically; (7) addresses particular characteristics of local context; (8) is well-integrated (a) through hierarchical levels, (b) across agencies, organizations, and departments, and (c) with daily operations and on-going development goals; (9) is based on the city's actual experience in a major event in the last twenty years. "Active" means that at least one of the following is true: (1) plan(s) is practiced regularly through training exercises; (2) plan(s) has been used in a real event in the last twenty years; (3) all involved parties are familiar with the contents of the plan(s) and are trained in its use.

The "planning indicator" can be evaluated most accurately through consultation with a city's local planning experts. Although its evaluation requires a subjective assessment and allows only three possible values, the "planning indicator" offers a level of comprehensiveness not possible with available completely objective indicators.

4.3.5.2. Resources Available Post-earthquake

The indicators "per capita Gross Domestic Product, in constant 1990 US dollars" (X_{R2}) and "average annual real growth in per capita GDP during previous ten years" (X_{R3}) represent the overall financial resources available for post-earthquake emergency response and recovery. Rather than estimating the actual value of available resources from each possible source (e.g., local and national government, earthquake insurance, private savings) and summing them, X_{R2} and X_{R3} simply convey how well the city's economy is doing in general, and assume that that information reflects the city's ability to finance an emergency response and recovery effort. As discussed in Section 4.3.2.3, "per capita GDP" is the best available representation of a city's economic power. "Average annual growth rate" is added to convey the economy's recent performance. It indicates whether the economy is currently growing or shrinking. An economy that has been shrinking in recent years will have become lean, and thus will be in a worse position to finance response and recovery than an economy that has been growing in recent years. "Per capita Gross Domestic Product, in constant 1990 US dollars" is calculated just as in X_{E2} and X_{E6}. To calculate "average annual real growth in per capita GDP during previous ten years," compute the annual change in per capita GDP for each of the previous ten years, and take the average of those ten values.

To evaluate the equipment and facility resources available for emergency response and recovery directly, it would be necessary to count the number of each type of equipment and facility that could be useful. The sample analysis addresses only two types of equipment and facility resources—housing and hospitals. The "housing vacancy rate" (X_{R4}) conveys the availability of the first; "number of hospitals per 100,000 residents" (X_{R5}), the second. Several experts (e.g., Comerio 1996; West 1996; and Eisner 1996) have indicated the importance of the housing vacancy rate at the time of an earthquake in helping to determine the city's emergency response and recovery capability.
The values of X_{R4} and X_{R5} can be estimated from censuses and country statistical yearbook data, but care should be taken to ensure that both public and private hospitals are included, since they may be tabulated by different organizations and reported separately. Data concerning other equipment and facilities may not be as easily or consistently available.

As with equipment and facilities, there are many types of trained manpower that could be counted, but only one is included in the sample analysis—physicians. The possibility of including the number of firefighters and police officers was explored as well, but the data were too fragmented to be included (see discussion Section 6.1). Data on the "number of physicians per 100,000 residents" (X_{R6}) are generally reported together with the hospital data.

The resource indicators (X_{R2} to X_{R6}) convey information about some of the resources necessary for an emergency response and recovery effort, but neglect many other types of resources. Financial resources from specific sources (e.g., insurance coverage for individual homeowners or businesses, residents' personal savings, businesses, relief organizations like the Red Cross, or foreign sources) are not included explicitly. No equipment resources (e.g., mobile homes for temporary housing, search-and-rescue equipment), no facility resources other than hospitals and housing (e.g., police and fire stations, health centers), and no trained manpower resources other than physicians (e.g., police officers, firefighters, nurses) are represented directly. Another omission from the set of resource indicators is that they do not address the availability of potential resources. Hospitals will be valuable resources if they are functional following an earthquake, and thus are able to treat the injured. However, if a hospital is damaged, it may not only forfeit its role as a resource, but instead become a liability. Finally, resources do not necessarily have to be local, and the sample analysis resource indicators do not indicate if a city will be able to acquire the necessary resources from outside sources.

4.3.5.3. Mobility and Access Post-earthquake

The degree of damage to the physical infrastructure will greatly influence the mobility within a city and access to a city following an earthquake. The vulnerability indicators convey this aspect of the Mobility and Access factor. Other determinants of post-earthquake mobility and access are represented by the last three emergency response and recovery indicators (X_{R7} to X_{R9}).

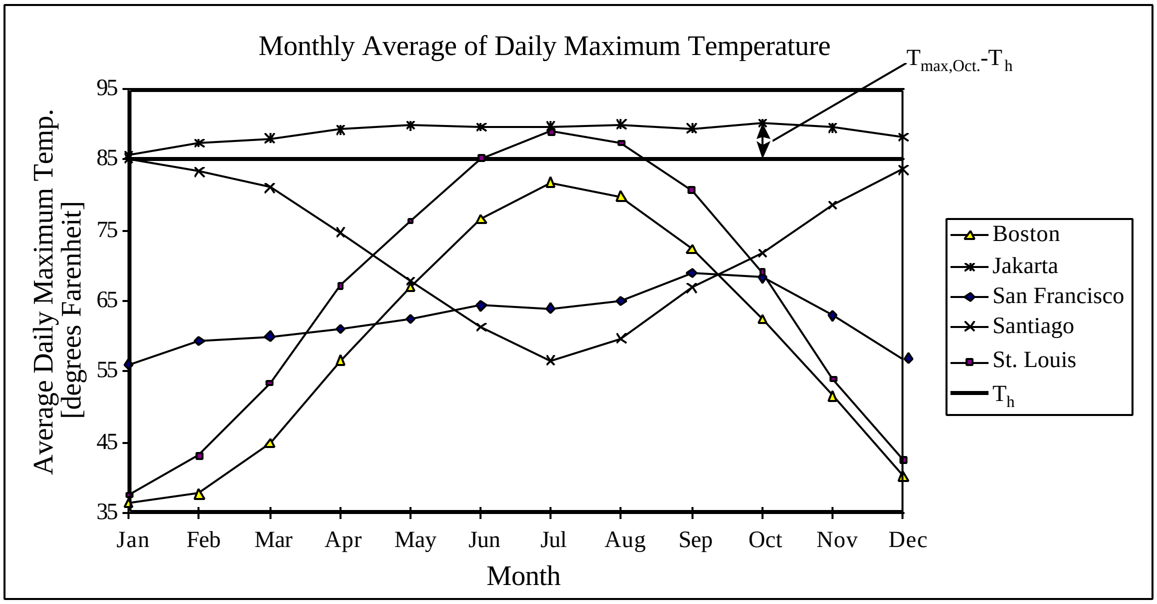
The "extreme weather indicator" (X_{R7}) represents the potential for severe post-earthquake weather (i.e., extreme hot or cold) to impede a response effort, and to increase the hardship for victims who are left homeless. Originally, X_{R7} was going to be defined using a direct measure of the likelihood of severe weather, the average number of days per year in which the temperature either reached at least 90°F or dropped to 32°F or below. Unfortunately, those data are not reported regularly for most cities outside of the USA. However, the National Climatic Data Center does compile and report the monthly average of daily minimum and maximum temperatures for all major cities (NCDC 1997). The "extreme weather indicator" was defined so that it is a function of the available data, but is well-correlated with the more direct measure that was originally proposed. The following expression defines the "extreme weather indicator":

$$X_{R7} = \sum_{m=Jan.}^{Dec.} (T_{max,m} - T_h) + \sum_{m=Jan.}^{Dec.} (T_c - T_{min,\,m}), \tag{4.9}$$

where $T_{max,m}$ and $T_{min,m}$ are the average daily maximum and minimum temperatures in month m, respectively; and T_h and T_c are the hot and cold threshold temperature constants, 85°F and 50°F, respectively. The quantities $(T_{max,m} - T_h)$ and $(T_c - T_{min,\,m})$ are displayed graphically in Figure 4.6. Using data for twenty-six U.S. cities, the values of T_h and T_c were determined to achieve the highest possible correlation coefficient (ρ=0.892) between X_{R7} and the average number of days per year in which the maximum temperature is at least 90°F or the minimum temperature is no more than 32°F.

"Population density" (X_{R8}) represents the idea that a densely populated city suffers from congestion in the transportation network, congestion that could impede the ability of emergency response workers to transport victims and resources through the city. The indicator X_{R8} is evaluated exactly the same way that X_{H6} and X_{V4} are.

A natural feature, such as a bay or mountains may control the physical spread of a city, resulting in an irregularly shaped city plan. Such an irregular shape may make it more difficult to move within a city. For example, the effort of response workers in the greater San Francisco metropolitan area, which surrounds a bay, would be hindered by the difficulty in crossing the bay as they move from one neighborhood to another. The "city layout indicator" (X_{R9}) conveys whether or not a city's emergency response and recovery effort might be made more difficult by this circumstance. It is evaluated as a simple binary function: $X_{R9} = 1$ if a city exhibits such an irregular layout, otherwise $X_{R9} = 0$. These three indicators do not represent possible effects of the city topography or remoteness from other cities on post-earthquake mobility and access.



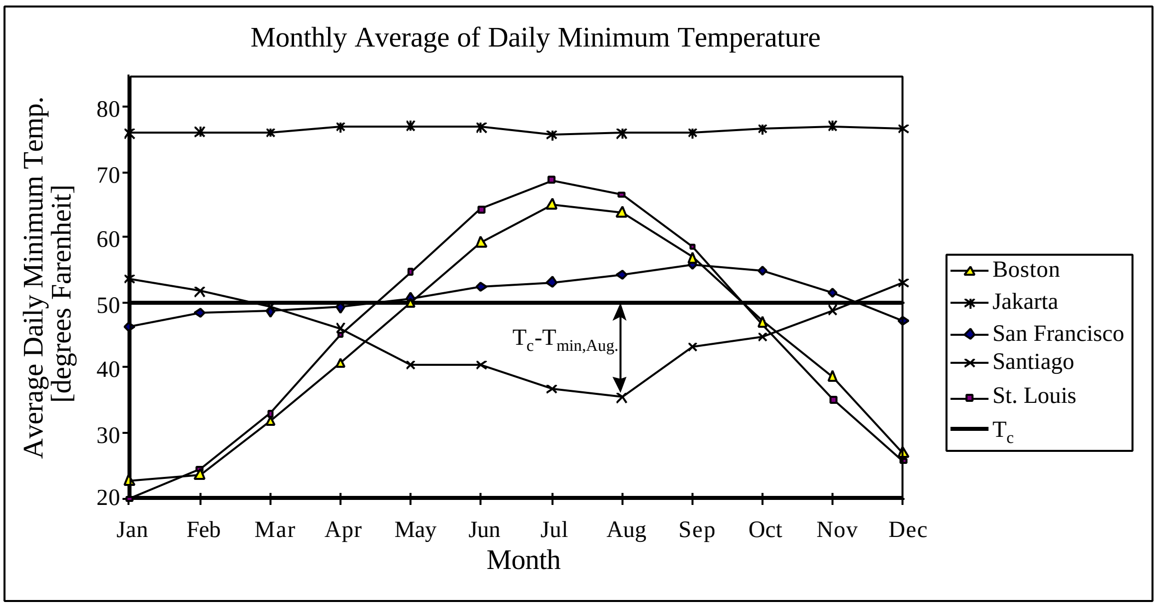


Figure 4.6. Graphical representation of "extreme weather indicator."
Sources: Ruffner and Bair (1987) and NCDC (1997).

Chapter Five
Mathematical Combination

5. Introduction

Once all the indicators that will be included in the Earthquake Disaster Risk Index have been selected, they must be combined mathematically to create the composite EDRI. Table 5.1 shows a schematic example of a table of indicator values for a sample of cities. The EDRI relies on the assumption that comparing the set of values associated with City A to those associated with City B should convey some information about the relative earthquake disaster risk of the two cities. The task of the mathematical combination is to combine the set of values for each city into a single number that captures this information. Determining the method of combination constitutes the last step in defining the term *earthquake disaster risk*. Section 2.1 defined earthquake disaster risk by identifying the factors that contribute to it. To understand the concept more fully, the way the factors interact and their relative importance must be established as well. This information is incorporated into the EDRI through the method by which the indicators are mathematically combined.

To convey information about the determinants of earthquake disaster risk for each city, separate composite indexes are calculated for the five main factors that contribute to the risk—Hazard, Exposure, Vulnerability, External Context, and Emergency Response and Recovery Capability. All the indicators that relate to Hazard are combined into the Hazard index, all the indicators that relate to Exposure are combined into the Exposure index, and likewise for the other three factors. The EDRI is a composite index of the five

Table 5.1. Schematic indicator-city table

Indicator	Cities				
	A	B	. . . j . . .	Y	Z
Ind. 1 Ind. 2 ⋮ Ind. i ⋮ Ind. n	*City A values*	*City B values*	x_{ij}	*City Y values*	*City Z values*
EDRI	$EDRI_A$	$EDRI_B$		$EDRI_Y$	$EDRI_Z$

main factor indexes. The following discussion of methods of combination relates to the construction of the five main factor indexes, as well as the EDRI. Every reference to combining indicators into the factor indexes applies equally to the combination of factors into the EDRI, and vice versa.

This chapter explores the many options for combination that were considered, explaining the advantages and disadvantages of each alternative, presenting the method that was ultimately selected for the sample analysis, and demonstrating the reasoning behind the choice. Four general approaches are considered: no combination, graphical methods, nonlinear combination, and linear combination. Once it is established that the sample analysis EDRI will be a linear combination, several alternative ways to perform each of the two main steps in creating a linear combination—scaling and weighting—are explored. Finally, the chapter summarizes the mathematical equations needed to evaluate the EDRI.

The method of combination chosen for the sample analysis represents one reasonable approach. There are other possibilities that are equally correct mathematically, and there is no way to prove that one method is better than another. Instead, the criteria by which the method of combination will be judged must be explicitly established up front. Then the final approach can be selected from the alternatives based on its ability to meet those criteria. The method of mathematical combination should:

1. Be able to achieve the goals of the EDRI, i.e.,
   (a) Convey the relative overall earthquake disaster risk (as defined in Section 2.1) at a point in time.
   (b) Convey the relative contribution[1] of each component factor to a city's overall earthquake disaster risk.
   (c) Convey the change in a city's relative overall earthquake disaster risk over time.
   (d) Be straightforward to develop, evaluate, and interpret.
2. Not require measuring earthquake disaster risk directly.
3. Not be sensitive to the values of just a few cities or indicators.
4. Be objective to the extent possible.

Ideally, the method of combination would not be sample-specific either, i.e., it would not require a sample of data, and it would not produce a different index if a different sample of data was used. Sample-specificity presents a disadvantage because it increases sensitivity to data quality and sample city selection, restricts the generality of the final index, requires that the entire analysis be repeated if a new city is added to the sample, and requires adjustments to track the EDRI over time. In the case of the EDRI, however, these disadvantages are not prohibitive. Ultimately, the EDRI should be evaluated for a single sample that will remain roughly constant over time, i.e., the set of all the world's largest cities. Since the combination can be calculated easily using spreadsheet software, reevaluating the results is easy to do. A principal goal of the EDRI is to measure the earthquake disaster risk of cities *relative to other cities*, not necessarily to some hypothetical "best" or "worst" situation, so it is appropriate to use a technique that relies on evaluating the risk with respect to other sample cities, i.e., a sample-specific one.

5.1. General approach

Four possible general approaches to the index combination were considered: (1) no combination, (2) graphical methods, (3) nonlinear combination, and (4) linear combination. This section discusses the advantages and disadvantages of each, explaining why the linear combination was ultimately selected for the sample analysis.

5.1.1. No combination

The possibility of not combining the indicators into a single composite index was explored. It is tempting to avoid the technical difficulties associated with the mathematical combination, and simply present the components of the concept being measured, allowing each user to combine them as he deems appropriate. For all the reasons discussed in Section 2.5, however, the usefulness of a single summary EDRI outweighs the desire to avoid the challenges associated with combining indicators. As long as the assumptions and techniques that guide the combination are explicit and clear, the user can interpret the combination based on his belief in the appropriateness of the approach. Furthermore, since the indicators that comprise the EDRI are presented as well as the EDRI, the user can always refer to the indicator values themselves, and disregard the final EDRI if he wishes.

5.1.2. Graphical methods

Two graphical methods developed by Wroclaw could be used for comparing the earthquake disaster risk of different cities (Hellwig 1972a, 1972b). In applying the first one to this project, the "distance from the ideal" approach, each city would be represented by a point P_i in n-space with coordinates (x_{1i}', x_{2i}', …, x_{ni}') equal to the scaled values of the n indicators (Fig. 5.1). Point P_o, the ideal, would have coordinates (x_{1o}', x_{2o}', …, x_{no}') such that x_{so} equals the minimum value of the indicator s over all cities (or the maximum value if an increase in s would result in a decrease in earthquake disaster risk). The value of the EDRI for city P_i would

[1] Refers to the *city-specific* relative contribution (Section 5.1.4).

be computed as c_{io}/c_o, where c_{io} is the distance between P_i and P_o, and c_o equals the mean plus two standard deviations of the c_{io} for all cities (i.e., $c_o = \bar{c}_o + 2s_{c_o}$). Each city's EDRI value would represent the distance between the city under consideration and the 'ideal" city, with respect to earthquake disaster risk. The value of the EDRI would always be positive, and almost always less than one.

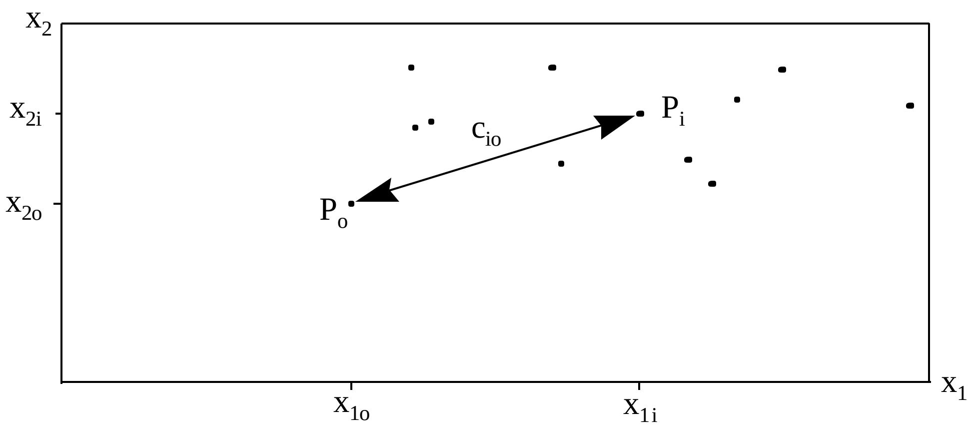


Figure 5.1. "Distance from ideal" graphical method of combination

The second graphical method would divide cities into groups that exhibit similar indicator values (i.e., similar levels of earthquake disaster risk). It also involves locating each city as a point P_i in n-space, and evaluating the distances between them (Fig. 5.2). The distance between points P_i and P_j is denoted c_{ij}. The value of c_i, the minimum c_{ij} for all j, measures the resemblance between P_i and its most similar city, P_j. The cities are grouped so that each city P_i is in a group with its most similar city P_j, and cities within the same group are never more than the critical distance $c_{(+)}$ apart, where $c_{(+)}$ equals the mean plus two standard deviations of the c_i for all cities (i.e., $c_{(+)} = \bar{c}_i + 2s_{c_i}$).

Wroclaw's techniques offer ways to rank cities according to their values for the set of indicators identified in Chapter 4. The procedures are simple, objective, and intuitively based. Nevertheless, neither presents an appropriate approach for the EDRI because neither conveys any information about the relative contributions of the different factors to the final ranking, and that is one of the main goals of the EDRI. By using the

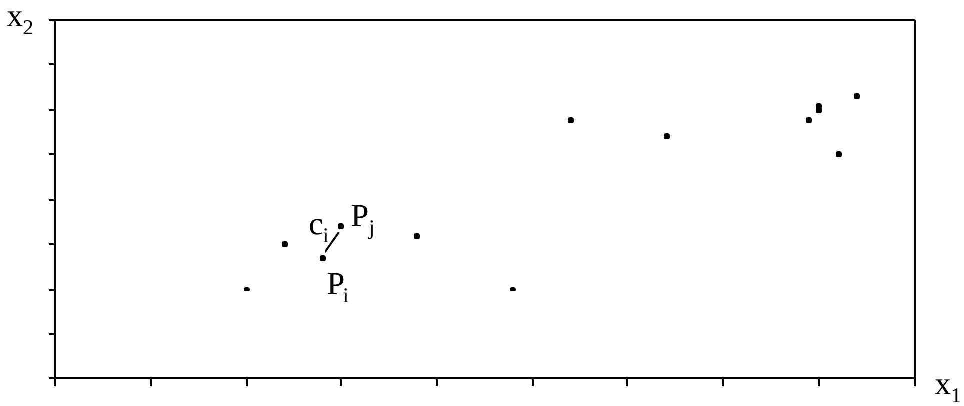


Figure 5.2. "Similar groups" graphical method of combination

distances between points, each implicitly weighs all the indicators equally. Furthermore, results from the "distance from the ideal" method are overly sensitive to the "ideal" indicator values, and the "similar groups" method does not distinguish among cities within the broad groupings. Depending on the sample, the second technique may result in too few or too many groups, and it may not be obvious how to label the groups.

5.1.3. Nonlinear combination

Perhaps the way to capture the concept of earthquake disaster risk most realistically is to combine the indicator values using a nonlinear function. A nonlinear function can represent the interactions that exist among the factors, and between the factors and the weights. For example, some argue that the relative importance (i.e., the weight) of the Emergency Response and Recovery Capability factor depends on the values of the Hazard and Vulnerability factors. The emergency response and recovery gains importance when there is more severe damage to the physical infrastructure. Unfortunately, while these interactions seem intuitively reasonable, there has been little systematic study either to prove that they exist, or to determine the exact form of the interactions. The function describing the variation of the weight of Emergency

Response and Recovery Capability versus the Hazard and Vulnerability, for example, remains unknown. With the current level of knowledge, the cost of introducing extra uncertainty and complexity into the model outweighs any possible benefits. The “perceived” exactness of the model would be inconsistent with the current understanding and quality of data. Finally, depending on the form of a nonlinear model, the relative contributions of each factor may not be clear.

5.1.4. Linear combination

If the EDRI is constructed as a linear combination, the EDRI value for city j would take the form:

$$EDRI_j = \sum_i c_{ij}, \quad (5.1)$$

where c_{ij} is the contribution of indicator i to the earthquake disaster risk of city j relative to other cities in the sample. Let x_{ij} in Table 5.1 be the value of the indicator i for city j. The value of the contribution c_{ij} depends on two comparisons: (1) how the value x_{ij} compares to the values of the same indicator for other cities, and (2) how the importance of indicator i to earthquake disaster risk compares to the importance of other indicators. In general, the contribution is computed in two steps—scaling and weighting. Scaling performs the first comparison by transforming each value, x_{ij}, into a corresponding scaled value, x_{ij}', that interprets the value relative to other values of the same indicator. Scaling also converts the indicators into compatible units of measurement. Weighting performs the second comparison by multiplying the scaled values of each indicator by a constant, unitless coefficient whose magnitude represents the importance of the indicator relative to other indicators. The form of the EDRI becomes:

$$EDRI = \sum_i w_i x_i', \quad (5.2)$$

where x_i' is the scaled value of indicator i, and w_i is the constant weight that represents the relative importance of indicator i.

There are two types of relative contributions associated with the EDRI: definition-related and city-specific. Weights describe the definition-related relative contributions of the five main factors to the EDRI. They are the same for all cities, because they relate to the concept of earthquake disaster risk, not the characteristics of a particular city. The assumptions about the definition of earthquake disaster risk (i.e., the relative importance of each of the five main factors to the concept) are isolated and made explicit in the weights. The city-specific relative contributions are captured in the relative factor values (H, E, V, C, and R). These are the relative contributions to which the second objective of the EDRI refers (Section 2.2). They describe the characteristics of each city. The city-specific relative contribution of one factor is the ratio of the value of that factor to the sum of the values of all factors. For example, the relative contribution of Hazard to City j's risk is:

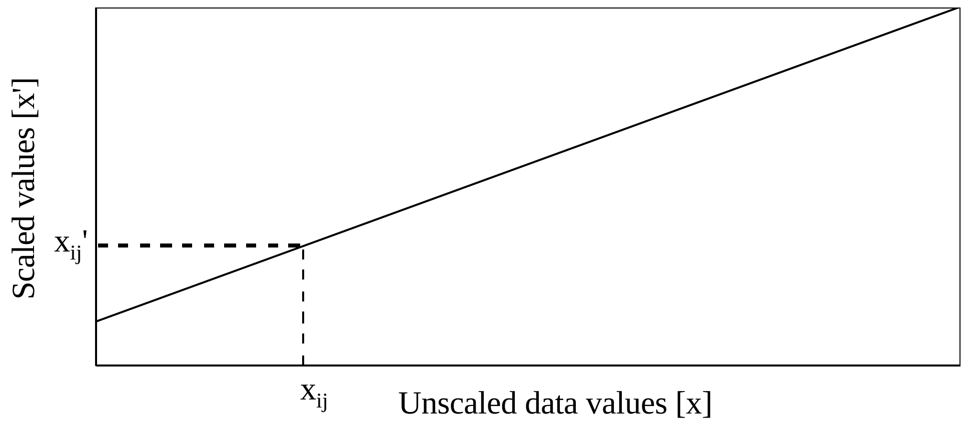
$$\text{Contribution of } H_j = H_j/(H_j + E_j + V_j + C_j + R_j). \qquad (5.3)$$

The interpretation of an x_{ij} value depends on the indicator to which it refers. An x_{ij} value of one means something different for the indicators "housing vacancy rate" and "per capita Gross Domestic Product in constant 1990 U.S. dollars," because the magnitudes characteristic of these two indicators are different. The values for "housing vacancy rate" will range from zero to one, while those for "per capita GDP" will be on the order of thousands. If the two values were added directly, the "per capita GDP" would dominate the "housing vacancy rate" in every case. Furthermore, a city-to-city difference of say, one-tenth (i.e., $x_{iA} - x_{iB} = 0.1$), takes on different meanings for the two indicators because their typical dispersions are different. For "housing vacancy rate" a difference of ten percent is very significant, while for "per capita GDP in constant 1990 U.S. dollars," a difference of ten cents is negligible. Scaling aims to make the interpretation of the x_{ij} values and the city-to-city differences consistent among indicators by transforming them so that all indicators take on values that are similar in magnitude and dispersion. Magnitude is controlled by forcing all indicators to have either the same mean or the same range of values, and dispersion is controlled by forcing all indicators to have either the same standard deviation or the same range of values. Most scaling techniques establish one or two benchmarks and compare the indicator value for each city to those benchmarks, and thereby to the values for other cities. Scaling is strictly a mathematical operation. It does not attempt to convey how each indicator relates to the overall earthquake disaster risk. Scaling also converts all component indicators into compatible units of measurement. The "housing vacancy rate" and "per capita GDP" values cannot be added directly, because the former is measured in percentage points; the latter in monetary units. Only after scaling has transformed all indicators so that have compatible magnitudes, dispersions, and units can the various indicator values be added.

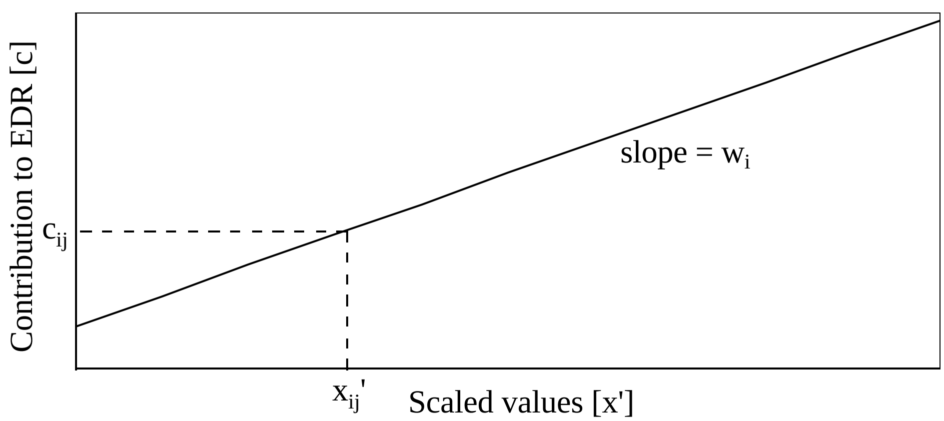
Once all the indicators have been scaled, their associated weights must be determined. As shown in Figures 5.3a and 5.3b, scaling transforms an indicator's unscaled value to the associated scaled value, and weighting relates the scaled value to c_{ij}, the contribution it makes to the relative earthquake disaster risk of city j. The weight of each indicator shows how important it is to the overall earthquake disaster risk. Determining the weights is the final step in defining *earthquake disaster risk*. Section 2.1 defined earthquake disaster risk by identifying the factors that contribute to it. To complete the understanding of the concept of earthquake disaster risk, the relative importance of each contributing factor must be established as well. Weighting achieves that task. Much research has been done to demonstrate how each factor plays a role in earthquake disaster risk. Unfortunately, the wealth of knowledge about earthquake disasters is spread among many people, each of whom is an expert in a different facet of the problem. The EDRI tries to capture the collective knowledge of all experts to define earthquake disaster risk as it is conceived by the group as a whole. Weights are correct only inasmuch as they achieve that goal.

The linear combination satisfies all of the four main goals of the EDRI. The final EDRI value for each city offers a quantitative ranking of the relative overall risk. The ratio of each factor to the sum of the values of all factors clearly and explicitly represents that factor's city-specific relative contribution to the overall earthquake disaster risk. The linear combination is simple to evaluate and interpret, yet provides meaningful results. **Almost all previously developed composite indexes (e.g., Human Development Index, the Economic**

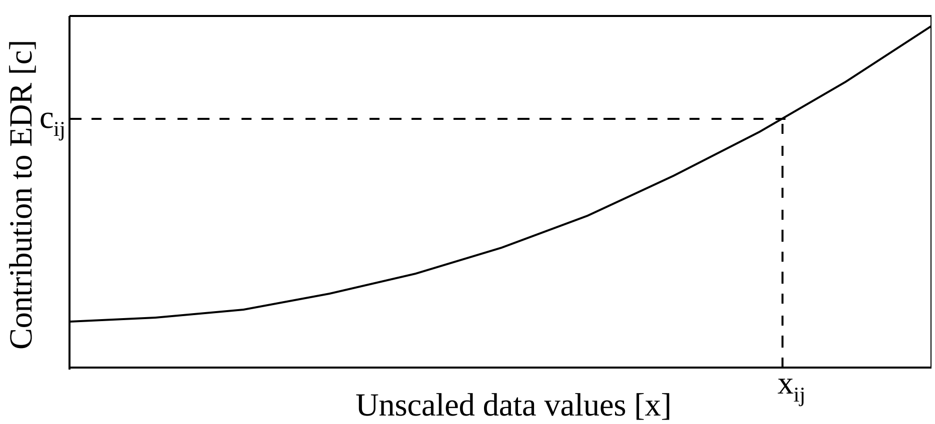
Freedom Index, Competitiveness Index, Consumer Price Index) have relied on the linear combination approach.



a. Scaling functions



b. Weighting functions



c. Contribution functions

Figure 5.3. Graphical comparison of scaling, weighting, and contribution functions

The principal disadvantage of expressing the EDRI as a linear combination is that it implies that no interactions exist among the indicators, or between the indicators and the weights. As discussed in Section 5.1.3, this assumption is undoubtedly incorrect. Since the exact form of those interactions is unclear, however, it is preferable to define the EDRI as a linear combination than to employ a highly uncertain nonlinear form. Furthermore, an EDRI that is essentially a linear combination can incorporate some nonlinearities through the use of indicators that are derived, nonlinear functions of the indicators for which data are gathered. The derived indicators that are used in the sample analysis include the "economic external context indicator," "$\exp^{(\text{MMI with a 50-year return period})}$," and "seismic code indicator," whose formulas are discussed in Chapter 4.

Another shortcoming of the linear combination becomes evident when examining extreme values. Intuitively, if a city has absolutely no hazard (i.e., zero chance of experiencing any ground shaking), its earthquake disaster risk should be zero as well. With the linear combination, however, if the city had nonzero values for any of the other four main factors, its risk would not be zero. Although this presents a hypothetical problem, in reality, no city could have absolutely zero hazard (or exposure or vulnerability), so this situation is not realistic.

5.1.5. Sample analysis solution

The general approach adopted in the sample analysis is a linear combination that includes several derived nonlinear indicators. For all the reasons discussed in Section 5.1.4, this approach provides the best available technique for mathematically combining the indicators into the composite EDRI. A summary of all the equations necessary to evaluate the EDRI follows:

$$\text{EDRI} = w_H H + w_E E + w_V V + w_C C + w_R R \qquad (5.4a)$$

$$H = w_{H1}x'_{H1} + w_{H2}x'_{H2} + w_{H3}x'_{H3} + w_{H4}x'_{H4} + w_{H5}x'_{H5} + w_{H6}x'_{H6} + w_{H7}x'_{H7} \quad (5.4b)$$

$$E = w_{E1}x'_{E1} + w_{E2}x'_{E2} + w_{E3}x'_{E3} + w_{E4}x'_{E4} + w_{E5}x'_{E5} + w_{E6}x'_{E6} \quad (5.4c)$$

$$V = w_{V1}x'_{V1} + w_{V2}x'_{V2} + w_{V3}x'_{V3} + w_{V4}x'_{V4} + w_{V5}x'_{V5} + w_{V6}x'_{V6} \quad (5.4d)$$

$$C = w_{C1}x'_{C1} + w_{C2}x'_{C2} + w_{C3}x'_{C3} \quad (5.4e)$$

$$R = w_{R1}x'_{R1} + w_{R2}x'_{R2} + w_{R3}x'_{R3} + w_{R4}x'_{R4} + w_{R5}x'_{R5} + w_{R6}x'_{R6} + w_{R7}x'_{R7} + w_{R8}x'_{R8} + w_{R9}x'_{R9} \quad (5.4f)$$

where H, E, V, C, and R are the values of the Hazard, Exposure, Vulnerability, External Context, and Emergency Response and Recovery Capability indexes, respectively; x'_i refer to the scaled values of the indicators listed in Figure 4.1; and w_i are the weights associated with each indicator.

5.2. Scaling

Seven possible techniques for scaling the indicators were considered before the final method, scaling with respect to the mean minus two standard deviations (see Sections 5.2.7 and 5.2.8), was selected for use in the sample analysis. Each of the following seven subsections describes one option, its advantages and disadvantages. The alternatives are summarized in Table 5.2 and Figure 5.4.

5.2.1. Contribution function

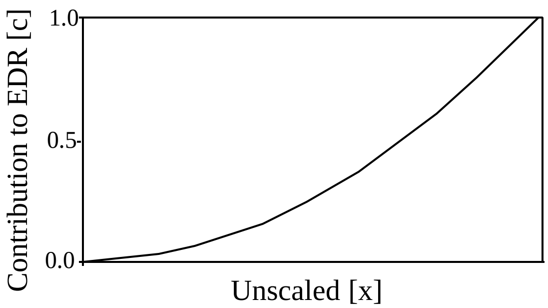
This first scaling option actually combines the tasks of scaling and weighting into a single step. The technique involves determining a function, $c_i(x_{ij})$, for each indicator i, that relates the unscaled indicator value x_{ij} directly to c_{ij}, the contribution that value makes to the earthquake disaster risk of city j relative to other cities in the sample
(Fig. 5.3c). Figure 5.5 presents a hypothetical example of one such function for the indicator "population." Comparing points A and B indicates that City A, with a population of $x_{pop,A}$, has a higher risk with respect to the population, than City B, with a population of $x_{pop,B}$. The indicator "population" would contribute ($c_{pop,A}$ - $c_{pop,B}$) more to the EDRI value for City A than

for City B. Once a contribution function has been developed for each indicator listed in Chapter 4, the $EDRI_j$ for city j is evaluated as the sum of the contribution of all the indicators, i.e., $EDRI_j = \sum_i c_i(x_{ij})$.

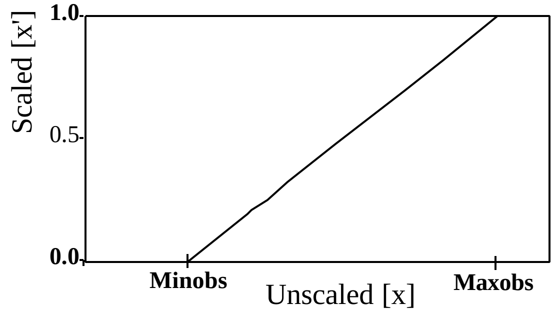
Table 5.2. Comparison of scaling techniques

Technique	Advantages	Disadvantages	Function	Range of scaled values
Contributions functions	• Can incorporate nonlinearities	• Combines scaling and weighting • Can't determine city-specific relative contributions	user-specified	user-specified
Min. and max. observed	• Simple to calculate, interpret • Objective	• Dependent on two values • Need adjustment to track over time • Sample-specific	$\frac{(x_{ij} - minob_i)}{(maxob_i - minob_i)}$	0 to 1
Min. and max. possible	• Easy to track over time • Simple to calculate, interpret • Not sample-specific	• Dependent on two values • Difficult to determine min. and max. possible • Subjective	$\frac{(x_{ij} - minps_i)}{(maxps_i - minps_i)}$	0 to 1
Base city and year	• Simple to calculate, interpret • Objective • Easy to track over time	• Dependent on one value • Sample-specific • Implicit weighting • Dependent on arbitrary choice of base city	$\frac{x_{ij}}{x_{i,base}}$	--∞ to +∞
Consistent 0 to 10 scale	• Easy to interpret • Not sample-specific	• Subjective • Low resolution	integers 0 to 10	0 to 10
Mean	• Objective • Easy to calculate	• Results in negative scaled values • Sample-specific • Need adjustment to track over time	$\frac{x_{ij} - \bar{x}_i}{s_i}$	-∞ to +∞
Mean minus two standard deviations*	• Objective • Easy to calculate	• Sample-specific • Need adjustment to track over time	$\frac{x_{ij} - (\bar{x}_i - 2s_i)}{s_i}$	-∞ to +∞

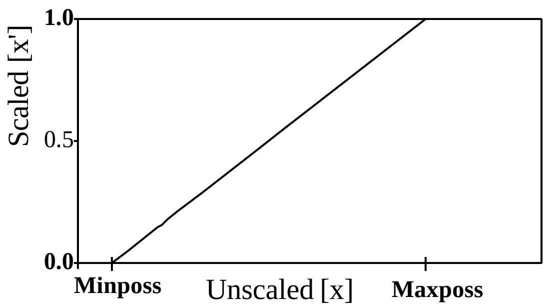
* Chosen for sample analysis.



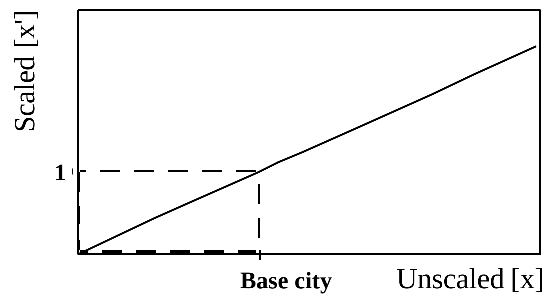
a. Contribution function



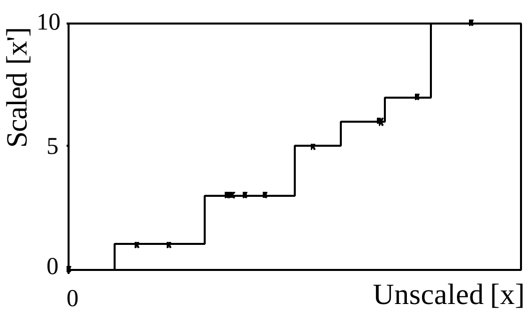
b. Scaling: Min. and max. observed values



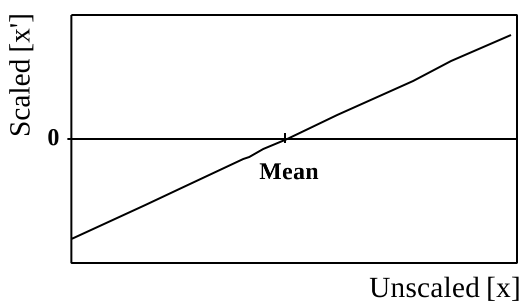
c. Scaling: Min. and max. possible values



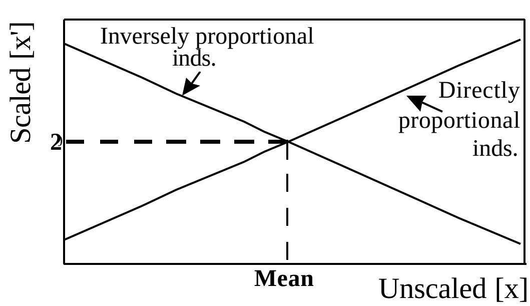
d. Scaling: Base city



e. Scaling: Zero to ten



f. Scaling: Mean



g. Scaling: Mean minus two stan. deviations

Figure 5.4. Graphical comparison of scaling techniques: (a) contribution function, (b) min. and max. observed, (c) min. and max. possible, (d) base city, (e) consistent zero to ten scale, (f) mean, (g) mean minus two standard deviations.

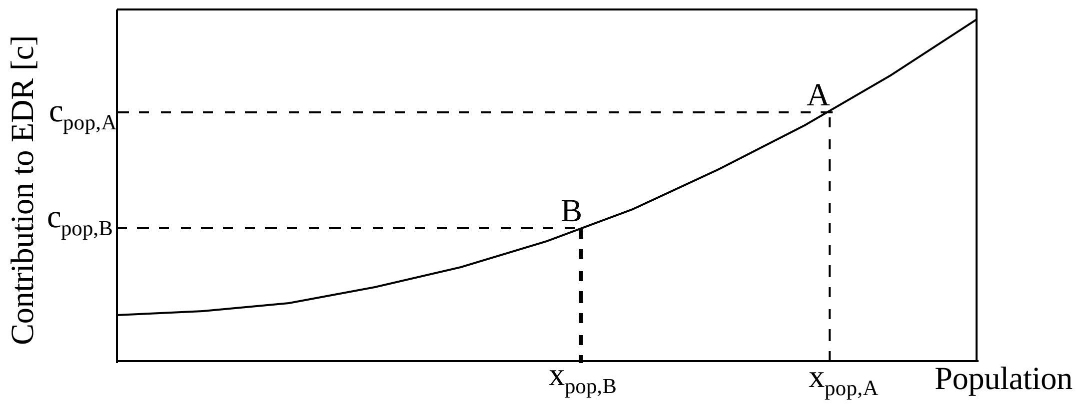


Figure 5.5. Hypothetical contribution function for the indicator "population"

The principal advantage of this technique is that it does not require the contribution of each factor be a linear function of the scaled values x_{ij}' (i.e., the weights do not have to be constant). While interactions among different factors (as in the example in Section 5.1.3) still cannot be addressed, this technique would allow the inclusion of any nonlinearities in the relationship of a single factor to the overall earthquake disaster risk. This technique avoids the task of assessing weight values explicitly.

Three major disadvantages prevent this approach from being the most attractive choice for the EDRI. First, the contribution functions must be determined by a very difficult subjective assessment. As discussed in Section 5.1.3, no real evidence exists to indicate what would be the correct form of the relationships between each factor and the overall risk, much less between an indicator that represents a factor and the overall risk. As with the nonlinear combination, the added complexity may introduce more uncertainty than benefit. Second, without separate weights, there is no clear way to separate the city-specific and definition-related relative contributions. It is impossible to determine the city-specific relative contributions of the various component factors to the overall risk, and that is one of the main objectives of the EDRI (Chapter 5 introduction; Criterion 1b).

Third, the contribution functions essentially perform the tasks of both scaling (i.e., making magnitudes, dispersions, and units consistent across indicators) and weighting (i.e., conveying the relative importance of each indicator to the overall risk). Merging the scaling and weighting into one step makes it difficult to know if the contribution function was determined because of scaling concerns, weighting concerns, or a combination of both. It is preferable to separate scaling and weighting. Since scaling is exclusively a mathematical exercise, all the subjectivity about the indicators' relative importance can be isolated in the weights. With the more transparent approach of separating scaling and weighting, the user can easily decide if he agrees with the subjective assessments included in the index combination, and alter them if not.

5.2.2. Minimum and maximum observed

Scaling may be achieved by normalizing with respect to the maximum and minimum values of that indicator that are observed in the sample of cities under consideration. Mathematically,

$$x_{ij}' = \frac{(x_{ij} - minobs_i)}{(maxobs_i - minobs_i)} \tag{5.5}$$

where x_{ij} is the unscaled value for indicator i and city j, x_{ij}' is the corresponding scaled value, and $maxobs_i$ and $minobs_i$ are the maximum and minimum values (over all cities j) of indicator i observed in the sample, respectively (Fig. 5.4b). The maximum and minimum observed values serve as the benchmarks in this scaling technique. Each city is evaluated relative to the cities that exhibit the highest and lowest risk with respect to each indicator. This scaling function makes all indicators exhibit similar magnitudes and dispersions by forcing them all to take on values between zero and one.

Because the maximum and minimum observed values will be different for different time periods and different city samples, this method does not allow consistent comparison over time or across samples. To overcome this difficulty and meet the criterion of enabling the EDRI to be tracked over time, a base time period could be established, and the maximum and minimum observed values for that time period would be used to evaluate the EDRI in every subsequent time period.

This alternative, which Briguglio (1995) used in the development of an index of the economic vulnerability of small island developing states, offers an objective, sample-specific, easily calculated, and easily interpreted way to scale the indicator values, but it suffers a significant disadvantage. The results of this scaling technique are completely dependent on the maximum and minimum observed values, and therefore are dangerously sensitive to the quality of data for those two values. Outlier values can skew the results seriously.

5.2.3. Minimum and maximum possible

The third approach, which is used in the Human Development Index (UNDP 1990-95) and the Physical Quality of Life Index (Morris 1979), is similar to the previous one, except the maximum and minimum values that are considered possible are used instead of the maximum and minimum values observed in the sample of cities. Mathematically,

$$x_{ij}' = \frac{(x_{ij} - \text{minposs}_i)}{(\text{maxposs}_i - \text{minposs}_i)} \qquad (5.6)$$

where x_{ij} is the unscaled value for indicator i and city j, x_{ij}' is the corresponding scaled value, and maxposs_i and minposs_i are the maximum and minimum values (over all cities j) of indicator i that are considered possible (Fig. 5.4c). As in the previous method, this approach makes all indicators exhibit similar magnitudes and dispersions by forcing them all to take on values between zero and one, and the maximum and minimum possible values serve as the benchmarks.

Unlike the similar technique with the maximum and minimum observed values, this one does not have a problem tracking the change in EDRI over time. It should be possible to assess the maximum and minimum possible values so that they will be large and small enough, respectively, to accommodate the indicator values as they change over time. This characteristic points to one of the method's main difficulties—how to assess the maximum and minimum possible values. Should they be the maximum and minimum possible in today's world? Over the next ten years? Forever? The maximum and minimum theoretically possible, or the maximum and minimum that can be practically expected? For example, theoretically, the "housing vacancy rate" can range from zero to one, but practically, it should never exceed, say 0.2. The results are completely dependent on, and therefore, dangerously sensitive to these two assessed values.

5.2.4. Base city and year

Another scaling possibility, used in the development of an index of country size (Jalan 1982), is to render every indicator unitless by normalizing it with respect to a single base city and year, i.e.,

$$x_{ij}' = \frac{x_{ij}}{x_{i,base}} \tag{5.7}$$

where x_{ij} is the unscaled value for indicator i and city j, x_{ij}' is the corresponding scaled value, and $x_{i,base}$ is the unscaled value for indicator i and the base city (Fig. 5.4d). In this case, there is a single benchmark, and there is no difficulty tracking EDRI over time because the benchmark does not vary with the time period. The scaled values can take on any nonnegative value. This alternative is objective, sample-specific, and easy to use. It also produces perhaps the most easily interpreted results because all cities are ranked relative to a single, real city, not a hypothetical "riskiest" or "least risky" city.

While the base city scaling causes the magnitudes of the different indicators to gather roughly around a value of one, it does not control magnitudes as restrictively as the other scaling options do, and it does not make all the indicators have similar dispersion. In failing to control dispersion, this technique introduces an implicit weighting into the mathematical combination. Consider two indicators. One has values spread between one and ten; the other between one and ten thousand. Because the dispersion characteristic of the first indicator is smaller than that of the second, a city-to-city difference of, say one, is more significant for the first indicator than the second. The base city scaling neglects this fact. Suppose the base city has a value of one for each of the two indicators. After being scaled with respect to the base city, the range of values for the first and second indicators will remain one to ten and one to ten thousand, respectively. That is, for the other cities in the sample, the first indicator will have much smaller values than the second, in effect reducing the weight of the first indicator relative to the second. Section 7.3 presents an illustration of this implicit weighting.

There are three principal drawbacks of scaling with respect to a base city and year. First, its inability to control dispersion introduces an undesirable implicit weighting effect, as discussed. Second, the effect of this technique is very sensitive to the essentially arbitrary choice of base city. If a base city is chosen that has a low value for indicator X_1 (relative to other cities) and a high value for indicator X_2 (relative to other cities), the other cities will take on scaled values that are high for X_1, and low for X_2. When the indicator values are added to compute the composite index, in effect, X_1 becomes more important to the other cities than X_2. On the other hand, if a base city is selected that has a relatively high value for indicator X_1 and a relatively low value for indicator X_2, the reverse will be true. The indicator X_1 becomes less important to the other cities than X_2. Third, the results are completely dependent on the data availability and quality for that base city.

5.2.5. Consistent zero to ten scale

The Economic Freedom Index (Johnson and Sheehy 1996) scales the component indicators by converting the natural measurement scale of each to a unitless scale from zero to ten, with ten being associated with the most freedom (Fig. 5.4e). Continuous indicators are scaled by discretizing the continuous scale into eleven parts, so that when the base year sample of countries (for the EDRI, it would be cities) are assigned values, there are an equal number of countries ranked with each value from zero to ten. Binary indicators are assigned possible values of zero and ten. For indicators that are measured by some classification scheme with more than two and less than infinite number of possible values, each possible state is assigned a number from zero to ten, again so that the higher values correspond to more freedom. The EDRI indicators could be scaled similarly.

This technique provides easily understandable scaled values, and achieves all the main criteria of the mathematical combination listed in the introduction to Chapter 5, but it has two disadvantages. First, it depends on the difficult, somewhat subjective task of determining the scale for each indicator individually. Care would be necessary to ensure that the scale conversions are determined solely on the basis of scaling concerns, without consideration of weighting issues (i.e., without considering the relative importance of the indicators). Second, converting all indicators to a zero to ten scale reduces the resolution of the results at the beginning of the calculation, while the other more quantitative methods carry more numerical precision through the calculations, rounding off the results at the conclusion of the analysis.

5.2.6. Mean

The scaling approach adopted in the World Competitiveness Index renders each indicator unitless by scaling it with respect to the mean of a sample of cities, i.e.,

$$x_{ij}' = \frac{(x_{ij} - \bar{x}_i)}{s_i} \tag{5.8}$$

where x_{ij} and x_{ij}' are the unscaled and scaled values for indicator i and city j, respectively; and $\bar{x}_i$ and s_i are the mean and standard deviation of a sample of cities for indicator i (Fig. 5.4f). This objective, sample-specific technique achieves consistency of magnitude and dispersion by making the mean of the scaled values equal to zero and the standard deviation equal to one, for every indicator. It uses a single benchmark, the mean of the sample of cities. Scaled values may range from negative to positive infinity. This method is as sensitive to the value of the mean, as the methods discussed in Sections 5.2.2, 5.2.3, and 5.2.4 are to the maximum and minimum observed values, the maximum and minimum possible values, and the base city value, respectively. However, the benchmark used in this method is much more stable than those used in the previously discussed approaches. The mean depends on the entire sample of data, not just one or two values. This method directly evaluates each city relative to all others (via the mean and standard deviation), while the others achieve the same comparison by evaluating each city relative to the benchmarks, and by transitivity, relative to each other.

To allow consistent EDRI comparisons at different time periods, a base year should be established, and the EDRI values for subsequent time periods should be evaluated using the mean and standard deviation of the sample of cities in the base year. The most disturbing disadvantage of scaling with respect to the mean, is that roughly half of the scaled values (and perhaps some of the EDRI values) will be negative. While a negative value simply indicates that the corresponding city falls below the mean for that indicator, it seems inappropriate to speak of a city having a negative level of risk.

5.2.7. Mean minus two standard deviations

This final scaling option, the one selected for the sample analysis, is similar to the option discussed in 5.2.6, but with a variation designed to relieve the undesirable characteristic of producing negative scaled values. Mathematically,

$$x_{ij}' = \frac{x_{ij} - (\bar{x}_i - 2s_i)}{s_i} = \frac{x_{ij} - \bar{x}_i}{s_i} + 2 \qquad (5.9)$$

where x_{ij}' and x_{ij} are the unscaled and scaled values for indicator i and city j, respectively; and $\bar{x}_i$ and s_i are the mean and standard deviation of a sample of cities for indicator i (Fig. 5.4g). This scaling function simply equals the scaling function of 5.2.6 translated upward two units. Instead of producing a set of scaled values with a mean of zero and a standard deviation of one, this scaling formula delivers a set of scaled values with a mean of two and a standard deviation of one. The result of this simple transformation is a scaling technique that shares all the benefits of the option discussed in 5.2.6, but will rarely produce negative values, thus making the results more easily understandable. A common rule of thumb says that there is a 95% chance that values will lie within two standard deviations of the mean (McClave and Dietrich 1988).

5.2.8. Inversely related indicators

All the discussions of scaling alternatives above assumed that the indicator value is directly proportional to a city's earthquake disaster risk. The scaling formulas presented are all increasing functions. They must be adjusted to treat indicators that are inversely related to earthquake disaster risk (e.g., "housing vacancy rate"). The following function is a variation of the scaling function in Section 5.2.7 that is suitable for use with inversely related indicators:

$$x_{ij}' = \frac{-x_{ij} + (\bar{x}_i + 2s_i)}{s_i} \tag{5.10}$$

It was defined so that it produces the same mean as Equation 5.9, and a slope that is equal in magnitude, but negative (Fig. 5.4g). Indicators scaled with the inverse form of the scaling function will still have a mean of two and standard deviation of one, so they remain consistent with the directly scaled indicators.

5.3. Weighting

No amount of clever mathematical manipulation will uncover the "correct" weights for the EDRI, because no single correct set of weights exists a priori. Rather, depending on the weights that are defined, the concept measured by the EDRI will vary. For example, if the weight of the Hazard factor is taken as one, and all other weights are zero, earthquake disaster risk is, in effect, defined as hazard. Experience and study indicate that there are other factors that are important in earthquake disaster risk, however, so the hazard weight should be less than one, and the weights of other factors should be greater than zero. Nevertheless, although there is no one set of "correct" weights, certainly some weight values will help achieve the goals of the EDRI more effectively than others. The "best" weights for the EDRI are those that most accurately represent the relative contributions of the corresponding indicators to the overall earthquake disaster risk, as it is defined in Section 2.1. The best technique for determining the weight values is the one that produces the best weight values while meeting the criteria listed in the introduction to Chapter 5. Three alternatives were considered for determining the weights to be used in the EDRI linear combination—regression, principal components analysis, and subjective assessments. In the sample analysis, the weights are normalized so that their sum equals one. This normalization does not affect the results, but allows the weights to be interpreted as the percentage by which the associated indicator contributes to earthquake disaster risk.

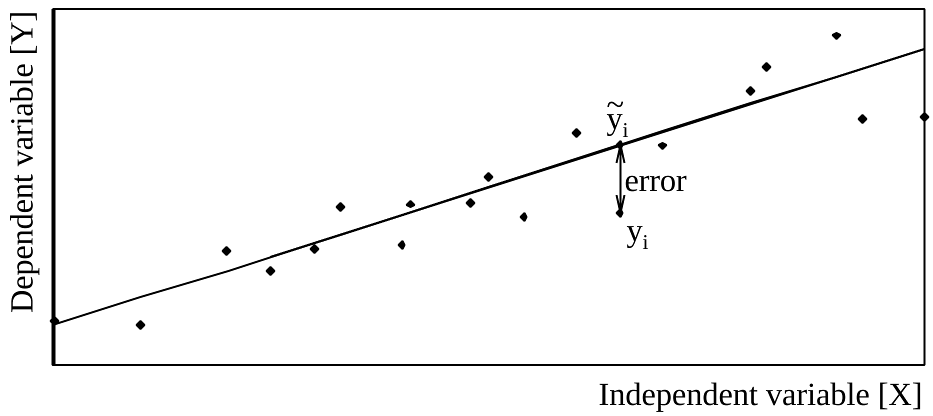
5.3.1. Regression

Multiple regression is a technique by which a model is derived to predict the values of a dependent random variable Y using the values of a set of independent variables $X_1, \ldots, X_n$. Multiple linear regression models take the form:

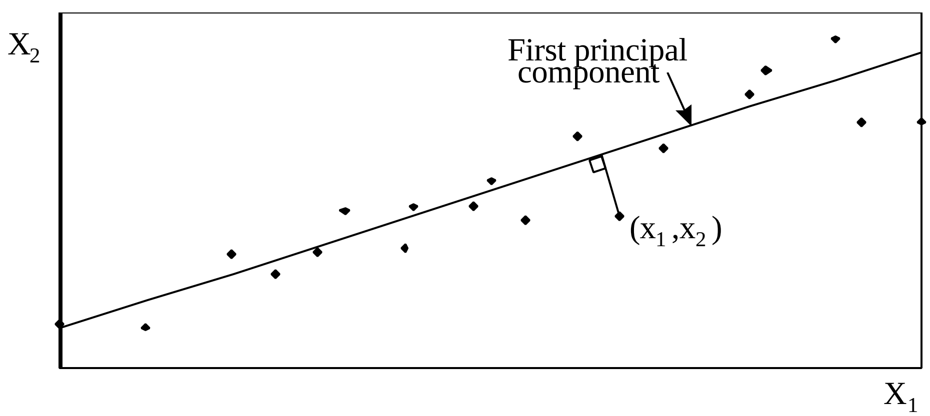
$$\tilde{y}_i = b_o + b_1 x_1 + \ldots + b_n x_n \,, \tag{5.11}$$

where $\tilde{y}_i$ is the predicted value of Y, and $x_1, \ldots, x_n$ are the values of the n independent variables. The quantity $|y_i - \tilde{y}_i|$, where y_i is the observed value of Y, describes the error between the observed and the predicted values of the variable Y (Fig. 5.6a). Using the least squares method, regression computes the constants $\beta_0, \ldots, \beta_n$ so that the model exhibits the smallest possible total error. Minimizing the sum of the squared errors ensures that the model describes the line of closest fit.

If one considers earthquake disaster risk to be the dependent variable, Y, the indicators listed in Chapter 4 to form the set of independent variables $X_1, \ldots, X_n$, and the weights $w_1, \ldots, w_n$ to be the constants $\beta_1, \ldots, \beta_n$, then multiple linear regression seems to be a promising technique for computing the weights. Using regression to determine the weights would ensure that the EDRI provides the "best" model for predicting earthquake disaster risk. Unfortunately, regression requires a set of data that includes values for the dependent variable, Y. Since the dependent variable, earthquake disaster risk, cannot be measured directly, it is impossible to use regression directly to determine the weights of the EDRI.



a. Regression analysis



b. Principal components analysis

Figure 5.6. Graphical comparison of regression and principal components analysis

5.3.2. Principal components analysis

Principal components analysis (PCA) offers another statistically-based technique for determining the weights in a composite index. While PCA can be applied to achieve several other goals, one of its uses is to derive weights for a composite index based on the first principal component of a set of variables. PCA was used in this way by Ram (1982) in developing a

Physical Quality of Life Index and a Basic Needs Fulfillment Index, and by Downes (1988) in developing a Country Size Index.

Principal components analysis "searches for a few uncorrelated linear combinations of the original variables that capture most of the information of the original variables" (Dunteman 1989). The weights of the combinations are "mathematically determined to maximize the variation of the linear composite, or equivalently, to maximize the sum of the squared correlations of the principal component with the original variables" (Dunteman 1989). The linear combinations (i.e., principal components) are ordered so that the first principal component has the largest variation, i.e., explains the highest percentage of the total variation in the original variables; the second principal component explains the second highest percentage, and so forth. The first principal component thus offers the single linear combination of the original variables that best summarizes the information captured in those variables, and the variation it explains provides a measure of how well it does so. In creating the EDRI then, using the first principal component weights would result in the EDRI that best captures the information in the indicators. Note, however, that while the first principal component will be the best single linear combination, it may not be a complete summary of the information in the original variables. The variation of each principal component measures how much information it contains.

Like regression, PCA can determine a line of closest fit to the values of a set of independent variables. However, PCA uses a different criterion to determine the closest fit, namely that the procedure should maximize the sum of squared correlations of the linear combination with the original variables. Graphically, instead of defining the line of closest fit as the one that minimizes the sum of squared distances between the observed values and predicted values *in the direction of the dependent variable*, principal components defines it as the line that minimizes the sum of squared distances between the observed values and their *perpendicular projections* onto the largest principal component (Dunteman 1989) (Fig. 5.6b).

The principal component method consists of four steps (see example in Section 5.3.4.1). First, the correlation matrix is determined for the set of indicators being combined. Second, the eigenvalues and eigenvectors of the correlation matrix are calculated. Third, each eigenvector is multiplied by the square root of the associated eigenvalue to obtain the factor loadings. Each principal component is defined as the linear combination of the indicators, with weights equal to their factor loadings. The first principal component is the one corresponding to the largest eigenvalue; the second principal component, to the second largest eigenvalue, and so forth. Fourth, the eigenvalue divided by the number of indicators being combined conveys the percentage of the total variation in the indicators that is explained by the associated principal component. Depending on how much of the total variation it explains, the first principal component weights may be used in the composite index of the indicators.

Principal components offers an objective, statistically-based, interpretable procedure for determining the weights. It can also provide a measure of how well the final linear combination represents the indicator values. Nevertheless, PCA is not appropriate for general use in the EDRI because it is based on the assumption that all the indicators being combined are well-correlated, and that is not the case for the EDRI (e.g., expected ground shaking is not related to population). PCA was used, however, to help determine the weights for the Physical Infrastructure Exposure factor because the indicators representing that factor are well-correlated (Section 5.3.4.1).

5.3.3. Subjective assessments

There are two possible approaches to using subjective assessments to determine the values of the weights in the EDRI combination formula. The first method, which is used in the sample analysis, consists of an assessor (or assessors) simply assigning values for the weights based on his (their) best judgment. The second asks the assessor(s) to assign ranks to the overall EDRI for a sample of cities. Assuming those assessed EDRI values are "correct," they are used as the dependent variable data, and a regression analysis is then performed to determine the weights for each component factor.

Obtaining subjective assessments is easy to do, but difficult to do well. The many issues associated with obtaining accurate subjective assessments (i.e., assessments that actually convey exactly the knowledge they attempt to capture) include determining who should make the assessments, how they should be elicited, and how they should be used. The assessments could be made by a single expert, many experts, experts in specific subject areas, or experts in specific geographical locations. The assessments may be obtained using questionnaires or interviews, and they may be aggregated in various ways, such as the Delphi method. Chhibber, Apostolakis, and Okrent (1992) summarize the many issues involved in obtaining expert opinion.

There are three principal disadvantages of both subjective assessment approaches. First, they lack a statistical or other explicitly replicable basis. Second, the assessor may not have the knowledge that the index developer hopes to elicit. Third, even if the assessor does have the knowledge, he may not be able to convey it accurately, because biases often corrupt subjective assessments. Tversky and Kahneman (1974) describe many of the biases to which subjective assessments are vulnerable. While the subjective assessment approaches are not ideal for these reasons, they constitute the only feasible option for the EDRI, and offer a reasonable way to capture the current state of understanding among earthquake risk experts about the relative importance of the various component factors to earthquake disaster risk. The first subjective assessment variation, assessing the weight directly, is preferable to the second because more focused assessments are generally easier to make. Furthermore, by performing the regression analysis on the assessments, the second method obscures the impact of those assessments, and requires that the entire regression analysis be repeated if any changes in the assessments are made.

5.3.4. Sample analysis solution

For the reasons discussed in the previous sections, direct subjective assessments of the weights were employed to determine all weight values, except those used in the Physical Infrastructure Exposure. The Physical Infrastructure Exposure weights were determined with the help of the principal component method (Section 5.3.4.1). While all other weights ultimately were established by the author alone, an attempt was made to assess whether or not well-known earthquake risk experts would agree with the weight values assessed by the author. That effort consisted of a questionnaire survey, the methodology, shortcomings, and findings of which are presented in Section 5.3.4.2. The final weight values used in the sample analysis are summarized in Section 5.3.4.3.

5.3.4.1. Physical Infrastructure Exposure weights

The indicators that describe the Physical Infrastructure Exposure—"population," "number of housing units," "per capita GDP," and "land area"—are well-correlated, and therefore are amenable to the principal component method of determining weights. The technique was performed both on all four indicators using the *Statistics of World Large Cities* data set, and on the first three indicators using the *Human Settlements Statistics* data set. There are not enough data points to include area in the Settlements data set analysis. Both data sets are described in Section 4.3.2.1. The resulting factor loadings are shown in Tables 5.3 and 5.4.

Table 5.3. Results of principal components analysis to determine Physical Infrastructure Exposure weights (*Statistics of World Large Cities* data set)

Indicator	Principal Component Factor Loadings			
	P.C. 1	P.C. 2	P.C. 3	P.C. 4
Population	0.83	0.25	0.38	0.32
Number of housing units	0.89	-0.24	0.11	-0.37
Per capita GDP	0.30	-0.85	-0.38	0.20
Land area	0.44	0.58	-0.69	0.01

Eigenvalue	1.76	1.17	0.78	0.28
Percent total variation explained	44%	29%	20%	7%

Table 5.4. Results of principal components analysis to determine Physical Infrastructure Exposure weights (*Human Settlements Statistics* data set)

Indicator	Principal Component Factor Loadings			
	P.C. 1	P.C. 2	P.C. 3	P.C. 4
Population	0.95	-0.20	0.24	---
Number of housing units	0.95	-0.18	-0.24	---
Per capita GDP	0.39	0.92	0.01	---
Land area	---	---	---	---
Eigenvalue	1.96	0.92	0.12	---
Percent total variation explained	65%	31%	4%	---

The correlation matrices, eigenvalues, and eigenvectors calculated in each analysis are presented in Appendix G. While the analysis suffers from imperfect data sets and would be better if the first principal components explained more of the total variation, the results of the first principal components suggest roughly that the "population" and "number of housing units" indicators should have equal weights, that the "per capita GDP" and "land area" indicators should have equal weights, and that the former should be a little more than twice the latter. As shown in Figure 5.8, the weights of "population" and "number of housing units" were taken to be 0.35, and the weights of "per capita GDP" and "land area" were assigned values of 0.15.

5.3.4.2. Questionnaire

A questionnaire was developed and distributed to a sample of experts in earthquake disaster risk to elicit their subjective assessments of the relative importance of the five main factors that contribute to a city's earthquake disaster risk—Hazard, Exposure, Vulnerability, External Context, and Emergency Response and Recovery Capability. Appendix H contains a copy of the questionnaire. Although it was not a scientific survey, an attempt was made to obtain a sample of respondents that represent a range of professional and geographical backgrounds. The survey participants, all experts with a holistic knowledge of earthquake disaster risk, either were identified through personal connections, or picked up the questionnaire at a poster session at the Eleventh World Conference on Earthquake Engineering in Acapulco, Mexico in June 1996. Eighteen questionnaires were returned out of about forty distributed. Two were incomplete, and thus were not included in the summary of results. Responses came from professors and practitioners in Australia (2), China, India, Japan (2), Mexico, Turkey, and the United States (10). The respondents' areas of expertise spanned a range of fields, including structural and geotechnical engineering, building construction, seismology, risk management, emergency response and recovery, sociology, regional planning, city planning, and public policy.

The questionnaire was designed to facilitate thoughtful assessments of weights representing the relative contributions of factors to earthquake disaster risk. It aimed to lead the respondent through a three-step thought process that began with relatively easy assessments and progressed to the assessments of interest, the more difficult assessments of the five relative factor weights (w_H, w_E, w_V, w_C, and w_R). The first step (Questions 1 to 10; part a) asked simple, qualitative, binary comparisons (e.g., "Which factor contributes more to earthquake disaster risk, Hazard or Exposure?"). The second step (Questions 1 to 10; part b) asked the respondent to refine the first-step assessments by giving quantitative responses to the same binary comparisons (e.g., *How much* more important is Hazard than Exposure?). The third step (Question 11) asked to synthesize the results of the binary comparisons into a five-way comparison of relative factor importance. Although the first ten questions provided no information that was not also contained in Question 11 (as many respondents noted), they were included to help lead the respondents to thoughtful answers.

Although the responses given in each of the three parts should provide the same information about the relative importance of the factors, in at least four of the questionnaires returned, the ratios of relative factor importance derived from Question 11 differed substantially from those assessed in Questions 1 to 10. This inconsistency could indicate that the respondent misinterpreted the questionnaire, or it simply could reflect the fact people are not naturally consistent. In any case, inconsistency across the three parts should not necessarily invalidate the Question 11 results. The primary purpose of Questions 1 to 10 was to force respondents to think about comparisons of relative factor importance slowly and carefully before making the final weight assessments. Whether or not the responses to those questions were consistent with the response for Question 11, the process of answering them was probably sufficient to achieve this goal.

Experts have not reached a consensus on the definitions of many key concepts in hazard studies (e.g., *risk*, *vulnerability*, *exposure*). In light of lingering differences in taxonomy, particularly across disciplines, the questionnaire included brief definitions to help ensure that all respondents were thinking of the same concepts as they made their assessments. Nevertheless, some comments received indicate that the concepts were not interpreted exactly as intended. Unfortunately, there is no way to know for certain the extent to which the differences in responses reflect different beliefs about the nature of earthquake disaster risk, and the extent to which they simply reflect different understandings of the factor definitions.

As mentioned, the questionnaire exercise was not a strictly scientific survey, rather an attempt to obtain a rough idea of the experts' gut feelings about the relative contributions of the five main factors to earthquake disaster risk. The results are summarized in Table 5.5 and Figure 5.7. Keeping in mind the methodological shortcomings discussed above, the responses lead to the following interesting observations.

First, some consensus exists among the respondents about what weight values are appropriate. Standard deviations for the five factor weights are relatively small, between 0.05 and 0.09 (see Table 5.5). The respondents apparently consider all five factors to contribute earthquake disaster risk. While it is a common public belief that hazard is by far the most important determinant of earthquake disaster risk, the experts appear to believe otherwise.

Table 5.5. Five main factor weights obtained from questionnaire survey

Respondent	Hazard	Exposure	Vulnerability	External Context	Emerg. Resp. & Recovery
	W_H	W_E	W_V	W_C	W_R
1	0.350	0.200	0.200	0.125	0.125
2	0.200	0.171	0.286	0.171	0.171
3	0.222	0.333	0.167	0.111	0.167
4	0.385	0.231	0.154	0.115	0.115
5	0.206	0.294	0.235	0.176	0.088
6	0.385	0.192	0.192	0.115	0.115
7	0.294	0.176	0.265	0.118	0.147
8	0.233	0.233	0.233	0.070	0.233
9	0.200	0.267	0.333	0.067	0.133
10	0.167	0.167	0.417	0.042	0.208
11	0.391	0.130	0.391	0.043	0.043
12	0.156	0.281	0.156	0.094	0.313
13	0.242	0.242	0.303	0.030	0.182
14	0.278	0.194	0.250	0.083	0.194
15	0.190	0.238	0.238	0.143	0.190
16	0.105	0.211	0.263	0.211	0.211

Mean	0.250	0.223	0.255	0.107	0.165
Standard Deviation	0.088	0.053	0.078	0.051	0.064
Coeff. of Variation	0.352	0.238	0.306	0.477	0.388
Minimum Value	0.110	0.130	0.150	0.030	0.040
Maximum Value	0.390	0.330	0.420	0.210	0.310

Note: Weights have been normalized so the sum of the five weights equals one.

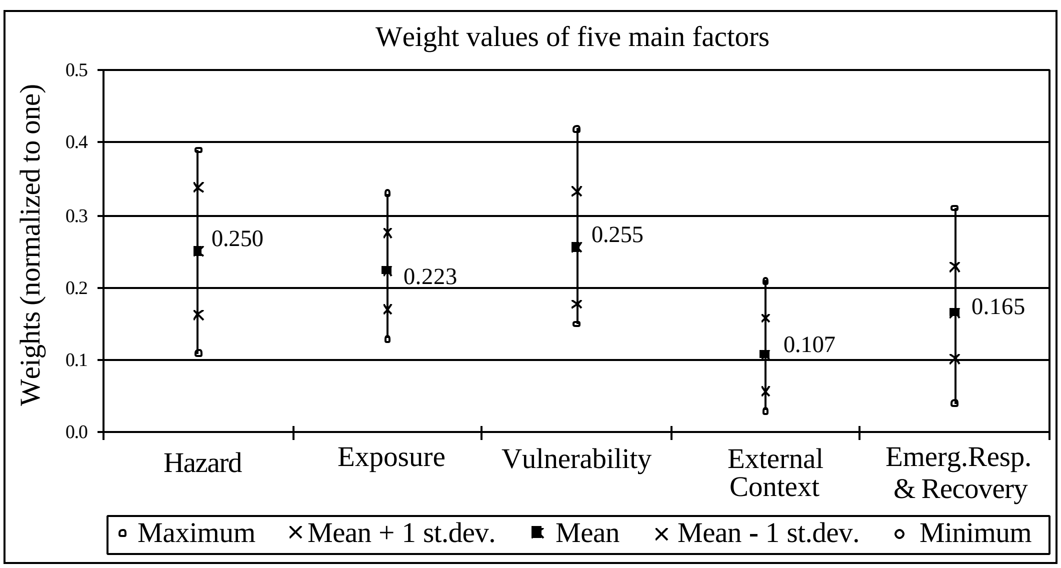


Figure 5.7. Summary of questionnaire survey results

Second, while the means of the Hazard, Exposure, and Vulnerability weights are all about 0.25, the means for Emergency Response and Recovery Capability and External Context weights are only about 0.16 and 0.11, respectively. The lower Response and Context weights could reflect a genuine belief by the respondents that those two factors contribute less to earthquake disaster risk than the other factors, or they could be due to the fact that Response and Context are less familiar concepts in earthquake risk assessment than the other three factors.

Third, the results provided guidelines for determining the weights that should be adopted in the Earthquake Disaster Risk Index ($w_H = w_E = w_V = 0.25$; $w_C = w_R = 0.125$), and suggested the range of weights that to be investigated in studying the sensitivity of the final EDRI values to the weight values (see Section 7.4).

5.3.4.3. Sample analysis solution

Table 5.6 summarizes the final weight values employed in the sample analysis. The values may be substituted directly into the equations in Section 5.1.5. Figure 5.8 illustrates how the values were derived by first assessing weights for the factor components. For example, the weight 0.298 for $e^{(\text{MMI w/50-year return period})}$ is the product of the three factor component weights: 0.7 for being part of ground shaking versus collateral hazards, 0.85 for bedrock ground shaking versus soft soil, and 0.5 for being part of short-, not long-term seismicity. Presenting the weights explicitly allows the users to see the assumptions about the definition-related relative contributions that were made in constructing the EDRI. If a user disagrees with any of these assumptions made about the relative importance of different factors, the values of the appropriate weights can be easily changed to reflect a different set of assumptions.

Table 5.6. Summary of sample analysis weights

Factor	Indicator	Weight name	Weight value
Hazard	exp(MMI w/50-year return period)	W_{H1}	0.298
	exp(MMI w/500-year return period)	W_{H2}	0.298
	Percentage urbanized area w/soft soil	W_{H3}	0.105
	Percentage urbanized area w/high liquefaction suscept.	W_{H4}	0.100
	Percentage of buildings that are wood	W_{H5}	0.050
	Population density	W_{H6}	0.050
	Tsunami potential indicator	W_{H7}	0.100
	HAZARD	W_H	0.250
Exposure	Population	W_{E1}	0.140
	Per capita GDP in constant 1990 US$	W_{E2}	0.060
	Number of housing units	W_{E3}	0.140
	Urbanized land area (sq.km.)	W_{E4}	0.060
	Population	W_{E5}	0.400
	Per capita GDP in constant 1990 US$	W_{E6}	0.200
	EXPOSURE	W_E	0.250
Vulner-ability	Seismic code indicator	W_{V1}	0.190
	City wealth indicator	W_{V2}	0.285
	City age indicator	W_{V3}	0.190
	Population density	W_{V4}	0.190
	City development speed indicator	W_{V5}	0.095
	Percentage of population aged 0-4 or 65+	W_{V6}	0.050
	VULNERABILITY	W_V	0.250
External Context	Economic external context indicator	W_{C1}	0.800
	Political country external context indicator	W_{C2}	0.100
	Political world external context indicator	W_{C3}	0.100
	EXTERNAL CONTEXT	W_C	0.125
Emerg. Resp. & Recovery	Planning indicator	W_{R1}	0.333
	Per capita GDP in constant 1990 US$	W_{R2}	0.133
	Avg. annual real growth in per cap. GDP in prev. 10 yrs.	W_{R3}	0.033
	Housing vacancy rate	W_{R4}	0.083
	Number of hospitals per 100,000 residents	W_{R5}	0.042
	Number of physicians per 100,000 residents	W_{R6}	0.042
	Extreme weather indicator	W_{R7}	0.111
	Population density	W_{R8}	0.111
	City layout indicator	W_{R9}	0.111
	EMERGENCY REPONSE & RECOVERY	W_R	0.125

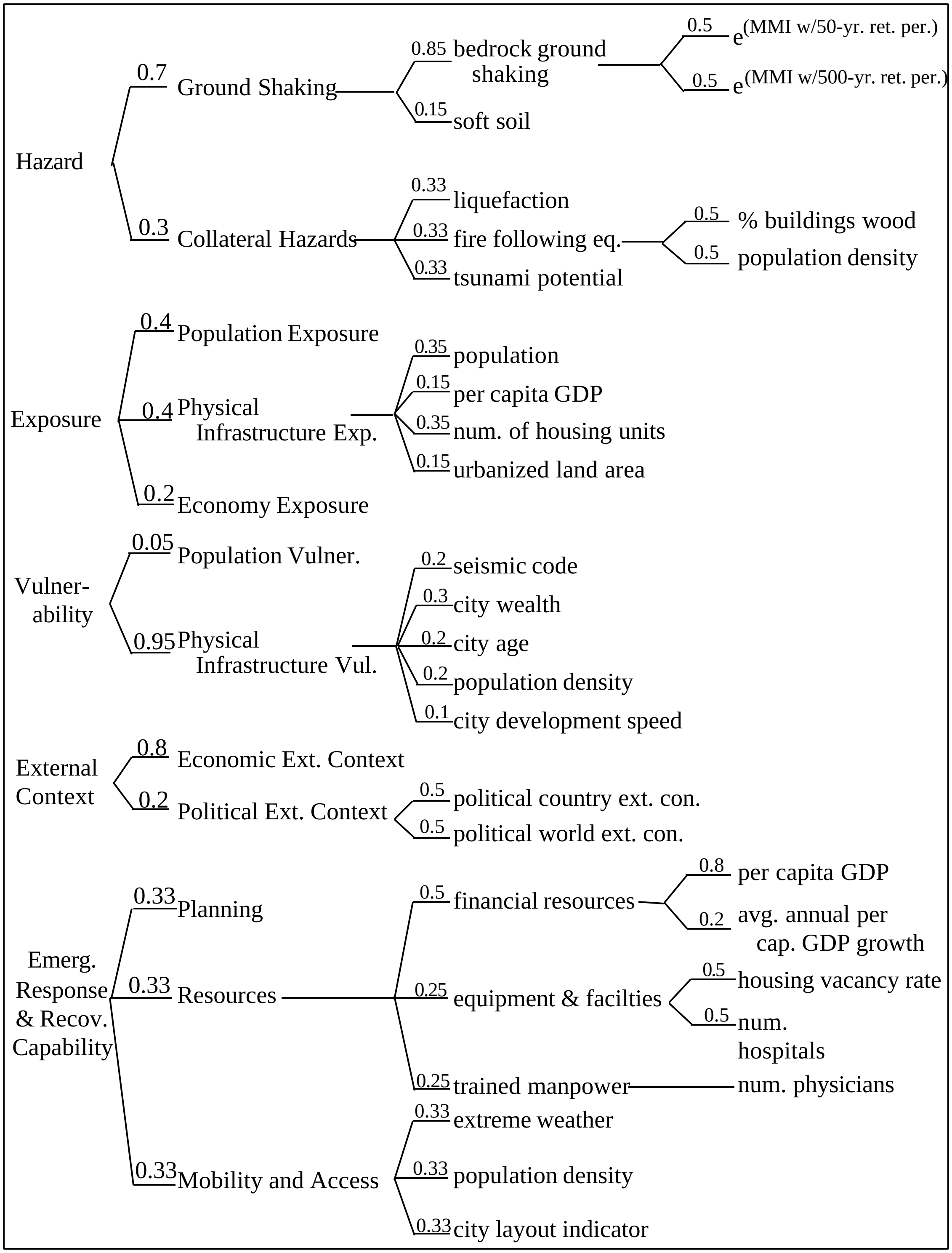


Figure 5.8. Factor component weights

5.4. Mathematical combination summary

Chapter 5 had two purposes: (1) to determine the best method by which to combine the indicators from Chapter 4 into the EDRI, and (2), in the process of completing the first goal, to identify the alternatives available for this type of combination, and to compare them systematically. To summarize the results of the first task, it was determined that the indicators listed in Figure 4.1 should be combined in two steps. First, the value x_{ij} for each indicator i and city j should be scaled using one of the following equations (reprinted from Sections 5.2.7 and 5.2.8):

$$x'_{ij} = \frac{x_{ij} - (\bar{x}_i - 2s_i)}{s_i} \tag{5.9}$$

if the indicator is directly-related to earthquake disaster risk,

$$x_{ij}' = \frac{-x_{ij} + (\bar{x}_i + 2s_i)}{s_i} \tag{5.10}$$

if the indicator is inversely-related to earthquake disaster risk. Second, the following equations are used to combine the scaled values into the five main factor indexes and the EDRI (reprinted from Section 5.1.5):

$$EDRI = w_H H + w_E E + w_V V + w_C C + w_R R \tag{5.4a}$$

$$H = w_{H1}x'_{H1} + w_{H2}x'_{H2} + w_{H3}x'_{H3} + w_{H4}x'_{H4} + w_{H5}x'_{H5} + w_{H6}x'_{H6} + w_{H7}x'_{H7} \tag{5.4b}$$

$$E = w_{E1}x'_{E1} + w_{E2}x'_{E2} + w_{E3}x'_{E3} + w_{E4}x'_{E4} + w_{E5}x'_{E5} + w_{E6}x'_{E6} \tag{5.4c}$$

$$V = w_{V1}x'_{V1} + w_{V2}x'_{V2} + w_{V3}x'_{V3} + w_{V4}x'_{V4} + w_{V5}x'_{V5} + w_{V6}x'_{V6} \tag{5.4d}$$

$$C = w_{C1}x'_{C1} + w_{C2}x'_{C2} + w_{C3}x'_{C3} \tag{5.4e}$$

$$R = w_{R1}x'_{R1} + w_{R2}x'_{R2} + w_{R3}x'_{R3} + w_{R4}x'_{R4} + w_{R5}x'_{R5} + w_{R6}x'_{R6} + w_{R7}x'_{R7} + w_{R8}x'_{R8} + w_{R9}x'_{R9} \tag{5.4f}$$

where H, E, V, C, and R are the values of the Hazard, Exposure, Vulnerability, External Context, and Emergency Response and Recovery Capability indexes, respectively; x'_i refer to the scaled values of the indicators listed in Figure 4.1; and w_i are the weights listed in Table 5.6.

Although many other composite indexes are available to measure a wide range of concepts, the publications in which they are described include little, if any, discussion of the mathematics of their combinations. Many composite indexes use a linear combination approach, but none explain why this method was chosen, or if other approaches were considered. At least five different scaling techniques and three different weighting approaches were represented among the many indexes that were examined in the literature survey, but again, none of the publications provided a systematic comparison of the alternative techniques available. It is not immediately obvious what, if any, implications are associated with choosing one scaling option or weighting technique over another. This chapter aimed to fill this gap in the literature by identifying and systematically comparing the various combination, scaling, and weighting alternatives available. This comparison provides a sound analytical basis for determining which methods are most appropriate for a given task, in particular for defining the EDRI and its associated factor indexes. Sections 7.3 and 7.4 provide some empirical comparison of the various scaling and weighting options.

Chapter Six
Data Gathering and Evaluation

6. Introduction

With the indicators selected and the method for their mathematical combination established, the theoretical component of the Earthquake Disaster Risk Index development process is essentially complete. This chapter describes the process of gathering data and evaluating the five main factors and the EDRI for a sample of cities. The discussion of data gathering identifies some potentially useful sources of data, common deficiencies in the available data, and approaches to overcome those deficiencies (Section 6.1). The procedure for evaluating the EDRI is outlined (Section 6.2), and the results of the data gathering and evaluation step in the sample analysis are presented (Section 6.2). The indicator selection and data gathering steps overlap considerably because an indicator cannot be included if the data to measure it are not available. Some of the issues discussed in Section 6.1, therefore, could have been included in Chapter 4. They are mentioned here instead, to keep all data-related issues together.

6.1. Data sources

As mentioned in Section 4.1, indicators should depend on data that is reliable, available in a consistent form for all the world's major cities, and relatively easy to collect. Data are reliable if the proportion of variance that is error variance is sufficiently small (Rossi and Gilmartin 1980). It will be impossible, in general, to obtain statistically-based, quantitative estimates of the error variance, but approximations can be surmised based on the quality of the data sources used, and on whether the required data values are reported directly or are estimated from related, available data. "In consistent form" indicates that the data for each indicator should refer to the same quantity across cities, and data for each city should refer to the same city boundaries across indicators. Data are considered relatively easy to collect if they are publicly available, and any user can obtain them in a reasonable amount of time, with limited or no financial expense. In the sample analysis, if the data could be gathered from the author's university, in a time frame of a couple of months[1] for ten cities, they were considered to be relatively easy to collect.

Sources of EDRI data come in three principal forms: compilations, focused sources, and personal communications. Compilations published by the United Nations, World Bank, International Monetary Fund, or other international organizations are a good starting point for the data gathering expedition. A single compilation can provide data for all or several cities, and presumably the task of ensuring consistency across indicators and cities has already been undertaken before the data are published. Sources focused on one or two topics and/or cities (e.g., journal articles, censuses, country-specific statistical yearbooks) can be used to fill in data that have not been compiled already. These sources provide more detailed data, but gathering information from many specific sources can be much more labor-intensive than using compilations, and it is difficult to ensure consistency across sources. Finally, personal interviews with local or topic experts can be particularly useful in providing subjective assessment information about, for example, emergency response and recovery planning, or seismic code enforcement. However, using personal interviews also may be more labor-intensive than using published material, and the data may reflect the biases of the information provider.

[1] In the sample analysis, data gathering was actually performed over the course of several months, because it was undertaken at the same time as the indicator selection step. Simultaneously determining which indicators to use and finding data for those indicators took more time than data gathering alone would if the indicator list was already established.

Several problems may be encountered in gathering data for the EDRI. The data simply may not exist, or they may exist, but not in the exact form in which they are needed. For example, "length of gas pipelines" was considered as a potential Exposure indicator. After an extensive library search and many conversations with local utilities personnel in Boston, St. Louis, and San Francisco, however, it became clear that that information simply does not exist in many cities. Accurate records were not kept at the time that many local pipelines were laid, so that even the utility companies may not know the length of pipeline in a given city.

Following are three situations in which data may exist, but still be problematic. First, data may be available, but not for the greater metropolitan areas defined in the EDRI. Most compilations published by international organizations, like the United Nations or World Bank, provide data by country. In the few compilations that present data by city (e.g., *Statistics of World Large Cities 1991*), the definition of what areas are included in the city are unclear, inconsistent across indicators, or different from those used in the EDRI, rendering the data unusable. "Number of police officers," under consideration as an Emergency Response and Recovery Capability indicator, was eventually omitted from the EDRI because the data, while they do exist, would be difficult to compile for different cities consistently. Police officers can be local, state, or federal employees, and each jurisdiction compiles the data on the number of police officers it employs separately. The quantity of interest to the EDRI is the total number of police officers in a given city—local, state, and federal. Counting only one type could be misleading, and compiling all three is difficult because it is not clear how many of the state and federal employees work within the greater metropolitan area of interest. "Per capita gas consumption," considered as an Exposure indicator alternative to "length of gas pipelines," provides another example of an indicator for which data theoretically exist, but are not compiled in a usable form. Some gas consumption data are available, but it is difficult or impossible to find the consumption level for exactly the areas contained in the specified city of interest. The data are available only disaggregated by company service area, state, or country, none of which coincide with the boundaries of the greater metropolitan area.

Second, data may not be available in a consistent, standardized form. Different cities may collect data using different units or using related, but different quantities. For example, many censuses report a break down of the number of housing units into categories based on the material used in the roof, but the set of possible materials varies from census to census. In the Philippines census, the categories of roof materials are galvanized iron/aluminum; tile/concrete/clay tile; half galvanized iron and half concrete; wood; cogon/nipa/anshaw; makeshift/salvaged/improvised; and asbestos/others. In the Chile census, the categories are zinc; concrete slab; slate; tiles; wood shingles; fonolita; straw and mud; and other. It is difficult to reconcile these different classification systems.

Third, for some indicators, data are available, but not for all major cities worldwide, or not for the year under consideration. For example, "average number of days per year that the temperature reaches 90°F or more, or 32°F or less" was considered as a possible extreme weather indicator for the Emergency Response and Recovery Capability factor, but data for it are readily available only for cities in the USA.

The data deficiencies described above may be addressed in a few ways. First, it may be possible to translate related data into a form that the EDRI can use through unit conversions. Land area may be reported in square kilometers, square miles, or hectares. Ground shaking may be presented in terms of MMI or PGA. Per capita Gross Domestic Product may be available in Yen for Japan and dollars for the USA. In all these cases, standard conversion formulas are available to make the data consistent for all cities. In some cases, more significant manipulation is required to derive the desired data from the available data. For example, in the sample analysis, since the Indonesian census reports the percentage of the population aged 0-4 or 65+ for urban Indonesia, but not for DKI Jakarta specifically, the latter quantity was estimated to be equal to the former. The number of housing units in Lima was available only for 1981, so the 1990 value was estimated as:

$$(\text{Num. housing units})_{1990} = (\text{Num. housing units})_{1981} * \left[\frac{\text{Population}_{1990}}{\text{Population}_{1981}}\right], \qquad (6.1)$$

assuming that the number of people per housing unit was the same for both years. For each indicator-city value, the degree of manipulation and estimation required to transform the data as reported into the data required by the EDRI values is reflected in the estimate of data uncertainty used in the sensitivity analysis (Section 7.5).

If the desired indicator data cannot be estimated reliably from related, available data, it may be necessary to select a different indicator to represent the concept of interest. The "economic external context indicator" was defined so that it relies only on available data. While the indicator originally hoped to measure the total economic exchange between the city and the world, the only related data available was the total economic exchange between the *country* and the world. Since a country's economic exchange may be distributed unevenly among its cities, it was necessary to develop the economic external context indicator used in the sample analysis to capture the concept using only available data (see Section 4.3.4.1).

Finally, if data for an indicator cannot be found directly or estimated from related, available data, and the indicator cannot be redefined to accommodate the data, it may be necessary to omit an indicator entirely. Since the EDRI aims to be as comprehensive as possible, omitting a concept should be considered a last resort. Nevertheless, if no reasonably reliable and consistent data can be found to evaluate a given indicator, it is better to omit that indicator than to incorporate an excessive amount of uncertainty into the model. In the sample analysis, for example, the exposure indicators do not attempt to measure the percentage of the population that lives in poverty because of the well-documented difficulties in obtaining consistent, reliable assessments of that quantity.

6.2. Evaluation procedure

The five main factors and the EDRI for a set of cities can be evaluated in three steps. First, an unscaled indicator-city table, like the sample analysis example in Table 6.2, should be completed. For some indicators, the values can be taken directly from the data source and entered into the table. For derived indicators, such as "economic external context indicator," "$e^{(\text{MMI with a fifty-year return period})}$," and "city development speed indicator," the indicator values must be calculated from the raw data before being entered into the unscaled indicator-city data table. To reduce data uncertainty, it is best to evaluate cities as consistently as possible. For each indicator, a single source and procedure should be used if possible. Second, the scaled indicator-city table should be completed. The scaled table is similar to the unscaled version, but with two variations. The value in each cell will be the scaled value x_{ij}' instead of the unscaled value x_{ij} (see Sections 5.2.7 and 5.2.8), and extra rows are included for the values of the five main factors and the EDRI. Third, as part of completing the scaled table, the values for the five main factor indexes and the overall EDRI can be computed for each city, using the appropriate linear combination equations and weights (see Section 5.1.5 and Table 5.6). Constructing the charts and figures that will be used to display this information in graphical form is discussed in Chapter 8.

Finally, when the main factor and EDRI values are evaluated in subsequent time periods, the scaling should be performed using the mean and standard deviation of the base year, to allow consistent comparison over time. Otherwise, a city's EDRI may rise substantially from one time period to the next, but if the values for every other city increase proportionally, the final EDRI will appear to have remained constant.

6.3. Sample analysis solution

In the sample analysis, data were gathered and the main factor and EDRI values were computed for ten cities for the year 1990. These steps were performed on real cities to explore the availability and quality of data for the indicator selection phase, to illustrate the data gathering and evaluation process for real cities, and to obtain results that could be used to demonstrate the subsequent sensitivity analysis, presentation, and interpretation steps of the process. The following sample analysis cities were selected to represent a variety of values for each of the main factors, and to explore a variety of data availability situations:

Boston, USA	Mexico City, Mexico
Istanbul, Turkey	San Francisco, USA
Jakarta, Indonesia	Santiago, Chile
Lima, Peru	St. Louis, USA
Manila, Philippines	Tokyo, Japan

The sample represents developing and industrialized countries, four continents, populations from two to thirty-five million people, and a range of levels of seismicity. As discussed in Section 2.4, it is critical to establish at the outset exactly what areas are included in each greater metropolitan area (city) in the analysis. Appendix B lists the areas (e.g., counties, cities) that are included in each of the ten sample analysis cities.

Table 6.1 summarizes for every indicator-city combination, the source(s) of the data used in the sample analysis. Some values were reported by the source(s) directly, and some were estimated from information provided in the sources. The number(s) in each cell corresponds to the reference(s) listed in Figure 6.1.

Table 6.1. Sample analysis data sources

Factor		Indicator	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Fran.	Santiago	St. Louis	Tokyo
Hazard	xh1	exp(MMI w/50-year return period)	20	18	20	14	6, 7	9	20	20	20	20
	xh2	exp(MMI w/500-year return period)	20	18	20	14	6, 7	9	20	20	20	20
	xh3	Percentage urbanized area w/soft soil	20	18	20	15	8	10	40	20	20	20
	xh4	Percentage urbanized area w/high liquefaction suscept.	20	18	20	15	8	10	20	20	20	20
	xh5	Percentage of buildings that are wood	65	---	64	13	5	19	65	32	65	64
	xh6	Population density (people/sq.km.)	21	16, 17	20, 30	11	4	2	21	32	21	1
	xh7	Tsunami potential indicator	33	33	33	33	33	33	33	33	33	33
Exposure	xe1	Population (1000s)	21	17	30	11	4	2	21	32	21	1
	xe2	Per capita GDP in constant 1990 US$	22	22	22	22	22	22	22	22	22	22
	xe3	Number of housing units (1000s)	21	17	30	11	5	2	21	32	21	1
	xe4	Urbanized land area (sq.km.)	21	3, 18	20	11	4	2, 3	21	32	21	1
	xe5	Population (1000s)	21	17	30	11	4	2	21	32	21	1
	xe6	Per capita GDP in constant 1990 US$	22	22	22	22	22	22	22	22	22	22
Vulner-ability	xv1	Seismic code indicator	45, 61	42, 45, 59, 60	42, 45, 50	41, 45, 53-55	45, 56	41, 45, 57, 58	43, 45, 46	41, 45, 51, 52	44, 45, 61	42, 45, 47-49
	xv2	City wealth indicator	22	22	22	22	22	22	22	22	22	22
	xv3	City age indicator	24	17, 23	28, 29, 30	11,23	4	2, 23	24	25, 26, 27	24	1
	xv4	Population density (people/sq.km.)	21	16, 17	20, 30	11	4	2	21	32	21	1
	xv5	City development speed indicator	24	17, 23	28, 29, 30	11,23	4	2, 23	24	25, 26, 27	24	1
	xv6	Percentage of population aged 0-4 or 65+	21	16	30	11	4	2	21	36	21	1
External Context	xc1	Economic external context indicator	37, 23, 21	17, 23, 37	23, 30, 37	11, 23, 37	4, 23, 37	2, 23, 37	21, 23, 37	23, 32, 37	21, 23, 37	1, 23, 37
	xc2	Political country external context indicator	21	17	30	11	4	2	21	32	21	1
	xc3	Political world external context indicator	21,22	17, 32	22, 30	11, 22	4, 22	2, 22	21, 22	22, 32	21, 22	1, 22
Emerg. Resp. & Recovery	xr1	Planning indicator	62	34	34	34	34	34	63	34	34	34
	xr2	Per capita GDP in constant 1990 US$	22	22	22	22	22	22	22	22	22	22
	xr3	Avg. annual real growth in per cap. GDP in prev. 10 yrs.	22	22	22	22	22	22	22	22	22	22
	xr4	Housing vacancy rate	21	---	---	13	5	---	21	32	21	1
	xr5	Number of hospitals per 100,000 residents	21	17	31	12	4	2	21	35	21	1
	xr6	Number of physicians per 100,000 residents	21	17	31	12	4	2	21	35	21	1
	xr7	Extreme weather indicator	38	39	39	39	39	39	38	39	38	39
	xr8	Population density (people/sq.km.)	21	16, 17	20, 30	11	4	2	21	32	21	1
	xr9	City layout indicator	34	34	34	34	34	34	34	34	34	34

Numbers refer to sources listed in Figure 6.1.

1. (Japan Statistics Bureau 1995)
2. (Mexico INEGI 1994 and 1995)
3. (Institut d'Estudis de Barcelona 1988)
4. (Philippines NEDA 1995)
5. (Philippines NSO 1992)
6. (Algermissen, Thenhaus, and Campbell 1996)
7. (Su 1978)
8. (Rantucci 1994)
9. (Wang et al. 1996)
10. (Romo, Jaime, and Resendiz 1988)
11. (Peru INE 1993)
12. (Webb and Baca 1993)
13. (Peru INEI 1994)
14. (Sharma and Candia-Gallegos 1992)
15. (Alva-Hurtado 1994)
16. (Turkey. Devlet Istatistik Enstitusu 1994)
17. (Turkey. Devlet Istatistik Enstitusu 1992)
18. (Erdik 1994)
19. (Mexico INEGI 1990-92)
20. (Windeler 1995-97)
21. (U.S. Bureau of the Census 1930-94)
22. (IMF 1996)
23. (UN. Population Division 1995b)
24. (U.S. Bureau of the Census 1930-94)
25. (Chile DGE 1931-35)
26. (Chile DEC 1963)
27. (Chile INE 1958-90)
28. (Indonesia BPS 1941-82)
29. (UN. Population Division 1995a)
30. (Indonesia BPS 1992)
31. (Indonesia NDIO 1993)
32. (Chile INE 1992a, 1992b)
33. (NGDC 1997)
34. (Author's assessment)
35. (Chile OPN 1993)
36. (Chile INE 1989)
37. (IMF 1995)
38. (Ruffner and Bair 1987)
39. (NCDC 1997)
40. (US Geological Survey 1994)
41. (Takizawa 1993)
42. (Watabe 1983)
43. (Martin 1993)
44. (Olshansky 1993)
45. (Hirosawa et al. 1992)
46. (SEAOC 1975, 1990)
47. (UNCRD 1995)
48. (RMS 1995)
49. (Otani 1995)
50. (Fraser 1983)
51. (Cruz 1989)
52. (Sarrazin 1992)
53. (Acuna 1992)
54. (Vega 1992)
55. (Zegarra 1987)
56. (Nakata 1991)
57. (Rosenblueth 1987)
58. (Marsh 1993)
59. (Gulkan and Ergunay 1984)
60. (Bayulke 1992)
61. (Morse 1989)
62. (Smith 1996)
63. (Eisner 1996)
64. (Romer 1995-97)
65. (Bouabid 1995-97)

Figure 6.1. Sources cited in Table 6.1.

Tables 6.2 and 6.3 are the unscaled and scaled sample analysis indicator-city tables, respectively. In the unscaled table, a few values are in bold to indicate that they were set equal to the mean of the corresponding indicator, because real data could not be obtained for that indicator-city combination during the sample analysis. The scaled

Table 6.2. Unscaled indicator-city data

Factor		Indicator	D/ I*	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	xh1	exp(MMI w/50-year return period)	D	446	992	164	2981	1339	164	1212	602	493	1339
	xh2	exp(MMI w/500-year return period)	D	3641	4447	735	6634	2208	493	4024	1998	4915	3641
	xh3	Percentage urbanized area w/soft soil	D	35%	15%	7%	25%	5%	50%	17%	4%	0%	10%
	xh4	Percentage urbanized area w/high liquefaction suscep	D	35%	7%	49%	25%	50%	5%	17%	4%	21%	20%
	xh5	Percentage of buildings that are wood	D	67%	**42%**	19%	4%	32%	2%	68%	59%	64%	60%
	xh6	Population density (people/sq.km.)	D	884.1	12161.1	12652.6	9862.8	19756.6	11999.6	1075.3	8130.9	745.2	8849.2
	xh7	Tsunami potential indicator	D	0	1	1	2	1	0	2	0	0	2
Exposure	xe1	Population (1000s)	D	5,686	5,328	8,228	6,397	7,928	16,621	6,253	4,311	2,493	35,467
	xe2	Per capita GDP in constant 1990 US$	D	25,610	1,749	1,521	564	623	2,705	25,312	2,088	20,181	25,833
	xe3	Number of housing units (1000s)	D	2,271	1,194	1,548	1,200	1,483	3,377	2,457	1,056	1,027	14,046
	xe4	Urbanized land area (sq.km.)	D	1336.8	796.4	487.7	698.5	572.4	1614.9	2099.4	346.5	993.5	3525.9
	xe5	Population (1000s)	D	5,686	5,328	8,228	6,397	7,928	16,621	6,253	4,311	2,493	35,467
	xe6	Per capita GDP in constant 1990 US$	D	25,610	1,749	1,521	564	623	2,705	25,312	2,088	20,181	25,833
Vulner-ability	xv1	Seismic code indicator	I	14.18	40.82	8.76	9.83	10.78	39.81	52.88	19.70	10.08	52.79
	xv2	City wealth indicator	I	2780	318	100	135	130	489	2981	258	2858	4631
	xv3	City age indicator	D	49.7	8.8	11.9	8.7	10.7	14.1	19.7	20.1	42.4	20.6
	xv4	Population density (people/sq.km.)	D	884.1	12161.1	12652.6	9862.8	19756.6	11999.6	1075.3	8130.9	745.2	8849.2
	xv5	City development speed indicator	I	106	18	22	18	20	23	37	32	89	36
	xv6	Percentage of population aged 0-4 or 65+	D	19.80%	14.80%	13.70%	14.30%	14.90%	15.20%	18.10%	16.70%	20.40%	14.70%
External Context	xc1	Economic external context indicator	D	3.43E+12	3.28E+11	5.73E+11	8.21E+10	2.56E+11	2.49E+12	4.15E+12	1.13E+11	6.59E+11	4.20E+13
	xc2	Political country external context indicator	D	0.0241	0.1096	1.0000	1.0000	1.0000	1.0000	0.0250	1.0000	0.0100	1.0000
	xc3	Political world external context indicator	D	1.54E+11	1.08E+10	2.78E+11	1.22E+10	3.79E+10	2.29E+11	1.58E+11	2.75E+10	5.03E+10	3.19E+12
Emerg. Resp. & Recovery	xr1	Planning indicator	I	3	3	1	3	1	3	4	1	3	4
	xr2	Per capita GDP in constant 1990 US$	I	25,610	1,749	1,521	564	623	2,705	25,312	2,088	20,181	25,833
	xr3	Avg. annual real growth in per cap. GDP in prev. 10	I	2.13%	2.93%	10.17%	-2.82%	-0.71%	-0.48%	0.29%	1.50%	2.20%	3.56%
	xr4	Housing vacancy rate	I	7.00%	**6.70%**	**6.70%**	8.70%	3.20%	**6.70%**	5.20%	3.50%	8.30%	11.00%
	xr5	Number of hospitals per 100,000 residents	I	1.88	1.60	1.99	3.19	2.17	0.85	1.45	1.83	1.98	5.57
	xr6	Number of physicians per 100,000 residents	I	332	180	36.5	172	32	187	299	68	253	164
	xr7	Extreme weather indicator	D	118.00	41.40	46.93	0.00	46.46	7.82	10.40	65.07	126.60	55.67
	xr8	Population density (people/sq.km.)	D	884.1	12161.1	12652.6	9862.8	19756.6	11999.6	1075.3	8130.9	745.2	8849.2
	xr9	City layout indicator	D	0	1	0	0	0	0	1	0	0	0

D = directly related to earthquake disaster risk. I = inversely related to earthquake disaster risk. If directly related to earthquake disaster risk, use equation 5.9 to scale; if inversely related, use equation 5.10 to scale.

Boldfaced values were set equal to the sample mean because real data could not be obtained.

Table 6.3. Scaled indicator-city data

Factor		Indicator	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	xh1	exp(MMI w/50-year return period)	1.370	2.023	1.034	4.397	2.437	1.034	2.285	1.557	1.426	2.437
	xh2	exp(MMI w/500-year return period)	2.191	2.612	0.677	3.751	1.445	0.551	2.391	1.335	2.855	2.191
	xh3	Percentage urbanized area w/soft soil	3.156	1.887	1.367	2.522	1.252	4.108	2.014	1.189	0.935	1.570
	xh4	Percentage urbanized area w/high liquefaction suscept.	2.701	1.029	3.515	2.104	3.597	0.909	1.626	0.850	1.865	1.805
	xh5	Percentage of buildings that are wood	2.975	2.000	1.131	0.540	1.630	0.478	3.013	2.667	2.860	2.706
	xh6	Population density	0.752	2.573	2.653	2.202	3.800	2.547	0.783	1.922	0.729	2.038
	xh7	Tsunami potential indicator	0.972	2.114	2.114	3.256	2.114	0.972	3.256	0.972	0.972	3.256
		HAZARD	**1.945**	**2.120**	**1.405**	**3.362**	**2.129**	**1.242**	**2.281**	**1.397**	**1.835**	**2.285**
Exposure	xe1	Population	1.571	1.534	1.831	1.644	1.801	2.692	1.629	1.430	1.243	4.625
	xe2	Per capita GDP in constant 1990 US$	3.266	1.251	1.232	1.151	1.156	1.332	3.241	1.279	2.808	3.285
	xe3	Number of housing units	1.825	1.553	1.642	1.555	1.626	2.104	1.872	1.518	1.511	4.794
	xe4	Urbanized land area (sq.km.)	2.092	1.535	1.217	1.435	1.305	2.379	2.878	1.072	1.738	4.348
	xe5	Population	1.571	1.534	1.831	1.644	1.801	2.692	1.629	1.430	1.243	4.625
	xe6	Per capita GDP in constant 1990 US$	3.266	1.251	1.232	1.151	1.156	1.332	3.241	1.279	2.808	3.285
		EXPOSURE	**2.078**	**1.463**	**1.612**	**1.491**	**1.579**	**2.237**	**2.157**	**1.382**	**1.717**	**4.284**
Vulner-ability	xv1	Seismic code indicator	2.638	1.196	2.931	2.873	2.821	1.251	0.544	2.339	2.859	0.548
	xv2	City wealth indicator	1.215	2.688	2.819	2.798	2.801	2.586	1.095	2.724	1.168	0.107
	xv3	City age indicator	4.043	1.166	1.384	1.159	1.297	1.538	1.930	1.963	3.525	1.995
	xv4	Population density	0.752	2.573	2.653	2.202	3.800	2.547	0.783	1.922	0.729	2.038
	xv5	City development speed indicator	-0.104	2.706	2.578	2.706	2.642	2.546	2.099	2.259	0.439	2.131
	xv6	Percentage of population aged 0-4 or 65+	3.484	1.388	0.927	1.178	1.430	1.556	2.772	2.185	3.736	1.346
		VULERABILITY	**1.923**	**2.030**	**2.418**	**2.298**	**2.625**	**2.071**	**1.269**	**2.283**	**1.913**	**1.171**
External Context	xc1	Economic external context indicator	1.847	1.608	1.627	1.589	1.602	1.774	1.902	1.591	1.633	4.827
	xc2	Political country external context indicator	0.803	0.976	2.774	2.774	2.774	2.774	0.805	2.774	0.775	2.774
	xc3	Political world external context indicator	1.734	1.588	1.860	1.589	1.615	1.810	1.738	1.605	1.628	4.833
		EXTERNAL CONTEXT	**1.731**	**1.542**	**1.765**	**1.707**	**1.721**	**1.878**	**1.776**	**1.711**	**1.547**	**4.622**
Emerg. Resp. & Recovery	xr1	Planning indicator	1.659	1.659	3.363	1.659	3.363	1.659	0.807	3.363	1.659	0.807
	xr2	Per capita GDP in constant 1990 US$	0.734	2.749	2.768	2.849	2.844	2.668	0.759	2.721	1.192	0.715
	xr3	Avg. annual real growth in per cap. GDP in prev. 10 yrs.	1.928	1.699	-0.374	3.344	2.740	2.675	2.454	2.108	1.908	1.518
	xr4	Housing vacancy rate	1.873	2.000	2.000	1.150	3.487	2.000	2.637	3.359	1.320	0.173
	xr5	Number of hospitals per 100,000 residents	2.283	2.502	2.198	1.283	2.063	3.073	2.611	2.321	2.205	-0.538
	xr6	Number of physicians per 100,000 residents	0.465	1.926	3.306	2.003	3.349	1.859	0.783	3.003	1.225	2.080
	xr7	Extreme weather indicator	3.538	1.757	1.886	0.795	1.875	0.977	1.037	2.308	3.738	2.089
	xr8	Population density	0.752	2.573	2.653	2.202	3.800	2.547	0.783	1.922	0.729	2.038
	xr9	City layout indicator	1.526	3.897	1.526	1.526	1.526	1.526	3.897	1.526	1.526	1.526
		EMERGENCY RESPONSE & RECOVERY	**1.632**	**2.242**	**2.548**	**1.780**	**2.908**	**1.931**	**1.448**	**2.695**	**1.694**	**1.122**
		EARTHQUAKE DISASTER RISK INDEX	**1.907**	**1.876**	**1.898**	**2.223**	**2.162**	**1.864**	**1.830**	**1.816**	**1.772**	**2.653**

indicator-city table includes the values of the five main factors and the EDRI. The factor and EDRI values are calculated using the scaled data in the same table, the equations in Section 5.1.5, and the weights from Table 5.6. Tables 6.4 and 6.5 are auxiliary tables that show the values of the components of each factor for each city (as in Figure 5.8), and the relative contributions of each of the five main factors to the EDRI, respectively. The factor component values are derived by combining only the indicators that relate to the specified factor component (listed in the third column of Table 6.4), rescaling the weights so that the sum of the included weights equals one. For example, ground shaking is calculated as: (6.2)

$$\text{Ground shaking} = \frac{w_{H1}}{(w_{H1} + w_{H2} + w_{H3})} x_{H1} + \frac{w_{H2}}{(w_{H1} + w_{H2} + w_{H3})} x_{H2} + \frac{w_{H3}}{(w_{H1} + w_{H2} + w_{H3})} x_{H3}$$

where x_{H1}, x_{H2}, and x_{H3} are "$e^{(\text{MMI with a fifty-year return period})}$," "$e^{(\text{MMI with a five-hundred-year return period})}$," and "percentage of urbanized area with soft soil," respectively; and w_{H1}, w_{H2}, and w_{H3} are the corresponding weights, presented in Table 5.6. For each of the five main factors, the city-specific relative contribution to the EDRI equals the ratio of the factor value divided by the sum of all five factor values (Section 5.1.4). For example, for Hazard,

$$\text{Relative contribution of Hazard} = \frac{H}{(H + E + V + C + R)} \qquad (6.3)$$

where H, E, V, C, and R are the values of the Hazard, Exposure, Vulnerability, External Context, and Emergency Response and Recovery Capability indexes, respectively. Note that the denominator is not equal to the EDRI value, because it does not include the factor weights.

Table 6.4. Factor component values

Factor	Factor components	Indicators included	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	Ground shaking	xh1-xh3	1.987	2.253	0.932	3.841	1.838	1.290	2.289	1.407	1.960	2.203
	Short-term seismicity	xh1	1.370	2.023	1.034	4.397	2.437	1.034	2.285	1.557	1.426	2.437
	Long-term seismicity	xh2	2.191	2.612	0.677	3.751	1.445	0.551	2.391	1.335	2.855	2.191
	Soft soil	xh3	3.156	1.887	1.367	2.522	1.252	4.108	2.014	1.189	0.935	1.570
	Collateral hazards	xh4-xh7	1.845	1.810	2.507	2.244	2.809	1.131	2.260	1.372	1.544	2.478
	Liquefaction	xh4	2.701	1.029	3.515	2.104	3.597	0.909	1.626	0.850	1.865	1.805
	Tsunami	xh5	0.972	2.114	2.114	3.256	2.114	0.972	3.256	0.972	0.972	3.256
	Fire following	xh6-xh7	1.863	2.287	1.892	1.371	2.715	1.513	1.898	2.295	1.794	2.372
	HAZARD		1.945	2.120	1.405	3.362	2.129	1.242	2.281	1.397	1.835	2.285
Exposure	Physical Infrastructure	xe1-xe4	1.992	1.499	1.583	1.507	1.568	2.235	2.143	1.385	1.646	4.442
	Population	xe5	1.571	1.534	1.831	1.644	1.801	2.692	1.629	1.430	1.243	4.625
	Economy	xe6	3.266	1.251	1.232	1.151	1.156	1.332	3.241	1.279	2.808	3.285
	EXPOSURE		2.078	1.463	1.612	1.491	1.579	2.237	2.157	1.382	1.717	4.284
Vulner-ability	Physical Infrastructure	xv1-xv5	1.840	2.064	2.497	2.357	2.688	2.098	1.190	2.288	1.817	1.161
	Population	xv6	3.484	1.388	0.927	1.178	1.430	1.556	2.772	2.185	3.736	1.346
	VULERABILITY		1.923	2.030	2.418	2.298	2.625	2.071	1.269	2.283	1.913	1.171
External Context	Economic	xc1	1.847	1.608	1.627	1.589	1.602	1.774	1.902	1.591	1.633	4.827
	Political	xc2-xc3	1.269	1.282	2.317	2.181	2.194	2.292	1.272	2.189	1.201	3.803
	EXTERNAL CONTEXT		1.731	1.542	1.765	1.707	1.721	1.878	1.776	1.711	1.547	4.622
Emerg. Resp. & Recovery	Planning	xr1	1.659	1.659	3.363	1.659	3.363	1.659	0.807	3.363	1.659	0.807
	Resources	xr2-xr6	1.298	2.323	2.258	2.173	2.960	2.451	1.632	2.804	1.426	0.674
	Financial resources	xr2-xr3	0.972	2.539	2.140	2.948	2.824	2.670	1.098	2.598	1.335	0.876
	Equipment & facility resources	xr4-xr5	2.771	3.001	2.798	1.622	3.700	3.382	3.499	3.787	2.350	-0.243
	Trained manpower resources	xr6	0.465	1.926	3.306	2.003	3.349	1.859	0.783	3.003	1.225	2.080
	Mobility and access	xr7-xr9	1.938	2.743	2.021	1.508	2.400	1.683	1.906	1.919	1.998	1.884
	EMERG. RESP. & RECOV.		1.632	2.242	2.548	1.780	2.908	1.931	1.448	2.695	1.694	1.122
	EDRI		1.907	1.876	1.898	2.223	2.162	1.864	1.830	1.816	1.772	2.653

Table 6.5. Relative contributions[2] of each factor to the overall EDRI values

	Hazard	Exposure	Vulnerability	External Context	Emerg. Resp. & Recovery
Boston	21%	22%	21%	19%	18%
Istanbul	23%	16%	22%	16%	24%
Jakarta	14%	17%	25%	18%	26%
Lima	32%	14%	22%	16%	17%
Manila	19%	14%	24%	16%	27%
Mexico City	13%	24%	22%	20%	21%
San Francisco	26%	24%	14%	20%	16%
Santiago	15%	15%	24%	18%	28%
St. Louis	21%	20%	22%	18%	19%
Tokyo	17%	32%	9%	34%	8%

Although the EDRI data requirements pale in comparison to those associated with engineering loss estimation methods, gathering data for each indicator and city still constitutes the most time- and labor-intensive step in the EDRI development process. Since there had been no previous international comparisons of urban earthquake risk like that that the EDRI aims to achieve, only limited effort had been made previously to compile the type of data needed for the EDRI. Even in fields that do have established mechanisms for gathering data, information is rarely compiled in a systematic, consistent way for greater metropolitan areas. Nevertheless, because these data restrictions were considered in selecting the indicators for the EDRI, the data needs can be met to produce useful results with a reasonable amount of effort. The findings presented here are examined in depth in the two chapters that follow. Chapter 7 explores the sensitivity of the results to the uncertainties involved in the analysis. Chapter 8 examines various ways of presenting the results to make them more easily accessible, and interpreting them to understand their meaning and implications fully.

[2] City-specific relative contributions (see Section 5.2.4 for explanation).

Chapter Seven

Sensitivity Analysis

7. Introduction

Although the EDRI development and evaluation was treated as a deterministic process in the preceding chapters, the analysis actually involves many uncertainties. To determine the robustness of the results, a sensitivity analysis was conducted to explore the potential effect of each of these uncertainties on the final values of the five main factors and of the EDRI. Since validation is not possible (see Section 2.5), the sensitivity analysis helps to determine if the results are meaningful, or if they are rendered insignificant when the uncertainties considered. Seven possible sources of uncertainty were investigated: indicator definitions, indicator selection, scaling function, weights, data uncertainty, sample city selection, and city boundary definitions. The procedure and results for each are described in Sections 7.1 to 7.7. The analysis aimed to determine the conclusions that can be drawn about the relative city ranks in light of these uncertainties, and to identify the specific indicators and cities that have the potential to affect the values of the main factors and of the EDRI most significantly. Because the EDRI measures only relative values, it is important to examine the sensitivity of relative, not absolute values. It does not matter if changing the scaling technique increases the EDRI of every city by the same amount, for example. Only changes in the *relative* city values are significant. Section 7.8 compares and summarizes the findings of the various components of the sensitivity analysis.

7.1. Indicator definitions

In many cases, it is possible to define an EDRI indicator in more than one way, so that each variation seems to measure exactly the same concept, but in a slightly different form. In some cases, the choice among the variations seems arbitrary. For example, “number of physicians per 100,000 residents” and “number of hospitals per 100,000 residents” could be defined instead as “number of residents per physician” and “number of residents per hospital.” It is not immediately obvious how much, or if, it would affect the final main factor and EDRI values if one of the alternative definitions was used in place of the ones presented in Chapter 4. To explore the effect of indicator definitions, alternative definitions were developed for three sample analysis indicators, the analysis was rerun using each in turn, and the new results were compared to the original results presented in Chapter 6. In addition to the alternative definitions for “number of physicians per 100,000” and “number of hospitals per 100,000,” an alternative definition of “population density” was taken to be the ratio of total population to total land area (versus the weighted average definition provided in Section 4.3.1.3).

Figure 7.1 displays a comparison of the original results with those derived using the alternative definitions. There is one figure for each of the five main factors and the EDRI, and on each figure, there is one curve for each set of analysis results. (Note that the scales for each figure are different.) The alternative definitions for “number of physicians per 100,000” and “number of hospitals per 100,000” had a negligible effect on the EDRI results. The most that the Emergency Response and Recovery Capability factor value changed for any city was 4.4% for Lima and the most that the EDRI value changed for any city was 0.4% for Lima. The alternative definition for “population density,” however, resulted in changes of 9.7% for the Vulnerability and 4.8% for the EDRI in Jakarta. Sensitivity to the definitions of “population density” is less disturbing than sensitivity to those for the “physician” and “hospital” indicators, because the choice of “population density” definition is supported by reasoning. The chosen “population density” definition represents the concept of interest more accurately than the alternative one. In the case of the “physician” and “hospital” indicators, the choice was arbitrary. It weakens the power of the EDRI if its results are sensitive to arbitrary changes. In this case, sensitivity to arbitrary changes in the indicator definitions does not appear significant.

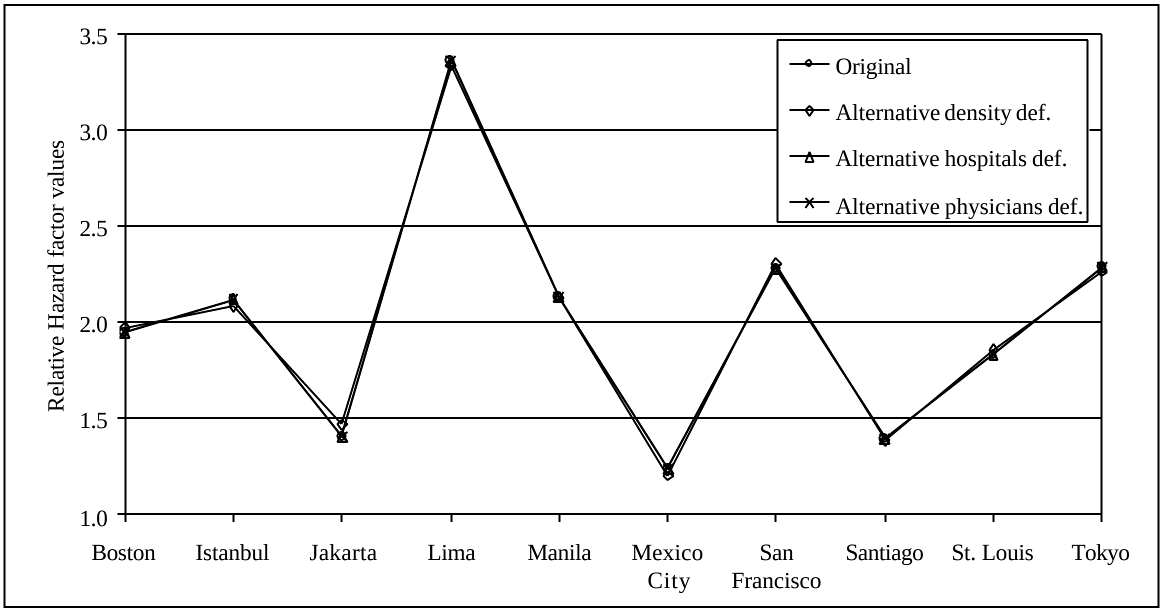


Figure 7.1a. Sensitivity of Hazard factor to indicator definitions

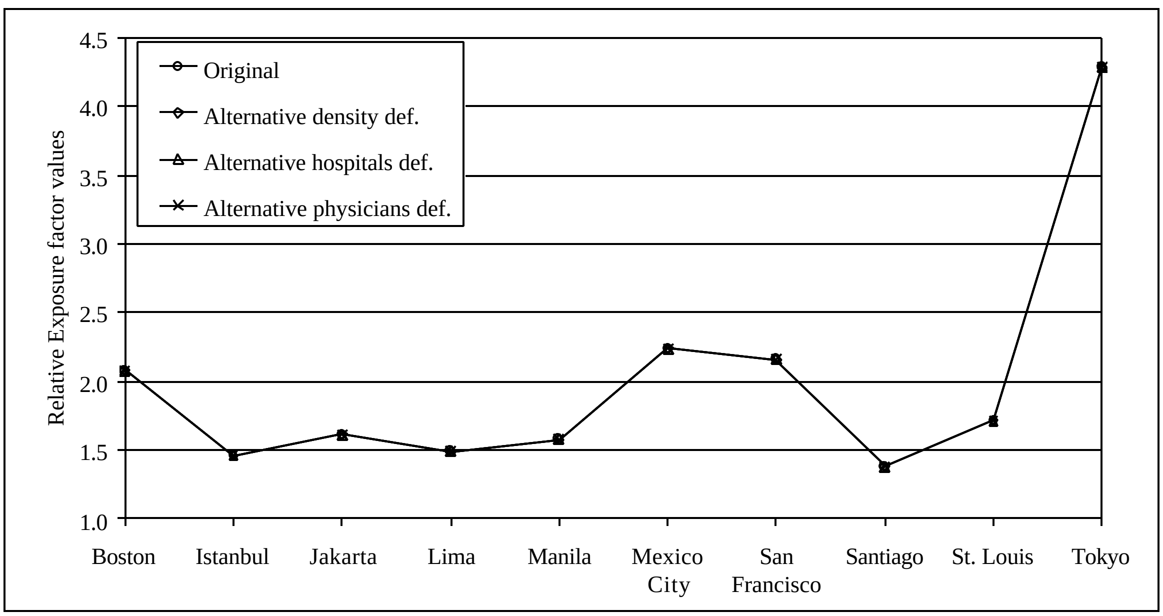


Figure 7.1b. Sensitivity of Exposure factor to indicator definitions

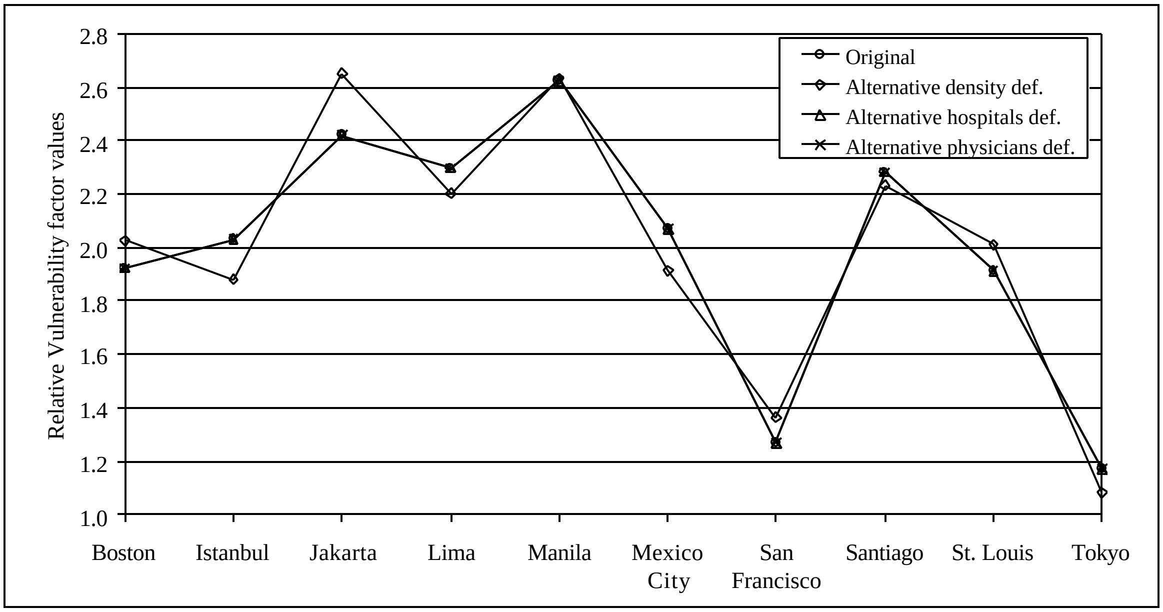


Figure 7.1c. Sensitivity of Vulnerability factor to indicator definitions

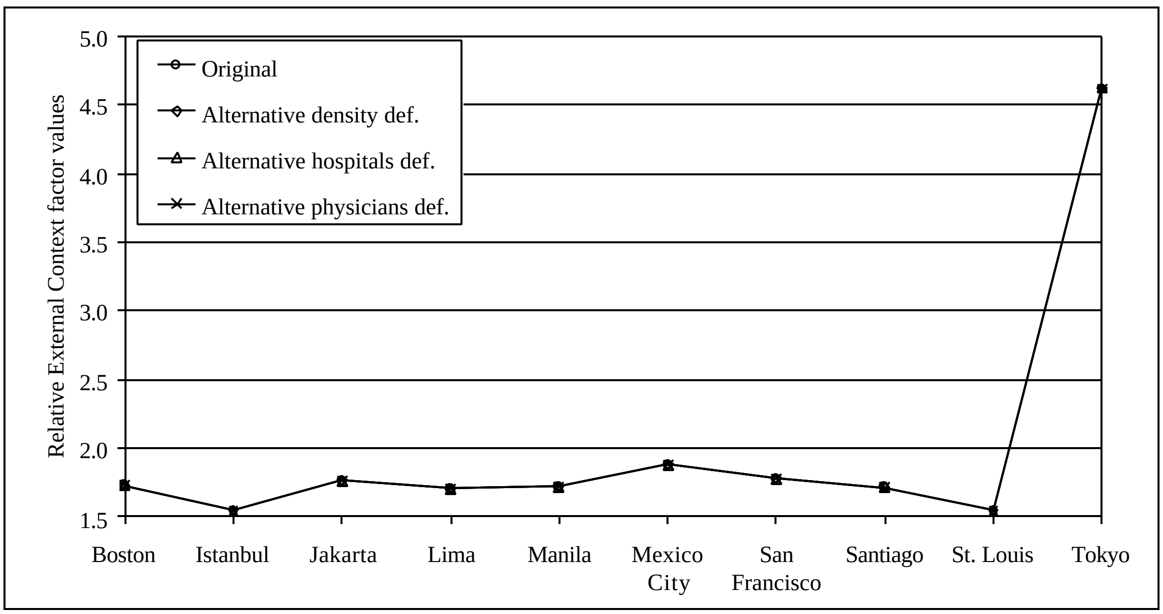


Figure 7.1d. Sensitivity of External Context factor to indicator definitions

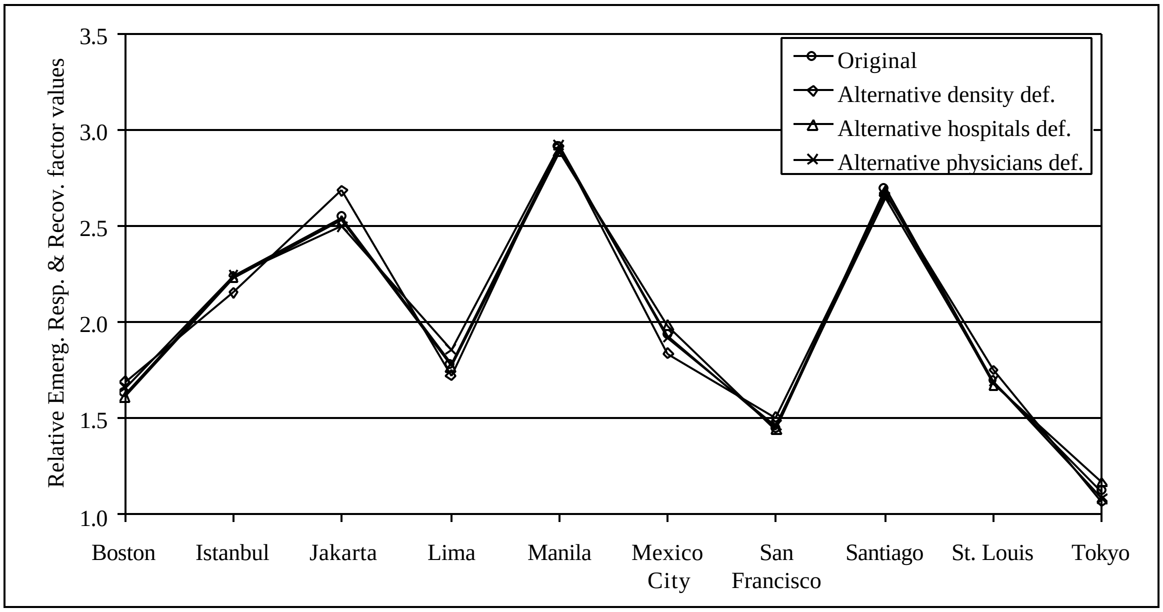


Figure 7.1e. Sensitivity of Emerg. Response and Recovery factor to indicator definitions

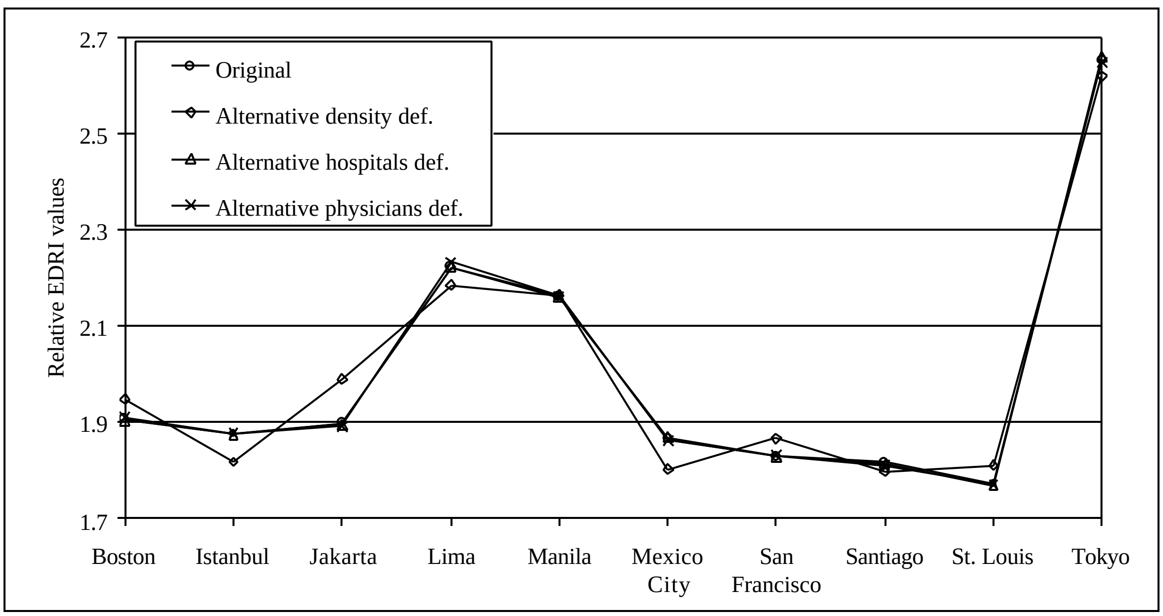


Figure 7.1f. Sensitivity of EDRI to indicator definitions

7.2. Indicator selection

The indicator selection phase of the six-step EDRI development process involved decisions not only about how to define each indicator, but also about which indicators to include and which to omit entirely. The next component of the sensitivity analysis explored the effect of omitting an indicator from the EDRI. A computer program entitled *sens.c* (Appendix I) was written to perform this and three other components of the sensitivity analysis (Sections 7.3 to 7.5). The program reads in the weights and the unscaled data values for each city and indicator, and calculates the five main factor and EDRI values for each city. It then recalculates those values for each of a series of trials. In each trial, the program makes a change in the input and repeats the evaluation, keeping track of the original results and those associated with the variation. Finally, the program computes some simple statistics, including the minimum and maximum values, and the mean and standard deviation over all relevant trials, for the main factors and the EDRI, for each city. A trial is considered relevant to a factor if it affects the value of that factor for at least one city. The indicator selection sensitivity analysis included thirty-six trials—one to omit each of the thirty-one indicators, and one to omit each of the five main factors.

The results of the indicator selection sensitivity are displayed in Figure 7.2. There is one figure for each of the five main factors and the EDRI. Five points are plotted for each city: the minimum and maximum values over all relevant trials, the mean, and the mean ±standard deviation for the set of all relevant trials. Omitting an indicator can affect the main factor and EDRI values significantly. Still, some city rankings are clear, even considering the range of values that could result from eliminating a single indicator. For example, the Exposure factor value should be greatest for Tokyo, even if one of the indicators is omitted. Furthermore, while it seems difficult to rank each city definitively if the possibility of changing the indicator set exists, for each main factor and the EDRI, the sample of cities can, with some confidence, be separated into groups with the similar values. For example, it seems that Santiago, Jakarta, Mexico City have relatively moderate Hazard; Boston, San Francisco, Tokyo, Manila, and Istanbul have relatively high Hazard; and Lima has a very high Hazard. Table 7.1 summarizes the suggested categorical groupings that are possible for each factor, for the indicator selection, weight, and data uncertainty components of the sensitivity analysis.

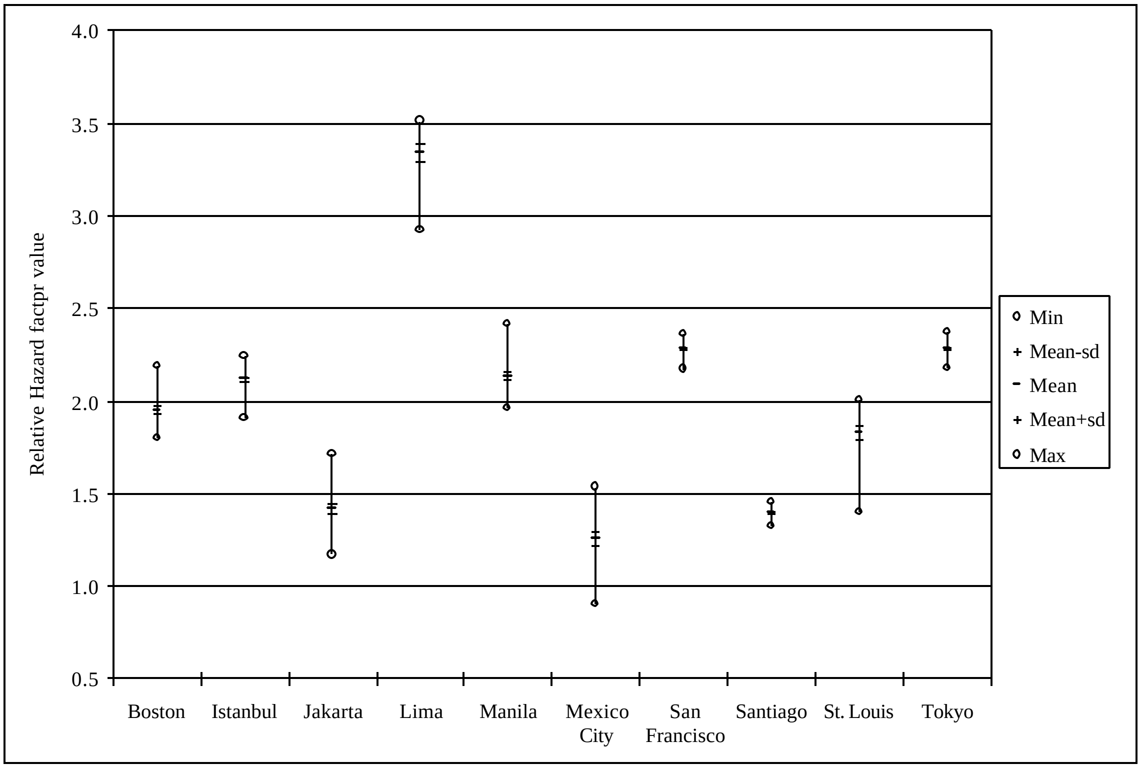


Figure 7.2a. Sensitivity of Hazard factor to indicator selection

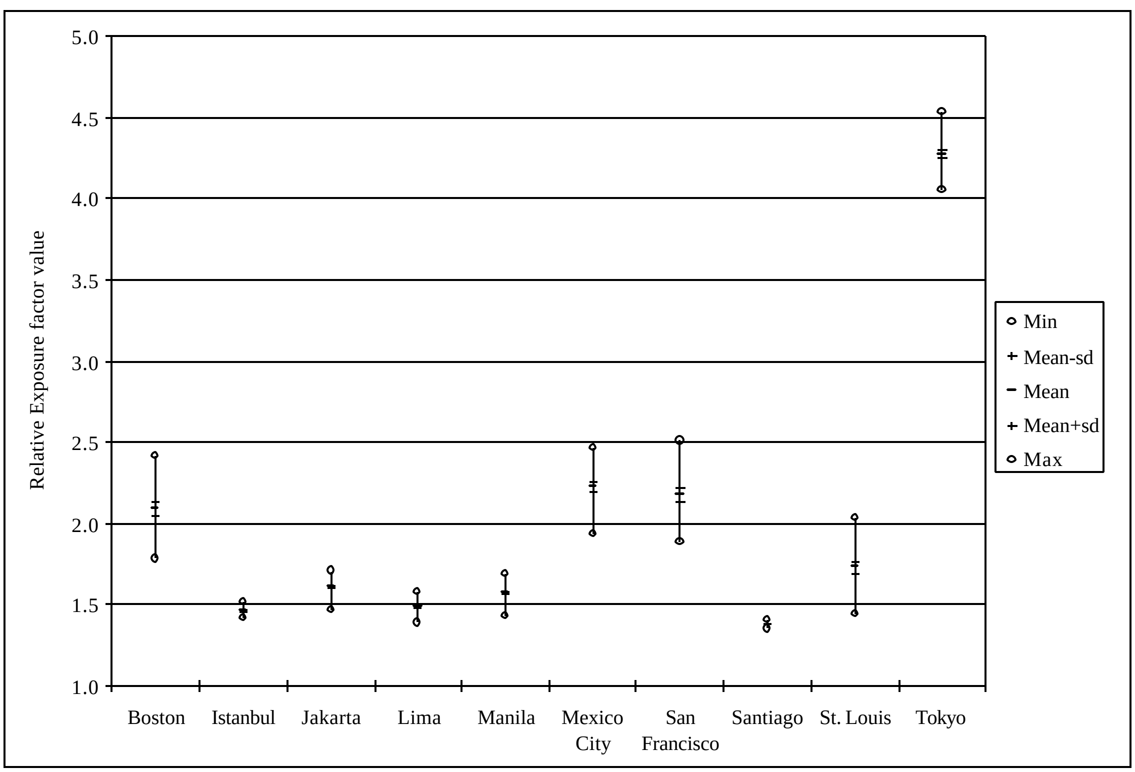


Figure 7.2b. Sensitivity of Exposure factor to indicator selection

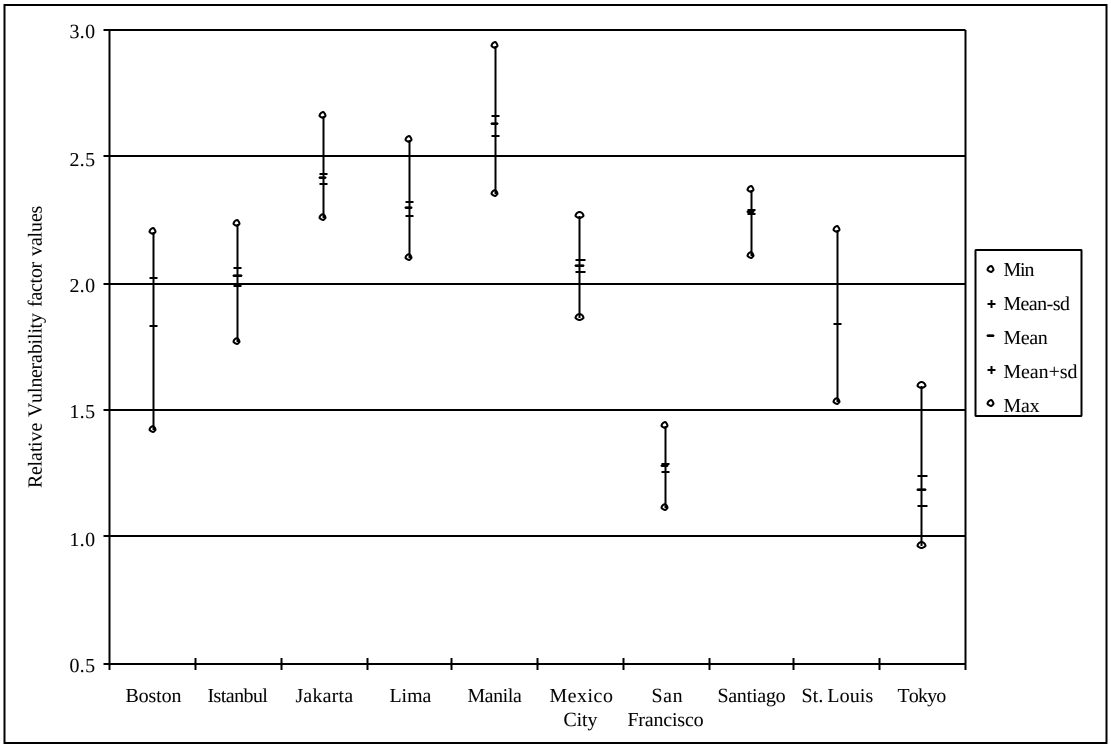


Figure 7.2c. Sensitivity of Vulnerability factor to indicator selection

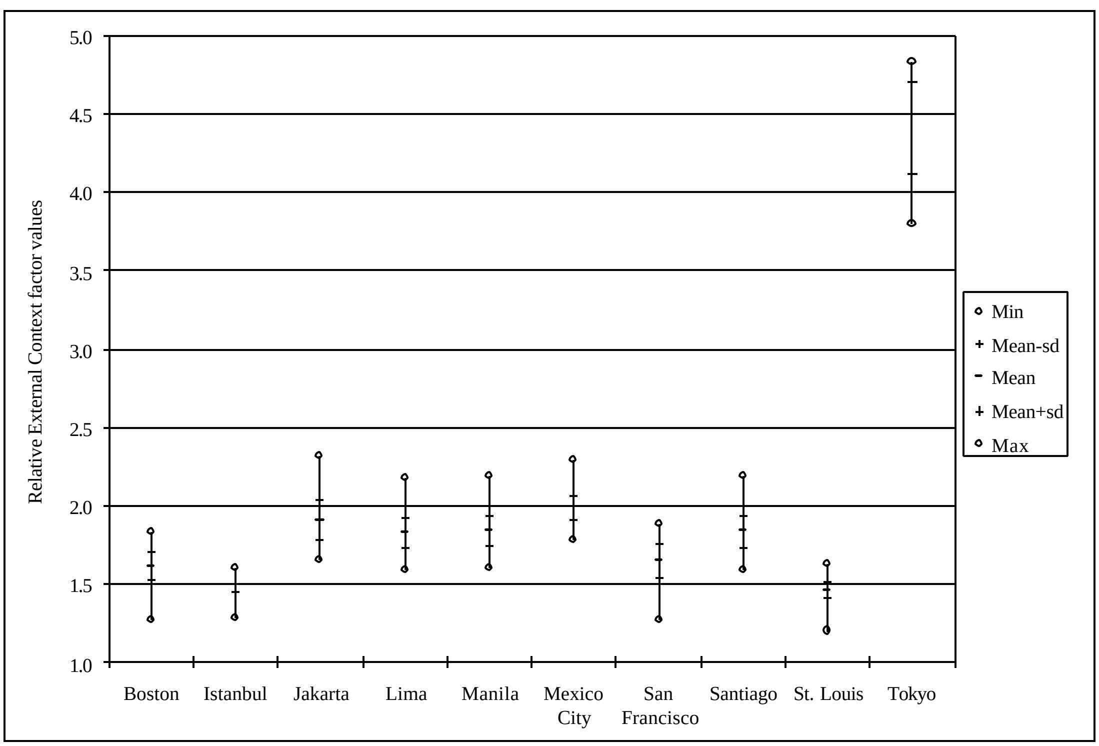


Figure 7.2d. Sensitivity of External Context factor to indicator selection

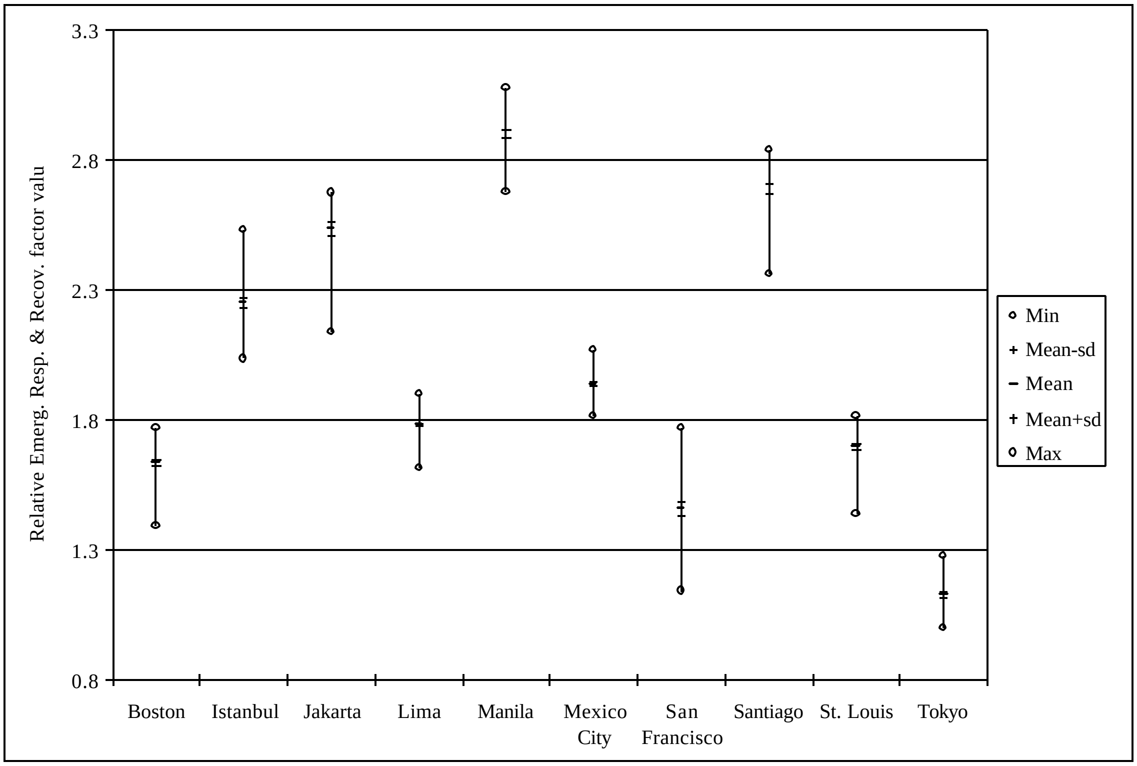


Figure 7.2e. Sensitivity of Emergency Response & Recovery factor to indicator selection

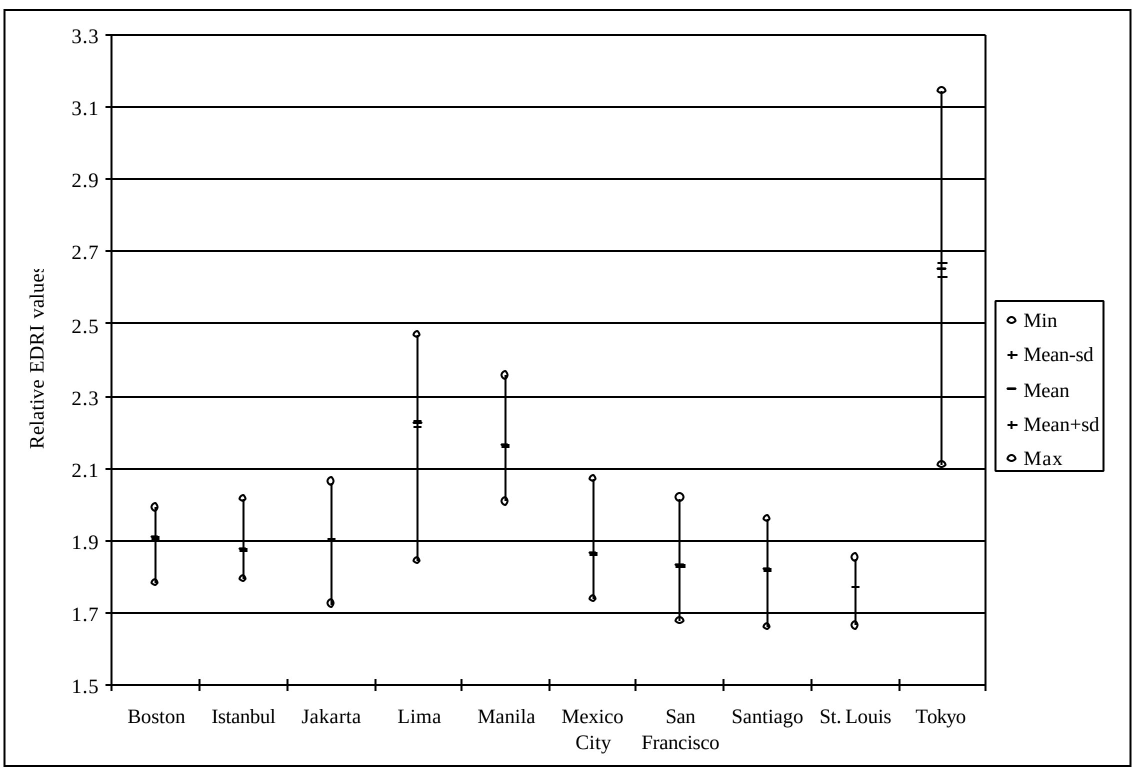


Figure 7.2f. Sensitivity of EDRI to indicator selection

Table 7.1. Summary of categorical groupings from sensitivity analysis

Categories are labeled from A to E, with A for the lowest values and E for the highest.

Sensitivity to indicator selection

	Influential indicators	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	---	C-D	C-D	B-C	E	D	B	D	B	C	D
Exposure	xe5, xe6	C-D	B-C	C	B-C	C	D	D	B	C	E
Vulnerability	xv2, xv3, xv4	B-C	B-C	C-D	C-D	C-D	B-C	A	C	B-C	A
External Context	xc1, xc2	B-C	B	C	C	C	C	B-C	C	B-C	E
Emerg. Resp. & Recov.	xr1, xr9	C	D	D-E	C	E	C-D	B-C	D-E	C	B
EDRI	xh, xe, xv	C	C	C-D	D	C-D	C-D	C	C	C	D-E

Sensitivity to weights

	Influential indicators	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	---	C	D	B	E	D	B	D	B	C	D
Exposure	xe5, xe6	D	B	C	B-C	C	D	D	B	C	E
Vulnerability	xv1, xv2, xv3	B-C	B-C	C	C	D	C	A	C	B	A
External Context	xc1, xc2	C	B	C	C	C	C	C	C	B	E
Emerg. Resp. & Recov.	xr1, xr2, xr7, x	C	D	D-E	C	E	D	C	E	C	B
EDRI		C	C	C	D	D	C	C	C	B	E

Sensitivity to data uncertainty

	Influential indicators	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	xh1, xh2	C-D	C-D	B	E	C-D	B	D	B	C	D
Exposure	xe5, xe6	D	B	C	B	C	D	D	B	C	E
Vulnerability	xv1	C	C	E	D	E	C	A	D	C	A
External Context	xc1	C	B	C	C	C	D	C	C	B	E
Emerg. Resp. & Recov.	xr1	C	C-E	D-E	C	E	C-D	C	D-E	C	B
EDRI	xr1, xh2	C	B-C	C	D	D	C	B-C	B-C	B	E

Eliminating some indicators has a more significant effect than others. For example, omitting "population" or "per capita GDP" causes the largest changes in the Exposure factor values. For the indicator selection, weight, and data uncertainty components of the sensitivity analysis, Table 7.1 lists the indicators that are most "influential" to each factor, i.e., those that lead to the minimum and maximum values over all relevant trials. The degree of sensitivity to the indicator selection uncertainty is similar across factors and cities.

The sensitivity of the results to the indicator selection need not be considered a deficiency in the EDRI. Changing the indicator set in effect alters the concept that the index measures, so the relative values of different cities can be expected to change as well. In the extreme, if all indicators except "population" are omitted, the resulting "EDRI" would measure not earthquake disaster risk, but the number of people in the city. One would not expect the city rankings to remain the same in that case.

7.3. Scaling

Section 5.2 introduced seven scaling techniques that were considered for use in the EDRI, and explained why scaling with respect to the mean minus two standard deviations was chosen for use in the sample analysis. The third component of the sensitivity analysis used the computer program *sens.c* to investigate the effect of the choice of scaling technique on the final main factor and EDRI values. The sample analysis was repeated four times, each time using one of the following scaling techniques: mean minus two standard deviations, minimum and maximum observed values, minimum and maximum possible values, and base city. Appendix J lists the maximum and minimum possible values that were used for the third scaling option.

Clearly, the scaled values will not be the same for each scaling technique. The values from the first will be centered around a mean of two; values from the second and third will remain between zero and one; and values from the fourth technique will be more varied, with the value for the base city, taken as San Francisco in the sample analysis, always equal to one.

Because the analysis aims to understand the relative values among cities, the ratio of the scaled value of one city to that of another city might be of interest. However, even the ratios of the scaled values of two cities will not be identical across scaling techniques. Table 7.2 illustrates that for each scaling technique, the ratio of the City A scaled value of indicator i to the City B scaled value of indicator i (x'_{iA}/x'_{iB}) measures a different quantity, and that therefore, the values of those ratios should not be expected to be equal for each technique.

Table 7.2. Comparison of scaling techniques tested in sensitivity analysis

Scaling method	Ratio of City A scaled value of indicator i to City B scaled value of i
Mean minus two standard deviations	$\frac{x'_{iA}}{x'_{iB}} = \frac{(x_{iA} - (\overline{x_i} - 2s_i))}{s_i} * \frac{s_i}{(x_{iB} - (\overline{x_i} - 2s_i))} = \frac{(x_{iA} - (\overline{x_i} - 2s_i))}{(x_{iB} - (\overline{x_i} - 2s_i))}$
Base city and year	$\frac{x'_{iA}}{x'_{iB}} = \frac{x_{iA}}{x_{i,basecity}} * \frac{x_{i,basecity}}{x_{iB}} = \frac{x_{iA}}{x_{iB}}$
Minimum and maximum	$\frac{x'_{iA}}{x'_{iB}} = \frac{(x_{iA} - \min_i)}{(\max_i - \min_i)} * \frac{(\max_i - \min_i)}{(x_{iB} - \min_i)} = \frac{(x_{iA} - \min_i)}{(x_{iB} - \min_i)}$

For a given indicator, if the above ratio (x'_{iA}/x'_{iB}) is greater than one for one scaling technique, it should be greater than one for all four techniques, although its exact value may vary. In general, except for the case of base city scaling, the same will hold true when considering the values of the five main factor and EDRI composite indexes instead of the values of a single indicator. The conclusion is not necessarily true when using the base city scaling technique, because that option introduces an implicit weighting that alters the relative importance of the indicators, and thereby alters the value of a composite index composed of those indicators (see Section 5.2.4).

Figure 7.3 presents the results of the scaling sensitivity analysis. There is one figure for each of the five main factors and the EDRI, and on each figure, there is one curve for each scaling technique. Despite the analytical evidence that the results derived using each of the four scaling techniques should not be identical, it turns out that the final

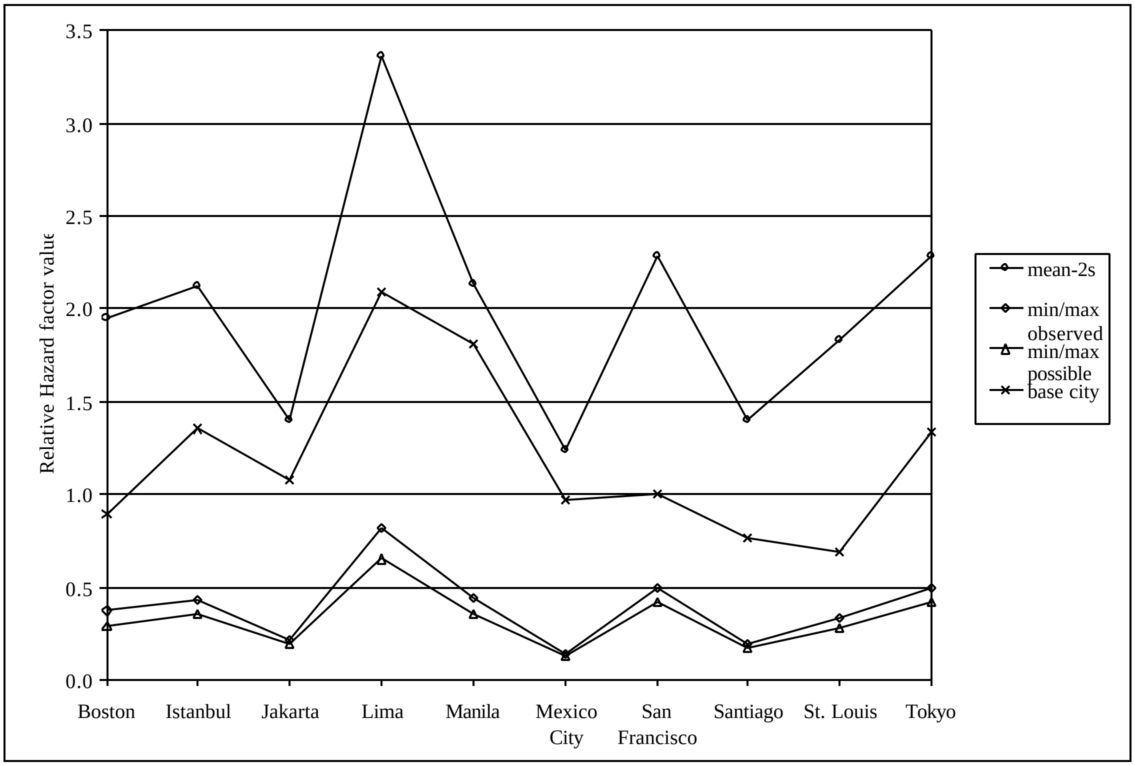


Figure 7.3a. Sensitivity of Hazard factor to scaling function

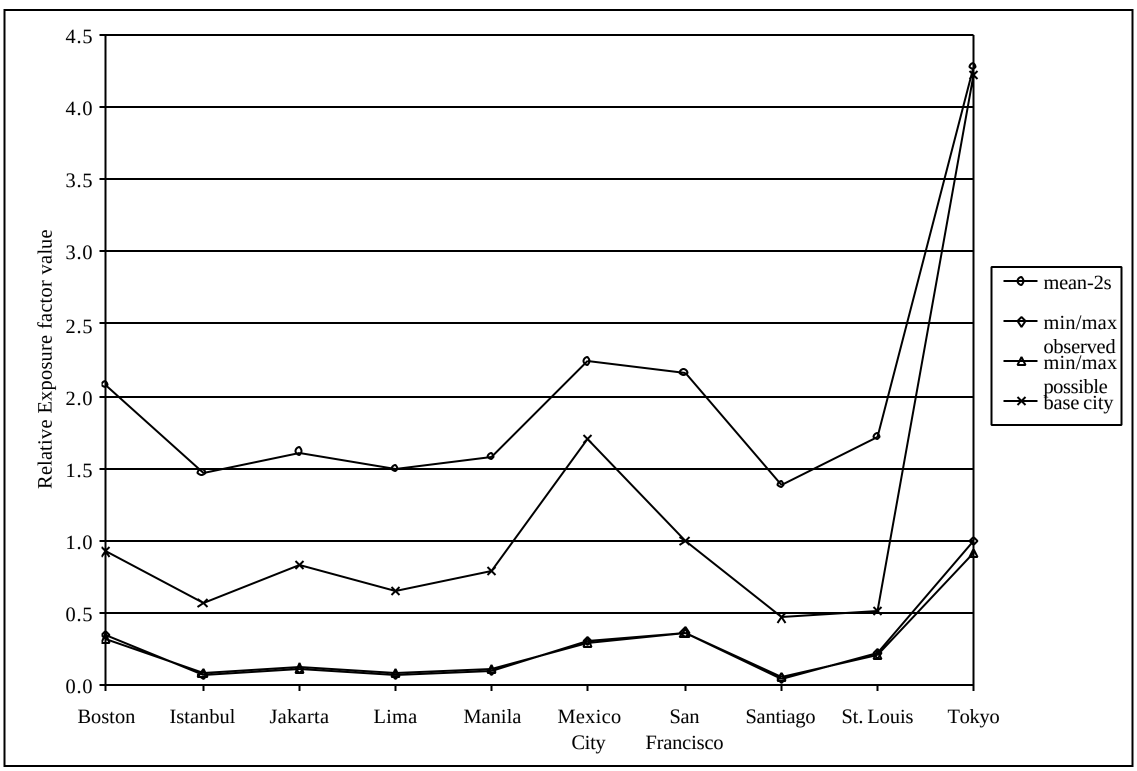


Figure 7.3b. Sensitivity of Exposure factor to scaling function

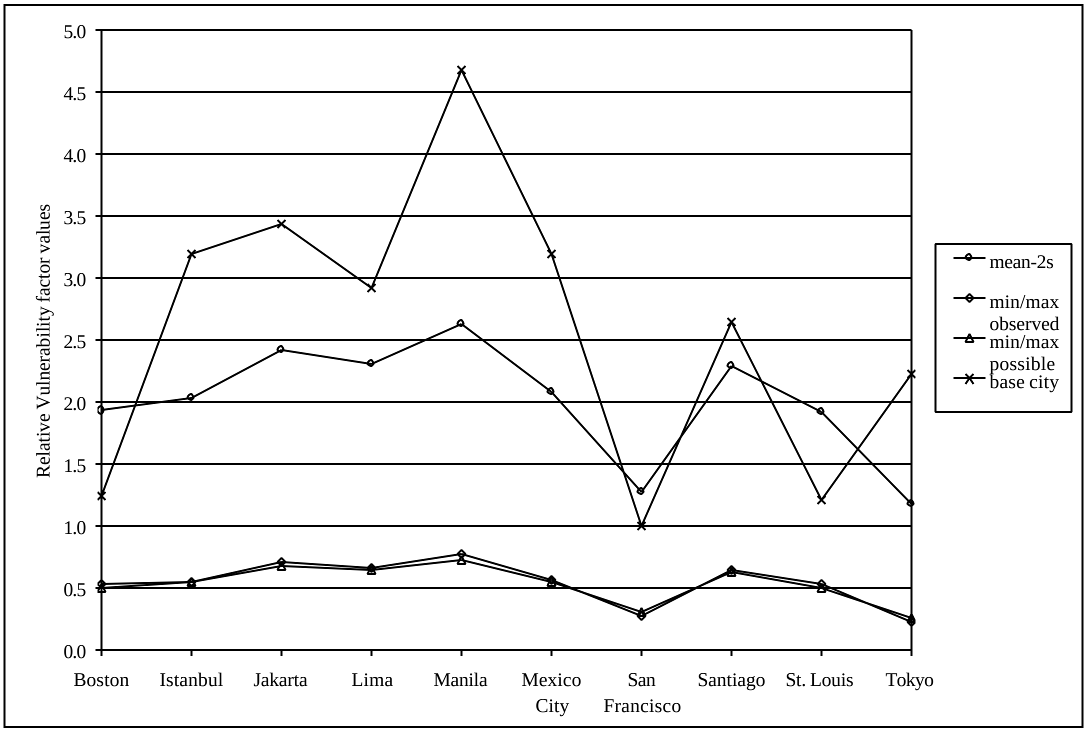


Figure 7.3c. Sensitivity of Vulnerability factor to scaling function

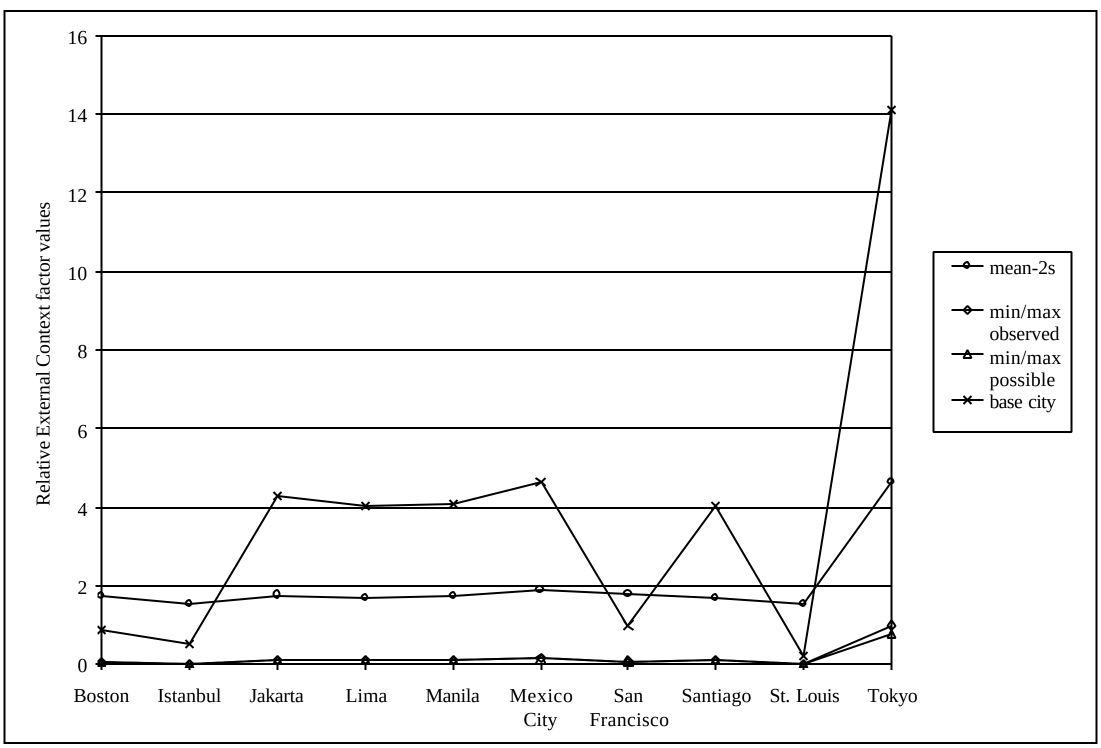


Figure 7.3d. Sensitivity of External Context factor to scaling function

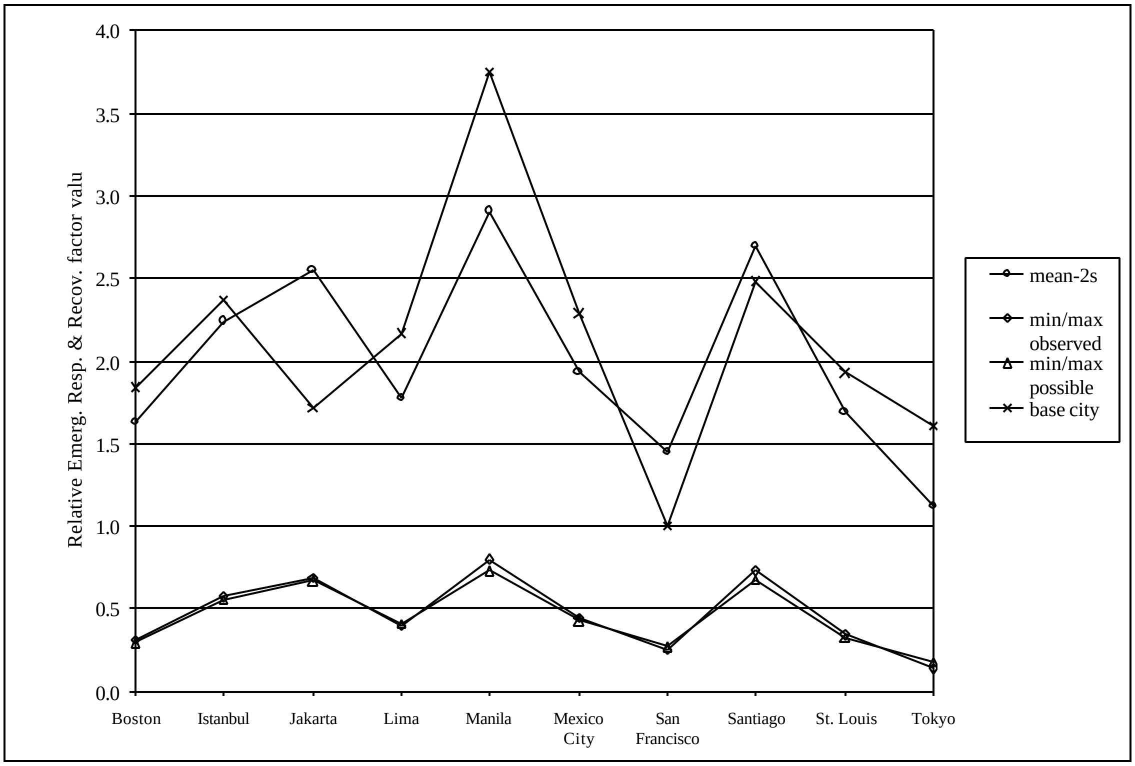


Figure 7.3e. Sensitivity of Emergency Response and Recovery factor to scaling function

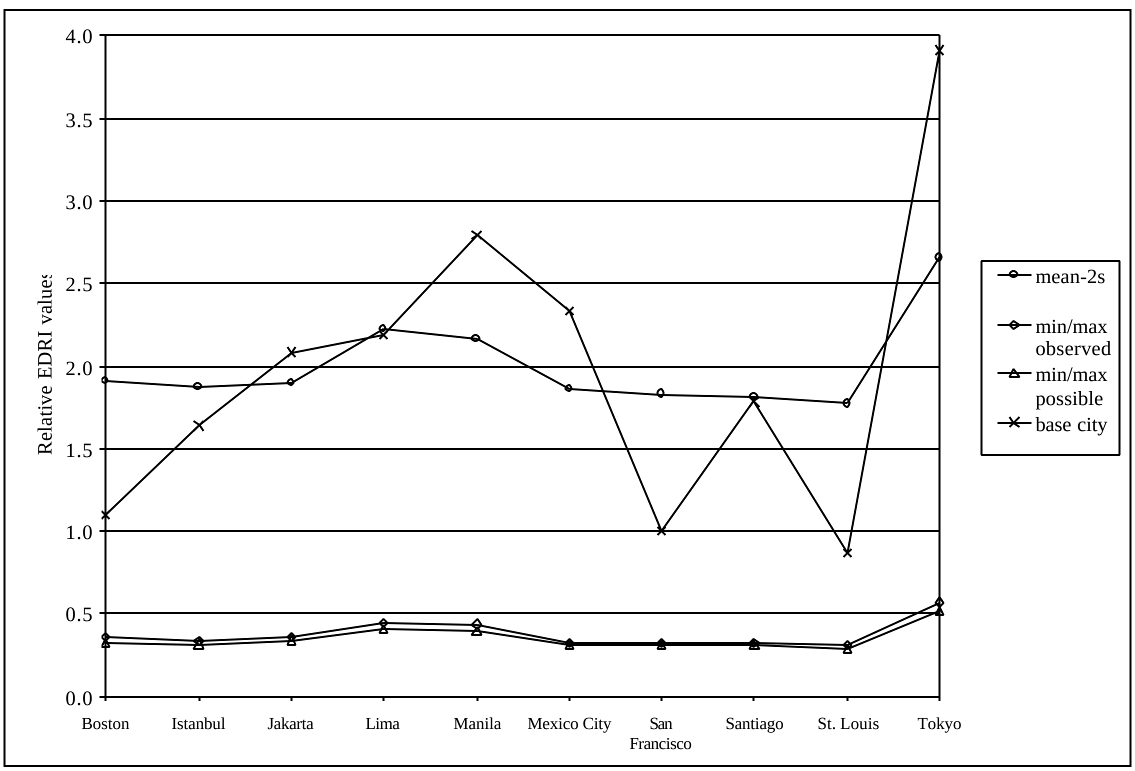
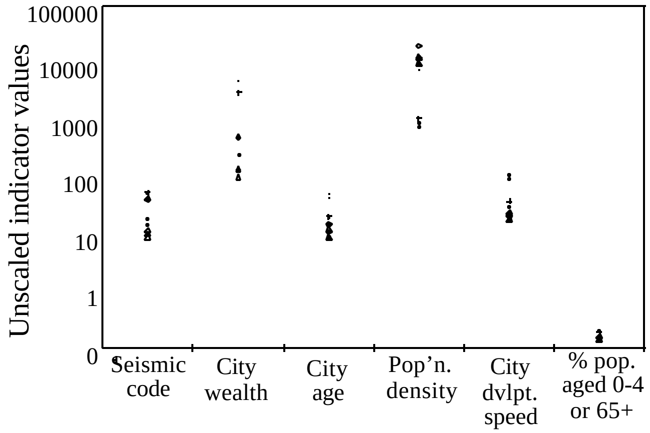
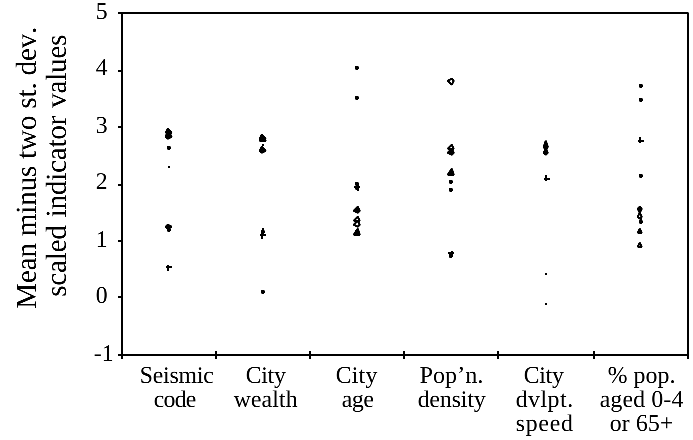


Figure 7.3f. Sensitivity of EDRI to scaling function

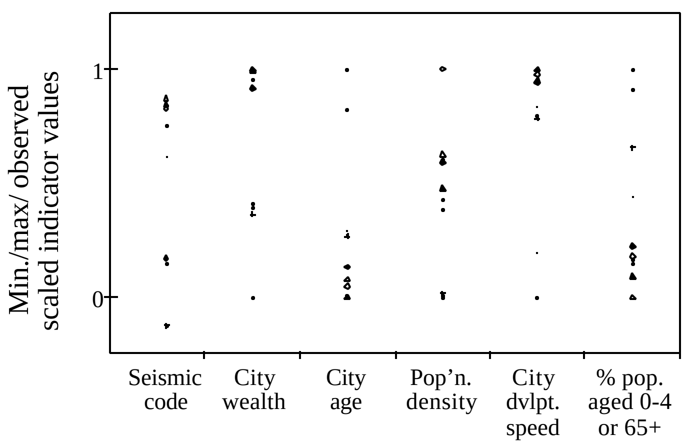
relative values of the five main factors and the EDRI are similar in most cases, as evidenced by the similar shapes of the four curves on a given plot. The base city technique provides a few notable exceptions. For example, while the other three techniques conclude that the Vulnerability in Tokyo is less than that in St. Louis, the base city method indicates that the reverse is true. This conclusion is the result of the implicit weighting associated with using San Francisco as the base city. Figure 7.4a shows how the range of values associated with each of the unscaled vulnerability indicators are very different (on the order of thousands for “population density”; tenths for “percentage of population aged 0-4 or 65+). When scaled with the mean minus two standard deviations and the minimum and maximum observed techniques, the values are forced to exhibit roughly similar magnitudes and dispersions across indicators (Figs. 7.4b and 7.4c). The same is not true of the base city method (Fig. 7.4d). Because San Francisco’s population density is relatively small compared to other cities, when using this technique with San Francisco as the base city, the scaled “population density” values become very large and spread out relative to the other indicator values. In effect, “population density” becomes more important than the other indicators. Therefore, because Tokyo’s “population density” is larger than St. Louis’s, and “population density” is given such a large implicit weight by the base city scaling technique, Tokyo’s overall Vulnerability value becomes larger than St. Louis’s with that scaling option. Similar examples of the implicit weighting effect of base city scaling can be seen in the Emergency Response and Recovery Capability and EDRI values.



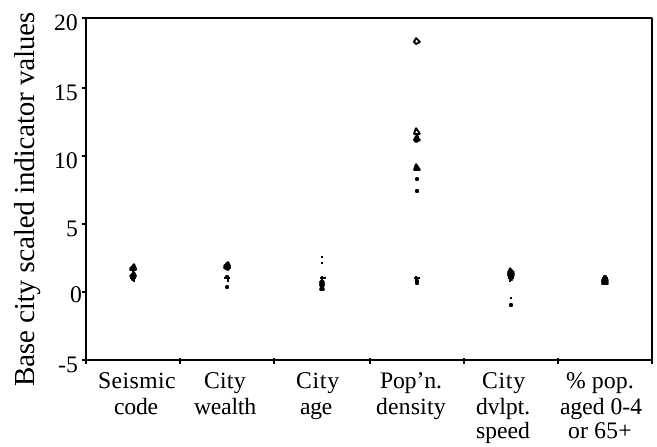
a. Dispersion of unscaled vulnerability indicators



b. Dispersion of vulnerability indicators scaled with mean minus two standard deviations



c. Dispersion of vulnerability indicators scaled with min. and max. observed values



d. Dispersion of vulnerability indicators scaled with base city

Figure 7.4. Illustration of implicit weighting effect of base city scaling technique

7.4. Weights

The computer program *sens.c* was employed again to explore the effect of the weights on the final main factor and EDRI values. The weight portion of the sensitivity analysis included seventy-two trials, one to change each of the thirty-one indicators and five main factor weights by +35%, and one to change each by -35%. The 35% value was taken from the fact that the coefficients of variation of the questionnaire factor weight assessments were approximately 0.35 (see Section 5.3.4.2). For each factor and city, the program computed the minimum and maximum values achieved over all seventy-two trials, and the mean and standard deviation of the same seventy-two values.

Some variation in the five main factor and EDRI values results when any single weight is altered by ±35% (Fig. 7.5). As with the indicator selection analysis, however, some city pair comparisons remain clear, even considering the range of values, and for each factor, the sample of cities can be divided into a few groups with similar ranking. Table 7.1 summarizes, for each factor, the suggested categorical groupings and the indicator weights that lead to the minimum and maximum values over all trials.

It should not be surprising that altering the values of the weights affects the final values of the main factors and the EDRI. Just as the indicator set helps define the concept that is being measured, so do the weight values. If the weights are changed, the concept being measured is too, and the city rankings corresponding to the new concept should not necessarily equal those associated with the original concept. In the extreme example given in Section 5.3, if the weight of the Hazard factor is taken as one, and all other factor weights are assumed to be zero, the resulting "EDRI" will measure a city's earthquake hazard, not it's earthquake disaster risk. Still, since the weight values are difficult to assess, it was hoped that the final results would not vary too drastically with minor changes in the assessments of the weights. The sensitivity analysis suggests that that is indeed the case.

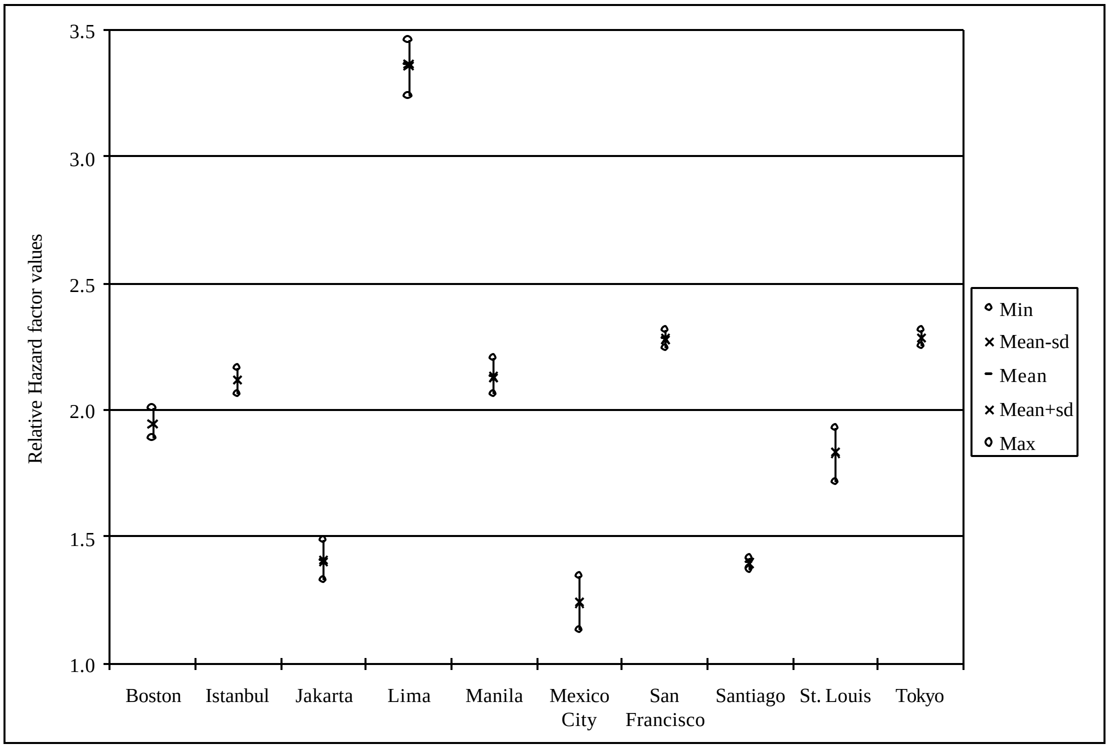


Figure 7.5a. Sensitivity of Hazard factor to weights

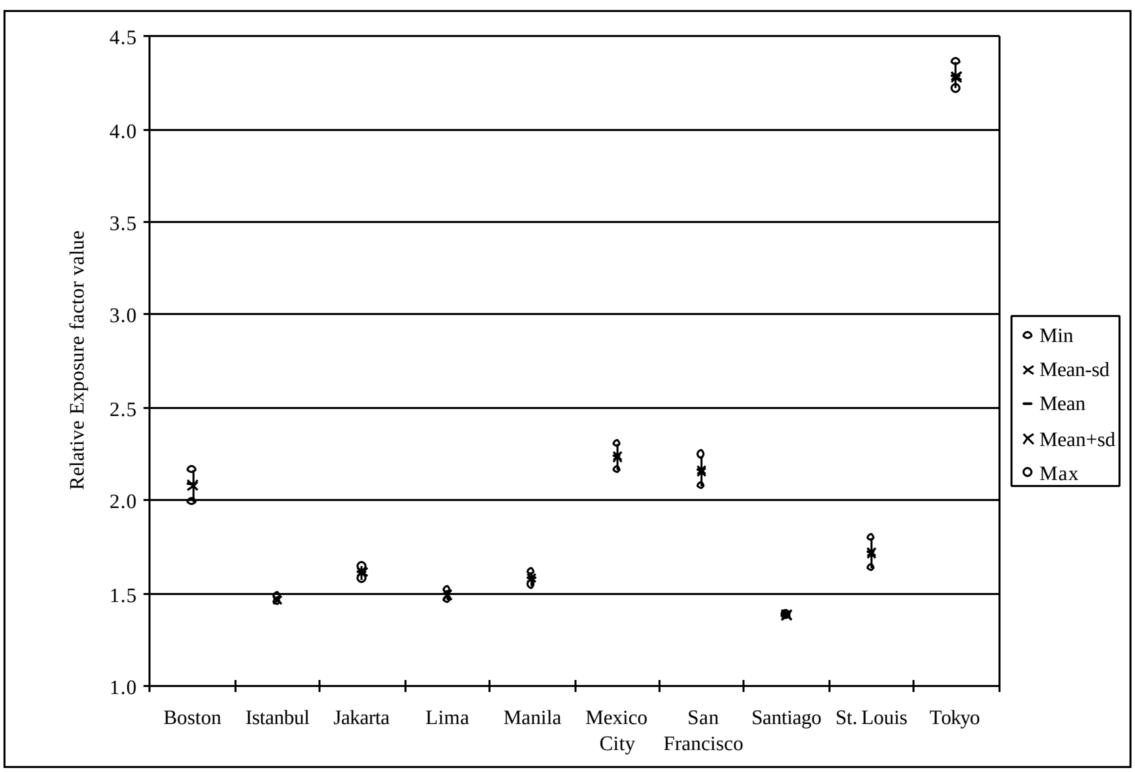


Figure 7.5b. Sensitivity of Exposure factor to weights

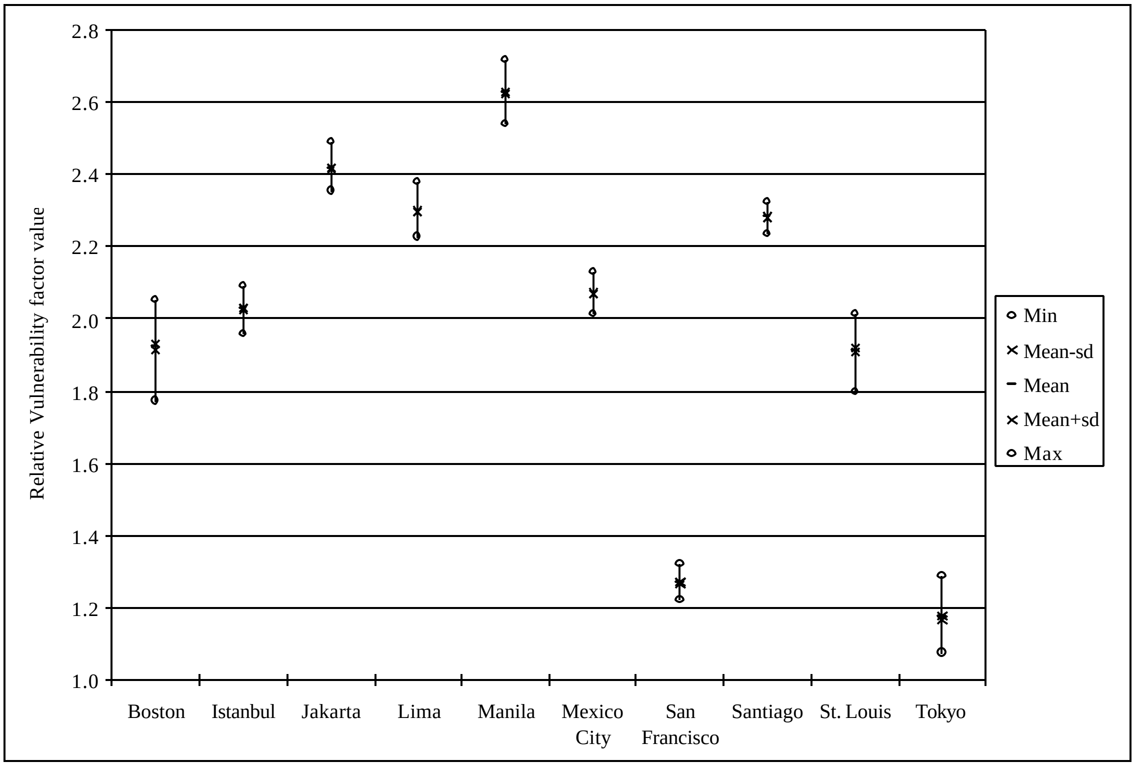


Figure 7.5c. Sensitivity of Vulnerability factor to weights

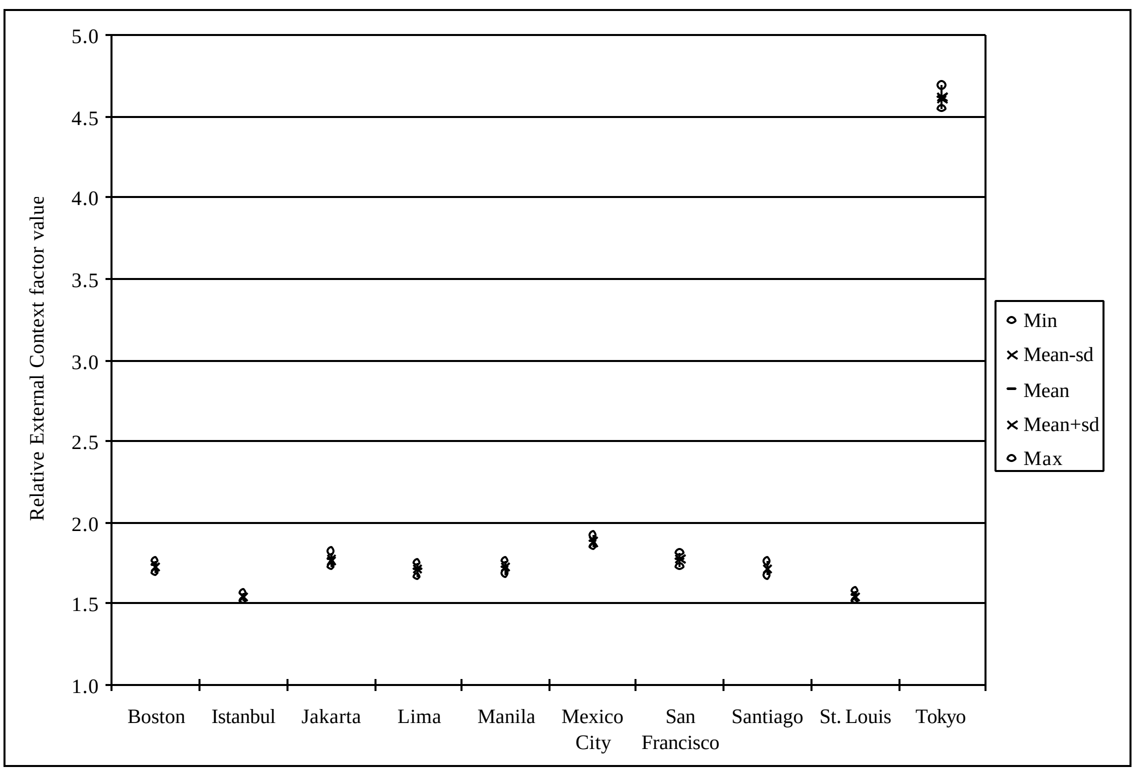


Figure 7.5d. Sensitivity of External Context factor to weights

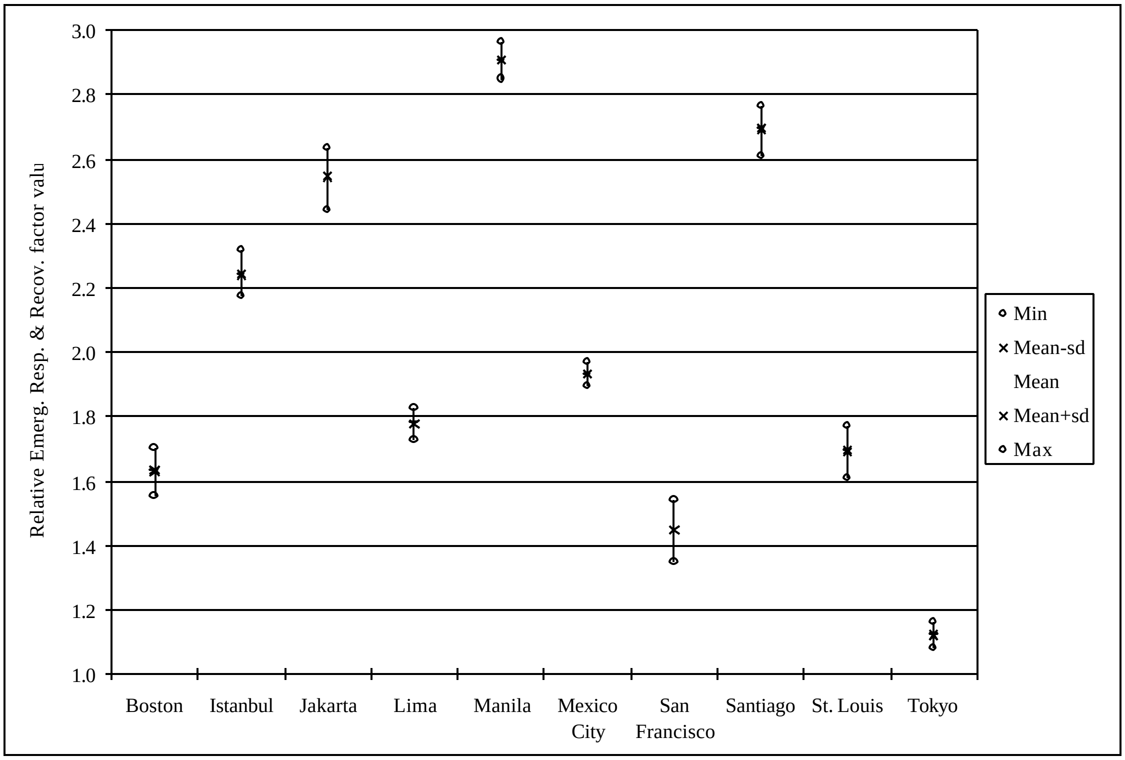


Figure 7.5e. Sensitivity of Emergency Response and Recovery factor to weights

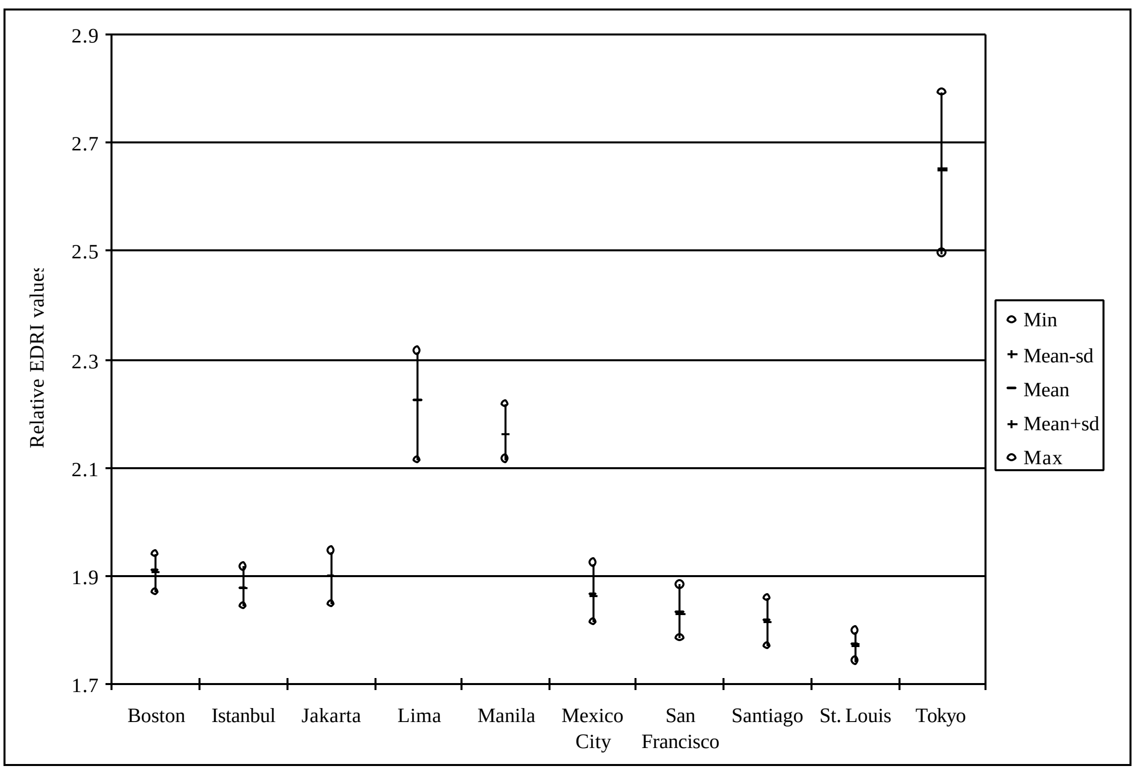


Figure 7.5f. Sensitivity of EDRI to weights

7.5. Data uncertainty

Since changing the indicator set, the weight values, or the scaling technique necessarily will and should change the final values of the main factors and the EDRI, sensitivity to those three components cannot be considered deficiencies in the EDRI model. On the other hand, sensitivity to data uncertainty theoretically is avoidable if the data are of sufficiently high quality. If the final results are too sensitive to data uncertainty, it does weaken their ultimate usefulness. The computer program *sens.c* was used once more to conduct the analysis of sensitivity to data uncertainty. The analysis included 620 trials, one to change each of the indicator-city values by $+\Delta x_{ij}$, and one to change each by $-\Delta x_{ij}$. The Δx_{ij} values (Appendix K) were assessed for each indicator-city combination separately based on the assumed quality of the associated data source, and the degree of estimation and manipulation required to extract the required data from the reported data.

As with the previously discussed sensitivity analysis results, varying the data to reflect the uncertainty in their values results in some variation in the final main factor and EDRI values. As shown in Figure 7.6, the variation is not uniform across factors or cities. Exposure and External Context exhibit noticeably smaller variations than the other factors, because they rely on data that are less uncertain than the other factors do (e.g., "population," "per capita GDP" are relatively more certain than "percentage of the urbanized area with high liquefaction susceptibility"). The standard deviations generally appear small for the data uncertainty because for a given city and factor, the relevant trials include any trial that changes the value for any city and indicator related to that factor. For example, the trial in which Boston's "population" indicator is increased by $\Delta x_{pop,Boston}$ is a relevant trial for Manila's Exposure, because changing the value for Boston changes the mean and standard deviation of "population," which in turn affects Manila's "population" and Exposure values, but only slightly. In general, for a given city, the minimum and maximum over all relevant trials are associated with changes to an indicator value for that city. They are not unlikely to occur.

Although cities cannot be compared as precisely when data uncertainty is considered, certain city comparisons are still possible, and the sample cities can be partitioned into groups with similar values with some confidence. Table 7.1 summarizes, for each factor, the suggested categorical groupings and the specific indicators that are responsible for the most significant variation in the final results.

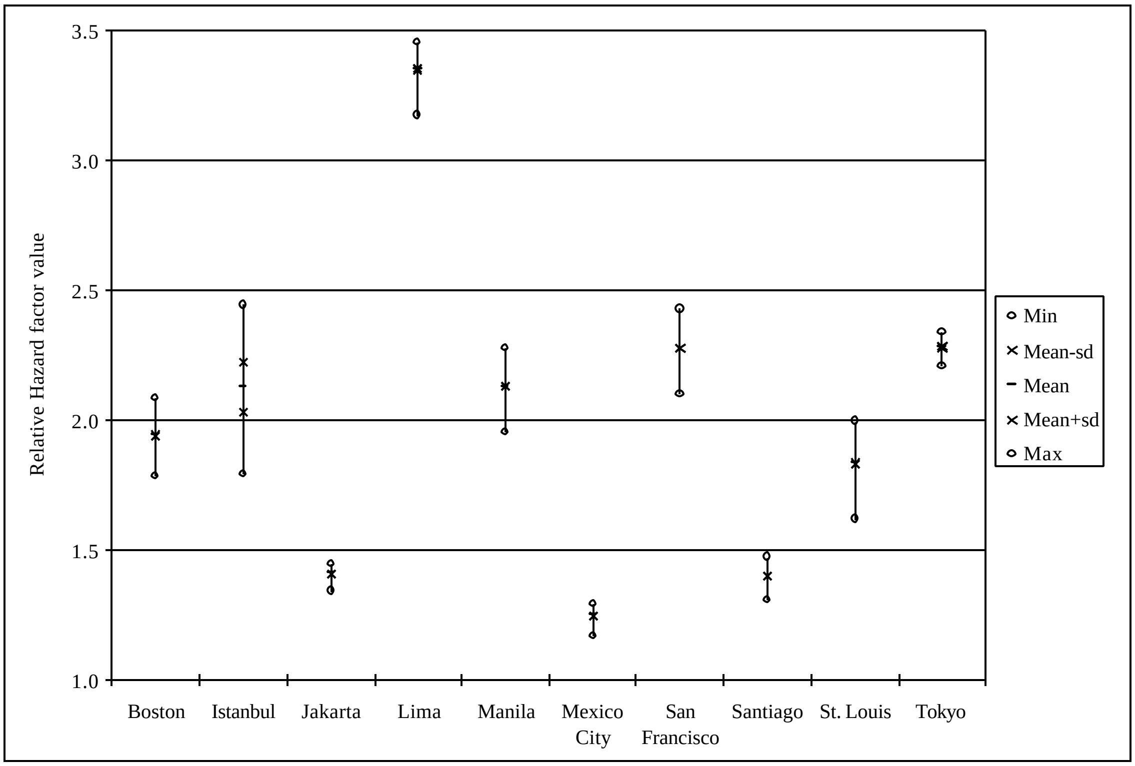


Figure 7.6a. Sensitivity of Hazard factor to data uncertainty

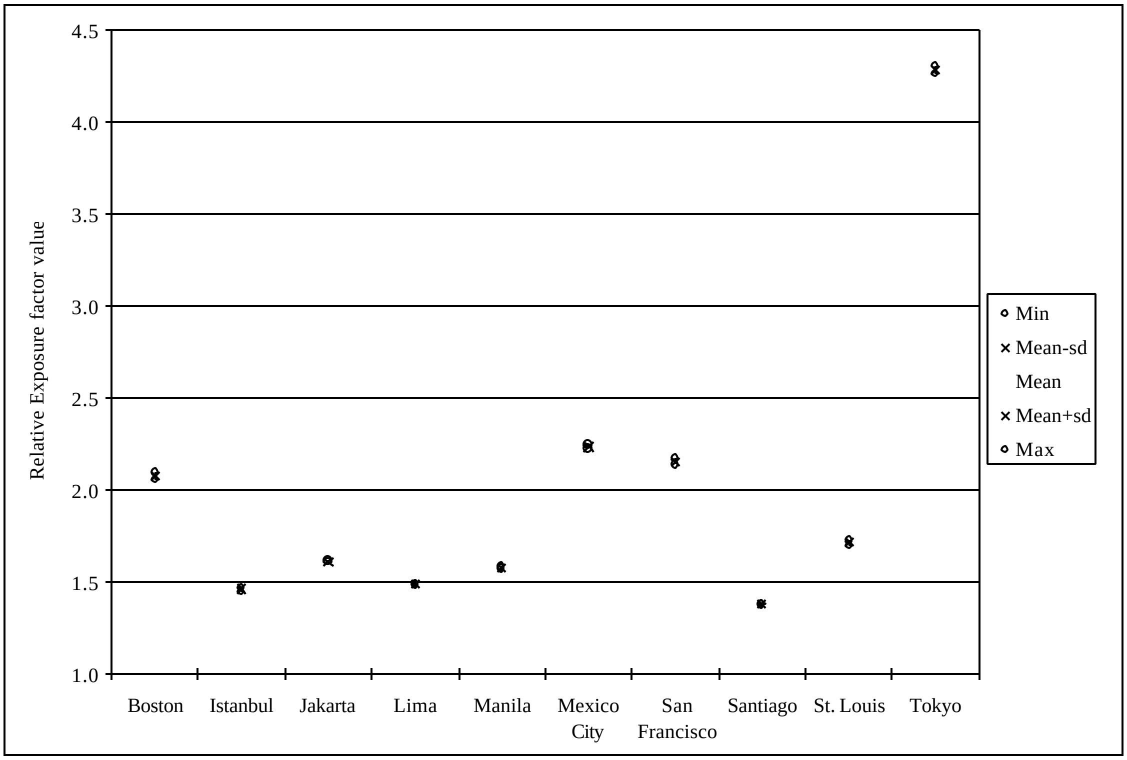


Figure 7.6b. Sensitivity of Exposure factor to data uncertainty

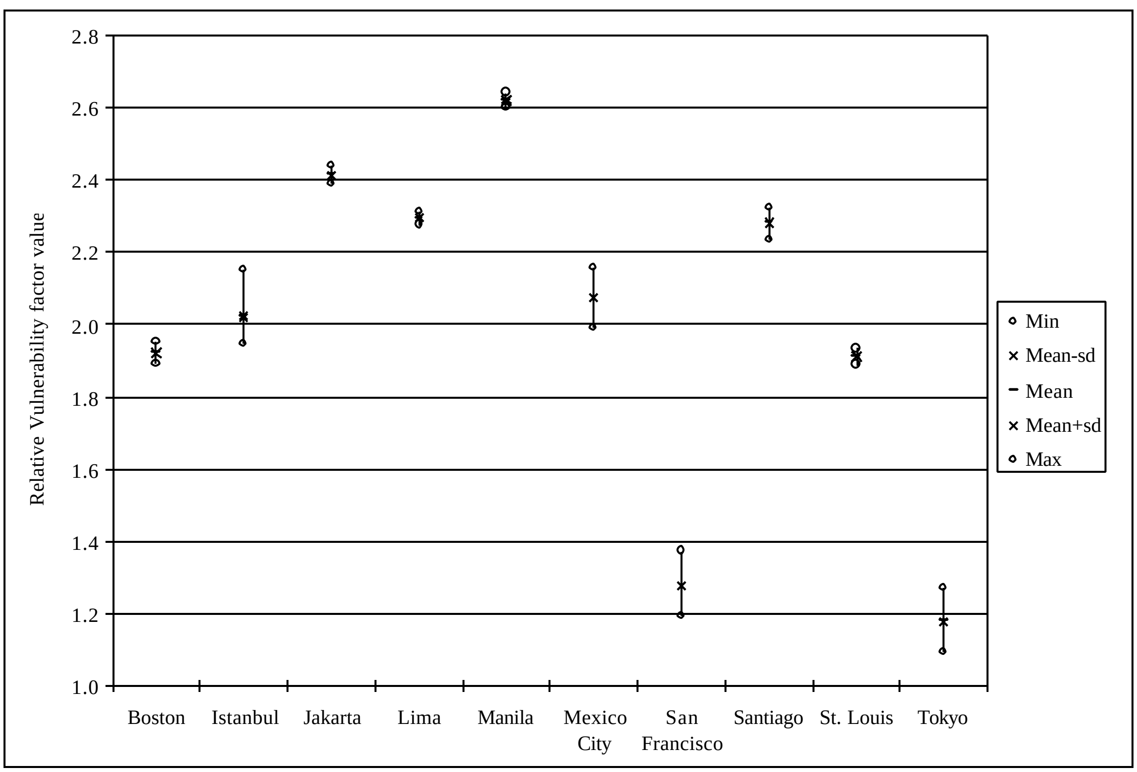


Figure 7.6c. Sensitivity of Vulnerability factor to data uncertainty

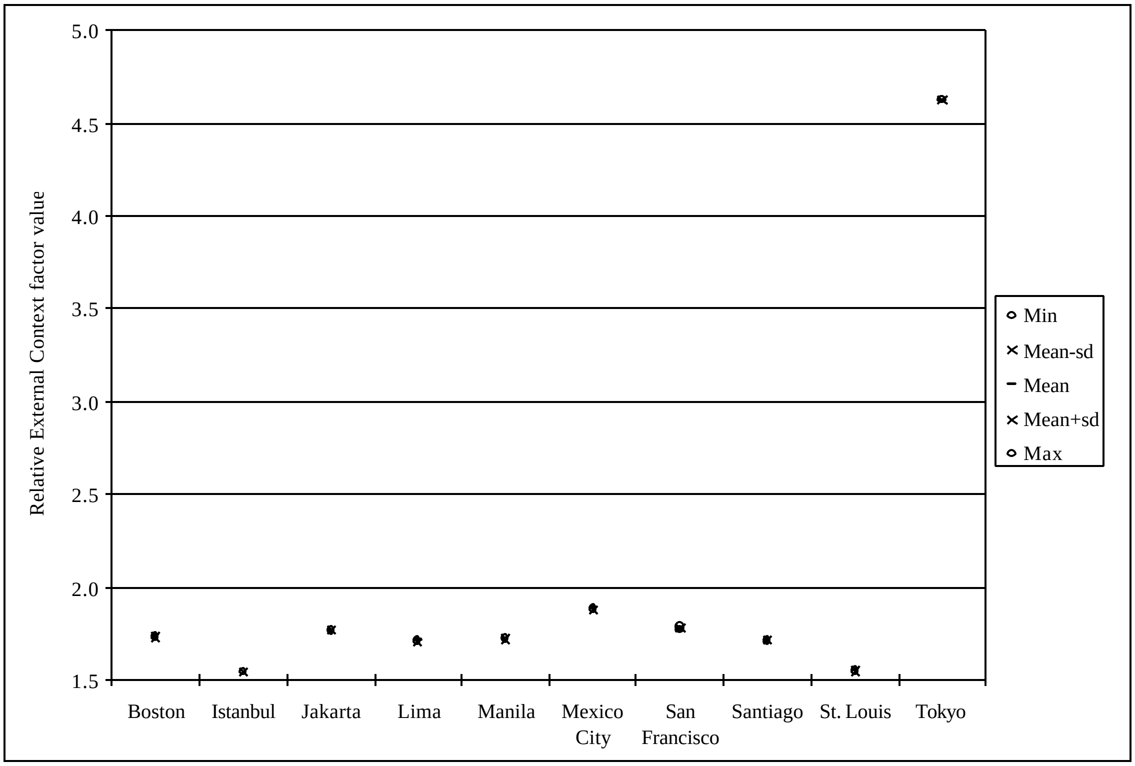


Figure 7.6d. Sensitivity of External Context factor to data uncertainty

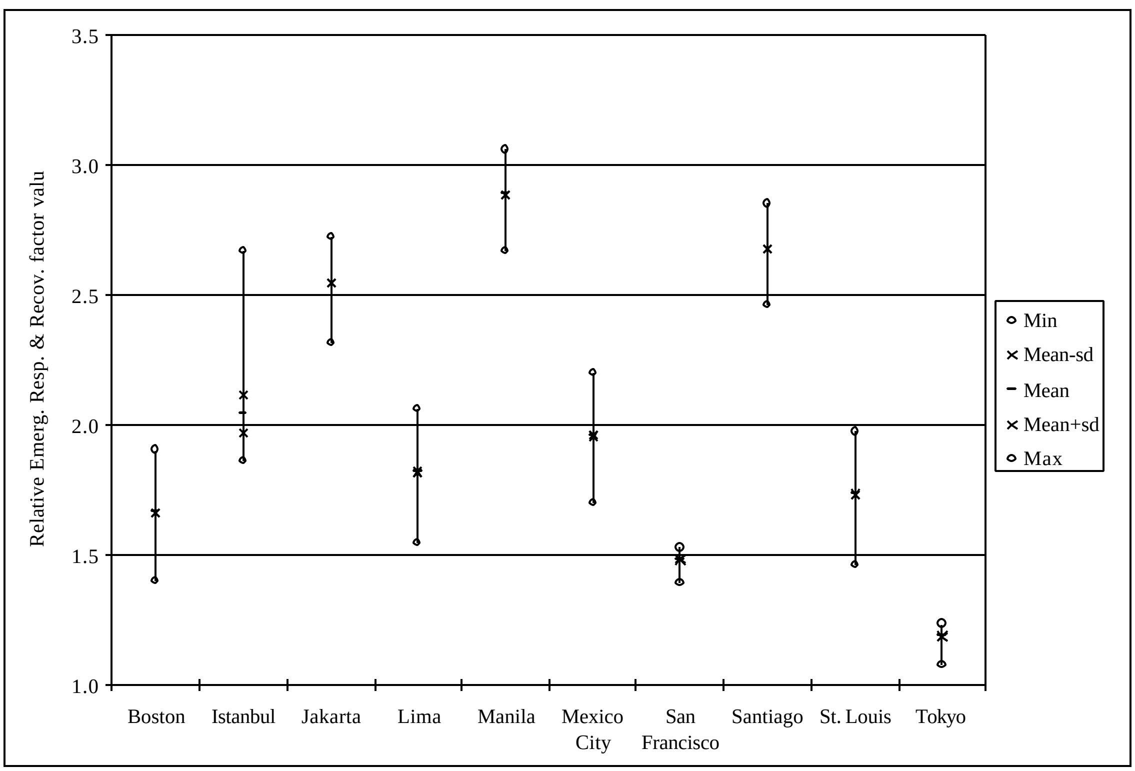


Figure 7.6e. Sensitivity of Emergency Response and Recovery factor to data uncertainty

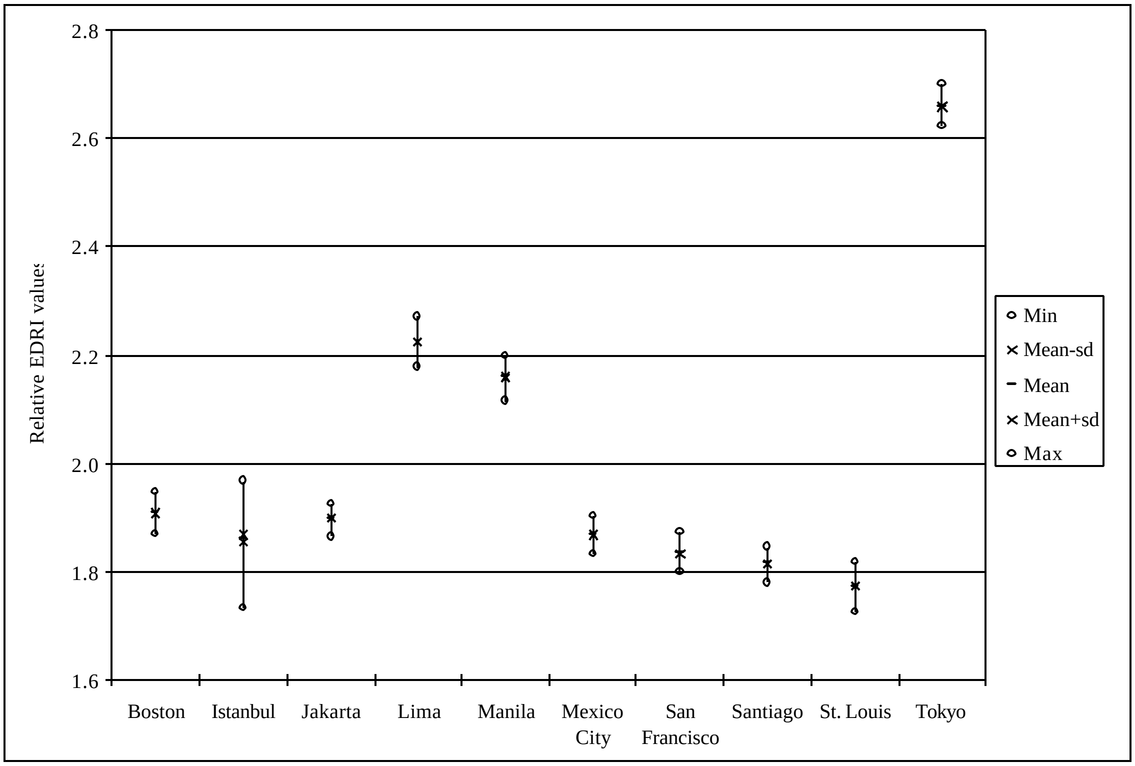


Figure 7.6f. Sensitivity of EDRI to data uncertainty

7.6. Sample city selection

Sensitivity of the final main factor and EDRI values to the set of cities used in the sample was conducted similarly to the indicator definition sample analysis. Three alternative sets of sample cities were considered, the EDRI evaluation was repeated using each, and the results were compared with those obtained for the original ten-city sample. The alternative sample city sets are (1) the original ten cities, not including Istanbul; (2) the original ten cities, not including Tokyo; and (3) the original ten cities, not including Tokyo or Istanbul.

The results of the original and the three alternative city samples are displayed in Figure 7.7. Removing Istanbul from the sample of cities did not affect the results significantly. For a given city, the main factor and EDRI values changed by less than 5%. Removing Tokyo from the sample of cities had a much more pronounced effect on the results, particularly for Exposure and External Context. For example, when Tokyo was removed, the value of the Mexico City

Exposure jumped from 2.237 to 3.502, and the ratio of Mexico City Exposure to Lima Exposure, from 1.500 to 2.193. As a result of the changes in Exposure and External Context, the overall EDRI values changed significantly as well. Removing both Tokyo and Istanbul produced results similar to those associated with removing only Tokyo.

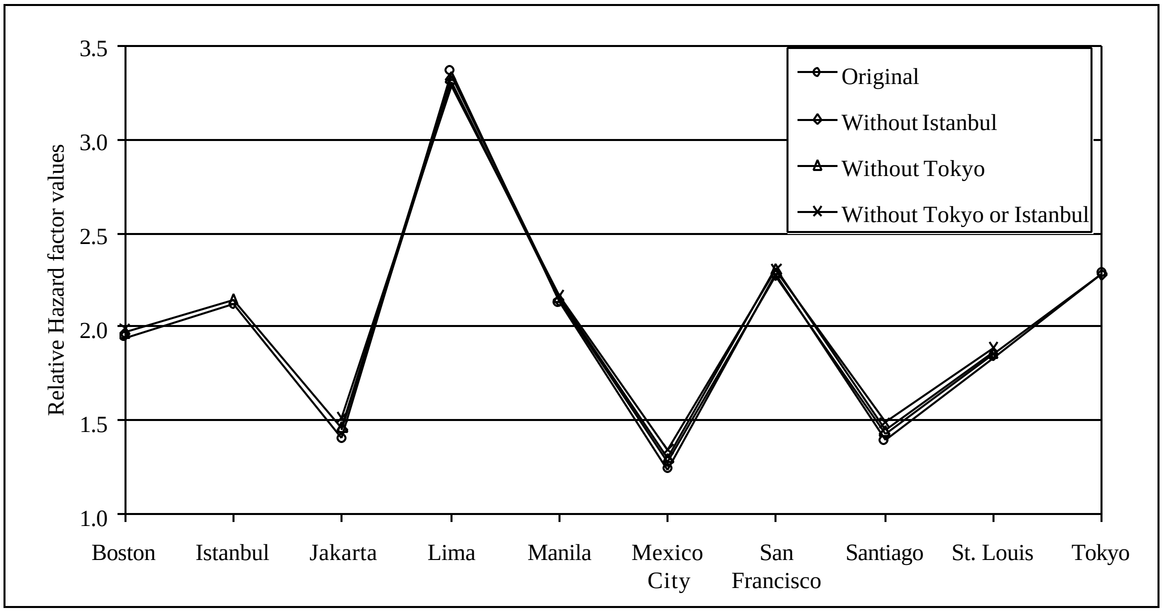


Figure 7.7a. Sensitivity of Hazard factor to city sample

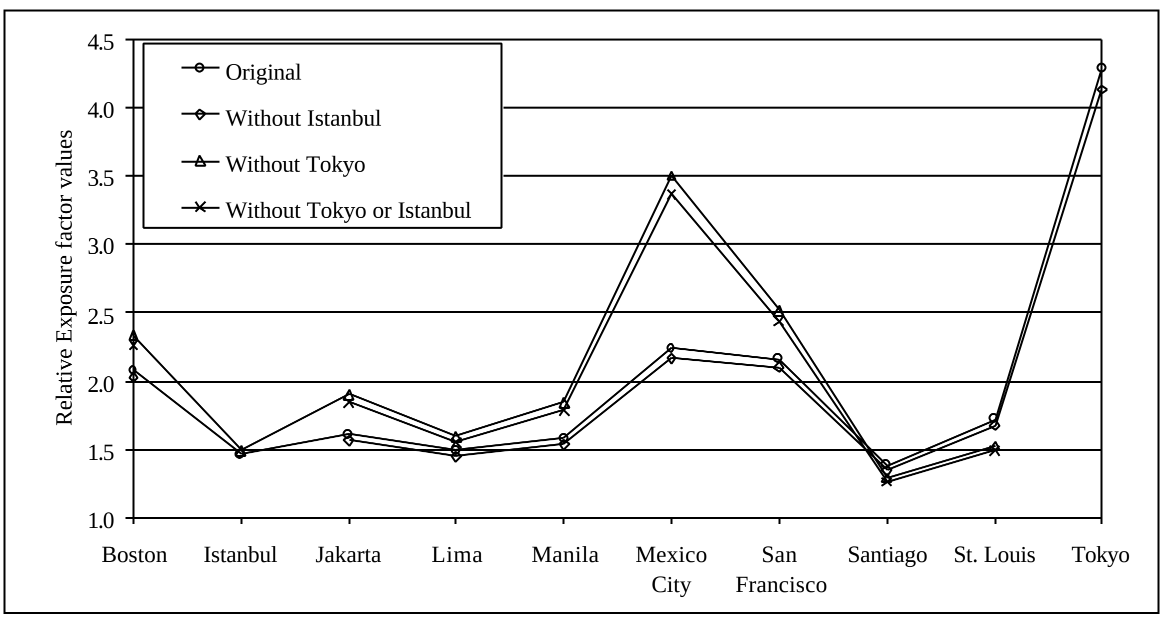


Figure 7.7b. Sensitivity of Exposure factor to city sample

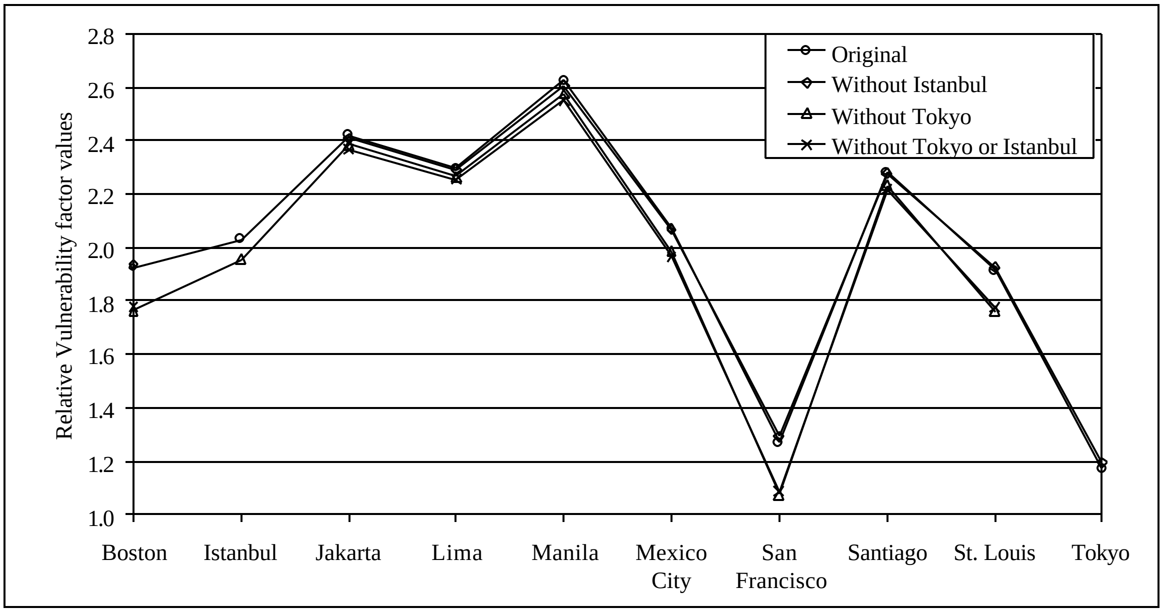


Figure 7.7c. Sensitivity of Vulnerability factor to city sample

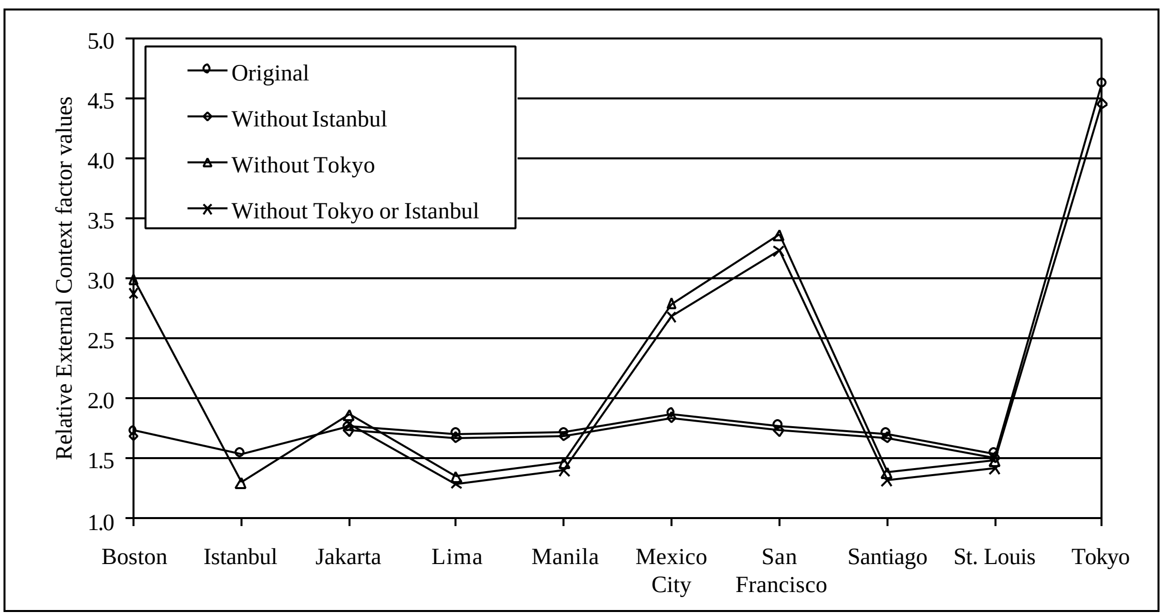


Figure 7.7d. Sensitivity of External Context factor to city sample

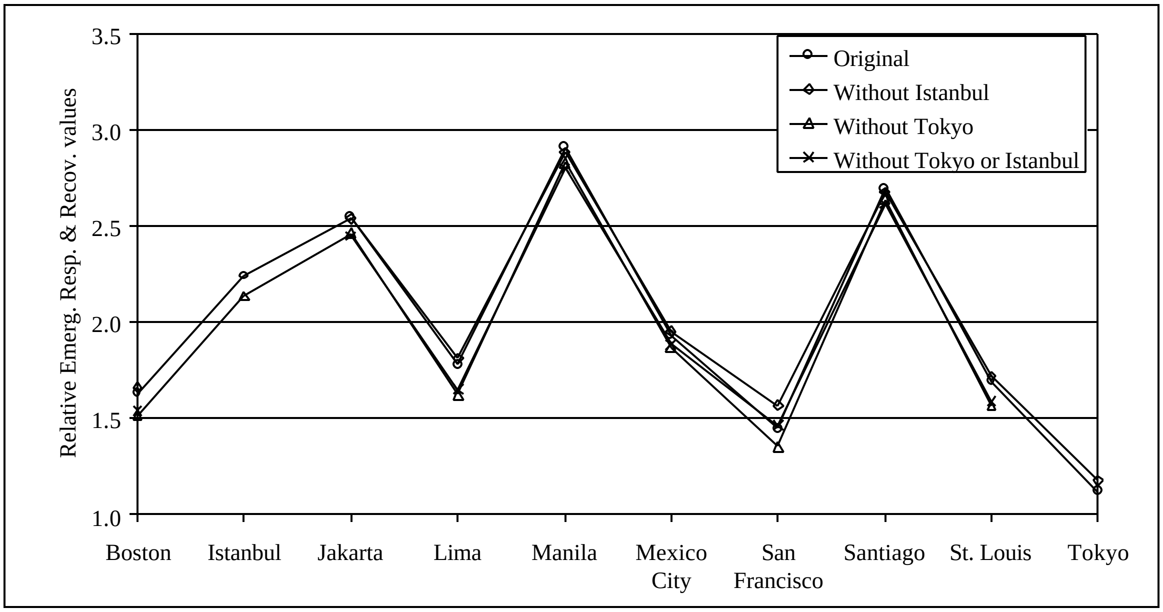


Figure 7.7e. Sensitivity of Emergency Response and Recovery factor to city sample

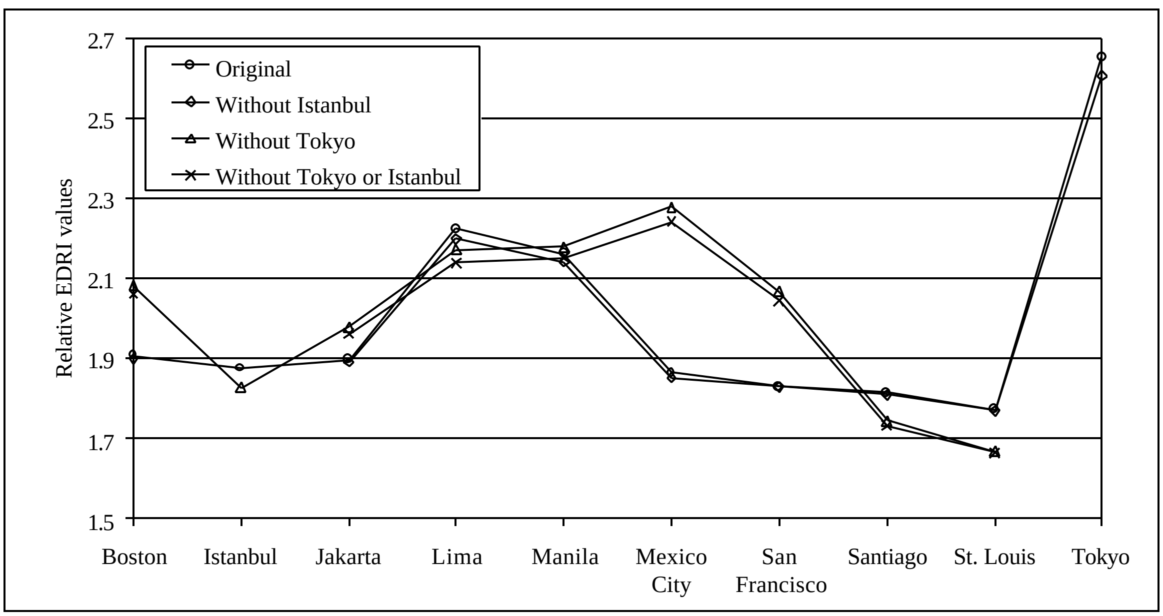


Figure 7.7f. Sensitivity of EDRI to city sample

While, at first glance, this limited investigation seems to suggest that the final main factor and EDRI results are quite sensitive to the city sample, that conclusion may not hold in general. When Istanbul is removed from the sample, the change in the results is negligible. The profound effect of removing Tokyo can be attributed to two extenuating circumstances. First, the original sample has only ten cities, so any effect is more pronounced when changing the sample from ten to nine cities, than it would be if it was changed from 301 to 300. Second, Tokyo is a city unique among all cities worldwide, in that it is so large and wealthy that it breaks the curves, so to speak, on Exposure and External Context. Ultimately, when the number of cities in the sample is on the order of two or three hundred, varying the sample by adding or removing a few cities should not have a significant effect on the results, especially if Tokyo is not among those cities that are added or removed.

7.7. City boundary definitions

The way in which each city is defined can affect the final EDRI values. Each city may be defined as only the area within its legal city limits, as an expansive greater metropolitan area that includes the downtown and the surrounding suburbs, or as any variation in between. In the sample analysis, each city is defined as a greater metropolitan area that includes several surrounding counties, prefectures, or similar administrative units (see Appendix B). Even without a detailed analysis, it is clear that if a city is defined by its legal city limits or some other standard instead, the results will change significantly. For example, the population of Tokyo prefecture is 11.9 million, versus 35.5 million in the five-prefecture greater metropolitan area. Similarly, if San Francisco is defined as the ten-county greater metropolitan area, the population density is 1075 people per sq. km.; if only the area contained within its legal city is used, the population density becomes 5947 people per sq. km. Clearly, the final main factor and EDRI values are highly sensitive to the city boundary definitions.

7.8. Conclusions

Each aspect of the sensitivity analysis explore the effects of a single variation in the EDRI input or model, e.g., one indicator-city unscaled data value, one weight, the scaling technique, *or* the sample of cities. These effects are not mutually exclusive, however. What would happen if the population of San Francisco was actually delta more than the assumed value, *and* the urbanized land area of Manila was actually delta less than the assumed value? While the sensitivity analysis would be more comprehensive if it investigated the effects of each combination of these variations, the large number of possible combinations makes such an analysis prohibitively complex. Instead, let it suffice to compute the sensitivity to each component individually, and note that in many cases, the effects of multiple changes will add linearly, since the EDRI is a linear combination, and that it is possible that even the rankings that held under all conditions tested in the above analyses (e.g., in all 620 data uncertainty trials, Lima exhibited the highest Hazard value) may change if multiple uncertainties are considered simultaneously.

Spearman's rank correlation coefficient (r_s) measures the correlation between two sets of ranks. The following formula is used to evaluate the Spearman coefficient when there are no ties in the ranks:

$$r_s = 1 - \left[\frac{6 \sum_i (u_i - v_i)^2}{n(n^2 - 1)} \right] \quad (7.1)$$

where u_i and v_i are the ranks of the *i*th observation in samples 1 and 2, respectively, and n is the number of pairs of observations (number of observations in each sample). In the case of the EDRI sensitivity analysis, each observation corresponds to one city in the sample (n = 10), one of the samples is always the original results from Chapter 6, and the other sample is from the results computed after the input data are varied.

Table 7.3 compares the results of five components of the sensitivity analysis—indicator definitions, indicator selection, scaling function, weight values, and data uncertainty. Sample city selection sensitivity is not included in the table, because each trial has a different number of cities, so the Spearman coefficient cannot be calculated. The Spearman coefficient values are all very high, indicating that the rankings do not change dramatically in the face of the various uncertainties, especially those associated with the weights and data. As expected, scaling produces the lowest Spearman

Table 7.3. Comparison of average Spearman rank correlation coefficient (r_s) values

	Components of sensitivity analysis				
	Indicator definition	Indicator selection	Scaling	Weights	Data uncertainty
Hazard	0.996	0.990	0.926	0.998	0.980
Exposure	1.000	0.994	0.953	1.000	1.000
Vulnerability	0.960	0.982	0.965	0.998	0.996
Ext. Context	1.000	0.984	0.823	0.994	1.000
Emer. Resp. & Recov.	0.992	0.996	0.953	1.000	0.996
EDRI	0.968	0.927	0.911	0.989	0.981
Num. of trials	3	36	3	72	620

coefficient values, because of the base city scaling option. Another way to compare the various components of the sensitivity analysis is simply by comparing Figures 7.1 to 7.3, and 7.5 to 7.7. As mentioned before, sensitivity to indicator selection, scaling function, weight values, and city boundary definitions do not indicate deficiencies in the EDRI model. Sensitivity to indicator definitions, data uncertainty, and the sample city selection, however, should be minimized if possible.

The results of the sensitivity analysis can be summarized in the following two conclusions. First, the many uncertainties involved in developing and evaluating the EDRI lead to a range of possible values for the main factor and EDRI of each city. In some cases, the ranges of values for two cities overlap, making it unclear which city has a higher value for the associated factor. Nevertheless, even considering the range of possible values, it is clear that some cities have higher factor or EDRI values than others. Furthermore, the sample of cities can be divided into groups with similar values (e.g., low, medium, and high Hazard). While establishing broad categorical groups is less precise than declaring than City A has a Hazard that is 1.35 times as large as that of City B, it is still extremely valuable information that is not currently available from any other source, at least not in such a systematically developed way. Even if all that can be confidently extracted from the results is that five cities have a low EDRI and the other five have a high EDRI, it may be that each of the five high EDRI cities have a high risk for a different reason, and the disaggregated results will show that. **The EDRI results are meaningful, even when the uncertainties in the analysis are considered.**

The second conclusion of the sensitivity analysis is that any improvement in the quality of data or the assessment of the weights will improve the ability of the EDRI to provide definitive conclusions about the relative values of the five main factors and the overall EDRI. It is worth some time and effort to make the input data as reliable as possible. Even with the limited resources available for the sample analysis presented here, however, the EDRI results provide valuable insights into the relative earthquake disaster risk of different cities.

Chapter Eight

Presentation and Interpretation of Results

8. Introduction

The tables and figures presented in Chapters 6 and 7 tell a story. They contain information that may not be immediately obvious at first glance into the sea of numbers. This chapter is about extracting that information and translating it into a language that its potential users can understand. The story describes the big picture of urban earthquake disaster risk—how serious it is, how widespread, how it compares among cities worldwide, and what contributes to it. There are also some smaller storylines that can be uncovered by examining groups of cities with similar characteristics (e.g., industrialized versus developing countries), or comparing pairs of factors or pairs of cities to determine specific information. Following a general discussion of the goals of the presentation phase of the EDRI development, this chapter introduces the results of the presentation and interpretation step for the sample analysis. The many graphical forms used to present the EDRI results are displayed and interpreted, until the entire story has been told.

8.1. Goals of the presentation

One of the primary potential uses of the EDRI is to raise awareness of the issues involved in urban earthquake disaster risk among decision-makers and interested members of the public, and to disseminate the current state of knowledge of earthquake risk. The presentation of the results, therefore, is critical to ensuring that the information contained in the EDRI is easily understood by its potential users.

Raising awareness requires capturing the attention of an audience that may not have a well-developed interest in the topic yet. The presentation, therefore, must be engaging. It should be creative, relying on whatever combination of figures, graphs, tables, and prose summaries convey the EDRI's information so that it is as clear, and easy to understand and interpret as possible, keeping in mind that the audience may range from experts within the earthquake community to the uninformed public. The presentation must convey the information contained in the EDRI accurately. There are many uncertainties in the EDRI analysis, so it would be irresponsible to imply a higher degree of precision than the analysis warrants. Nonetheless, as the sensitivity analysis demonstrates, the EDRI does contain a lot of valuable information, and that should be communicated.

As a summary of urban earthquake risk worldwide, the EDRI should serve as a starting point for earthquake risk information. It cannot possibly convey all the relevant information that is currently known, but it can provide summary and comparative information about the many aspects of our natural, built, and social environments that contribute to earthquake risk, and the wide range of geographical areas that are affected by the problem. That synopsis can help raise awareness of the nature and magnitude of urban earthquake risk, and spark interest in the challenge of mitigating that risk. The EDRI presentation should raise questions, and direct the user to other sources that can provide more detailed information. Specifically, the presentation of the EDRI analysis results should convey the relative overall earthquake disaster risk of different cities, relative values of each of the five main contributing factors across cities, and relative contributions of the main factors within each city.

8.2. Sample analysis solution

Consider three possible forms of presentation for the EDRI results: categorical groupings, the numerical form used in Chapter 6, and a rescaled numerical rating system. Using categorical groupings has the advantage of being easy to understand, particularly if the categories are given labels with intuitive understanding, such as *Low*, *Medium*, and *High* earthquake disaster risk. The disadvantage of the approach is that the low resolution makes it impossible to distinguish between cities at the low and high ends of a category. The second option, using the scaled EDRI values from Table 6.3 directly, has higher resolution, but is not user-friendly. Expressing a city's EDRI value as a number to three decimal places makes the values appear more precise than they are. For most users, a simple integer rating scale from one to one hundred would be easier to understand than an open-ended scale in which cities have values between 1.772 and 2.653. For this reason, the final main factor and EDRI values are rescaled for the presentation using the following equation:

$$F_{\text{rescaled for presentation}} = \left[99 * \frac{(F_{\text{scaled as in Chap. 6}} - \text{minvalue})}{(\text{maxvalue} - \text{minvalue})} \right] + 1 \tag{8.1}$$

where minvalue and maxvalue are taken as zero and five in the sample analysis, respectively, and F can be any of the five main factors or the EDRI. It would be possible to use different values for minvalue and maxvalue, but zero and five seem natural choices given the sample analysis factor and EDRI values, as explained below. The resulting values of the five main factors and the EDRI will be expressed as integers between one and one hundred.[1] Given the Section 5.2.3 discussion of the deficiencies of the scaling with respect to minimum and maximum possible values, it may seem inappropriate to perform this final rescaling. Nevertheless, the circumstances associated with the task make this scaling technique appropriate in this case. These rescaled final main factor and EDRI values are not going to be combined into any other composite index, so the choice of minimum and maximum possible values will have no consequence, except to determine how clustered or dispersed the values appear in Figures 8.1 and 8.2. This final scaling puts artificial bounds on the range of possible EDRI values, when the EDRI is meant to measure risk on an open-ended scale. Nevertheless, from the user's point-of-view, there would appear to be bounds anyway, because even if the values were not rescaled, a range still would be chosen for the y-axis of Figures 8.1 and 8.2. That range would probably be zero to five. By using zero and five for the minvalue and maxvalue then, the final

[1] The scaling does not include the value zero in its range, because while the risk in some cities may be relatively very small, there is always some risk.

rescaling simply serves to change the values of the y-axis from zero to five, to one to one hundred. The relative heights of the sample city columns in the graph appear the same with or without the final rescaling. Finally, this technique achieves the goal of expressing the final main factor and EDRI values as simple integers that are more agreeable to the user than the alternative fractional values.

8.2.1. Overall EDRI and five main factor values

The first components of the presentation of the sample analysis results are the bar charts that represent the overall EDRI, the five main factors, and their components. Those tables and their accompanying table of values are displayed in Figures 8.1 and 8.2, and Table 8.1. As discussed in the previous section, to improve the presentation and interpretation, the relative values of the EDRI, the five main factors, and their components have been rescaled so that the values range from one to one hundred. Using Figures 8.1 and 8.2, the results are briefly discussed below, factor by factor.

According to Figure 8.2a, both short- and long-term seismicity are highest for Lima. Short-term seismicity is also relatively high in Istanbul, Manila, San Francisco, and Tokyo. Long-term seismicity, however, is highest in Boston, Istanbul, San Francisco, St. Louis, and Tokyo. Combining the short- and long-term seismicity with the soft soil indicator results in overall ground shaking component values that are dominated by Lima, roughly similar for Boston, Istanbul, Manila, San Francisco, St. Louis, and Tokyo, and somewhat less for Jakarta, Mexico City, and Santiago. The relative values of the collateral hazard component are highest for Jakarta, Manila, and Tokyo, driven by the liquefaction, liquefaction and fire, and tsunami hazards, respectively. Collateral hazard is lowest for Mexico City and Santiago.

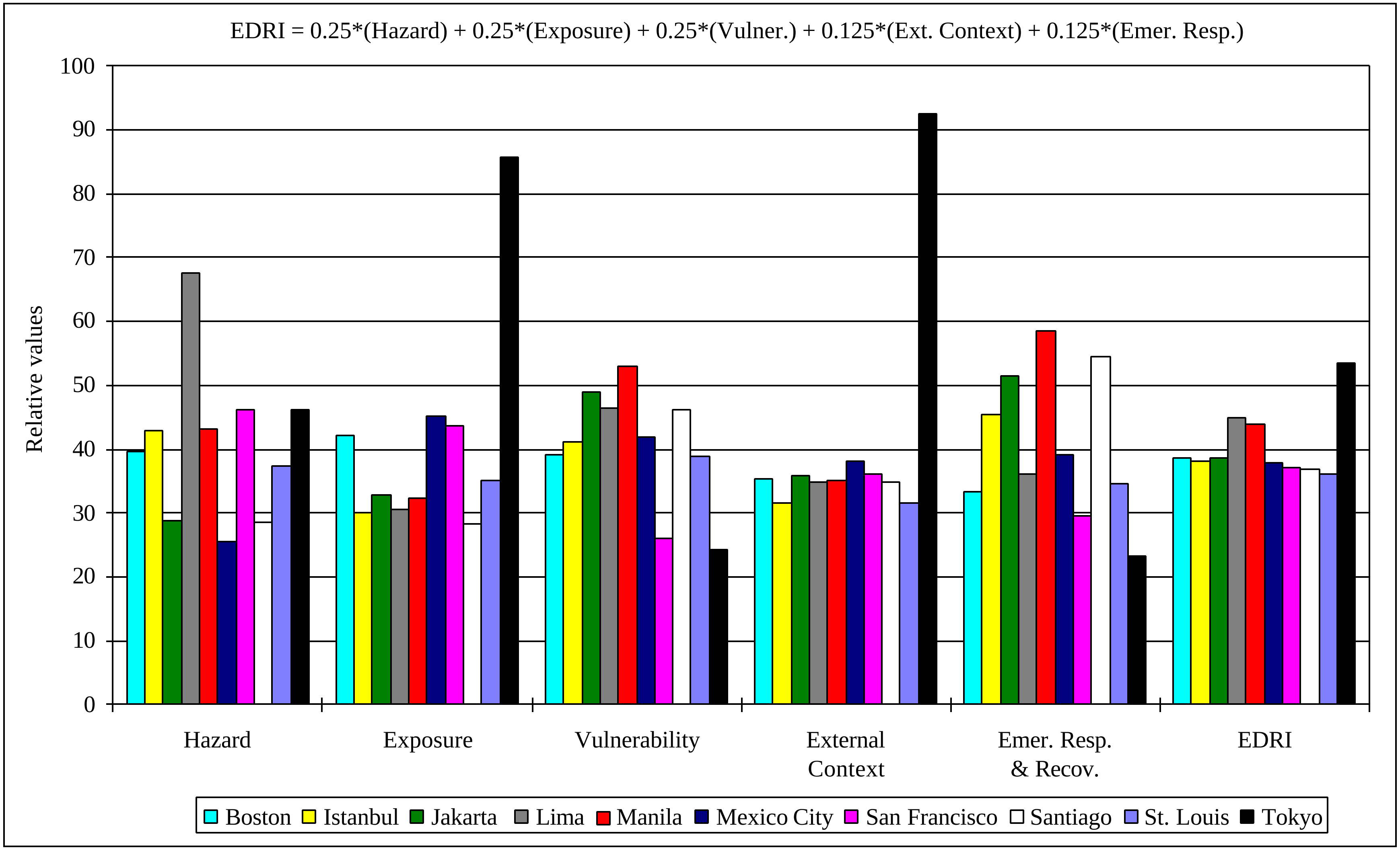


Figure 8.1. Sample analysis results: Relative values of EDRI and five main factors

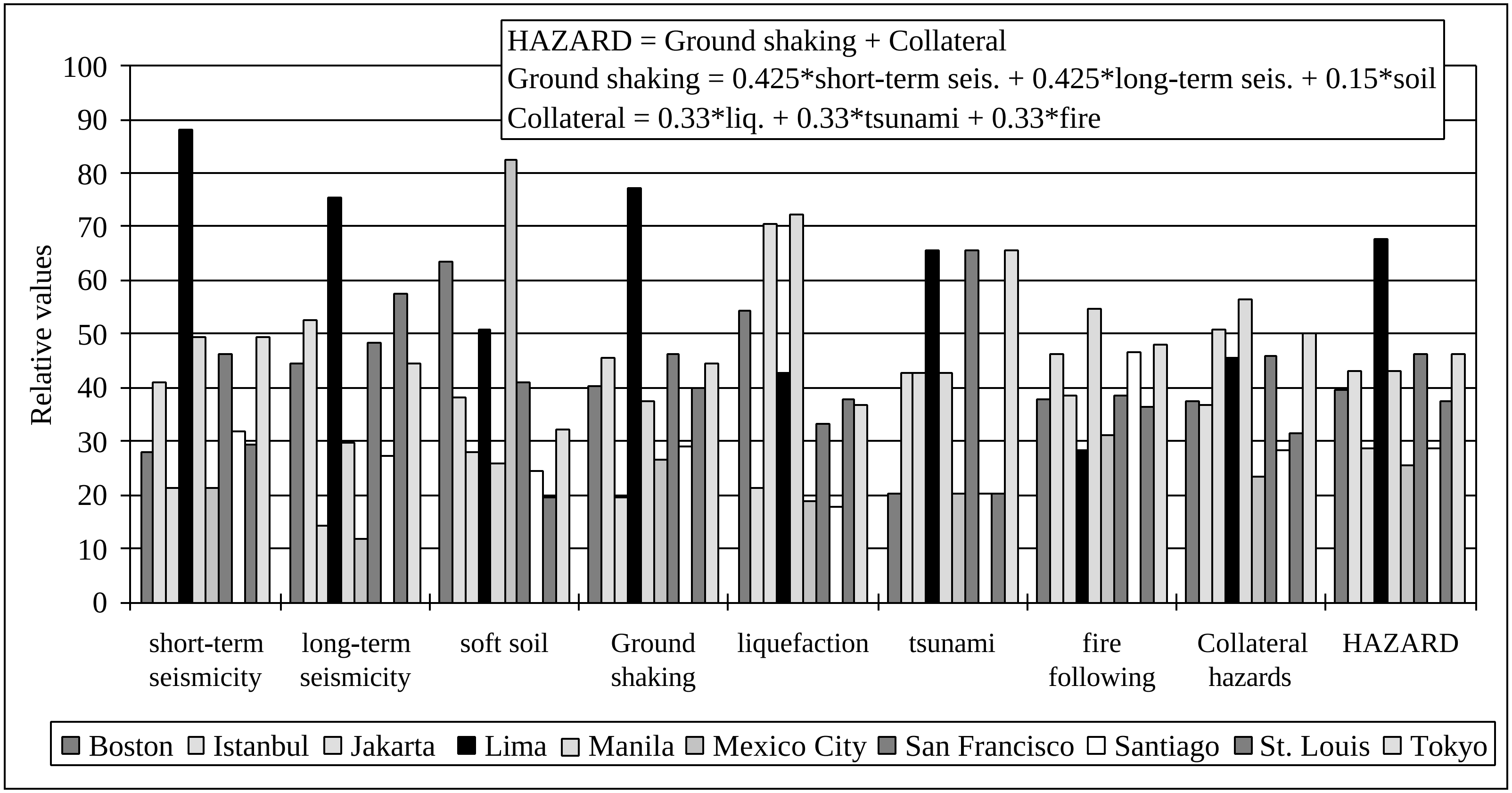


Figure 8.2a. Sample analysis results: Relative values of Hazard components

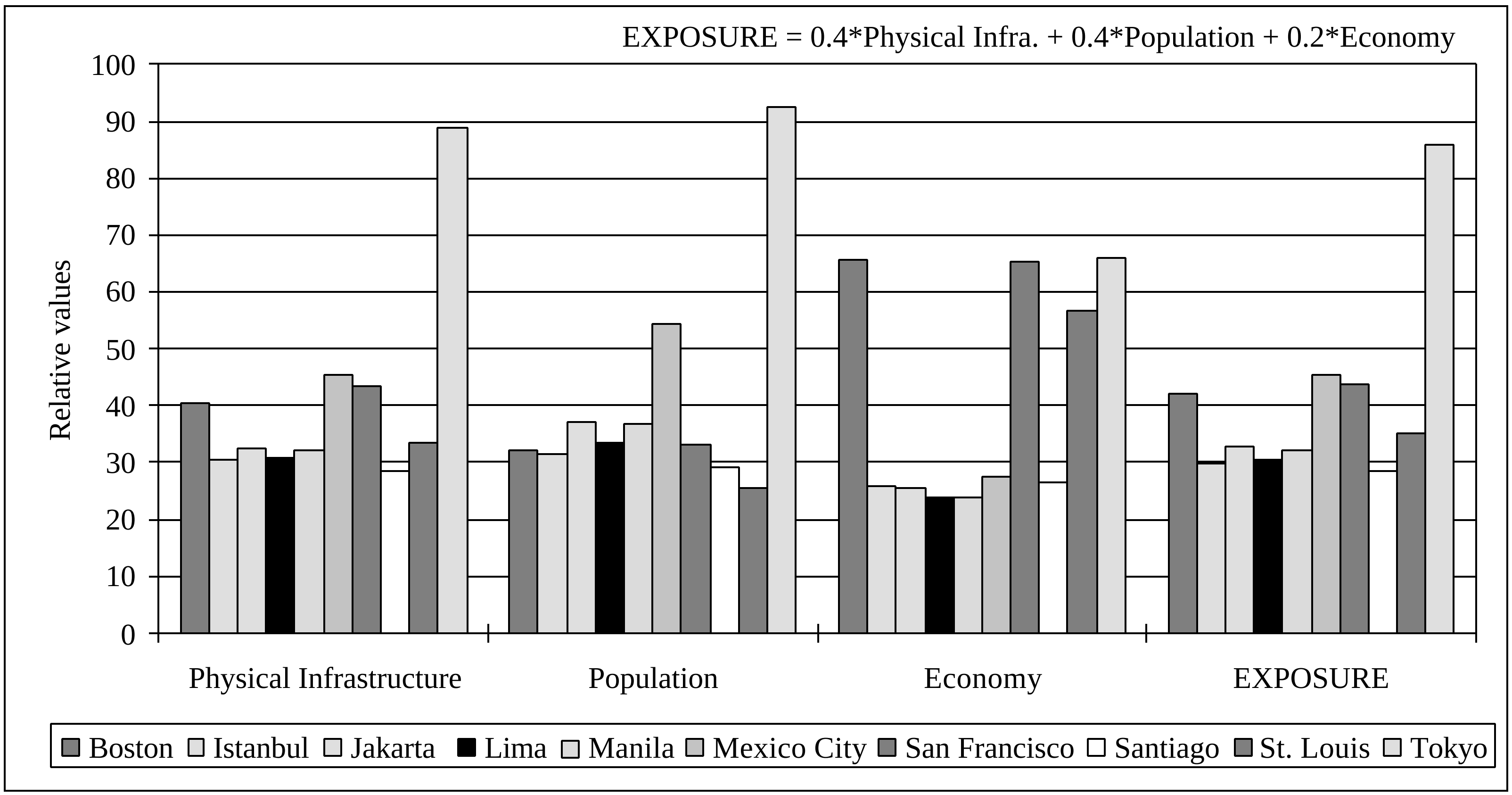


Figure 8.2b. Sample analysis results: Relative values of Exposure components

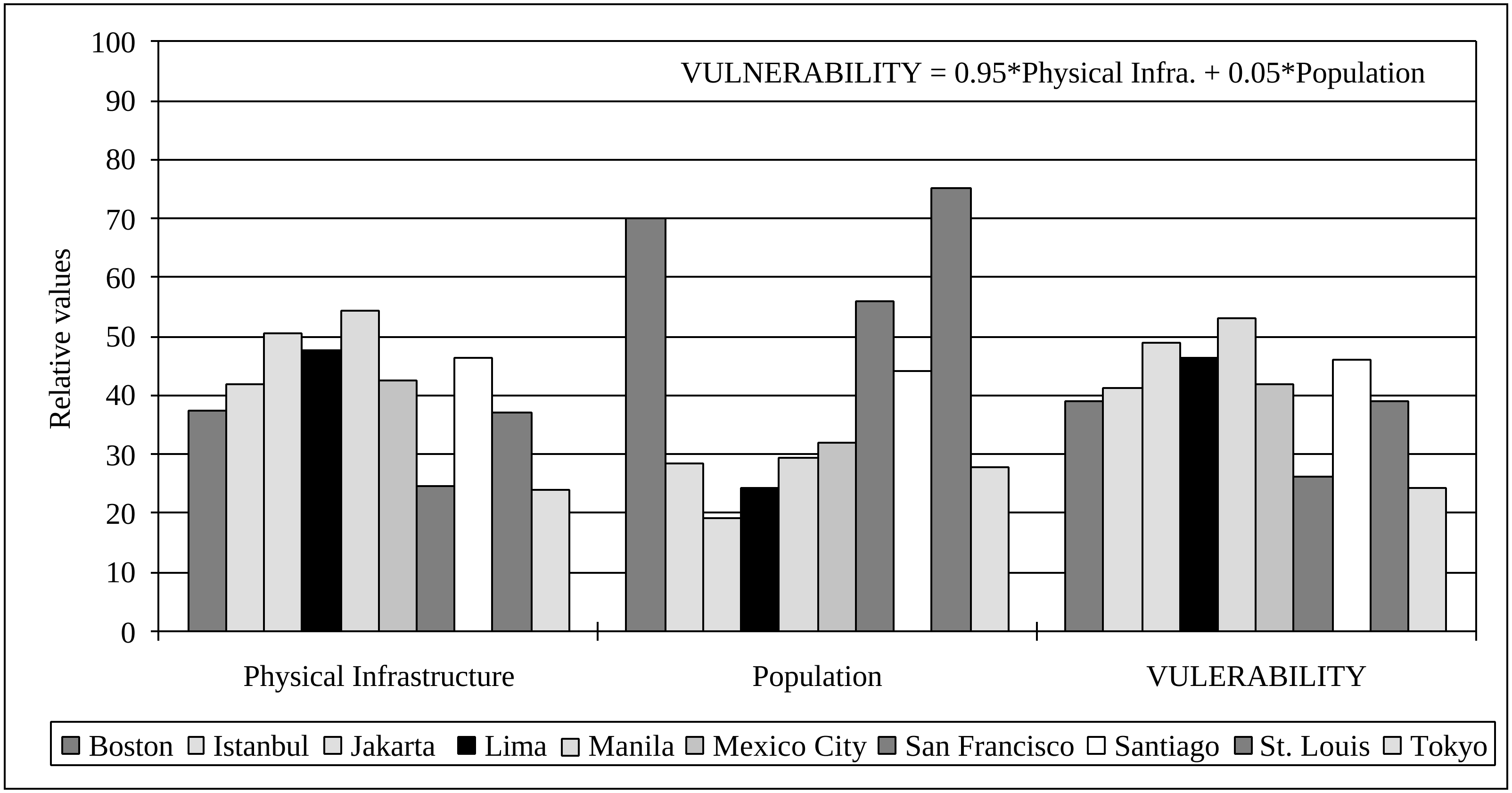


Figure 8.2c. Sample analysis results: Relative values of Vulnerability components

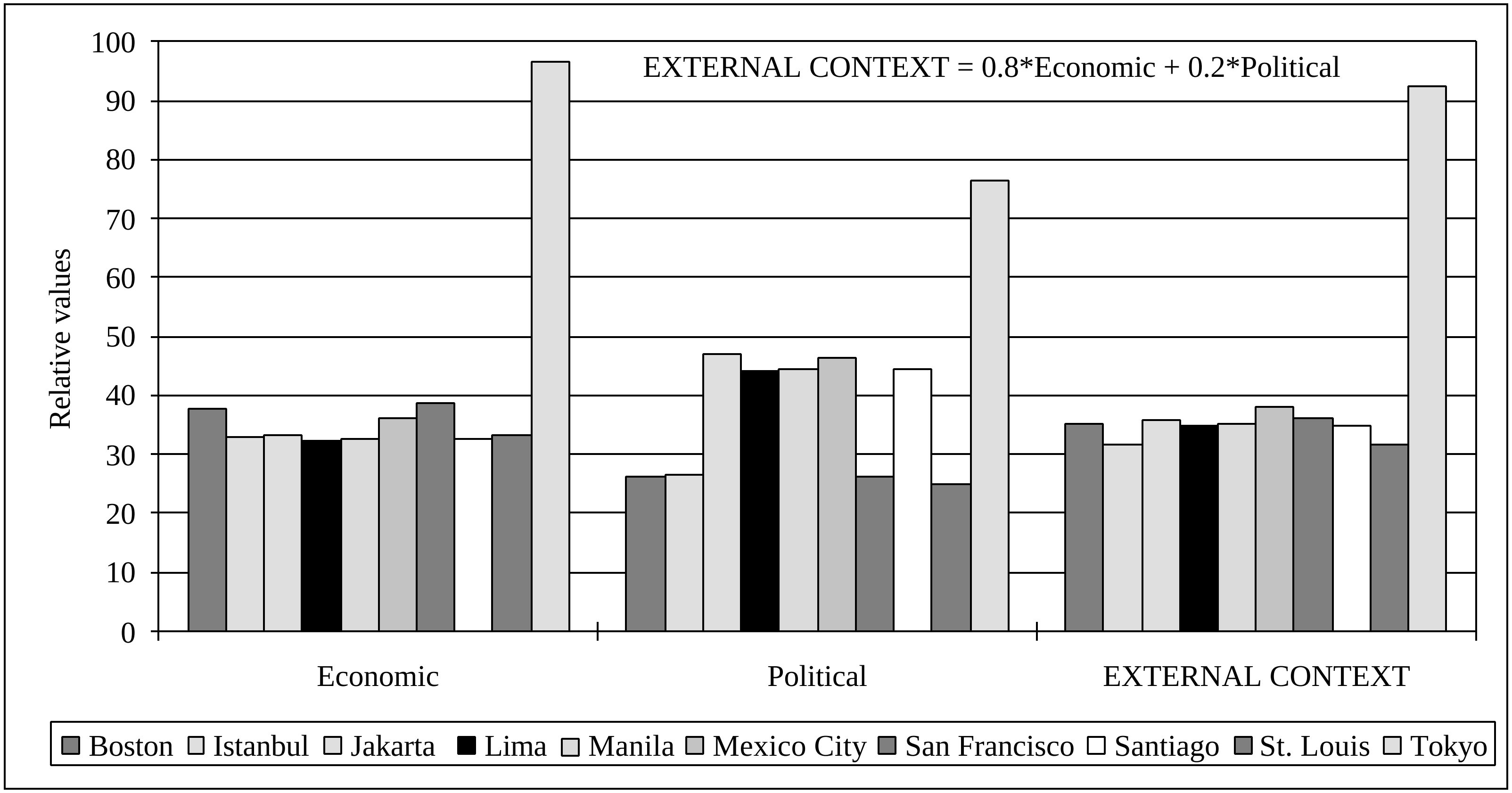


Figure 8.2d. Sample analysis results: Relative values of External Context components

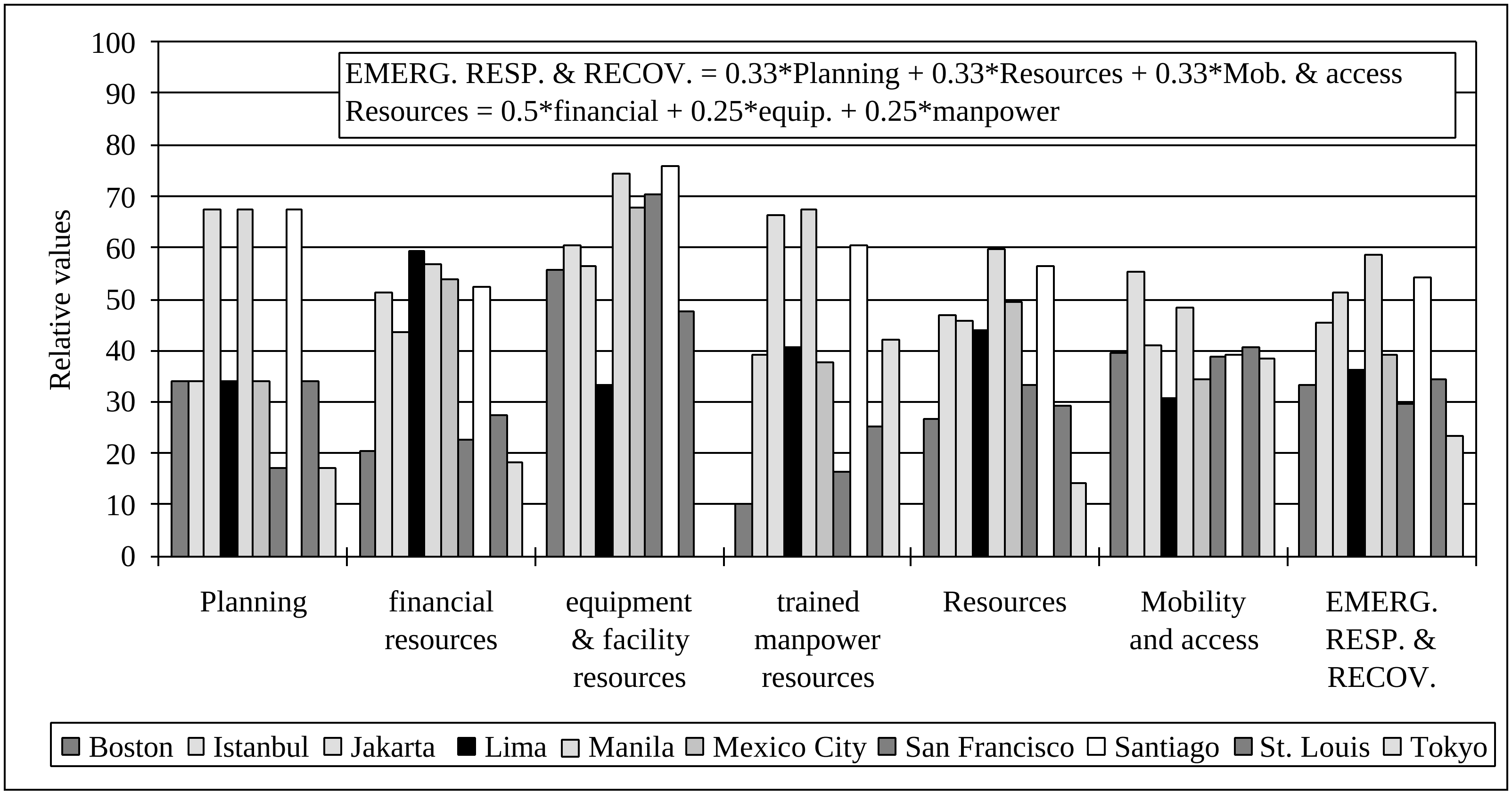


Figure 8.2e. Sample analysis results: Relative values of Emergency Response. and Recovery components

Table 8.1. Sample analysis results for Figures 8.1. and 8.2

Factor	Indicators included	Factor components	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	xh1	short-term seismicity	28	41	21	88	49	21	46	32	29	49
	xh2	long-term seismicity	44	53	14	75	30	12	48	27	58	44
	xh3	soft soil	63	38	28	51	26	82	41	25	20	32
	xh1-xh3	Ground shaking	40	46	19	77	37	27	46	29	40	45
	xh4	liquefaction	54	21	71	43	72	19	33	18	38	37
	xh5	tsunami	20	43	43	65	43	20	65	20	20	65
	xh6-xh7	fire following	38	46	38	28	55	31	39	46	37	48
	xh4-xh7	Collateral hazards	38	37	51	45	57	23	46	28	32	50
		HAZARD	40	43	29	68	43	26	46	29	37	46
Exposure	xe1-xe4	Physical Infrastructure	40	31	32	31	32	45	43	28	34	89
	xe5	Population	32	31	37	34	37	54	33	29	26	93
	xe6	Economy	66	26	25	24	24	27	65	26	57	66
		EXPOSURE	42	30	33	31	32	45	44	28	35	86
Vulner-ability	xv1-xv5	Physical Infrastructure	37	42	50	48	54	43	25	46	37	24
	xv6	Population	70	28	19	24	29	32	56	44	75	28
		VULERABILITY	39	41	49	46	53	42	26	46	39	24
External Context	xc1	Economic	38	33	33	32	33	36	39	33	33	97
	xc2-xc3	Political	26	26	47	44	44	46	26	44	25	76
		EXTERNAL CONTEXT	35	32	36	35	35	38	36	35	32	93
Emerg. Resp. & Recovery	xr1	Planning	34	34	68	34	68	34	17	68	34	17
	xr2-xr3	financial resources	20	51	43	59	57	54	23	52	27	18
	xr4-xr5	equipment & facility resources	56	60	56	33	74	68	70	76	48	-4
	xr6	trained manpower resources	10	39	66	41	67	38	16	60	25	42
	xr2-xr6	Resources	27	47	46	44	60	50	33	57	29	14
	xr7-xr9	Mobility and access	39	55	41	31	49	34	39	39	41	38
		EMERG. RESP. & RECOV.	33	45	51	36	59	39	30	54	35	23
		EDRI	39	38	39	45	44	38	37	37	36	54

Tokyo dominates the physical infrastructure and population components, and therefore the overall values of the Exposure factor (Fig. 8.2b). Boston, Mexico City and, San Francisco have the next highest physical infrastructure exposure. Mexico City holds a commanding second place for population exposure. Economy exposure has two tiers, the three U.S. cities and Tokyo having substantially higher values than the other cities.

Physical infrastructure vulnerability is highest in Jakarta, Lima, Manila, and Santiago; lowest in San Francisco and Tokyo (Fig. 8.2c). Boston, San Francisco, and St. Louis post the highest values for the much less important population component. Overall vulnerability rankings are lowest for San Francisco and Tokyo, and highest for Jakarta, Lima, Manila, and Santiago.

Figure 8.2d shows that Tokyo dominates both major components of External Context, economic and political. Boston, Mexico City, and San Francisco have the next highest economic external context values. Jakarta, Lima, Manila, Mexico City, and Santiago, all country capitals, constitute the next highest tier of political external context values.

Planning values are concentrated at three levels (Fig. 8.2e). Jakarta, Manila, and Santiago have the highest values for planning (i.e., associated with the worst planning and highest risk); San Francisco and Tokyo have the lowest values; and the remaining cities are in the middle. Tokyo is set apart with the lowest value for resources (i.e., it has the most resources available), with the U.S. cities being the three runners-up. Manila and Santiago have the highest resources values (i.e., they have the fewest resources). Most cities have similar mobility and access values, except Istanbul and Manila, which are somewhat higher, and Lima and Mexico City, which are slightly lower.

Combining the five main factors results in overall EDRI values that are similar for most cities (36 to 39). Only Tokyo is significantly set apart with a relative EDRI value (54) that is much higher than the other cities, because of its high exposure and external context values.

Lima and Manila exhibit the next highest overall earthquake disaster risk, with values of 45 and 44, respectively.

8.2.2. Relative contributions of different factors

A pie chart for each city in the sample analysis displays the city-specific relative contributions of the five main factors to the overall EDRI of that city (Fig. 8.3). In interpreting the information in Figure 8.3, remember that the five main factor weights are not included in the computation of relative contribution percentages (see Section 6.3).

Two observations are immediately clear on comparison of the ten figures. First, in every city, all five factors contribute significantly to the risk. Only in two cases does a factor have a relative contribution of less than 10%. Second, the relative contributions are not the same from city to city. The factor contributions are most uneven in Tokyo, where Exposure and External Context contribute 32% and 34%, respectively, and Vulnerability and Emergency Response and Recovery Capability contribute 9% and 8%, respectively. Boston and St. Louis, however, show a very even distribution across factors. For those two cities, all five factors contribute 18% to 22%.

Perhaps more interesting than a comparison of the evenness of the distribution across factors, is a comparison of *which* factors contribute the most, relative to other factors, for each city. For Lima and San Francisco, Hazard contributes the most, with Exposure a close second for San Francisco. Vulnerability and Emergency Response and Recovery Capability produce the highest relative contribution for Jakarta (V: 25%; R: 26%) , Manila (V: 24%; R: 27%), and Santiago (V: 24%; R: 28%). In Mexico City, Hazard (13%) contributes significantly less than the other factors; and Exposure contributes the most (24%). Tokyo and Istanbul exhibit opposite distributions. In Tokyo, Exposure and External Context contribute the most of all factors, while in Istanbul they contribute the least, 16% each.

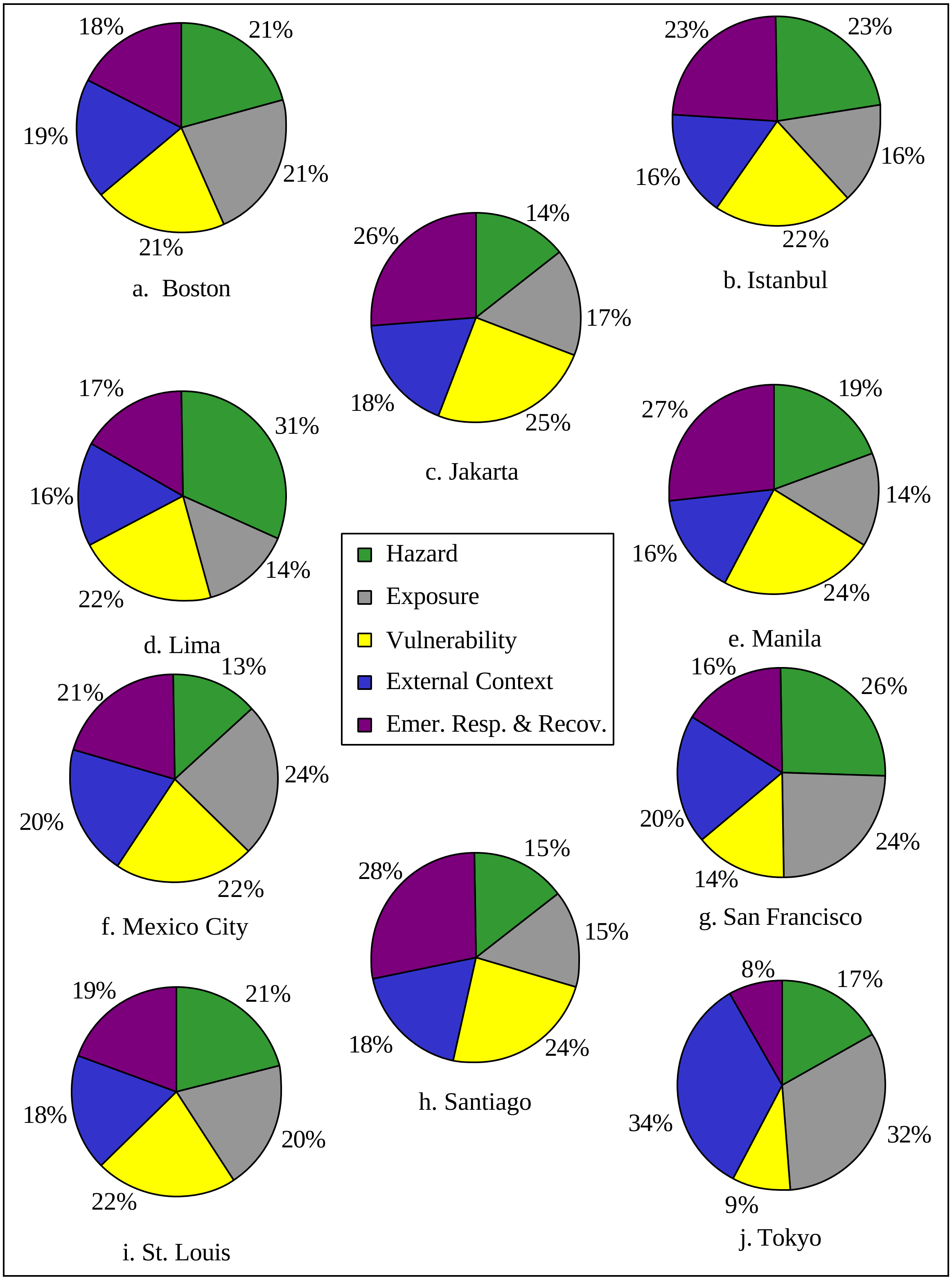


Figure 8.3. Sample analysis results: Relative contributions of five main factors to EDRI

8.2.3. Earthquake disaster risk map

The maps most often associated with earthquake risk are seismicity maps, isoseismal maps showing the distribution of damage due to an actual earthquake, and ground shaking and loss estimation maps with contours displaying expected levels of ground shaking and loss for a region. Seismicity maps are the only ones generally plotted for the entire world. Plotting earthquake disaster risk on a world map, and comparing it to a world seismicity map would illustrate vividly that urban earthquake disaster risk exists all over the world, not only along the plate boundaries. Figure 8.4 presents the sample analysis version of an Earthquake Disaster Risk Map. There is a column at the location of each city in the sample analysis. The total height of the column is proportional to the relative overall EDRI value (shown in brackets), and the relative heights of the layers describe the relative contributions of the five main factors to that city's earthquake disaster risk.

8.2.4. City summaries

Since some potential EDRI users may have a particular interest in one or more specific cities, it is helpful to reiterate the most pertinent information for each city in city summary pages. The idea is modeled after the Economic Freedom Index presentation of a two-page summary of results for each country (Johnson and Sheehy 1996). Figure 8.5 shows an example of a city EDRI summary for Tokyo.

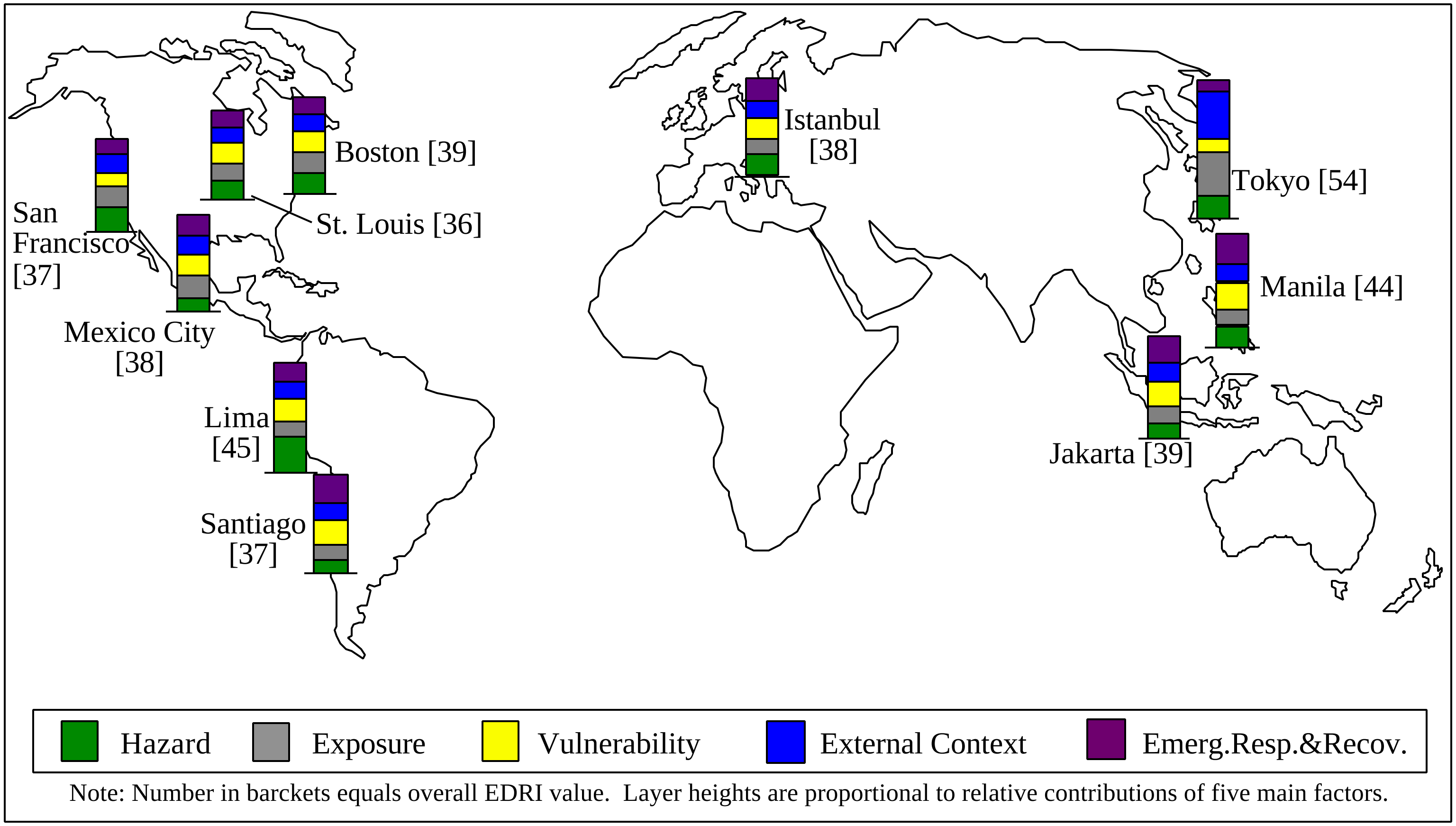
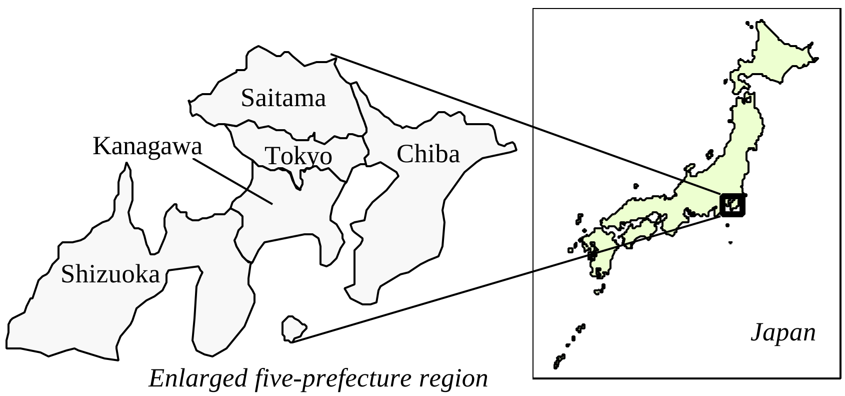


Figure 8.4. Earthquake disaster risk map

Tokyo, Japan
EDRI City Summary

Located at the intersection of four major tectonic plates, in one of the most seismically active countries in the world, Tokyo exhibits a relatively high short-term and long-term seismicity. A serious threat of fire following earthquake, and the possibility of a tsunami, place Tokyo third out of the ten-city sample in collateral hazards factor component, giving it an overall hazard value second only to Lima.



Tokyo dominates population and physical infrastructure exposure, sharing the lead in economy exposure with the U.S. cities, and putting it in a commanding position as the city with the largest overall exposure. It also dominates all components of external context, thanks to its role as a leading financial and political center for Japan and the world.

A wealthy city with a long history of seismic codes and emergency planning for earthquakes, Tokyo has the lowest physical infrastructure and overall vulnerability, and the best emergency response and recovery capability rating in the ten-city sample.

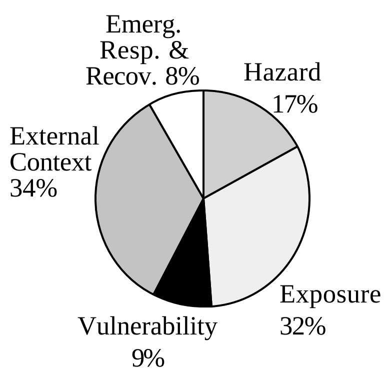


Figure 8.5. Example of a city summary for Tokyo, Japan

Tokyo, Japan
EDRI City Summary

	Indicator	Tokyo	Average	St. Dev.
xh1	exp(MMI w/50-year return period)	1339	973	838
xh2	exp(MMI w/500-year return period)	3641	3274	1919
xh3	Percentage urbanized area w/soft soil	10%	17%	16%
xh4	Percent. urb'd. area w/high liquefaction suscept.	20%	23%	17%
xh5	Percentage of buildings that are wood	60%	42%	26%
xh6	Population density (people per sq. km.)	8849	8910	5955
xh7	Tsunami potential indicator	2.0	0.9	0.9
xe1	Population (1000s)	35,467	9,248	9,479
xe2	Per capita GDP in constant 1990 US$	25,833	10,955	11,287
xe3	Number of housing units (1000s)	14,046	2,767	3,820
xe4	Urbanized land area (sq.km.)	3525.9	1157.1	967.8
xe5	Population (1000s)	35,467	9,248	9,479
xe6	Per capita GDP in constant 1990 US$	25,833	10,955	11,287
xv1	Seismic code indicator	52.79	25.96	18.48
xv2	City wealth indicator	4631	1533	1600
xv3	City age indicator	20.6	20.3	13.6
xv4	Population density	8849.2	8910.3	5955.4
xv5	City development speed indicator	36.0	39.4	29.8
xv6	Percent. of population aged 0-4 or 65+	14.70%	16.08%	2.34%
xc1	Economic external context indicator	4.20E+13	4.96E+12	1.24E+13
xc2	Political country external context ind.	1.0000	0.6517	0.4839
xc3	Political world external context indicator	3.19E+12	3.81E+11	9.37E+11
xr1	Planning indicator	4.00	2.60	1.17
xr2	Per capita GDP in constant 1990 US$	25,833	10,955	11,287
xr3	Avg. ann. real per cap. GDP growth, prev. 10 yrs.	3.56%	2.24%	3.53%
xr4	Housing vacancy rate	11.00%	7.14%	2.68%
xr5	Num. hospitals per 100,000 residents	5.57	2.11	1.33
xr6	Num. physicians per 100,000 residents	164	167.4	100.1
xr7	Extreme weather indicator	55.67	50.85	40.95
xr8	Population density	8849.2	8910.3	5955.4
xr9	City layout indicator	0.00	0.18	0.40

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Risk Management Solutions, Inc. 1995. *What if the 1923 Earthquake Strikes Again?: A Five-Prefecture Tokyo Region Scenario*. Menlo Park, Calif.: RMS.

UNCRD. 1995. *Comprehensive Study of the Great Hanshin Earthquake*. Res. Report Series, no. 12. Nagoya, Japan: UNCRD.

Figure 8.5 (cont'd). Example of a city summary for Tokyo, Japan

8.2.5. Group comparisons

The EDRI results may be compared for groups of cities with similar characteristics. While the insight gained through these comparisons may be more powerful in the context of a larger set of sample cities, the idea can be illustrated using the ten cities in the sample analysis. The ten cities are divided into those located in high development countries and those in medium development countries, as defined by the *Human Development Report 1995* (UNDP 1990-95). Boston, Mexico City, San Francisco, Santiago, St. Louis, and Tokyo comprise the first group; the remaining four cities comprise the second. Figure 8.6 displays the average five main factor and EDRI values for each group. It seems intuitively understandable that the Vulnerability and Emergency Response and Recovery Capability would be higher in the medium development cities, while the External Context would be higher in the high development cities. Figure 8.6 also suggests that differences in the factor values largely compensate for one another, because the overall EDRI values for the two groups are similar.

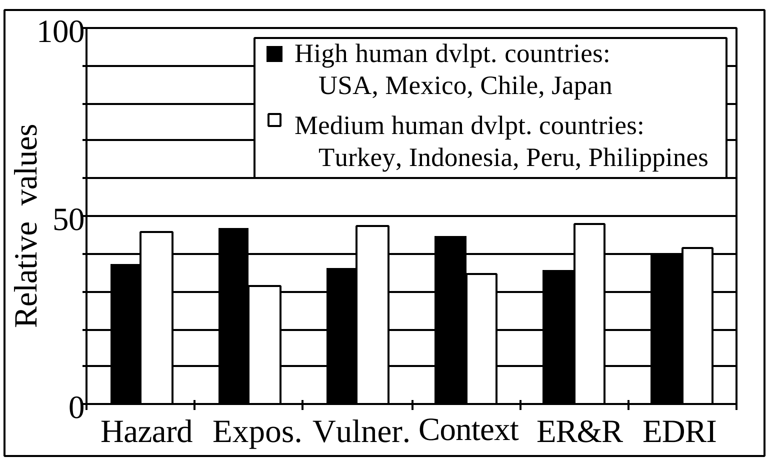

Figure 8.6. Comparison of EDRI for cities with high and medium human development

8.2.6. Hazard versus earthquake disaster risk

A comparison between the Hazard factor values and the EDRI values provides another interesting smaller story that can be extracted from the EDRI results. Figures 8.7 and 8.8 offer a couple examples of the several ways in which the comparison can be illustrated. Figure 8.7 plots EDRI versus the Hazard factor, and divides the grid into four quadrants: Low Hazard-Low EDRI, Low Hazard-High EDRI, High Hazard-High EDRI, High Hazard-Low EDRI. The quadrant boundaries correspond to the mean values for the sample of cities. While the figure suggests that a high EDRI implies a high Hazard, the converse is not true. A high Hazard value does not imply a high EDRI. Furthermore, some cities exhibit similar EDRI values, but very different Hazard values (e.g., Santiago and San Francisco), while others have a similar Hazard, but different EDRI (e.g., Tokyo and San Francisco). Figure 8.8 compares the factor values for San Francisco and Tokyo. The columns illustrate clearly that the two cities have the same value for the Hazard factor, but because of differences in the remaining four factors, particularly Exposure and External Context, the final EDRI value is significantly higher in Tokyo than in San Francisco. Both figures demonstrate that the two concepts—hazard and earthquake disaster risk—are related, but not equivalent.

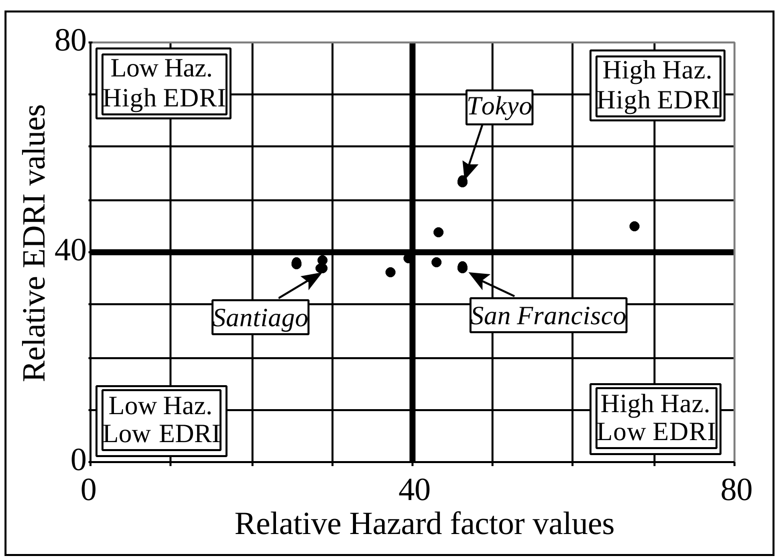

Figure 8.7. Comparison of EDRI and Hazard factor

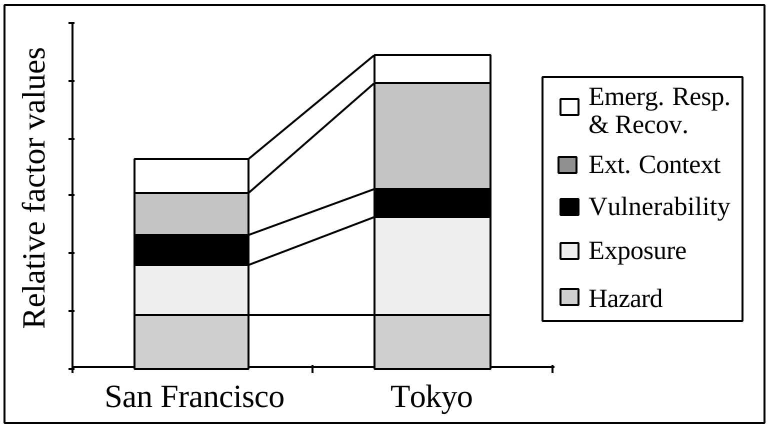

Figure 8.8. Equal Hazard, unequal EDRI

8.3. Reminders

Throughout the interpretation of the EDRI results, the limitations of the EDRI development should be kept in mind. The difficulties of the indicator selection process led to the omission of some of the concepts of the conceptual framework. The EDRI's linear form means that some nonlinearities and dependencies are not conveyed. The sensitivity analysis indicates that there is some uncertainty in the values of the factor and EDRI values for all cities. Finally, the EDRI goals were stated explicitly in Section 2.2. The index aims to measure earthquake disaster risk as it was defined in Section 2.1. It includes all impact parameters, not only financial losses and not only deaths. It conveys the risk only as it is understood relative to other cities, not on an absolute scale. No information is provided about the distribution of risk within each city. While the EDRI can provide some potentially very useful information, these characteristics should be noted repeatedly to ensure that it is not misinterpreted or misused.

Chapter Nine

Future Work and Conclusions

9. Introduction

This final chapter looks to the future through a discussion of some natural extensions of the EDRI project described in the previous eight chapters. It explores refinements that might improve the EDRI, and suggests possible variations of the index that might be useful to specific users. The chapter concludes with some final summary thoughts on the contributions of this study.

9.1. Future work

Future work related to the Earthquake Disaster Risk Index could proceed in one of two directions: refining the index, or developing variations of it. As with any research project, time and resource constraints imposed limitations on the scope of the EDRI development and evaluation. As a result, each of the six steps in the EDRI development procedure could be repeated and refined to produce a similar, but improved EDRI. The conceptual framework could be expanded to address the interactions among factors more fully. The indicator selection process could be improved by exploring more indicator options, and buttressing those choices with more analytical or empirical evidence that the indicators represent that factors for which they are proxies. In keeping with the possible inclusion of factor interactions in the conceptual framework, the mathematical combination could be altered to model nonlinearities and dependencies among the indicators. The determination of the weights also provides a significant opportunity for refining the EDRI. A more comprehensive, scientific questionnaire survey might be conducted to provide more support for the assessment of weights. A similar survey might be used to verify the final index rankings of the five main factors and the overall EDRI.

In the data gathering and evaluation step, the more time and effort spent reducing the uncertainty in the data, the better the final EDRI results will be. Additional effort might go toward more personal communications with subject and local area experts, or continuing library research. Another obvious goal of future work is to evaluate more cities, gradually expanding the ten-city sample until the EDRI of all major cities in the world have been assessed. Many options exist to improve the presentation of the EDRI results. When a larger set of cities has been evaluated, a glossy booklet, like the Human Development Report or the Economic Freedom Index report, could be published. A colorful, laminated, poster-size Earthquake Disaster Risk map might be created, with paragraphs of explanation, tables, and other auxiliary information filling in the space around the edge of the map. Finally, a software package could be developed that takes raw data for each city and indicator as input, performs the evaluation and sensitivity analysis for the EDRI, and produces the final tables and figures as output. The package might include some databases that would be useful for all cities, such as the historical tsunami database, or population and GDP data for all countries. It also could offer flexibility in, for example, the choice of weight values, the deltas used in the sensitivity analysis, and form of the final output. Such a software tool could make it easy for any potential user to evaluate the EDRI for any set of cities.

The development of variations on the EDRI constitutes the second vein of possible future work. As mentioned in Section 2.2, one reason that the objectives of the EDRI were stated explicitly at the beginning of the development procedure was to guide the decisions encountered during the process. If the objectives are altered to reflect the needs of a specific user, some aspects of the development and evaluation will have to be changed as well. Different users might be interested in measuring a slightly different concept than the earthquake disaster risk defined in Section 2.1. They may have different resources available for gathering data, or they might be focused on a different unit of study or a specific subset of cities. In each case, the basic development and evaluation procedure of the EDRI described in this study should be able to accommodate the user's specific needs. It only may be necessary to modify the specific factors that are included in the conceptual framework, change the set of indicators, use a different sample for the evaluation, and/or present the results differently.

The following are some of the possible variations of the EDRI that might be desirable to specific users. A multi-hazard disaster risk index would be similar to the EDRI, but would address the risk due to hurricanes, tornadoes, floods, and/or technological hazards, as well as earthquakes. The Hazard and Vulnerability factors of the conceptual framework for such an index would have to be altered, and therefore the indicators chosen to represent those factors would change as well. A multi-hazard index would be even more comprehensive, following the emerging social science paradigm's shift away from a hazard-based approach. It would be especially useful to government and international aid organizations that are less concerned about the agent of damage, loss, and disruption, than the magnitude and distribution of that impact.

A national government or national organization might be interested in a country-specific EDRI, i.e., one that is evaluated only for cities within the specified country. Some modifications will be necessary to tailor the EDRI to the specific circumstances of the country of interest. For example, the country's data availability situation may be different than that for a set of international cities, and the External Context will take on a different role for a country-specific EDRI. Similarly, while some aspects of earthquake disaster risk make more sense for a greater metropolitan area than an entire country, an EDRI that uses a country as the unit of study might be useful for some international organizations, and it would gain the advantage of improved data availability compared to that associated with cities or regions.

Another variation of the EDRI might focus on one or more specific impact parameters, rather than all possible impact parameters. For example, an insurance company, reinsurance company, or bank might be interested only in the economic aspects of earthquake disaster risk.

A revised EDRI that measures, not earthquake disaster risk as it is defined in Section 2.1, but an economic earthquake risk, might be of more interest to those users.

9.2. Conclusions

The research presented in this dissertation establishes a methodology for the development of the many possible variations of the EDRI that are discussed in the previous section. It lays out the development procedure so that future researchers can repeat the process, altering the details to fit their specific goals and resources. It includes both an outline of the steps involved, and many specifics about the particular issues that arise in the course the development of the EDRI. The previous eight chapters explore the current state of knowledge of earthquakes and their effects on the life of a greater metropolitan area, the challenges and options for the selection of indicators to represent a city's earthquake disaster risk, the mathematics of composite index construction, the data availability situation for cities worldwide, the procedure for performing a sensitivity analysis, and the issues and possibilities for presentation of the index results. With this methodology established, future researchers can create variations of the EDRI with relative ease.

In addition to the methodology, this project offers two substantive products. The first is the EDRI itself, an easy-to-understand summary of urban earthquake disaster risk. The index can raise awareness of the nature and magnitude of urban earthquake disaster risk, and spark interest in the challenge of mitigating that risk. It is the user interface for the second product, the conceptual framework of earthquake disaster risk on which the index is based. The framework is the behind-the-scenes support that helps to interpret the findings of the EDRI, and can provide a launching point for further investigation of the concepts that the EDRI represents. Although the development proceeded in the other order, a user would see the EDRI results first, then to pursue his investigation of the topic, would learn more about the conceptual framework and its component factors. Both the conceptual framework and the final index are significant. The former provides meaning to the index; the latter summarizes and delivers the information to the user. This project has demonstrated that it is possible to create a meaningful Earthquake Disaster Risk Index that allows direct comparison of the overall earthquake disaster risk of cities worldwide, and describes the relative contributions of various factors to that overall risk.

Appendix A

Selected Previously Proposed Definitions of *Disaster*

Quantitative, operational definitions

- A disaster is an event which causes ten deaths, and/or affects one hundred people, and/or leads to an appeal for international assistance (International Federation of Red Cross and Red Crescent Societies, and the Centre for Research on the Epidemiology of Disasters 1994).
- A disaster is an event for which at least one of the following is true(U.S. OFDA 1990):
  i. The "Chief U.S. Diplomatic Mission in an affected country determined that a disaster existed which warranted U.S. government response."
  ii. It causes more than five deaths.
  iii. The sum of the number of deaths and the number of people injured is greater than twenty-four.
  iv. More than one thousand people are affected.
  v. It causes damage greater than $1 million.

Qualitative, comprehensive definitions

- Natural disasters are one type of social crisis. Disaster "refers to a condition in which the traditional structure, due to the impact of a precipitating geophysical event, is destroyed and/or no longer collectively defined as an appropriate guide for social behavior in the altered system. Within a community a disaster represents a crisis of relatively high intensity." The event "creates demands upon the community system that cannot be met by its traditional, institutional structure—including its set of community-emergency and emergency-relevant organizations. In such a setting, significant alterations in community structure can be observed to occur as the system develops an emergent, disaster structure to facilitate its response to the event and increase its capability to fulfill the created demands" (Wenger 1978).

- Disasters as "social disruption and changes brought about by the physical agent and its impact" (Quarantelli 1978).
- A "sudden and disruptive impact in which disaster demands exceed the capabilities of routine social structures in the community" (Kreps 1978).
- Natural disasters create needs in a community often unmet by established organizations (Forrest 1978).
- Disaster is a crisis which exceeds the capacity of society to manage it (Anderson 1992).
- Disaster is an "event associated with the impact of a natural hazard, which leads to increased mortality, illness and/or injury, and destroys or disrupts livelihoods, exceptional and requiring external assistance for recovery" (Cannon 1994).
- A disaster is "an event, concentrated in time and space, in which a society (or a community) undergoes severe danger and incurs such losses to its members and physical appurtenances that the social structure is disrupted and the fulfillment of all or some of the essential functions of the society is prevented" (Fritz 1961).
- "A major incident is a serious disruption to life, arising with little or no warning, causing or threatening death or serious injury to, or rendering homeless, such numbers of persons in excess of those which can be dealt with by the public services operating under normal procedures, and which calls for the special mobilisaton and organization of those services." (U.K. Humberside County Council).

Appendix B

Sample City Definitions

Boston, USA

Includes the following ten counties (according to the U.S. Census-defined Boston Consolidated Metropolitan Statistical Area):

Bristol, Massachusetts
Essex, Massachusetts
Middlesex, Massachusetts
Norfolk, Massachusetts
Plymouth, Massachusetts
Suffolk, Massachusetts
Worcester, Massachusetts
Hillsborough, New Hampshire
Rockingham, New Hampshire
Stafford, New Hampshire

Istanbul, Turkey

Includes the following fifteen district municipalities (Institut d'Estudis Metropolitans de Barcelona 1988):

Adalar
Bakirkoy
Besiktas
Beykoz
Beyoglu
Eminonu
Eyup
Fatih
Gaziosmanpasa
Kadikoy
Kartal
Sariyer
Sisli
Uskudar
Zeytinbinburnu

Jakarta, Indonesia

Defined as DKI Jakarta, which is equivalent to the following:

Jakarta Selatan
Jakarta Timur
Jakarta Pusat
Jakarta Barat
Jakarta Utara

Lima, Peru

Defined as the sum of Lima and Callao Provinces, which is equivalent to the sum of the following forty-nine districts; forty-three in Lima, six in Callao (Institut d'Estudis Metropolitans de Barcelona 1988):

Lima Province:

Lima
Ancon
Ate
Barranco
Brena
Carabayllo
Chaclacayo
Chorrillos
Cieneguilla
Comas
El Agustino
Independencia
Jesus Maria
La Molina
La Victoria
Lince
Los Olivos
Lurigancho
Lurin
Magdalena del mar
Magdalena la vieja
Miraflores
Pachacamac
Pucusana
Puente piedra
Punta Hermosa
Punta Negra
Rimac
San Bartolo
San Borja
San Isidro
San Juan de Lurigancho
San Juan de Miraflores
San Luis
San Martin de Porres
San Miguel
Santa Anita
Santa Maria del Mar
Santa Rosa
Santiago de Surco
Surquillo
Villa El Salvador
Villa Maria del Triunfo

Constitutional Province of Callao:

Callao
Bellavista
Carmen de la Legua Reynoso
La Perla
La Punta
Ventanilla

Manila, Philippines

Defined as the National Capital Region (NCR), which is equivalent to the sum of the following four cities and thirteen municipalities (Institut d'Estudis Metropolitans de Barcelona 1988):

- Manila City
- Caloocan City
- Pasay City
- Quezon City
- Las Pinas
- Makati
- Malabon
- Mandaluyong
- Marikina
- Muntinlupa
- Navotas
- Paranaque
- Pasig
- Pateros
- San Juan del Monte
- Taguig
- Valenzuela

Mexico City, Mexico

Includes the entire Federal District, plus the following fifty-three districts from the State of Mexico (Institut d'Estudis Metropolitans de Barcelona 1988):

- Acolman
- Amecameca
- Atenco
- Atizapan de Zaragoza
- Atlautla
- Axapusco
- Ayapango
- Coacalco
- Cocotitlan
- Coyotepec
- Cuautitlan Izcalli
- Cuautitlan de Romerio Rubio
- Chalco
- Chiautla
- Chicoloapan
- Chiconcuac
- Chimalhuancan
- Ecatepec
- Ecatzingo
- Huehuetoca
- Huixquilucan
- Isidro Fabela
- Ixtapaluca
- Jaltenco
- Jilotzingo
- Juchitepec
- Melchor Ocampo
- Naucalpan
- Nextlapan
- Nezahualcoyotl
- Nicolas Romero
- Nopaltepec
- Otumba
- Ozumba
- Papalotla
- La Paz
- Sn. Martin de las Piramides
- Tecamac
- Temamatla
- Temascalapa
- Tenango del Aire
- Teotihuacan
- Teoloyucan
- Tepetlaoxtoc
- Tepetlixpa
- Tepotzotlan
- Texcoco
- Tezoyuca
- Tlalmanalco
- Tlalnepantla
- Tultepec
- Tultitlan

Zumpango

San Francisco, USA

Includes the following ten counties (according to the U.S. Census-defined San Francisco Consolidated Metropolitan Statistical Area):

Alameda	Santa Clara
San Mateo	Santa Cruz
Contra Costa	Sonoma
Marin	Napa
San Francisco	Solano

Santiago, Chile

Defined as Provincia Santiago, which is equivalent to the sum of the following thirty-two comunas (Institut d'Estudis Metropolitans de Barcelona 1988):

Santiago	Penalolen	Estacion Central
Independencia	La Florida	Cerrillos
Conchali	San Joaquin	Maipu
Huechuraba	La Granja	Quinta Normal
Recoleta	La Pintana	Lo Prado
Providencia	San Ramon	Pudahuel
Vitacura	San Miguel	Cerro Navia
Lo Barnechea	La Cisterna	Renca
Las Condes	El Bosque	Quilicura
Nunoa	Pedro Aguirre	
La Reina	Cerda	
Macul	Lo Espejo	

St. Louis, USA

Includes the following eleven counties and one city (according to the U.S. Census-defined St. Louis Consolidated Metropolitan Statistical Area):

Clinton, Illinois	Jefferson, Missouri
Jersey, Illinois	Lincoln, Missouri
Madison, Illinois	St. Charles, Missouri
Monroe, Illinois	St. Louis County, Missouri
St. Clair, Illinois	Warren, Missouri
Franklin, Missouri	St. Louis City, Missouri

Tokyo, Japan

Includes the following five prefectures (RMS 1995):

Saitama
Chiba
Tokyo
Kanagawa
Shizuoka

Appendix C

Emergency Response and Recovery Tasks

The following questions elucidate what is involved in each of the twelve tasks associated with post-earthquake emergency response and recovery. Sources: California Seismic Safety Commission (1990); Tierney (1985); UNDHA (1994); UNDRO (1979); UNDRO (1984); and UNDRO (1986).

Emergency management system

1. Does the city have a general emergency response plan?
2. Who developed the city plan?
3. How old is the city plan?
4. Has the city plan ever been executed? When? Have there been exercises to practice execution of the plan?
5. What is the quality of the city plan?
   a. Is the plan comprehensive, yet as simple as possible?
   b. Does the plan include an earthquake-specific section?
   c. Is the plan both organizational and operational? Does it define and organize roles and responsibilities well? Is it usable?
   d. Is the plan well-integrated?
      i. through all hierarchical levels, i.e., community, city, county, nation, region (esp. for island nations), and international? Does it include direction for inter-jurisdictional coordination (e.g., mutual aid agreements)?

ii. across agencies, organizations, and departments (e.g., government agencies, Red Cross, utilities) through task forces, emergency councils, or other arrangements? Does it include direction for interorganizational coordination?

iii. with daily operations and on-going development goals?

e. Does the plan include detailed information about who is responsible for which specific subtasks, and how to prioritize and perform those subtasks?

f. Does the plan clearly define a set of standard priorities?

g. Does the plan define a control structure that:

i. has an established physical location for headquarters?

ii. allows for mobile management operations?

iii. has procedures for delegation of responsibility and authority?

iv. has liaison capability to other jurisdictions, organizations, and the public?

v. includes local officials in all major decisions (not just national or international officials)?

vi. allows close monitoring of actions?

vii. offers a good balance between being centralized (no duplication) and being dispersed (can cover many tasks simultaneously, has redundancy)?

viii. relies on written, not verbal communication when possible?

ix. provides a clear chain of command for each operation?

x. relies on a minimum number of coordination meetings, but includes representatives from all sectors in those meetings?

h. Does the plan incorporate the capabilities of existing organizations, the military, volunteers, and the resources of affected people?

i. Does the plan rely on existing organizations, rather than creating new ones, whenever possible?

j. Does the plan call for a quick, but comprehensive impact assessment to focus (confirm or alter) anticipated needs and priorities?

k. Does the plan establish procedures for giving and receiving information?

6. Are all involved personnel aware of the capabilities and limitations of the city plan, and well-trained in its use?
7. Which, if any, specific organizations and agencies (e.g., hospitals, fire departments, law enforcement) have their own specialized emergency response plans?
8. Repeat items 2-6 for plans related to specific organizations and agencies.

Communications

1. Are there established interorganizational communications links (e.g., between government agencies, relief organizations, utilities)? Are there established relationships and equipment hookups among the organizations?
2. Are there established interjurisdictional (local, national, international) communication links (relationships and equipment)?
3. Are there arrangements for officials to gather information from the public (for damage assessment) and disseminate information to the public ("big picture" impact assessment and instructions)?
    a. Is there a partnership between the local government and the media to guide information transfer between officials and the public?
    b. Is there a prepared format for conveying information to the public that spells out the consequences of the threat and the probability of occurrence, and that is specific, urgent, repeated, and presented by someone with public confidence?
    c. Is there a public information/press relations officer to talk to media representatives and other groups (e.g., all the people in a certain area, all teachers)?
4. Do all involved organizations know who to talk to, what information to convey, what information to request, and what form of communication to use?
5. Will damage to normal equipment be minimized so that it remains functional after an earthquake?
6. Are there redundant and alternate emergency systems of communication (two-way radios, cellular phones, fax and computer lines, dispatch and 911 systems, microwave systems) to

replace normal systems that are not functioning? Does the design of the emergency communications systems consider:

a. the distances over which communications will be needed?
b. the nature of terrain?
c. the type of communication product desired (e.g., voice, hard copy)?
d. the degree of reliability needed?
e. the acceptable duration of delay?
f. the volume of communication (quantity and lengths of messages)?
g. if two-way communication is needed?
h. if equipment will be reliable in adverse operational conditions?
i. if additional maintenance facilities or operator training are needed?
j. the degree of compatibility needed between communication lines?
k. the expected number of trained personnel available to operate?
l. the costs?

Financial arrangements

1. Have pre-disaster arrangements been made to provide timely financial assistance to households, businesses, local governments, and communities for relief and reconstruction, in both the short- and long-term?
    a. Are there any programs to assist households?
    b. Are there any programs to assist businesses?
    c. Are there any subsidy programs?
    d. Are there any assistance programs from government agencies, private sources, or voluntary associations?
    e. Do households, businesses, or governments have earthquake insurance?
        i. What is the market penetration for each sector (residential, commercial, governmental)?
        ii. What are the terms of the coverage?
        iii. Is the coverage reliable?

2. Does a State of Emergency declaration trigger emergency financial arrangements?
3. How difficult will it be, in terms of money, time, and political will, to develop financial arrangements of the type discussed in item 1, after the earthquake?
4. Is there an Emergency Reserve Fund, Emergency Funding Committee, or equivalent body that is empowered to vote on funding if the normal governing body is not in session when the disaster occurs?
5. Are there provisions to provide streamlined delivery of assistance? Have arrangements been made:
    a. for post-disaster waivers of customs duties for relief supplies, and of landing fees for crafts carrying them?
    b. for post-disaster price controls?
    c. to provide compensation to people giving personal services or people whose property is used by emergency relief officials?

Legislation

1. Will relief workers have the necessary legal power to execute relief measures without delay?
2. If legal holdups are expected to delay the provision of relief, how costly (in terms of time and money) are they expected to be?
3. Has pre-disaster legislation established channels to request and receive international assistance efficiently? Does it define who gives what relief, under what circumstances, and how to file relief requests? Does the legislation include arrangements for duty exemption, granting landing and overflying rights, lifting border-crossing restrictions, establishing the chain of command when international teams are involved, exchange of information, and cost-sharing?

Damage assessment

1. Are there established procedures to determine the type, degree, location, and geographic distribution (centralized or dispersed) of casualties and damage immediately after an

earthquake (especially impact on medical services, water supply, liquid waste disposal, shelter, food, and transport)?

   a. Is it clear who is responsible for what portion of the information gathering, and how the information can be interpreted to determine short- and long-term needs?
   b. Is there a procedure to obtain information fromthe public (telephone reports)?
   c. Are there arrangements for using aerial photography to collect information?

2. Are there resources (e.g., people, authority, money) that will be available to perform the damage assessment?
3. Is there a pre-prepared city profile available that includes: hazard and/or risk maps, information on the structural vulnerability, economic situation, number and location of people who may be especially vulnerable (e.g., minorities, elderly)?

Search and rescue

1. Are there established procedures to locate and rescue any survivors trapped in collapsed structures?
2. Are there local resources that will be available to help with the search and rescue?
   a. Is there skilled manpower (search-and-rescue teams, fire and law enforcement officers)?
   b. Are there dog teams, sound equipment, or debris-moving equipment available?
3. Are there established procedures and the necessary communications links to summon international search-and-rescue teams?

Secondary hazard control

1. Are there established procedures to prevent and suppress fires following an earthquake?
2. Is there general public awareness about how to prevent post-earthquake fires?
3. Have the gas companies implemented any fire prevention efforts?
4. Are there nearby resources (e.g., skilled fire fighters, fire-fighting equipment) to suppress fires?

5. Are there established procedures to remove and dispose of hazardous debris following an earthquake?
6. Are there nearby resources (e.g., manpower, debris-moving equipment) to remove the hazardous debris?
7. Will there be a special need for sanitation control? If so, are there established procedures and available resources to ensure adequate standards of sanitation?

Health care

1. Are there established procedures to asses the type and quantity of health care needs? These needs may be based on: general information about the extent and area of damage, population affected, and functional damage to public services (e.g., transportation and utility networks), plus detailed inventory of functional health facilities and their capabilities (e.g., status of facilities, availability of medical staff and medical supplies).
2. Are there plans describing how to provide on-site first aid to injured, to transport injured to health care facilities, and to treat patients at the health care facilities as effectively and efficiently as possible?
3. Are there established communications links among medical providers?
4. Will there be enough skilled personnel (e.g., search-and-rescue teams, emergency medical technicians) available to provide first aid?
5. Will there be enough ambulances, and open transportation routes to transport the injured to health care facilities?
6. To what extent will health care facilities remain functional? Functional includes having enough equipment, staff, medical supplies, medicine, working lights, water, utilities, power for machinery, record-keeping, working elevators or alternate transport; and not being flooded by pipeline breaks.
7. Are there provisions to minimize structural and non-structural damage to hospitals and other health care facilities?
8. Are there provisions to minimize damage to utilities serving hospitals, or provide backup service through emergency generators, emergency water supply systems, etc.?

Mass care

1. Are there established procedures to assess the type and quantity of basic needs that are required (e.g., emergency food and water, water containers, blankets, cooking utensils, clothes)?
2. Are there established procedures and resources to provide, in a timely manner and with as little waste as possible, basic needs to those who do not have them and cannot receive them from family or friends?
   a. Are there established procedures to request, receive, and distribute needed relief supplies from private sources, stockpiles, local, national, and/or international governments?
   b. Will the equipment necessary for receipt and distribution of supplies (trucks, manpower, temporary distribution headquarters) be available?
   c. Are there tanker trucks available to deliver water, and plans to use water from pools and reservoirs?

Shelter

1. Are there established procedures and resources to assess how many people need shelter and for how long, what kind of shelter is appropriate for them, and how to provide it?
2. In estimating shelter needs and determining the most appropriate and accessible emergency shelter types, are the following considered:
   a. number of housing units destroyed or not functional?
   b. capability of community "coping mechanisms" to provide emergency shelter with family and friends?
   c. feasibility and likelihood of survivors making their own shelter with salvaged materials?
   d. weather conditions?

e. accessibility of impacted areas?
f. risks of secondary disaster?
g. manpower at site capable of helping erect emergency shelter?
h. language, religious, and cultural needs?
i. desire for family cohesiveness?
j. desire to minimize distance from shelters to work, schools, stores, and community?

3. Are there established procedures and resources to provide short-term shelter: establish sites, shelters, and facilities to support shelters (e.g., bathrooms)?
   a. Are there local facilities, schools, churches, community centers that may be used for short-term shelter?
   b. Are there established procedures and necessary communications links to request additional short-term shelter from outside sources (e.g., mobile homes, tents, campers)?
4. Are there established procedures and resources to provide long-term shelter: help with reconstruction, or provide long-term (more than two weeks) temporary shelter (establish sites, shelters, and facilities to support shelters)?
   a. Are there local sites and facilities that may be used for long-term shelter?
   b. Are there established procedures and necessary communications links to request additional long-term temporary shelter from outside sources (e.g., mobile homes, tents, campers)?

Clean-up

1. Are there established procedures to reposition undamaged items that are moved during an earthquake?
2. Are there established procedures to repair damaged items?
3. Are there established procedures to remove destroyed items?
4. Is there equipment and manpower to clear debris created by damaged and collapsed structures, and to unblock transportation routes?
5. Are there established procedures to find and bury the dead?

Restoration of services

1. Are there established procedures and resources to restore utility services?

Appendix D

Physical Infrastructure Exposure Data Sets

D.1. Physical Infrastructure Exposure data set from *Compendium of Human Settlements Statistics 1995* (UN Centre for Human Settlements 1995).

	Country	City	Real per capita GDP [PPP$], 1993	Population	Num. of occupied housing units	Total electricity consumption per day [1000 kwh]	Total annual water consumption [1000 cu.m.]	Num. of motor vehicles	Num. of data points (out of 6)
1	Angola	Luanda	674	923,842					2
2	Burkina Faso	Ouagadougou	780	459,826					2
3	Ethiopia	Addis Ababa	420	1,423,111	259,555				3
4	Ghana	Accra	2,000	957,157					2
5	Kenya	Nairobi	1,400	1,324,570					2
6	Mali	Bamako	530	658,275	105,394				3
7	South Africa	Cape Town	3,127	2,614,051	495,000	3,817,791	259,959	522,488	6
8		Pretoria	3,127	442,664	127,680	5,177,830	98,919	597,671	6
9	Tunisia	Tunis	4,950	815,795	168,464				3
10	Canada	Montreal	20,950	3,127,240	1,239,909				3
11		Ottawa	20,950	920,855	266,738				3
12		Toronto	20,950	3,893,045	1,316,623				3
13	Cuba	Havana	3,000	2,119,059	500,198	2,708,132	438,887		5
14	Guatemala	Guatemala City	3,400	754,243	140,917				3
15	Honduras	Tegucigalpa	2,100	539,590	102,573	421,721	30,274	54,043	6
16	Mexico	Mexico City	7,010	15,047,685	3,120,673				3
17		Guadalajara	7,010	2,870,417					2
18		Monterrey	7,010	2,590,545					2
19	USA	Chicago	24,680	8,065,633		70,852,787			3
20		Los Angeles	24,680	14,531,529		21,742,536			3
21		New York	24,680	18,087,251		35,474,230			3
22		Washington DC	24,680	3,923,574		9,848,445			3
23	Bolivia	La Paz	2,510	669,400	156,500				3
24	Chile	Santiago	8,900	3,902,315					2
25	Colombia	Bogota	5,790	4,154,404	847,523	785,952		58,209	5
26		Cali	5,790	1,429,026	253,794	311,136		21,828	5
27		Medellin	5,790	2,121,174	275,208	538,112		32,675	5
28	Ecuador	Guayaquil	4,400	1,508,444	319,900				3
29		Quito	4,400	1,100,847	262,709				3
30	Peru	Lima	3,320	6,011,036	1,099,242		324,047	206,942	5
31	Venezuela	Caracas	8,360	1,822,465					2
32	India	Bombay	1,240	8,243,405		9,276,780		612,291	4
33		Calcutta	1,240	3,305,006		5,616,100		537,441	4
34		Delhi	1,240	5,729,283				2,064,000	3
35		Madras	1,240	3,841,396		2,623,085	110,827	686,556	5

	Country	City	Real per capita GDP [PPP$], 1993	Population	Num. of occupied housing units	Total electricity consumption per day [1000 kwh]	Total annual water consumption [1000 cu.m.]	Num. of motor vehicles	Num. of data points (out of 6)
36	Indonesia	Bandung	3,270	1,810,917		1,181,419	24,552	246,831	5
37		Jakarta	3,270	9,406,477	1,740,214	5,917,812	111,503	1,435,731	6
38	Iraq	Baghdad	3,413	3,842,000	419,876			421,837	4
39	Japan	Osaka	20,660	2,623,801	963,380			726,834	4
40		Sapporo	20,660	1,671,742	572,850			663,575	4
41		Tokyo	20,660	8,163,573	3,112,590			2,545,027	4
42		Yokohama	20,660	3,220,331	1,001,800			1,058,719	4
43	Korea, Repub. of	Incheon	9,710	1,816,827		4,243,166	177,486	179,952	5
44		Pusan	9,710	3,795,181		7,341,267	326,252	346,846	5
45		Seoul	9,710	10,618,395		16,027,052		138,775	4
46		Taegu	9,710	2,227,715		5,794,947	218,513	293,896	5
47	Myanmar	Yangon	650	2,513,023					2
48	Pakistan	Karachi	2,160	5,208,132	811,850				3
49		Lahore	2,160	2,988,486	447,509				3
50	Singapore	Singapore	19,350	2,705,115		14,194,400	374,222	542,352	5
51	Thailand	Bangkok	6,350	6,370,000	902,871	1,516,763	*646,830*	1,644,018	6
52	Turkey	Ankara	4,210	3,306,327				299,771	3
53		Istanbul	4,210	5,842,985				605,933	3
54		Izmir	4,210	2,317,829				232,178	3
55	Viet Nam	Ho Chi Minh	1,040	2,795,140					2
56	Austria	Vienna	19,115	1,531,346	717,608	5,704,724	129,912	654,671	6
57	Bulgaria	Sofia	4,320	1,201,719		5,203,000	193,269		4
58	France	Paris	19,140	2,135,197					2
59	Germany	Berlin (West)	18,840	2,130,525	1,043,719				3
60		Hamburg	18,840	1,626,220	779,605				3
61		Munich	18,840	1,206,683	626,425				3
62	Hungary	Budapest	6,059	2,016,774	775,523	6,124,189	32,182	540,076	6
63	Italy	Rome	18,160	2,693,383	988,543				3
64	Netherlands	Amsterdam	17,340	702,444	363,740			255,155	4
65	Norway	Oslo	20,370	461,190	244,434	3,242,000		213,459	5
66	Poland	Warsaw	4,702	1,655,272	581,454		*191,329*		4
67	Romania	Bucharest	3,727	2,067,545	761,156	3,225,200	367,677	345,372	6
68	Russian Federation	Moscow	4,760	8,677,177	2,879,323	34,647,000		644,736	5
69		St. Petersburg	4,760	4,435,167	1,457,732	19,206,000		323,173	5
70	Spain	Barcelona	13,660	1,643,541					2
71		Madrid	13,660	3,010,499					2
72	Sweden	Stockholm	17,900	674,680				259,235	3
73	Ukraine	Kiev	3,250	2,559,312	833,000		411,026		4
74	Australia	Brisbane	18,530	1,149,401					2
75		Melbourne	18,530	2,832,893					2
76		Sydney	18,530	3,364,858					2

Number of data points (out of 76)	76	76	41	29	19	35
Mean	9,489	3,433,526	806,922	10,440,123	235,140	571,780
Standard deviation	7,963	3,397,374	750,421	14,822,308	165,130	563,708

Sources:

[1] GDP data: UNDP. *Human Development Report 1996*. New York: UN.

[2] All other data: UN Centre for Human Settlements (Habitat). *Compendium of Human Settlements Statistics 1995*. 5th issue. New York: UN.

Notes:

Source [1] data is for 1993.

Source [2] data is for as close to 1990 as possible, but may be for any year 1980-92.

A few entries have been adjusted as noted:

Bamako, Tunis, Guat. city, Moscow, and St. Pete. entries have been adjusted assuming 1.1 households per housing unit.

Bangkok water consumption reduced by 10% because data included Nonthaburi and Samut Prakan.

Warsaw water consumption increased by 20% because data included only household consumption.

D.2. Physical Infrastructure Exposure data set from *Statistics of World Large Cities 1991* (TMG 1991).

	Country	City	Real per capita GDP [PPP$]	Population	Num. of dwellings	Land area [sq.km.]	Electricity consumption [1000 kwh]	Gas consumption [1 mill. kcal]	Water supply [1000 cu.m.]	Length of roads [km]	Num. of telephone subscrip-tions	Num. of establish-ments	Num. of data points (out of 10)
1	Egypt	Alexandria	3,540	2,893,000		899					52,000		4
2	Egypt	Cairo	3,540	6,399,000		214	6,288,600		1,047,457	4,750	757,098	4,191	8
3	Ethiopia	Addis Ababa	330	1,686,300	263,751	217	409,778		38,012	1,120	84,471	46,484	9
4	South Africa	Johannesburg	3,799	896,000	193,300	450	5,797,969	2,062,940	124,852	2,692	763,565		9
5	USA	Chicago	23,760	3,021,912	1,154,800	228	69,149,000	7,158,799	1,426,460	5,917	5,084,344	116,931	10
6	USA	Detroit	23,760	1,117,000	550,000	362			889,571	4,502	830,000	35,653	8
7	USA	Houston	23,760	1,729,720	764,224		1,431,000	3,893,560	478,300	15,393			7
8	USA	Los Angeles	23,760	3,070,710	1,189,475	1,207	19,100,000	3,134,675	722,020		3,904,905		8
9	USA	New York	23,760	7,218,534	2,949,300	782	29,390,000	6,114,145	2,028,991	10,303	2,957,000		9
10	USA	Philadelphia	23,760	1,646,156	698,868	129	11,841,285	19,154,609	1,980	2,565	5,100,000	23,619	10
11	Canada	Montreal	20,520	1,752,585	443,560	494	14,240,129	2,300,000		2,194	3,030,000	38,045	9
12	Cuba	Havana	3,412	2,096,054	555,036	727	2,769,663	657,496	375,117	489	236,277	16,231	10
13	Mexico	Guadalajara	7,300	2,047,455		188			6,307		517,800		5
14	Mexico	Mexico City	7,300	10,263,275	1,747,102	1,483	18,499,143		36,483		1,290,274	265,160	8
15	Argentina	Buenos Aires	8,860	3,078,011	1,216,325	200	5,177,700	2,992,614	763,951	2,534	1,205,400		9
16	Brazil	Belem	5,240	1,418,533			1,138,920			707,519	240,293		5
17	Brazil	Belo Horizonte	5,240	2,331,528	182,808	335	2,900,000		263,416	2,981	285,000		8
18	Brazil	Brasilia	5,240	1,567,709		5,771	1,729,917						4
19	Brazil	Curitaba	5,240	1,537,324		432	1,966,209	40,119	66,023		572,163		7
20	Brazil	Fortaleza	5,240	1,588,709	255,096	336	1,193,837		30,268		91,329		7
21	Brazil	Nova Iguacu	5,240	1,460,000	328,993	764	1,174,796			312	32,032		7
22	Brazil	Porto Alegre	5,240	1,254,890	239,337	469	2,021,689		176,078		180,115	14,811	8
23	Brazil	Recife	5,240	1,293,400		209	1,590,849		172,651	2,905	211,184		7
24	Brazil	Rio de Janiero	5,240	5,603,388	1,301,104	910	11,765,185	328,896	555,737		1,295,320		8
25	Brazil	Salvador	5,240	1,927,667	299,028	324	1,645,429		403,029				6
26	Brazil	Sao Paolo	5,240	11,097,954		1,509	19,569,589	130,151	779,119	724	4,652,226	24,842	9
27	Chile	Santiago	8,410	5,342,913		2,026					710,563		4
28	Colombia	Bogota	5,480	4,672,324		1,587	5,770,632		273,090	1,313	943,076		7
29	Colombia	Cali	5,480	1,642,200	298,645	564	2,274,237		132,822		209,628		7
30	Colombia	Medellin	5,480	1,643,339	333,341	395	5,818,068		173,851	147	445,130		8
31	Ecuador	Guayaquil	4,350	1,572,615		1,098	1,489,644		62,871				5
32	Peru	Lima	3,300	6,053,900	1,074,000	3,850				7,900	270,343	202,225	7
33	Uruguay	Montevideo	6,070	1,309,200	420,000	542	1,979,808		87,900		223,034	35,320	8
34	Venezuela	Maracaibo	8,520	1,248,853		543		206,965	80,952,979	8,954	118,783		7
35	Bangladesh	Chittagong	1,230	1,391,877		65	349,879		14		18,051	51,924	7

	Country	City	Real per capita GDP [PPP$]	Population	Num. of dwellings	Land area [sq.km.]	Electricity consumption [1000 kwh]	Gas consumption [1 mill. kcal]	Water supply [1000 cu.m.]	Length of roads [km]	Num. of telephone subscrip-tions	Num. of establish-ments	Num. of data points (out of 10)
36	Bangladesh	Dacca	1,230	12,380,000	518,612	7,470	1,083,370	12,253	109,846		53,461	51,110	9
37	China	Anshan	1,950	1,375,500		622	4,428,000		11,303	339	29,213		7
38	China	Botou	1,950	1,180,500		2,153	2,537,000		21,759	393	29,691		7
39	China	Changchun	1,950	2,069,100		1,116	1,865,000		16,041	664	64,407		7
40	China	Changsha	1,950	1,301,200		367	902,000		24,588	384	42,947		7
41	China	Chengdu	1,950	2,776,200		1,382	1,870,000		39,063	582	65,210		7
42	China	Chongqing	1,950	1,471,100		1,534	6,211,000	151,700	31,651	1,190	34,345	40,920	9
43	China	Dalian	1,950	2,368,500		2,415	3,390,000		18,631	680	65,589		7
44	China	Fushun	1,950	1,334,700		675	4,210,000		22,658	349	32,494		7
45	China	Fuzhou	1,950	1,269,100		1,043	1,273,000		27,238	412	40,602		7
46	China	Guangzhou	1,950	3,543,900		1,444	4,040,460	56,260,061	823,070	945	337,913		8
47	China	Guiyang	1,950	1,488,100		2,436	2,848,000		13,403	152	10,635		7
48	China	Hangzhou	1,950	1,328,400		430	2,017,000		33,644	498	67,676		7
49	China	Harbin	1,950	2,798,200		1,637	2,623,000		26,715	1,627	90,038		7
50	China	Huainan	1,950	1,173,200		1,091	1,472,000		108,685	309	12,080		7
51	China	Jilin	1,950	1,253,400		1,213	4,173,000		9,671	448	29,195		7
52	China	Jinan	1,950	2,215,000	1,190,133	1,943	4,228,850	316,396	173,910	934	40,007	18,771	10
53	China	Kaohsiung	1,950	1,374,231	295,384	154			363,722	619	484,512	68,935	8
54	China	Kunming	1,950	1,505,100		2,081	1,862,000		10,425	255	33,729		7
55	China	Lanzhou	1,950	1,482,200		1,632	4,942,000		36,829	455	53,875		7
56	China	Liupanshui	1,950	1,798,900		6,272	739,000		597	49	8,950		7
57	China	Nanchang	1,950	1,326,200		617	1,836,720		25,974	265	43,455		7
58	China	Nanjiang	1,950	2,469,000		947	4,016,000		94,554	819	93,375		7
59	China	Peking	1,950	6,920,500		2,738	10,638,000		88,181	2,784	469,378		7
60	China	Pinxiang	1,950	1,376,900		2,765	630,000		2,520	29	7,576		7
61	China	Qingdo	1,950	2,036,300		1,103	3,682,130	13,730	10,349	583	3,809	4,671	9
62	China	Qiqihar	1,950	1,365,000		4,365	2,352,000		11,667	611	26,784		7
63	China	Shanghai	1,950	7,777,900		749	20,328,000	4,530	218,698	1,340	233,400		8
64	China	Shenyang	1,950	4,502,200		3,495	4,585,000		54,519	976			6
65	China	Shijianzhuang	1,950	1,296,900		307	2,602,000		32,515	338	54,393		7
66	China	Tai'an	1,950	1,402,700		2,089	113,000		3,451	644	11,517		7
67	China	Taipei	1,950	2,702,678	660,024	272	7,711,093	276,481,211	483,888	1,387	1,186,350	204,815	10
68	China	Taiyan	1,950	1,907,300		1,460	5,039,020	129,000	133,840	538		8,714	8
69	China	Tangshan	1,950	1,488,800		1,090	344,878		8,791	518	39,908	3,450	8
70	China	Tianjin	1,950	5,697,700		4,276	9,125,000		65,810	2,901	188,213		7

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71	China	Wuhan	1,950	3,706,700		1,607	5,461,000		81,297	1,141	107,554		7
72	China	Xi'an	1,950	2,708,000		1,100	2,772,000		32,547	1,016	110,741	20,521	8
73	China	Zaozhuang	1,950	1,700,800		3,065	2,971,000		9,240	497	10,288		7
74	China	Zhengzhou	1,950	1,662,300	248,491	1,010	3,390,610	75	24,037	340	173,232	2,295	10
75	China	Zibo	1,950	2,433,200	202,308	2,961	3,895,240	177,516	123,610	2,508	20,383	5,682	10
76	India	Ahmedabad	1,230	2,854,988		190	1,675,274		130,921	1,214	138,114		7
77	India	Bangalore	1,230	3,326,723	223,227	151				1,294	115,625		6
78	India	Bombay	1,230	8,578,000		438	1,526,786		593,904				5
79	India	Delhi	1,230	8,250,500		1,483	5,600,000	168,000	630,102	18,073	514,280		8
80	India	Hyderabad	1,230	2,093,488		169	571,034				61,675		5
81	India	Madras	1,230	3,785,600	64,922	170	1,541,829	636,600	112,634	2,581	113,422	2,081	10
82	Indonesia	Bandung	2,950	1,404,360			41,776	66,645	3,451		21,500	28,118	7
83	Indonesia	Jakarta	2,950	7,003,267	1,114,575	663	5,917,812	122,376	140,810	3,583	325,101	565,532	10
84	Indonesia	Semarang	2,950	1,096,271		373	267,582		8,932			1,550,934	6
85	Indonesia	Surabaja	2,950	2,431,547		290				550	76,058		5
86	Iran	Esfahan	5,420	986,753		202	934,307	1,372,271	54,768	162	67,833		8
87	Iran	Mashhad	5,420	2,086,600	249,162	156	1,548,005	2,485			60,610	87,949	8
88	Iran	Teheran	5,420	6,964,700	1,154,746	567	7,043,749	346,000	312,000	3,654		280,165	9
89	Iraq	Baghdad	3,413	2,350,000		863	1,423,700		158,320		106,467		6
90	Japan	Fukuoka	20,520	1,237,062	419,740	336	6,092,243	1,603,718	130,526	3,571	750,823	75,613	10
91	Japan	Hiroshima	20,520	1,085,705	361,560	740	5,846,860	1,216,028	139,229	3,511	538,817	57,737	10
92	Japan	Kawasaki	20,520	1,173,603	388,360	143	8,817,191	3,593,029	159,352	2,358	550,968	44,973	10
93	Japan	Kitakyushu	20,520	1,026,455	343,220	782	6,387,417	1,444,340	116,475	3,764	509,625	61,073	10
94	Japan	Kobe	20,520	1,477,410	482,440	544	6,804,813	3,401,909	185,520	5,006	686,246	82,770	10
95	Japan	Kyoto	20,520	1,461,103	516,320	610	6,669,560	4,370,520	209,733	3,051	761,240	105,383	10
96	Japan	Nagoya	20,520	2,154,793	716,420	326	13,056,422	5,511,279	283,757	6,062	1,254,081	153,129	10
97	Japan	Osaka	20,520	2,623,801	963,380	220	19,169,124	10,190,148	487,405	3,873	1,940,459	276,229	10
98	Japan	Sapporo	20,520	1,671,742	572,850	1,121	5,060,824	1,221,793	157,570	4,811	817,200	78,768	10
99	Japan	Tokyo	20,520	8,163,573	3,112,590	618	45,741,359	25,390,476	1,144,719	11,377	5,810,773	665,863	10
100	Japan	Yokohama	20,520	3,220,331	1,001,800	432	12,450,594	7,283,980	404,471	8,522	1,418,200	117,945	10
101	Korea, Repub. of	Inchon	9,250	1,616,017	274,245	208	4,680,412	362,618	131,608	896	437,688	59,365	10
102	Korea, Repub. of	Pusan	9,250	3,857,312	427,308	526	6,531,786	251,611	290,284	1,750	1,108,124	155,100	10
103	Korea, Repub. of	Seoul	9,250	10,627,790	1,463,081	605	16,027,052	502,213	1,005,588	7,376	3,929,984	483,986	10
104	Korea, Repub. of	Taegu	9,250	2,288,441	300,295	456	3,773,640	14,598,500	193,491,527	111	625,783	97,856	10
105	Pakistan	Lahore	2,890	3,808,661		328				493			4

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106	Philippines	Manila	2,550	1,835,290	150,642	38	1,661,769	7,300	59,900	766	119,800	30,320	10
107	Philippines	Quezon City	2,550	1,504,361	210,810	154				1,142			5
108	Singapore	Singapore	18,330	2,647,100		623	11,734,800	668,700	296,934	2,810	1,220,000		8
109	Syria	Aleppo	4,960	1,191,151						6,026			3
110	Syria	Damascus	4,960	1,219,448						3,021			3
111	Thailand	Bangkok	5,950	5,546,937		1,565	15,828,600		866,673	2,785	1,011,498		7
112	Turkey	Ankara	5,230	2,632,906	628,071	788	799,998	51,776	92,738	3,455	395,000		9
113	Turkey	Istanbul	5,230	5,560,908		1,512					348,286		4
114	Turkey	Izmir	5,230	2,023,100		1,500					130,354		4
115	Viet Nam	Ho Chi Minh City	1,010	3,934,000		2,029					380,743		4
116	Austria	Vienna	18,710	1,545,663	847,087	415	8,238,300		215,000	2,753	1,294,806	66,127	9
117	Bulgaria	Sofia	4,250	1,206,908		1,310			258,666		252,000		5
118	Czechoslovakia	Prague	7,190	1,214,885	516,127	496	3,590,972	11,613,800	158,693	2,566	815,417		9
119	France	Paris	19,510	2,152,333	1,282,000	105	8,837,000	8,060	207,597		1,310,000	262,820	9
120	German Demo. Rep.	East Berlin	21,120	1,260,921	603,658	403					623,670		5
121	Germany, Fed'l Rep.	West Berlin	21,120	2,130,525	1,074,821	480	10,327,000	1,014,500	183,900	2,937	1,228,325	87,217	10
122	Germany, Fed'l Rep.	Hamburg	21,120	1,626,220	787,258	755	11,974,362	12,585,910	120,978	3,889	1,072,500	77,735	10
123	Germany, Fed'l Rep.	Munich	21,120	1,268,366	655,077	311	5,901,803	21,714,305	132,595	2,263	995,279	71,070	10
124	Hungary	Budapest	6,580	2,104,700	823,000	525	6,048,276	20,624,656	322,966	3,134	809,463		9
125	Italy	Milan	18,090	1,449,403	703,379	182	4,979,227	739,026	252,236	1,396	1,139,645	107,908	10
126	Italy	Naples	18,090	1,204,149	310,997	117	3,005,971	1,083,645,726	148,825,250	701	508,942	49,760	10
127	Italy	Rome	18,090	2,817,227	1,337,247	1,508	6,728,653	658,348	388,800	4,500	1,142,485	124,235	10
128	Italy	Torino	18,090	1,002,813	445,932	130	3,279,577	595,600	184,775	1,393	737,965	72,591	10
129	Poland	Warsaw	4,830	1,671,376	586,956	485					392,170	3,697	6
130	Romania	Bucharest	2,840	2,318,889	942,799	1,820	4,550,237	2,849,200	476,518	1,874	581,000		9
131	Spain	Barcelona	13,400	1,714,355	699,031	99	4,476,575	2,141,864	145,978	1,237	851,483	82,837	10
132	Spain	Madrid	13,400	3,102,846	1,181,414	606	7,098,254		233,258		1,890,010	116,686	8
133	United Kingdom	Birmingham	17,160	992,500	395,680	264	5,272,512	9,684,000	116,942	2,120	24,491,000		9
134	United Kingdom	London, Greater	17,160	6,770,435		1,579					3,340,300	166,218	5
135	Yugoslavia	Belgrade		1,216,000	517,988	360	4,639,474		162,615	1,233	524,502	4,226	8
136	Australia	Melbourne	18,220	3,043,500	1,086,614	6,129				22,786			5
137	Australia	Sydney	18,220	3,530,953	1,225,257	12,407	20,191,430	48,951	471,203	20,307	1,628,506	190,215	10
138	USSR	Alma-Ata	4,270	1,121,395	302,499	180	2,770,000	820,400	276,872	1,235	236,757		9
139	USSR	Baku	2,550	1,794,874		794	6,067	2,971,000	517,359	2,180	216,935		8
140	USSR	Chelyabinsk	6,140	1,143,000		486	13,314,000	5,546,200	238,860		166,524		7

	Country	City	Real per capita GDP [PPP$]	Population	Num. of dwellings	Land area [sq.km.]	Electricity consumption [1000 kwh]	Gas consumption [1 mill. kcal]	Water supply [1000 cu.m.]	Length of roads [km]	Num. of telephone subscrip-tions	Num. of establish-ments	Num. of data points (out of 10)
141	USSR	Dnepropetrovsk	5,010	1,179,000				5,331,100	225,586		162,343		5
142	USSR	Donetsk	5,010	1,148,936		541		1,725,900	204,669		164,780		6
143	USSR	Erevan	2,420	1,199,000		90		2,320,600	485,701		231,162		6
144	USSR	Gorky	6,140	1,438,000		334		3,832,800	288,725		228,744		6
145	USSR	Kazan	6,140	1,094,000		285		3,387,800	211,964		102,243		6
146	USSR	Kharkov	5,010	1,611,000		303		3,440,100	305,630		275,926		6
147	USSR	Kiev	5,010	2,572,212		777	8,493,000	6,230,800	514,829		623,501		7
148	USSR	Kuibyshev	6,140	1,257,268	357,926	459	8,180,000	3,454,400	298,066		188,443		8
149	USSR	Leningrad	6,140	4,990,749		570	19,248,000	10,826,900	939,335	3,069	1,593,130		8
150	USSR	Minsk	6,440	1,607,077		159	6,336,000	3,883,600	230,970		364,934		7
151	USSR	Moscow	6,140	8,875,579		1,059	34,914,000	24,920,300	2,125,791		3,542,610		7
152	USSR	Novosibirsk	6,140	1,436,000		447	5,551,000	1,081,400	329,598		214,665		7
153	USSR	Odessa	5,010	1,115,000			2,666,000	1,365,500	199,419		151,702		6
154	USSR	Omsk	6,140	1,148,000		436	8,906,000		125,303		118,795		6
155	USSR	Perm	6,140	1,091,000			5,735,000	4,852,500	167,466		93,362		6
156	USSR	Rostov-na-Donu	6,140	1,020,000		372	5,844,000	1,681,100	209,489		120,115		7
157	USSR	Sverdlovsk	6,140	1,404,016	405,200	1,025		3,789,900	189,535	1,325	208,487		8
158	USSR	Tashkent	2,650	2,060,206		250	4,757,000	3,488,500	717,658		310,765		7
159	USSR	Tblisi	2,300	1,246,936		349	3,319,000	2,000,700	406,205		217,825		7
160	USSR	Ufa	6,140	1,083,000			8,976,000	4,958,300	183,822		101,600		6

	Real per capita GDP [PPP$]	Population	Num. of dwellings	Land area [sq.km.]	Electricity consumption [1000 kwh]	Gas consumption [1 mill. kcal]	Water supply [1000 cu.m.]	Length of roads [km]	Num. of telephone subscrip-tions	Num. of establish-ments
Number of data points (out of 160)	159	160	74	151	132	84	138	110	146	61
Mean	7,437	2,647,654	700,010	1,098	6,667,131	20,665,946	3,330,065	9,239	837,873	128,681
Standard deviation	7,066	2,228,199	546,849	1,534	8,704,193	121,334,069	21,721,001	67,303	2,240,394	226,165

Sources:

[1] GDP data: UNDP. *Human Development Report 1995*. New York: UN.

[2] All other data: Tokyo Metropolitan Government. Bureau of General Affairs. Statistical Division. 1992. *Statistics of World Large Cities 1991*.

Notes:

Electricity consumption = Total (domestic + industrial) consumption of electric light and power

Gas consumption = Total (domestic + industrial) gas consumption

Water supply = Total (domestic + industrial) water supply

Source [1] data is for 1992.

Source [2] data is for as close to 1990 as possible, but may be for any year in the 1980s.

Appendix E

Sample Analysis Evaluation of "seismic code indicator"

Seismic code benchmark years

Benchmark yr.	Boston	Istanbul	Jakarta	Lima	Manila	Mex. City	San Fran.	Santiago	St. Louis	Tokyo
1	1975	1975	1983	1977	1981	1987	1988	1966	1989	1981
2		1968	1970	1968	1972	1976	1976	1949		1971
3		1949			1959	1957	1956	1935		1950
4		1940				1942	1947			1924
5							1933			1920

Sophistication rating of seismic codes between benchmark years [s_k]

Inter-benchmark period k										
post-b.y. 1	0.8	0.9	0.9	0.9	0.9	1.0	1.0	0.9	0.9	1.0
b.y.2 to b.y.1	0.1	0.8	0.8	0.5	0.8	0.9	0.9	0.5	0.1	0.9
b.y.3 to b.y.2		0.5	0.1	0.1	0.5	0.8	0.8	0.3		0.8
b.y.4 to b.y.3		0.3			0.1	0.3	0.5	0.1		0.3
b.y.5 to b.y.4		0.1				0.1	0.3			0.1
pre-b.y.5							0.1			

Percentage of 1990 city population that arrived between benchmark years [p_k]

Inter-benchmark period k										
post-b.y. 1	6.0	44.7	13.7	38.7	22.7	3.6	3.0	31.8	0.1	8.4
b.y. 2 thru b.y.1	94.0	16.1	32.6	20.4	22.9	21.5	15.9	27.7	99.9	13.1
b.y. 3 thru b.y.2		23.6	53.8	40.9	24.2	45.9	27.8	13.6		34.7
b.y. 4 thru b.y.3		8.0			30.1	18.9	13.3	26.9		15.2
b.y. 5 thru b.y.4		7.6				10.1	13.4			2.6
pre-b.y.5							26.6			26.0

Enforcement rating [e]

Qualitative	Excellent	Average	Poor	Poor	Poor	Average	Excellent	Below Average	Excellent	Excellent
Numerical	1.0	0.6	0.2	0.2	0.2	0.6	1.0	0.4	1.0	1.0

Code factor rating [X_{V1}]

Unscaled	14.18	40.82	8.76	9.83	10.78	39.81	52.88	19.70	10.08	52.79
Scaled	2.64	1.20	2.93	2.87	2.82	1.25	0.54	2.34	2.86	0.55

* Higher value = better code, lower risk

Sophistication level s_k	Category description
0.1	No regulations.
0.3	No theory. Only base shear as percent of weight.
0.5	Rudimentary base shear equation.
0.8	Some of the basic components of a seismic code.
0.9	All of the basic components of a seismic code.
1.0	Refinement of code with all basic components.

Enforce-ment level e	Category description
1.0	Excellent
0.8	Above Average
0.6	Average
0.4	Below Average
0.2	Poor

$$X_{V1} = e*[\Sigma_k(s_k)*(p_k)]$$

Appendix F

External Context Indicator Values for 319-city Data Set

	[A]		[B]		[C]		[D]		[E]	
	City	Scaled X_{C1} Economic external context	City	Scaled X_{C2} Political country external context	City	Scaled X_{C3} Political world external context	City	Total political external context	City	External Context factor C
							=0.5*[B] + 0.5*[C]		=0.8*[A] + 0.2*[D]	
1	Tokyo	13.925	Abidjian	3.656	Washington D.C.	16.016	Washington D.C.	9.836	Tokyo	12.498
2	New York	12.982	Accra	3.656	Tokyo	9.920	Tokyo	6.788	New York	10.799
3	Los Angeles/ Riv./ SB	8.728	Addis Ababa	3.656	Berlin	5.967	Berlin	4.812	Los Angeles/ Riv./ SB	7.373
4	Paris	5.549	Algiers	3.656	Paris	5.047	Paris	4.351	Paris	5.309
5	London	5.191	Alma-Ata	3.656	Rome	4.768	Rome	4.212	London	4.970
6	Essen	5.022	Amman	3.656	London	4.514	London	4.085	Essen	4.377
7	Osaka	3.923	Amsterdam	3.656	Sacramento	3.469	Ottawa	3.459	Washington D.C.	3.865
8	Chicago	3.795	Ankara	3.656	Ottawa	3.261	Teheran	3.443	Osaka	3.521
9	Milan	3.030	Athens	3.656	Teheran	3.230	Madrid	3.382	Chicago	3.387
10	San Francisco/ San Jose	2.913	Baghdad	3.656	Madrid	3.108	Beijing	3.151	Berlin	3.088
11	Mexico City/ Naucalpan	2.801	Baku	3.656	New York	2.688	Amsterdam	3.109	Mexico City/ Naucalpan	2.844
12	Frankfurt	2.748	Bangkok	3.656	Dusseldorf	2.687	Delhi	3.097	Milan	2.769
13	Moscow	2.667	Beijing	3.656	Beijing	2.646	Seoul	3.038	Rome	2.687
14	Berlin	2.657	Belgrade	3.656	Amsterdam	2.561	Pyongyang	3.038	San Jose	2.670
15	Philadelphia	2.567	Berlin	3.656	Delhi	2.537	Stockholm	3.022	Seoul	2.621
16	Seoul	2.517	Bogota	3.656	Riv./ SB	2.493	Naucalpan	3.015	Frankfurt	2.511
17	Shanghai	2.488	Brasilia	3.656	Seoul	2.419	Brussels	2.982	Madrid	2.499
18	Cologne	2.445	Brazzaville	3.656	Pyongyang	2.419	Brasilia	2.933	Beijing	2.428
19	Naples	2.394	Brussels	3.656	Columbus	2.391	Helsinki	2.898	Philadelphia	2.388
20	Detroit	2.385	Bucharest	3.656	Stockholm	2.389	Copenhagen	2.893	Toronto	2.351
21	Toronto	2.384	Budapest	3.656	Naucalpan	2.373	Ankara	2.887	Dusseldorf	2.350
22	Dusseldorf	2.376	Buenos Aires	3.656	Osaka	2.363	Buenos Aires	2.873	Shanghai	2.301
23	Washington D.C.	2.372	Cairo/ Shubra El-Khemia	3.656	Munich	2.358	Cape Town	2.854	Cologne	2.286
24	Sao Paulo	2.341	Cape Town	3.656	Brussels	2.308	Pretoria	2.854	Naples	2.273
25	Hamburg	2.309	Caracas	3.656	Toronto	2.300	Riyadh	2.850	Brussels	2.245
26	Rome	2.306	Conakry	3.656	Stuttgart	2.269	Jakarta	2.847	Sao Paulo	2.240
27	Stuttgart	2.286	Copenhagen	3.656	Brasilia	2.210	Bangkok	2.826	Detroit	2.239
28	Madrid	2.278	Dakar	3.656	Nagoya	2.206	Warsaw	2.823	Amsterdam	2.228
29	Beijing	2.247	Damascus	3.656	Hanover	2.161	Athens	2.801	Teheran	2.222
30	Dallas	2.242	Dar es Salaam	3.656	Sapporo	2.161	Baghdad	2.798	Jakarta	2.214
31	Miami/ Ft. Lauderdale	2.228	Delhi	3.656	Chicago	2.160	Lisbon	2.797	Stuttgart	2.213
32	Hong Kong	2.190	Dhaka	3.656	Atlanta	2.142	Dublin	2.777	Khemia	2.190
33	Montreal	2.189	Dublin	3.656	Helsinki	2.139	Khemia	2.777	Delhi	2.173
34	Houston	2.161	Guatemala City	3.656	Copenhagen	2.130	Caracas	2.773	Hamburg	2.167
35	Munich	2.157	Hanoi	3.656	Ankara	2.118	Kuala Lumpur	2.770	Stockholm	2.167
36	Bombay	2.127	Harare	3.656	Boston	2.116	Metro Manila	2.764	Pyongyang	2.164
37	Boston	2.127	Havana	3.656	Essen	2.109	Singapore	2.764	Bangkok	2.159
38	Birmingham	2.127	Helsinki	3.656	Buenos Aires	2.089	Bogota	2.761	Ottawa	2.152
39	Tianjin	2.122	Hong Kong	3.656	Indianapolis	2.089	Budapest	2.758	Buenos Aires	2.134
40	Manchester	2.120	Jakarta	3.656	San Jose	2.063	Brazzaville	2.754	Singapore	2.127
41	St. Petersburg	2.065	Kabul	3.656	Naples	2.061	Lagos	2.752	Munich	2.123
42	Brussels	2.061	Kampala	3.656	Cape Town	2.051	Santiago	2.750	Dallas	2.122
43	Jakarta	2.056	Khartoum	3.656	Pretoria	2.051	Rabat	2.749	Lauderdale	2.110
44	Calcutta	2.051	Kiev	3.656	Riyadh	2.043	Yangon	2.747	Montreal	2.100
45	Cairo/ Shubra El-Khemia	2.044	Kinshasa	3.656	Jakarta	2.038	Bucharest	2.747	Riyadh	2.082

	[A]		[B]		[C]		[D]		[E]	
	City	Scaled X_{C1} Economic external context	City	Scaled X_{C2} Political country external context	City	Scaled X_{C3} Political world external context	City	Total political external context	City	External Context factor C
46	San Diego	2.035	Kuala Lumpur	3.656	Sydney	2.038	Khartoum	2.746	Copenhagen	2.072
47	Barcelona	2.029	Kuwait City	3.656	Philadelphia	2.014	Damascus	2.746	Metro Manila	2.071
48	Rio de Janeiro	2.018	La Paz	3.656	Bangkok	1.996	Dhaka	2.741	Lagos	2.061
49	Amsterdam	2.008	Lagos	3.656	Warsaw	1.990	Kuwait City	2.739	Houston	2.055
50	Rotterdam	2.006	Lima	3.656	Milan	1.988	Yaounde	2.732	Boston	2.048
51	Sydney	1.999	Lisbon	3.656	Detroit	1.984	Tunis	2.731	Cape Town	2.046
52	Atlanta	1.997	London	3.656	Phoenix	1.982	Lima	2.731	Athens	2.044
53	Bangkok	1.992	Luanda	3.656	Melbourne	1.971	Abidjian	2.729	Helsinki	2.041
54	Minneapolis	1.981	Lusaka	3.656	Hiroshima	1.964	Quito	2.727	Bombay	2.037
55	Mannheim	1.973	Madrid	3.656	Florence	1.963	Addis Ababa	2.726	Birmingham	2.032
56	Phoenix	1.970	Managua	3.656	Denver	1.961	Nairobi	2.725	Lisbon	2.031
57	Singapore	1.967	Maputo	3.656	Dallas	1.957	Guatemala City	2.723	Ankara	2.031
58	Nagoya	1.960	Metro Manila	3.656	Miami/ Ft. Lauderdale	1.954	Montevideo	2.722	Caracas	2.031
59	St. Louis	1.957	Mexico City/ Naucalpan	3.656	Oklahoma City	1.952	Dakar	2.722	Warsaw	2.027
60	Istanbul	1.956	Minsk	3.656	Kyoto	1.949	Accra	2.722	Manchester	2.026
61	Stockholm	1.953	Montevideo	3.656	Barcelona	1.948	Harare	2.722	Brasilia	2.025
62	Buenos Aires	1.949	Moscow	3.656	Athens	1.946	Santo Domingo	2.722	Santiago	2.023
63	Baltimore	1.948	Mugdisho	3.656	Houston	1.939	La Paz	2.721	Bogota	2.018
64	Pyongyang	1.945	Nairobi	3.656	Baghdad	1.939	San Jose	2.721	Sydney	2.016
65	Melbourne	1.943	Ottawa	3.656	Lisbon	1.938	Panama City	2.721	Kuala Lumpur	2.015
66	Delhi	1.942	Panama City	3.656	Montreal	1.938	Amman	2.720	Dublin	2.012
67	Leeds	1.926	Paris	3.656	Kitakyushu	1.934	Kinshasa	2.719	Pretoria	2.011
68	Seattle	1.926	Port-au-Prince	3.656	Lille	1.929	Kampala	2.718	Lima	2.007
69	Vienna	1.925	Prague	3.656	Cologne	1.924	Lusaka	2.718	Tianjin	2.006
70	Tampa	1.920	Pretoria	3.656	Sendai	1.918	Dar es Salaam	2.718	Budapest	2.004
71	Kiev	1.918	Pyongyang	3.656	Mashhad	1.915	Port-au-Prince	2.718	Dhaka	1.999
72	Teheran	1.917	Quito	3.656	Tabriz	1.912	Maputo	2.716	Bucharest	1.996
73	Cleveland	1.914	Rabat	3.656	Edmonton	1.910	Managua	2.715	Baghdad	1.993
74	Pittsburgh	1.914	Riga	3.656	San Diego	1.908	Sacramento	2.521	Kuwait City	1.993
75	Hanover	1.913	Riyadh	3.656	Birmingham	1.903	Dusseldorf	2.247	Damascus	1.990
76	Kitakyushu	1.908	Rome	3.656	Manchester	1.901	Lahore	2.224	Tunis	1.988
77	Bielefeld	1.908	San Jose	3.656	Dublin	1.897	Toronto	2.215	Rabat	1.987
78	Turin	1.906	San Juan	3.656	Cairo/ Shubra El-Khemia	1.897	Sydney	2.081	Abidjian	1.987
79	Metro Manila	1.897	Santiago	3.656	Turin	1.897	New York	2.066	Brazzaville	1.986
80	Zurich	1.897	Santo Domingo	3.656	Lucknow	1.896	Munich	1.990	Yangon	1.985
81	Vancouver	1.893	Seoul	3.656	Minneapolis	1.892	Los Angeles/ Riv./ SB	1.953	Kinshasa	1.985
82	Denver	1.893	Singapore	3.656	Brisbane	1.892	Melbourne	1.942	Khartoum	1.984
83	Riyadh	1.890	Sofia	3.656	Caracas	1.890	Stuttgart	1.920	Panama City	1.982
84	Nuremberg	1.890	Stockholm	3.656	St. Louis	1.884	Osaka	1.913	Santo Domingo	1.982
85	Lagos	1.888	Tashkhent	3.656	Kuala Lumpur	1.884	Columbus	1.893	Nairobi	1.982
86	Pusan	1.885	Tbilisi	3.656	Zurich	1.883	Auckland	1.856	Yaounde	1.981
87	Katowice	1.878	Teheran	3.656	Baltimore	1.881	Hanover	1.836	Quito	1.981
88	Shenyang	1.876	Tokyo	3.656	Marseilles	1.875	Sao Paulo	1.832	Montevideo	1.981
89	Aachen	1.872	Tripoli	3.656	Seattle	1.873	Tel Aviv-Yafa	1.813	Addis Ababa	1.981
90	Norfolk	1.870	Tunis	3.656	Metro Manila	1.872	Nagoya	1.812	Sacramento	1.980
91	Copenhagen	1.867	Vienna	3.656	Salt Lake City	1.871	Karachi	1.811	Dakar	1.980
92	Karachi	1.867	Warsaw	3.656	Tampa	1.871	Guayaquil	1.809	Amman	1.980
93	Kansas City	1.863	Washington D.C.	3.656	Singapore	1.871	Zurich	1.796	Accra	1.980
94	Lyons	1.861	Yangon	3.656	Genoa	1.869	Essen	1.795	Guatemala City	1.980
95	Karlsruhe	1.859	Yaounde	3.656	Cleveland	1.869	Surabaja	1.793	Harare	1.980
96	Milwaukee	1.858	Yerevan	3.656	Pittsburgh	1.869	Naples	1.790	San Jose	1.979
97	Marseilles	1.857	Lahore	2.619	Sao Paulo	1.866	Lucknow	1.785	Lusaka	1.979
98	Cincinnati	1.856	Toronto	2.130	Bogota	1.865	Aleppo	1.783	Dar es Salaam	1.979
99	Madras	1.855	Sydney	2.124	Lyons	1.862	Sapporo	1.783	La Paz	1.979
100	Athens	1.854	Melbourne	1.914	Hamburg	1.861	Brisbane	1.778	Barcelona	1.978
101	Saarland	1.854	Auckland	1.909	Shiraz	1.861	Bandung	1.777	Maputo	1.978
102	Portland	1.852	Guayaquil	1.840	Budapest	1.860	Barcelona	1.775	Kampala	1.978
103	Wuhan	1.849	Karachi	1.826	Esfahan	1.859	Semarang	1.759	Port-au-Prince	1.978
104	Kyoto	1.849	Tel Aviv-Yafa	1.823	Chengdu	1.857	Chicago	1.758	Managua	1.977
105	Bremen	1.849	Dusseldorf	1.807	Taegu	1.857	Atlanta	1.748	Calcutta	1.972
106	San Antonio	1.848	Sao Paulo	1.798	Vancouver	1.856	Montreal	1.746	San Diego	1.951
107	Caracas	1.846	Aleppo	1.781	Mannheim	1.852	Boston	1.732	Rio de Janeiro	1.948
108	Sacramento	1.845	Surabaja	1.760	Brazzaville	1.851	Taegu	1.728	Atlanta	1.947
109	Cape Town	1.844	Banghazi	1.754	Norfolk	1.849	Milan	1.725	Melbourne	1.943
110	Genoa	1.844	Bandung	1.732	Lagos	1.848	Mashhad	1.718	Rotterdam	1.933
111	Guangzhou	1.842	Zurich	1.709	Kansas City	1.846	Indianapolis	1.717	Nagoya	1.930
112	Santiago	1.841	Semarang	1.699	Santiago	1.844	Tabriz	1.714	Phoenix	1.907
113	Kharkov	1.840	Lucknow	1.673	Milwaukee	1.843	Edmonton	1.710	Minneapolis	1.906

	[A]		[B]		[C]		[D]		[E]	
	City	Scaled X_{C1} Economic external context	City	Scaled X_{C2} Political country external context	City	Scaled X_{C3} Political world external context	City	Total political external context	City	External Context factor C
114	Lisbon	1.840	Brisbane	1.664	Leeds	1.843	Maracaibo	1.707	Istanbul	1.901
115	New Orleans	1.839	Medellin	1.625	Bombay	1.842	Medellin	1.706	Hanover	1.898
116	Sapporo	1.838	Maracaibo	1.624	Cincinnati	1.842	Florence	1.703	Mannheim	1.897
117	Bogota	1.833	Munich	1.622	Rabat	1.842	San Francisco/ San Jose	1.701	Lahore	1.895
118	Lille	1.832	Peshawar	1.603	Portland	1.840	Peshawar	1.694	St. Louis	1.885
119	Buffalo	1.832	Barcelona	1.602	Patna	1.840	Belo Horizonte	1.694	Baltimore	1.877
120	Florence	1.831	Taegu	1.599	Zhengzhou	1.840	Chengdu	1.688	Zurich	1.877
121	Columbus	1.831	Sacramento	1.574	Adelaide	1.839	Istanbul	1.681	Leeds	1.860
122	Hyderabad	1.830	Khulna	1.573	Perth	1.839	Khulna	1.676	Seattle	1.859
123	Tel Aviv-Yafa	1.830	Stuttgart	1.571	Yangon	1.839	Bombay	1.674	Karachi	1.856
124	Jeddah	1.829	Casablanca	1.566	San Antonio	1.838	Casablanca	1.673	Tampa	1.854
125	Chongqing	1.829	Belo Horizonte	1.564	Jinan	1.837	Philadelphia	1.673	Kitakyushu	1.854
126	Indianapolis	1.829	Montreal	1.555	Bucharest	1.837	Adelaide	1.670	Turin	1.853
127	Tashkhent	1.829	Istanbul	1.551	Bielefeld	1.836	Patna	1.669	Cleveland	1.849
128	Bangalore	1.828	Cali	1.543	Khartoum	1.836	Perth	1.669	Pittsburgh	1.849
129	Warsaw	1.828	Katowice	1.540	Damascus	1.835	Rio de Janeiro	1.668	Columbus	1.844
130	Belgrade	1.828	Donetsk	1.538	Calcutta	1.834	Katowice	1.668	Denver	1.843
131	Helsinki	1.827	Ibadan	1.530	Hyderabad	1.833	Lille	1.667	Vancouver	1.843
132	Orlando	1.827	Santiago de los Caballos	1.523	New Orleans	1.832	Cali	1.663	Bielefeld	1.843
133	Kuala Lumpur	1.826	Mashhad	1.522	Nuremberg	1.831	Calcutta	1.657	Katowice	1.836
134	Algiers	1.826	Rio de Janeiro	1.521	Bhopal	1.831	Zhengzhou	1.656	Pusan	1.834
135	Lima	1.826	Chengdu	1.520	Providence-Warwick	1.830	Hiroshima	1.656	Nuremberg	1.828
136	Chengdu	1.825	Naples	1.519	Saarland	1.830	Detroit	1.655	Sapporo	1.827
137	Ottawa	1.825	Tabriz	1.517	Lahore	1.830	Ibadan	1.655	Tel Aviv-Yafa	1.826
138	Harbin	1.825	Hanover	1.511	Rotterdam	1.828	Hyderabad	1.654	Shenyang	1.818
139	Taipei	1.825	Edmonton	1.509	Buffalo	1.827	Phoenix	1.654	Auckland	1.815
140	Taegu	1.824	Bombay	1.506	Madras	1.827	Birmingham	1.654	Aachen	1.813
141	Providence-Warwick	1.823	Thessaloniki	1.504	Dhaka	1.826	Bhopal	1.652	Madras	1.812
142	Guadalajara	1.823	Adelaide	1.501	Aachen	1.826	Manchester	1.651	Brisbane	1.812
143	Xian	1.822	Perth	1.499	Surabaja	1.826	Taejon	1.651	Norfolk	1.812
144	Memphis	1.822	Patna	1.499	Nanjing	1.825	Jinan	1.651	Lyons	1.811
145	Johannesburg	1.821	Douala	1.497	Orlando	1.824	Cologne	1.651	Marseilles	1.810
146	Brisbane	1.820	Cordoba	1.496	Taejon	1.824	Santiago de los Caballos	1.648	Kyoto	1.808
147	Alexandria	1.820	Salvador	1.483	Belo Horizonte	1.823	Cordoba	1.648	Indianapolis	1.806
148	Dublin	1.820	Essen	1.481	Bandung	1.822	Shiraz	1.648	Surabaja	1.806
149	West Palm Beach	1.820	Calcutta	1.480	Kuwait City	1.822	Thessaloniki	1.646	Florence	1.806
150	Belo Horizonte	1.820	Taejon	1.478	Guangzhou	1.822	Kyoto	1.646	Kansas City	1.806
151	Salt Lake City	1.819	Valencia	1.477	Karlsruhe	1.821	Salvador	1.646	Taegu	1.805
152	Edmonton	1.819	Hyderabad	1.476	Memphis	1.820	Esfahan	1.645	Bandung	1.805
153	Oklahoma City	1.819	Zhengzhou	1.472	Shijiazhuang	1.820	Turin	1.643	Wuhan	1.801
154	Tripoli	1.818	Bhopal	1.472	Changsha	1.820	Rotterdam	1.643	Karlsruhe	1.801
155	Dnepropetrovsk	1.818	Jeddah	1.471	West Palm Beach	1.819	Madras	1.643	Milwaukee	1.801
156	Nanjing	1.818	Jinan	1.465	Semarang	1.819	Denver	1.642	Cincinnati	1.800
157	Ankara	1.817	Osaka	1.463	Hefei	1.817	Vancouver	1.640	Guayaquil	1.800
158	Louisville	1.817	Milan	1.462	Louisville	1.816	Dallas	1.640	Genoa	1.799
159	Casablanca	1.817	Dnepropetrovsk	1.460	Pusan	1.815	Miami/ Ft. Lauderdale	1.638	Lille	1.799
160	Prague	1.817	Madras	1.459	Rio de Janeiro	1.815	Oklahoma City	1.637	Saarland	1.799
161	Monterrey	1.816	Rotterdam	1.458	Wuhan	1.815	Kitakyushu	1.637	Guangzhou	1.798
162	Dalian	1.816	Porto Alegre	1.450	Bangalore	1.814	Douala	1.637	Chengdu	1.798
163	Ahmedabad	1.816	Pusan	1.447	Guadalajara	1.811	Jeddah	1.632	Edmonton	1.797
164	Budapest	1.815	Curitiba	1.447	Jaipur	1.811	Pusan	1.631	Portland	1.796
165	Donetsk	1.815	Maracay	1.445	Istanbul	1.811	Houston	1.629	Aleppo	1.795
166	Novosibirsk	1.815	New York	1.444	Frankfurt	1.811	Valencia	1.629	Hyderabad	1.795
167	Nizhni Novgorod	1.815	Guadalajara	1.443	Bremen	1.810	Nanjing	1.628	Lucknow	1.795
168	Odessa	1.814	Florence	1.442	Salvador	1.808	Guadalajara	1.627	Belo Horizonte	1.795
169	Jinan	1.814	Alexandria	1.442	Yaounde	1.807	Porto Alegre	1.626	San Antonio	1.792
170	Dhaka	1.814	Shiraz	1.434	Tunis	1.806	Sendai	1.626	Bremen	1.791
171	Porto Alegre	1.813	Kharkov	1.434	Nanning	1.806	Curitiba	1.624	Jeddah	1.790
172	Perth	1.813	Nanjing	1.432	Hangzhou	1.805	Guangzhou	1.624	Semarang	1.789
173	Inchon	1.813	Esfahan	1.431	Lima	1.805	Marseilles	1.620	Casablanca	1.788
174	Lahore	1.813	Medan	1.426	Shenyang	1.803	Shijiazhuang	1.620	Bangalore	1.786
175	Ekaterinburg	1.812	Guangzhou	1.426	Tel Aviv-Yafa	1.803	Changsha	1.619	Maracaibo	1.785
176	Bandung	1.812	Vancouver	1.424	Nanchang	1.803	Genoa	1.618	New Orleans	1.785
177	Recife	1.811	Bangalore	1.420	Abidjian	1.803	Bangalore	1.617	Mashhad	1.784
178	Changchun	1.810	Shijiazhuang	1.420	Porto Alegre	1.802	Hefei	1.614	Perth	1.784
179	Taiyuan	1.810	Changsha	1.419	Puebla de Zaragoza	1.802	Maracay	1.613	Guadalajara	1.784
180	Adelaide	1.809	Nagoya	1.418	Kunming	1.802	Alexandria	1.611	Oklahoma City	1.783
181	Surabaja	1.809	Recife	1.416	Auckland	1.802	San Diego	1.611	Adelaide	1.782

	[A]		[B]		[C]		[D]		[E]	
	City	Scaled X_{C1} Economic external context	City	Scaled X_{C2} Political country external context	City	Scaled X_{C3} Political world external context	City	Total political external context	City	External Context factor C
182	Samara	1.809	Lvov	1.414	Curitiba	1.802	Wuhan	1.611	Jinan	1.781
183	Bucharest	1.809	Odessa	1.412	Trivandrum	1.801	Jaipur	1.610	Tabriz	1.781
184	Omsk	1.807	Los Angeles/ Riv./ SB	1.412	Cordoba	1.800	Lyons	1.609	Nanjing	1.780
185	Zaporozhye	1.807	Hefei	1.411	Harbin	1.800	Medan	1.607	Alexandria	1.779
186	Chelyabinsk	1.806	Jaipur	1.410	Xian	1.799	Recife	1.606	Medellin	1.778
187	Salvador	1.806	Puebla de Zaragoza	1.407	Guiyang	1.799	Puebla de Zaragoza	1.605	Buffalo	1.778
188	Kuwait City	1.806	Ho Chi Minh City	1.407	Quito	1.797	Minneapolis	1.602	Harbin	1.776
189	Hiroshima	1.806	Wuhan	1.406	Fuzhou	1.796	Hamburg	1.601	Porto Alegre	1.776
190	Pune	1.805	Lille	1.405	Recife	1.796	Leeds	1.597	Hiroshima	1.776
191	Kazan	1.805	Sapporo	1.405	Karachi	1.796	St. Louis	1.597	Johannesburg	1.775
192	Ufa	1.805	Birmingham	1.404	Katowice	1.796	Fortaleza	1.596	Orlando	1.774
193	Perm	1.805	Manchester	1.402	Taiyuan	1.795	Baltimore	1.595	Salvador	1.774
194	Maracaibo	1.805	Johannesburg	1.401	Addis Ababa	1.795	Mannheim	1.595	Zhengzhou	1.774
195	Auckland	1.805	Barranquilla	1.400	Monterrey	1.795	Nanning	1.594	Peshawar	1.774
196	East Rand	1.804	Fortaleza	1.399	Nairobi	1.794	Johannesburg	1.593	Xian	1.774
197	Fortaleza	1.804	Izmir	1.397	Jeddah	1.793	Izmir	1.593	Salt Lake City	1.774
198	Lvov	1.804	Columbus	1.395	Fortaleza	1.793	Hangzhou	1.592	Providence-Warwick	1.772
199	Izmir	1.804	Mendoza	1.393	Changchun	1.792	Seattle	1.591	Taipei	1.772
200	Zhengzhou	1.804	Turin	1.390	Inchon	1.792	Trivandrum	1.591	Chongqing	1.770
201	Rostov-on-Don	1.803	St. Petersburg	1.390	Guatemala City	1.791	Salt Lake City	1.590	Recife	1.770
202	Sendai	1.803	Ujung Pandang	1.389	Lanzhou	1.791	Tampa	1.590	Monterrey	1.770
203	Durban	1.803	Nanning	1.382	Hohhot	1.790	Mendoza	1.590	Patna	1.770
204	Kunming	1.803	Zaporozhye	1.381	Maracaibo	1.789	Barranquilla	1.589	Taejon	1.770
205	Volgograd	1.803	Gdansk	1.381	Montevideo	1.789	Cleveland	1.588	Cali	1.770
206	Medan	1.803	Trivandrum	1.380	Thessaloniki	1.789	Pittsburgh	1.588	Memphis	1.769
207	Kanpur	1.802	Hangzhou	1.379	Taipei	1.788	Shenyang	1.588	Khulna	1.769
208	Sofia	1.802	Monterrey	1.379	Izmir	1.788	Nanchang	1.587	West Palm Beach	1.768
209	Tunis	1.802	Cologne	1.377	Dakar	1.788	Monterrey	1.587	Sendai	1.768
210	Abidjian	1.802	Shenyang	1.373	Accra	1.788	Ujung Pandang	1.587	Esfahan	1.767
211	Tangshan	1.802	Nanchang	1.372	Medan	1.788	Kunming	1.586	Ibadan	1.767
212	Guiyang	1.801	Goiania	1.371	Harare	1.788	Harbin	1.583	Thessaloniki	1.766
213	Krasnoyarsk	1.801	Rosario	1.371	Santo Domingo	1.788	Bielefeld	1.582	Bhopal	1.766
214	Lanzhou	1.801	Kunming	1.371	Goiania	1.788	Gdansk	1.581	Curitiba	1.766
215	Curitiba	1.801	Ekaterinburg	1.370	Mendoza	1.786	Xian	1.580	Inchon	1.766
216	Saratov	1.801	Adana	1.370	La Paz	1.786	Guiyang	1.580	Shiraz	1.765
217	Kinshasa	1.801	Cracow	1.370	Peshawar	1.786	Goiania	1.579	Valencia	1.765
218	Pretoria	1.801	Lodz	1.368	San Jose	1.786	Nuremberg	1.578	Louisville	1.765
219	Mashhad	1.801	Genoa	1.368	Medellin	1.786	Adana	1.577	Cordoba	1.765
220	Voronezh	1.801	Palembang	1.366	Panama City	1.786	Rosario	1.577	Santiago de los Caballos	1.764
221	Damascus	1.801	Marseilles	1.365	Belem	1.786	Saarland	1.577	Medan	1.763
222	Kaohsiung	1.801	Harbin	1.365	Johannesburg	1.786	Norfolk	1.577	Douala	1.763
223	Kwangju	1.800	East Rand	1.363	Aleppo	1.786	Inchon	1.576	Shijiazhuang	1.763
224	Ho Chi Minh City	1.800	Belem	1.362	Kwangju	1.786	Fuzhou	1.576	Changsha	1.763
225	Anshan	1.800	Rostov-on-Don	1.362	Urumqi	1.785	Kansas City	1.575	Taiyuan	1.763
226	Qiqihar	1.800	Xian	1.362	Adana	1.784	Cracow	1.575	Fortaleza	1.763
227	Lodz	1.800	Guiyang	1.361	Ujung Pandang	1.784	Taiyuan	1.574	Changchun	1.762
228	Fushun	1.800	Inchon	1.361	Rosario	1.784	Belem	1.574	Izmir	1.762
229	Nanchang	1.800	Durban	1.359	Amman	1.783	Aachen	1.574	Ahmedabad	1.760
230	Hangzhou	1.800	Nizhni Novgorod	1.359	Shanghai	1.783	Lodz	1.574	Dalian	1.760
231	Qingdao	1.800	Chicago	1.356	Cali	1.783	Palembang	1.574	Maracay	1.760
232	Valencia	1.799	Lyons	1.356	Valencia	1.782	Milwaukee	1.573	Kunming	1.760
233	Taejon	1.799	Ufa	1.356	Bursa	1.782	Cincinnati	1.573	Jaipur	1.760
234	Urumqi	1.799	Fuzhou	1.356	Kinshasa	1.782	East Rand	1.572	Hefei	1.760
235	Changsha	1.799	Bursa	1.354	Palembang	1.781	Portland	1.572	Hangzhou	1.758
236	Fuzhou	1.799	Chittagong	1.354	East Rand	1.781	Karlsruhe	1.570	Puebla de Zaragoza	1.758
237	Shijiazhuang	1.799	Atlanta	1.353	Gdansk	1.781	San Antonio	1.570	East Rand	1.758
238	Jilin	1.799	Taiyuan	1.353	Casablanca	1.781	Durban	1.570	Nanning	1.757
239	Aleppo	1.798	Leeds	1.352	Durban	1.781	Bursa	1.568	Nanchang	1.757
240	Luanda	1.798	Chelyabinsk	1.352	Alexandria	1.781	Changchun	1.568	Guiyang	1.757
241	Nagpur	1.798	Kazan	1.351	Kampala	1.781	New Orleans	1.567	Durban	1.756
242	Brasilia	1.798	Boston	1.349	Maracay	1.781	Providence-Warwick	1.566	Lodz	1.755
243	Baotou	1.798	Hiroshima	1.347	Ibadan	1.781	Lanzhou	1.565	Fuzhou	1.754
244	Nanning	1.798	Perm	1.347	Cracow	1.780	Buffalo	1.564	Gdansk	1.754
245	Lucknow	1.798	Indianapolis	1.345	Tianjin	1.780	Chittagong	1.564	Lanzhou	1.754
246	West Rand	1.798	Changchun	1.343	Lodz	1.780	Hohhot	1.563	Ujung Pandang	1.753
247	Gdansk	1.798	Kyoto	1.343	Lusaka	1.780	Orlando	1.562	Trivandrum	1.753
248	Luoyang	1.798	Samara	1.342	Srinagar	1.780	Frankfurt	1.562	Barranquilla	1.753
249	Minsk	1.798	Hamburg	1.342	Dar es Salaam	1.780	Kwangju	1.562	Kwangju	1.753

	[A]		[B]		[C]		[D]		[E]	
	City	Scaled X_{C1} Economic external context	City	Scaled X_{C2} Political country external context	City	Scaled X_{C3} Political world external context	City	Total political external context	City	External Context factor C
250	Esfahan	1.798	Krasnoyarsk	1.342	Khulna	1.779	Bremen	1.562	Cracow	1.753
251	Alma-Ata	1.798	San Francisco/ San Jose	1.340	Leon de los Aldamas	1.779	Taipei	1.561	Mendoza	1.752
252	Panama City	1.797	West Rand	1.340	Port-au-Prince	1.779	Memphis	1.560	Palembang	1.752
253	Tabriz	1.797	Lanzhou	1.340	Ciudad Jarez	1.779	West Rand	1.559	Belem	1.752
254	Rabat	1.797	Kitakyushu	1.339	West Rand	1.779	West Palm Beach	1.559	Adana	1.752
255	Handan	1.797	Kwangju	1.338	Guayaquil	1.779	Louisville	1.558	Pune	1.752
256	Cracow	1.797	Voronezh	1.338	Tijuana	1.778	Urumqi	1.555	Goiania	1.751
257	Santo Domingo	1.797	Novosibirsk	1.338	Manaus	1.778	Shanghai	1.551	Rosario	1.750
258	Jaipur	1.797	Hohhot	1.337	Barranquilla	1.777	Davao	1.550	Urumqi	1.750
259	Guayaquil	1.797	Mannheim	1.337	Campinas	1.777	Manaus	1.550	West Rand	1.750
260	Surat	1.797	Saratov	1.337	Maputo	1.776	Faisalabad	1.548	Bursa	1.749
261	Datong	1.797	Volgograd	1.334	Santos	1.776	Leon de los Aldamas	1.548	Hohhot	1.749
262	Semarang	1.797	Sendai	1.334	Douala	1.776	Ciudad Jarez	1.547	Kanpur	1.749
263	Campinas	1.797	Taipei	1.334	Ahmedabad	1.776	Srinagar	1.546	Chittagong	1.749
264	Maracay	1.797	Philadelphia	1.332	Chongqing	1.775	Tijuana	1.546	Tangshan	1.748
265	Medellin	1.797	Bielefeld	1.328	Pune	1.775	Tianjin	1.546	Kaohsiung	1.747
266	Puebla de Zaragoza	1.796	Detroit	1.327	Dalian	1.775	Gujranwala	1.545	Anshan	1.747
267	Palembang	1.796	Phoenix	1.327	Kanpur	1.775	Campinas	1.545	Qiqihar	1.747
268	Cali	1.796	Davao	1.325	Nagpur	1.774	Rawalpindi	1.543	Fushun	1.747
269	Belem	1.796	Omsk	1.325	Santiago de los Caballos	1.774	Multan	1.543	Qingdao	1.747
270	Nairobi	1.796	Nuremberg	1.325	Davao	1.774	Santos	1.543	Campinas	1.746
271	Thessaloniki	1.796	Urumqi	1.325	Chittagong	1.774	Hyderabad	1.542	Jilin	1.746
272	Hefei	1.796	Saarland	1.324	Bogor	1.774	Bogor	1.539	Leon de los Aldamas	1.746
273	Daqing	1.796	Denver	1.323	Surat	1.774	Ahmedabad	1.539	Nagpur	1.746
274	Wuxi	1.796	Dallas	1.323	Faisalabad	1.774	Tanjung Karang	1.538	Faisalabad	1.746
275	Xuzhou	1.796	Miami/ Ft. Lauderdale	1.322	Tangshan	1.774	Pune	1.537	Manaus	1.746
276	Benxi	1.795	Faisalabad	1.322	Tanjung Karang	1.774	Chongqing	1.537	Baotou	1.745
277	Yichun	1.795	Aachen	1.322	Managua	1.774	Kanpur	1.536	Luoyang	1.745
278	Hohhot	1.795	Oklahoma City	1.322	Kaohsiung	1.774	Dalian	1.536	Ciudad Jarez	1.745
279	Amman	1.795	Manaus	1.321	Anshan	1.774	Nagpur	1.536	Davao	1.745
280	Adana	1.795	Houston	1.320	Qiqihar	1.774	Surat	1.535	Surat	1.745
281	Jixi	1.795	Shanghai	1.320	Fushun	1.774	Tangshan	1.535	Tijuana	1.745
282	Montevideo	1.795	Karlsruhe	1.319	Qingdao	1.774	Kaohsiung	1.535	Santos	1.745
283	Banghazi	1.795	Leon de los Aldamas	1.317	Gujranwala	1.774	Coimbatore	1.535	Handan	1.745
284	Ujung Pandang	1.795	Gujranwala	1.316	Coimbatore	1.774	Kochi	1.535	Datong	1.744
285	Jinzhou	1.795	Ciudad Jarez	1.315	Kochi	1.774	Anshan	1.535	Srinagar	1.744
286	Leon de los Aldamas	1.795	San Diego	1.315	Jilin	1.774	Qiqihar	1.535	Gujranwala	1.744
287	Santos	1.795	Frankfurt	1.313	Vadodara	1.774	Vadodara	1.535	Bogor	1.744
288	Coimbatore	1.795	Campinas	1.313	Indore	1.774	Indore	1.535	Rawalpindi	1.744
289	Faisalabad	1.795	Tijuana	1.313	Madurai	1.774	Madurai	1.535	Daqing	1.743
290	Shantou	1.795	Bremen	1.313	Baotou	1.774	Fushun	1.535	Multan	1.743
291	Shiraz	1.795	Rawalpindi	1.313	Ulhasnagar	1.774	Qingdao	1.535	Wuxi	1.743
292	Dakar	1.795	Srinagar	1.313	Visakhapatnam	1.774	Ulhasnagar	1.534	Xuzhou	1.743
293	Kochi	1.795	Multan	1.312	Luoyang	1.774	Visakhapatnam	1.534	Benxi	1.743
294	Ibadan	1.795	Minneapolis	1.312	Varanasi	1.774	Varanasi	1.534	Yichun	1.743
295	Bogor	1.795	Tianjin	1.311	Rawalpindi	1.774	Jilin	1.534	Tanjung Karang	1.743
296	Patna	1.795	St. Louis	1.311	Ludhiana	1.774	Ludhiana	1.534	Hyderabad	1.743
297	Vadodara	1.795	Hyderabad	1.310	Handan	1.774	Agra	1.534	Jixi	1.743
298	Indore	1.795	Baltimore	1.310	Multan	1.774	Baotou	1.534	Coimbatore	1.743
299	Madurai	1.795	Santos	1.309	Agra	1.774	Luoyang	1.534	Jinzhou	1.743
300	Douala	1.795	Seattle	1.309	Datong	1.774	Jabalpur	1.534	Kochi	1.743
301	Quito	1.795	Salt Lake City	1.308	Jabalpur	1.774	Handan	1.534	Vadodara	1.743
302	Bursa	1.795	Tampa	1.308	Hyderabad	1.774	Datong	1.534	Indore	1.743
303	Chittagong	1.795	Cleveland	1.308	Allahabad	1.774	Allahabad	1.534	Madurai	1.743
304	Ciudad Jarez	1.795	Pittsburgh	1.308	Jamshedpur	1.774	Jamshedpur	1.534	Shantou	1.743
305	Suzhou	1.795	Norfolk	1.305	Meerut	1.774	Meerut	1.534	Ulhasnagar	1.743

306	Bhopal	1.795	Kansas City	1.304	Vijayawada	1.774	Vijayawada	1.534	Visakhapatnam	1.742
307	Ulhasnagar	1.795	Bogor	1.304	Daqing	1.774	Dhanbad	1.534	Varanasi	1.742
308	Visakhapatnam	1.794	Milwaukee	1.304	Dhanbad	1.774	Kozhikode	1.534	Suzhou	1.742
309	Manaus	1.794	Cincinnati	1.304	Wuxi	1.774	Daqing	1.534	Ludhiana	1.742
310	Varanasi	1.794	Portland	1.303	Xuzhou	1.774	Wuxi	1.534	Fuxin	1.742
311	Fuxin	1.794	San Antonio	1.303	Kozhikode	1.774	Xuzhou	1.534	Liuzhou	1.742
312	Liuzhou	1.794	Tanjung Karang	1.303	Benxi	1.774	Benxi	1.534	Agra	1.742
313	Ludhiana	1.794	New Orleans	1.302	Yichun	1.774	Yichun	1.534	Jabalpur	1.742
314	Tijuana	1.794	Providence-Warwick	1.302	Jixi	1.774	Jixi	1.534	Allahabad	1.742
315	Yangon	1.794	Buffalo	1.301	Jinzhou	1.774	Jinzhou	1.534	Jamshedpur	1.742
316	Addis Ababa	1.794	Ahmedabad	1.301	Shantou	1.774	Shantou	1.534	Meerut	1.742
317	Goiania	1.794	Orlando	1.301	Suzhou	1.774	Suzhou	1.534	Vijayawada	1.742
318	Lusaka	1.794	Memphis	1.300	Fuxin	1.774	Fuxin	1.534	Dhanbad	1.742
319	Dar es Salaam	1.794	West Palm Beach	1.300	Liuzhou	1.774	Liuzhou	1.534	Kozhikode	1.742

Notes:

All data are for 1990.

The capital of Nigeria moved from Lagos to Abuja in 1991.

Sources:

Population data: United Nations. 1995. *World urbanization prospects: 1994 revision*. New York: UN.

Total foreign trade data: International Monetary Fund. 1995. *Balance of payments yearbook 1995*. IMF.

GDP data: International Monetary Fund. 1996. *International financial statistics yearbook 1996*. IMF.

Appendix G

Principal Components Analysis of Physical Infrastructure Exposure Data Sets

G.1. Physical Infrastructure Exposure data set from *Compendium of Human Settlements Statistics 1995* (UN Centre for Human Settlements 1995).

Correlation matrix [R]

Population	1.000	0.880	0.189
Num. housing units	0.880	1.000	0.206
Per capita GDP (PPP$)	0.189	0.206	1.000

Eigenvectors [v]

	Principal component		
	3	**2**	**1**
Population	0.705	-0.208	0.678
Num. housing units	-0.709	-0.187	0.680
Per capita GDP (PPP$)	0.014	0.960	0.279

Eigenvalues [e]	0.120	0.919	1.961
Percentage variation explained	4.0%	30.6%	65.4%

Factor loadings [v*sqrt(e)]

Population	0.244	-0.199	0.949
Num. housing units	-0.245	-0.179	0.953
Per capita GDP (PPP$)	0.005	0.920	0.391

Factor loadings--Normalized so the sum over all indicators is one.

Population			0.41
Num. housing units			0.42
Per capita GDP (PPP$)			0.17

Sources:
[1] GDP data: UNDP. *Human Development Report 1996*. New York: UN.
[2] All other data: UN Centre for Human Settlements (Habitat). *Compendium of Human Settlements Statistics 1995*. 5th issue. New York: UN.

G.2. Physical Infrastructure Exposure data set from *Statistics of World Large Cities 1991* (TMG 1991).

Correlation matrix [R]

Population	1.000	-0.053	0.603	0.247
Per capita GDP (PPP$)	-0.053	1.000	0.347	-0.093
Num. of housing units	0.603	0.347	1.000	0.175
Land area (sq.km.)	0.247	-0.093	0.175	1.000

Eigenvectors [v]

	Principal component			
	4	**3**	**2**	**1**
Population	0.608	0.431	0.235	0.624
Per capita GDP (PPP$)	0.382	-0.434	-0.785	0.223
Num. of housing units	-0.696	0.127	-0.218	0.672
Land area (sq.km.)	0.010	-0.781	0.530	0.330

Eigenvalues [e]	0.280	0.784	1.175	1.761
Percentage variation explained	7.0%	19.6%	29.4%	44.0%

Factor loadings [v*sqrt(e)]

Population	0.322	0.381	0.254	0.828
Per capita GDP (PPP$)	0.202	-0.384	-0.851	0.296
Num. of housing units	-0.369	0.113	-0.236	0.892
Land area (sq.km.)	0.005	-0.691	0.575	0.438

Factor loadings--Normalized so the sum over all indicators is one.

Population				0.34
Per capita GDP (PPP$)				0.12
Num. of housing units				0.36
Land area (sq.km.)				0.18

Sources:

[1] GDP data: UNDP. *Human Development Report 1995*. New York: UN.

[2] All other data: Tokyo Metropolitan Government. Bureau of General Affairs. Statistical Division. 1992. *Statistics of World Large Cities 1991*.

Appendix H
Questionnaire

June 23, 1996

Dear Earthquake Professional,

As part of my doctoral thesis I am developing a multidisciplinary Earthquake Disaster Risk Index (EDRI) that will:

1. allow straightforward comparison of the relative overall earthquake disaster risk of different cities throughout the world, and
2. describe the relative contributions of various factors to that overall risk.

The following questionnaire is intended to capture the opinions of experts concerning the relative importance of the five main factors comprising a city's earthquake disaster risk—Hazard, Exposure, Vulnerability, Response Capability, and External Context.

Please take a few minutes to complete this questionnaire. Return it now, or take it with you and send your response to the mailing address, e-mail address, or fax number listed below. If you include your return address in Question 14, I will forward a copy of the results to you when they are available.

Thank you very much for your time and interest.

Sincerely,

Rachel Davidson

DEFINITIONS

In completing this survey, please apply the following definitions of earthquake disaster and of the five main factors of which it is comprised:

Earthquake disaster is a function of not only the physical impact of an earthquake (as determined by the hazard, exposure, and vulnerability of the infrastructure), but also the response capability of the affected city, and the perceived relevance of the physical impact to the city and to world affairs. The social, economic, political, and cultural context of the damage determines whether an earthquake will create a disaster situation and how extensively its effect will be felt.

Hazard refers to the likelihood of each of the possible levels of severity of ground shaking, and of collateral hazards like fire, landslide, liquefaction, and tsunami.

Exposure conveys the number and geographical distribution of the city's population, buildings, and lifelines.

Vulnerability describes how easily the components of the infrastructure can be damaged and the population can be harmed in the absence of any response activities. The vulnerability depends on the (1) structural types, (2) quality of design and construction, (3) changes in structural condition since construction, including the effects of aging, maintenance, damage in previous earthquakes, and retrofitting, (4) expected nonstructural and content damage, and (5) extent of redundancy in the utility and transportation networks.

Response Capability defines how effectively and efficiently a city can recover from short- and long-term impact. Response relates to (1) the level of pre-earthquake operational and organizational planning, (2) the financial, manpower, equipment, and facility resources available, and (3) the ability to gain access to the city and maneuver within it following an event.

External Context describes the extent to which damage to a city affects those who live outside the city. It is included in recognition of the fact that, depending on cities' prominence with respect to economics, politics, transportation, and culture, damage to certain cities may create a more significant ripple effect than damage to others.

QUESTIONS

In answering Questions 1 to 10, it may be helpful to use the following scenario to conceptualize the proposed comparisons.

> Consider two hypothetical cities, City A and City B. Suppose that you have assessed the two cities with respect to each of the five factors defined above (i.e., Hazard, Exposure, ..., External Context). Assume that the factors are defined so that a higher factor value always corresponds to higher overall risk. You have determined that the two cities are identical in every way, except that:
>
> a. Factor 1 is greater in City A than in City B, and
> b. Factor 2 is greater, by the same margin, in City B than in City A.

Would you consider City A to have an overall earthquake disaster risk that is higher than, lower than, or roughly equivalent to that of City B?

In your opinion, which of the two factors in each box is more important in determining a city's earthquake disaster risk? Circle the appropriate letter.

1a.	A. Hazard B. Exposure C. About the same

2a.	A. Exposure B. Vulnerability C. About the same

3a.	A. Response Capability B. External Context C. About the same

4a.	A. Exposure B. External Context C. About the same

5a.	A. Hazard B. External Context C. About the same

6a.	A. Vulnerability B. Response Capability C. About the same

7a.	A. Hazard B. Vulnerability C. About the same

8a.	A. Exposure B. Response Capability C. About the same

9a.	A. Hazard B. Response Capability C. About the same

10a.	A. Vulnerability B. External Context C. About the same

What ratio of Factor 1 to Factor 2 describes the relative importance of the two factors?
____
_

For example, if Exposure is twice as important as Hazard, write Hazard:Exposure::1:__2__.
____
_

1b. Hazard:Exposure::1:_____

2b. Exposure: Vulnerability::1:_____

3b. Response Cap.: External Context::1:_____

4b. Exposure: External Context::1:_____

5b. Hazard: External Context::1:_____

6b. Vulnerability: Response Cap.::1:_____

7b. Hazard: Vulnerability::1:_____

8b. Exposure: Response Capability::1:_____

9b. Hazard: Response Capability::1:_____

10b. Vulnerability: External Context::1:_____

11. Assign weighting factors, w_i, such that

a. w_i describes the relative importance of factor i to the overall earthquake disaster risk of a city.

b. Each weight w_i has a value from 1 to 10 (i.e., $1 \le w_i \le 10$ for all w_i).

c. The factor(s) that are MOST important have a weight w_i=10, and all other factors are weighted relative to the most important one(s). The sum of the weights is unimportant.

FACTOR i	**WEIGHT w_i**
Hazard	____________
Exposure	____________
Vulnerability	____________
Response Capability	____________
External Context	____________

12. List any factors that, in your opinion, are important in determining a city's earthquake disaster risk, but were not considered in this survey.

13. What is your field of expertise?____

In which country do you live?____

14. (Optional) If you are interested in receiving a copy of the results of this survey, please write the address or fax number to which they can be sent:

____

____

____

____

Factor		Indicator	Minimum possible value	Maximum possible value
Hazard	xh1	exp(MMI w/50-year return period)	20	4024
	xh2	exp(MMI w/500-year return period)	148	8103
	xh3	Percentage urbanized area w/soft soil	0%	75%
	xh4	Percentage urbanized area w/high liquefaction suscept.	0%	75%
	xh5	Percentage of buildings that are wood	0%	90%
	xh6	Population density (people/sq. km.)	300	25000
	xh7	Tsunami potential indicator	0	2
Exposure	xe1	Population (1000s)	2,000	40,000
	xe2	Per capita GDP in constant 1990 US$	200	30,000
	xe3	Number of housing units (1000s)	1,000	18,000
	xe4	Urbanized land area (sq.km.)	100	2000
	xe5	Population (1000s)	2,000	40,000
	xe6	Per capita GDP in constant 1990 US$	200	30,000
Vulner-ability	xv1	Seismic code indicator	2	60
	xv2	City wealth indicator	50	5000
	xv3	City age indicator	5	55
	xv4	Population density (people/sq. km.)	300	25,000
	xv5	City development speed indicator	10	120
	xv6	Percentage of population aged 0-4 or 65+	10.00%	25.00%
External Context	xc1	Economic external context indicator	100	5.50E+13
	xc2	Political country external context indicator	0.0005	1
	xc3	Political world external context indicator	2.00E+08	6.00E+12
Emerg. Resp. & Recovery	xr1	Planning indicator	1	4
	xr2	Per capita GDP in constant 1990 US$	200	30,000
	xr3	Avg. annual real growth in per cap. GDP in prev. 10 yrs.	-15%	15%
	xr4	Housing vacancy rate	0%	20%
	xr5	Number of hospitals per 100,000 residents	0.5	10.0
	xr6	Number of physicians per 100,000 residents	10	500
	xr7	Extreme weather indicator	0	300
	xr8	Population density (people/sq. km.)	300	25,000
	xr9	City layout indicator	0	1

Appendix I

Code for *sens.c* Sensitivity Analysis Computer Program

```
/*********************************************************************
*   Rachel Davidson     February 19, 1997
*
*   Program to perform a sensitivity analysis on the EDRI results for a sample of cities
*
*   Input results for EDRI analysis from file "SensIn".
*   Output senstivity results into files "SensOut1," "SensOut2," and "SensOut3"
*
*   Compile with: gcc sens.c -lm -o sens -lrecipes_c
*
*********************************************************************/

#include <stdio.h>
#include <math.h>
#include <nrutil.h>

#define m 10                                        /* number of cities in sample */

#define nmax 10                                           /* max of nh, .., nr, 5 */
#define SWAP(a,b) itemp=(a)=(b); (b)=itemp;             /* for ranking function */
#define M  11                                        /* for ranking function */
#define NSTACK 50                               /* for ranking function */
#define basecity 2          /* num. of city used as base city in scaling w.r.t. base city */

/*********************************************************************
* Function prototypes
*********************************************************************/

void scale(
      int option,
      int inv,
    double X[],
    double Xprime[],
    double minposs,
    double maxposs
);

void normwgts(
      int numwgts,
```

```
    double wgts[]
);
```

```
void lincombo(
	int numterms,
	double wgts[],
	double X[][m],
	double combo[]
);

void rank(
	unsigned long n,
	double arr[],
	unsigned long ranks[]
);

void updatestats1(
	double min1[][m],
	double max1[][m],
	double mean1[][m],
	double sd1[][m],
	double sum1[][m],
	double sumsq1[][m],
	double F[][m+1],
	double Forig[][m+1],
	int t,
	int tskip[6],
	int min1trial[][m],
	int max1trial[][m]
);

void printstats1(
	double min1[][m],
	double max1[][m],
	double mean1[][m],
	double sd1[][m],
	int min1trial[][m],
	int max1trial[][m],
	FILE *fpout3
);

double calcrs(
	unsigned long U[],
	unsigned long V[]
);

/*********************************************************
******
* Main program
**********************************************************
*****/

main()
{
	FILE *fpin;			/* file pointer to read input file */
	FILE *fpout1;			/* file pointer to write to output file 1 */
	FILE *fpout2;			/* file pointer to write to output file 2 */
	FILE *fpout3;			/* file pointer to write to output file 3 */

	int n[6];		/* num. of indicators for each main factor and EDRI */
	double x[5][nmax][m];		/* matrix of unscaled data x values */
	double xorig[5][nmax][m];	/* original matrix of unscaled data x */
	double xprime[6][nmax][m];		/* matrix of scaled x values */
	double w[6][nmax];				/* weights */
	double worig[6][nmax];			/* original weights */
	double dw;				/* percent change for weights */
	int inv[5][nmax];			/* inverse-direct indicator */
	double minposs[5][nmax];  /* min. possible value for scaling */
	double maxposs[5][nmax];  /* max. possible value for scaling */
	int dupe[5][nmax];			/* duplicate indicator id */
	int dup;
	int option;			/* to identify which scaling option to use */
	double d[5][nmax][m];		/* deltas for data uncertainty */
	double Forig[6][m+1];		/* original main factor and EDRI values */
				/* ranks of orig. main factor & EDRI values */
```

```
	unsigned long Forigranks[6][m+1];
	int i, j, k, p, q, r, s;		/* looping indices */
	int t;						/* number of trials */
	int tskip[6];			/* num. trials to skip in updating stats1 */
	double F[6][m+1];		/* calculated  main factor & EDRI values */
					/* ranks of main factor & EDRI values */
	unsigned long Franks[6][m+1];
	double sum1[6][m];			/* sum for main factor & EDRI values */
	double sumsq1[6][m];		/* sumsq for main factor & EDRI values */
	double min1[6][m];			/* min for main factor & EDRI values */
	double max1[6][m];			/* max for main factor & EDRI values */
	double mean1[6][m];		/* mean for main factor & EDRI values */
	double sd1[6][m];	/* standard dev. for main factor & EDRI values */
	int min1trial[6][m];			/* num. of the trial that gives min1 */
	int max1trial[6][m];			/* num. of the trial that gives max1 */
	double rs2[6];			/* Spearman rank correlation coefficient */

	/******************************************************
*****
	* Open input and output files
	* Read input from files "SensIn", and print input data to SensOut1

	******************************************************
*****/

	if((fpin = fopen("SensIn", "r") ) == NULL) {
		printf("Couldn't open input file SensIn.");
	}
	if((fpout1 = fopen("SensOut1", "wr")) == NULL) {
		printf("Couldn't open output file SensOut1.");
	}
	if((fpout2 = fopen("SensOut2", "wr")) == NULL) {
		printf("Couldn't open output file SensOut2.");
	}
	if((fpout3 = fopen("SensOut3", "wr")) == NULL) {
		printf("Couldn't open output file SensOut3.");
	}

	fprintf(fpout1, "\nInput data.\n\nFactor    Num. inds.");

	for(i=0; i<6; i++) {
		fscanf(fpin, "%d", &n[i]);
		fprintf(fpout1,"\n  %d          %d", i, n[i]);
	}

	fprintf(fpout1,"\n\nFactor   Indicator weights");
	for(i=0; i<6; i++) {
		for(j=0; j<n[i]; j++) {
			fscanf(fpin, "%lf", &w[i][j]);
			worig[i][j] = w[i][j];
		}
		fprintf(fpout1,"\n  %d ", i);
		for(j=0; j<n[i]; j++) {
			fprintf(fpout1," %6.4lf", w[i][j]);
		}
	}

	fscanf(fpin, "%lf", &dw);
	fprintf(fpout1,"\n\ndw = %5.3lf", dw);

	fprintf(fpout1,"\n\nFactor   Indicators (1=Direct. 0=Inverse)");
	for(i=0; i<5; i++) {
		for(j=0; j<n[i]; j++) {
			fscanf(fpin, "%d", &inv[i][j]);
		}
		fprintf(fpout1,"\n  %d   ", i);
		for(j=0; j<n[i]; j++) {
			fprintf(fpout1,"  %d", inv[i][j]);
		}
	}

	fprintf(fpout1,"\n\nFactor   Minimum possible values for scaling");
```

```
for(i=0; i<5; i++) {
	for(j=0; j<n[i]; j++) {
		fscanf(fpin, "%lf", &minposs[i][j]);
	}
	fprintf(fpout1,"\n  %d   ", i);
	for(j=0; j<n[i]; j++) {
		fprintf(fpout1,"%9.2e", minposs[i][j]);
	}
}

fprintf(fpout1,"\n\nFactor   Maximum possible values for scaling");
for(i=0; i<5; i++) {
	for(j=0; j<n[i]; j++) {
		fscanf(fpin, "%lf", &maxposs[i][j]);
	}
	fprintf(fpout1,"\n  %d   ", i);
	for(j=0; j<n[i]; j++) {
		fprintf(fpout1,"%9.2e", maxposs[i][j]);
	}
}

fprintf(fpout1,"\n\nFactor   Indicators (Duplicate id. 0=no dups.)");
for(i=0; i<5; i++) {
	for(j=0; j<n[i]; j++) {
		fscanf(fpin, "%d", &dupe[i][j]);
	}
	fprintf(fpout1,"\n  %d   ", i);
	for(j=0; j<n[i]; j++) {
		fprintf(fpout1,"  %d", dupe[i][j]);
	}
}

for(i=0; i<5; i++) {
	fprintf(fpout1,"\n\nFactor %d raw data values", i);
	for(j=0; j<n[i]; j++) {
		fprintf(fpout1,"\n");
		for(k=0; k<m; k++) {
			fscanf(fpin, "%lf", &x[i][j][k]);
			xorig[i][j][k] = x[i][j][k];
			fprintf(fpout1,"%9.2e", x[i][j][k]);
		}
	}
}

for(i=0; i<5; i++) {
	fprintf(fpout1,"\n\nFactor %d delta values", i);
	for(j=0; j<n[i]; j++) {
		fprintf(fpout1,"\n");
		for(k=0; k<m; k++) {
			fscanf(fpin, "%lf", &d[i][j][k]);
			fprintf(fpout1,"%9.2e", d[i][j][k]);
		}
	}
}
fprintf(fpout1,"\n\n\nOutput data\n");


/*******************************************************
*****
* Evaluate original five main factor and EDRI results and print in
*	SensOut2:
*		Scale all x[i][j][k] values
*		Evaluate five main factor and EDRI values
*		Calculate city ranks with respect to each of five main factors
*			and EDRI
*******************************************************
*****/

option = 0;				/* scaled all unscaled data x values */
for(i=0; i<5; i++) {
	for(j=0; j<n[i]; j++) {
		scale(option, inv[i][j], x[i][j], xprime[i][j], minposs[i][j],
```

```
                        maxposs[i][j]);
                }
        }

        fprintf(fpout2, "\nOriginal main factor and EDRI values\n\nCity:\n");
        for(k=0; k<m; k++) {
                fprintf(fpout2, "      %d", k);
        }
        fprintf(fpout2, "\nFactor:");

        for(i=0; i<6; i++) {            /* calculate five main factor and EDRI values */
                lincombo(n[i], w[i], xprime[i], Forig[i]);
                rank(m, Forig[i], Forigranks[i]);                       /* calculate ranks */
                if(i!=5) {
                        for(k=0; k<m; k++) {
                                xprime[5][i][k] = Forig[i][k];
                        }
                }
                fprintf(fpout2, "\n%d", i);
                for(k=0; k<m; k++) {
                        fprintf(fpout2, " %6.3lf", Forig[i][k]);
                }
        }
        fprintf(fpout2, "\n");


        /*****************************************************
*****
        * Initialize statistics set 1 and number of trials t

        *****************************************************
*****/

        for(i=0; i<6; i++) {
                for(k=0; k<m; k++) {
                        sum1[i][k] = 0;
                        sumsq1[i][k] = 0;
                        min1[i][k] = Forig[i][k];
                        max1[i][k] = Forig[i][k];
                        min1trial[i][k] = 0;
                        max1trial[i][k] = 0;
                }
                tskip[i] = 0;
        }
        t = 0;




        /*****************************************************
*****
        * Perform sensitivity analysis to data uncertainty
        *****************************************************
*****/

        fprintf(fpout1,"\nSensitivity to data uncertainty.\n");
        fprintf(fpout2,"\nSensitivity to data uncertainty.\n");
        for(s=0; s<2; s++) {                    /* loop through +delta and -delta */
                for(p=0; p<5; p++) {            /* loop through five main factors */
                        for(q=0; q<n[p]; q++) {    /* loop thru all inds. in each factor */
                                for(r=0; r<m; r++) {            /* loop through all cities */
                                        t++;                            /* increment num. trials */
                                        if (s==0) {                     /* change x by +delta */
                                                x[p][q][r] = x[p][q][r] + d[p][q][r];
                                                        /* check if indicator is used more than once */
                                                if (dupe[p][q] != 0) {
                                                        dup = dupe[p][q];
                                                        for(i=0; i<5; i++) {
                                                                for(j=0; j<n[i]; j++) {
                                                                        if (dupe[i][j] == dup) {
                                                                          x[i][j][r] = x[i][j][r] + d[i][j][r];
                                                                        }
```

```
                    }
                }
            }
        } else if (s==1) {                          /* change x by -delta */
            x[p][q][r] = x[p][q][r] - d[p][q][r];
                /* check if indicator is used more than once */
            if (dupe[p][q] != 0) {
                dup = dupe[p][q];
                for(i=0; i<5; i++) {
                    for(j=0; j<n[i]; j++) {
                        if (dupe[i][j] == dup) {
                            x[i][j][r] = x[i][j][r] - d[i][j][r];
                        }
                    }
                }
            }
        }                                                   /* scale x values. */
                    /*calculate factor & EDRI values & ranks */
        option = 0;
        scale(option, inv[p][q], x[p][q], xprime[p][q],
            minposs[p][q], maxposs[p][q]);
        for(i=0; i<6; i++) {
            lincombo(n[i], w[i], xprime[i], F[i]);
            rank(m, F[i], Franks[i]);
            if (i!=5) {
                for(k=0; k<m; k++) {
                    xprime[5][i][k] = F[i][k];
                }
            }                                               /* calculate r_s */
            rs2[i] = calcrs(Franks[i], Forigranks[i]);
        }

    if (s==0) {
        fprintf(fpout1, "\nTrial %4d.  Value x[%d][%d][%d]"
    } else if (s==1) {
        fprintf(fpout1, "\nTrial %4d.  Value x[%d][%d][%d]"
```

```
                        }
                    updatestats1(min1, max1, mean1, sd1, sum1, sumsq1, F,
                        Forig, t, tskip, min1trial, max1trial);
                                        /* print results to "SensOut2" */
                    fprintf(fpout2, "\nT%d\t", t);
                    for(k=0; k<m; k++) {
                        fprintf(fpout2, "%d     ", k);
                    }
                    fprintf(fpout2, "rs2");

                    for(i=0; i<6; i++) {
                        fprintf(fpout2, "\n%3d  ", i);
                        for(k=0; k<m; k++) {
                            fprintf(fpout2, "%6.3lf", F[i][k]);
                        }
                        fprintf(fpout2, "%6.3lf", rs2[i]);
                    }
                    fprintf(fpout2, "\n");
                            /* reset unscaled data to their original values, */
                            /* and rescale them for next sensitivity analysis */
                        for(i=0; i<5; i++) {
                            for(j=0; j<n[i]; j++) {
                                for(k=0; k<m; k++) {
                                    x[i][j][k] = xorig[i][j][k];
                                }
                            }
                        }
                    }
                }
            }
        }
        option = 0;
        for(i=0; i<5; i++) {
            for(j=0; j<n[i]; j++) {    "is changed by +%6.3lf.", t, p, q, r, d[p][q][r]);
                scale(option, inv[i][j], x[i][j], xprime[i][j], minposs[i][j],
                    maxposs[i][j]);"is changed by -%6.3lf.", t, p, q, r, d[p][q][r]);
```

```
		}
	}

	/******************************************************
*****
	* Print statistics set #1 results of sensitivity analysis:
	*   min, max, mean, s.d. over all trials for each factor-city
	* For sensitivity to data uncertainty

	******************************************************
*****/

	fprintf(fpout3,"\n\nSensitivity to data uncertainty.\n");
	printstats1(min1, max1, mean1, sd1, min1trial, max1trial, fpout3);



	/******************************************************
*****
	* Initialize statistics set 1 and number of trials t
	******************************************************
*****/

	for(i=0; i<6; i++) {
		for(k=0; k<m; k++) {
			sum1[i][k] = 0;
			sumsq1[i][k] = 0;
			min1[i][k] = Forig[i][k];
			max1[i][k] = Forig[i][k];
			min1trial[i][k] = 0;
			max1trial[i][k] = 0;
		}
		tskip[i] = 0;
	}
	t = 0;

	/******************************************************
*****
	* Perform sensitivity analysis to weights
	******************************************************
*****/

	fprintf(fpout1,"\n\nSensitivity to weights.\n");
	fprintf(fpout2,"\n\nSensitivity to weights.\n");
	for(s=0; s<2; s++) {				/* loop through +dw and -dw */
		or(p=0; p<6; p++) {			/* loop through all factors and EDRI */
			for(q=0; q<n[p]; q++) {	/* loop thru all inds. for each factor */
				t++;

				if (s==0) {			/* change w by +dw percent */
					w[p][q] = w[p][q]*(1+dw);
						/* renormalize weights so their sum equals one */
					normwgts(n[p], w[p]);
				} else if (s==1) {		/* change w by -dw percent */
					w[p][q] = w[p][q]*(1-dw);
						/* renormalize weights so their sum equals one */
					normwgts(n[p], w[p]);
				}
					/* calculate factor and EDRI values, and ranks */
				for(i=0; i<6; i++) {
					lincombo(n[i], w[i], xprime[i], F[i]);
					rank(m, F[i], Franks[i]);
					if(i!=5) {
						for(k=0; k<m; k++) {
							xprime[5][i][k] = F[i][k];
						}
					}					/* calculate r_s */
					rs2[i] = calcrs(Franks[i], Forigranks[i]);
				}
					/* calculate statistics & print results in SensOut2 */
				if (s==0) {
					fprintf(fpout1, "\nTrial %4d.  Value w[%d][%d] is"
```

```
                " changed by +%6.3lf percent.", t, p, q, dw);
        } else if (s==1) {
            fprintf(fpout1, "\nTrial %4d.  Value w[%d][%d] is"
                " changed by  -%6.3lf percent.", t, p, q, dw);
        }
        updatestats1(min1, max1, mean1, sd1, sum1, sumsq1, F,
            Forig, t, tskip, min1trial, max1trial);

        fprintf(fpout2, "\nT%d\t", t);
        for(k=0; k<m; k++) {
            fprintf(fpout2, "%d     ", k);
        }
        fprintf(fpout2, "rs2");

        for(i=0; i<6; i++) {
            fprintf(fpout2, "\n%3d  ", i);
            for(k=0; k<m; k++) {
                fprintf(fpout2, "%6.3lf", F[i][k]);
            }
            fprintf(fpout2, "%6.3lf", rs2[i]);
        }
        fprintf(fpout2, "\n");
                        /* reset weights to their original values */
        for(i=0; i<6; i++) {
            for(j=0; j<n[i]; j++) {
                w[i][j] = worig[i][j];
            }
        }
      }
    }
  }

  /*****************************************************
*****
  * Print statistics set #1 results of sensitivity analysis:
  *   min, max, mean, s.d. over all trials for each factor-city
  * For sensitivity to weights
  *****************************************************
*****/

  fprintf(fpout3,"\n\nSensitivity to weights\n");
  printstats1(min1, max1, mean1, sd1, min1trial, max1trial, fpout3);


  /*****************************************************
*****
  * Initialize statistics set 1 and number of trials t
  *****************************************************
*****/

  for(i=0; i<6; i++) {
      for(k=0; k<m; k++) {
          sum1[i][k] = 0;
          sumsq1[i][k] = 0;
          min1[i][k] = Forig[i][k];
          max1[i][k] = Forig[i][k];
          min1trial[i][k] = 0;
          max1trial[i][k] = 0;
      }
      tskip[i] = 0;
  }
  t = 0;


  /*****************************************************
*****
  * Perform sensitivity analysis to indicator selection
  *****************************************************
*****/

  fprintf(fpout1,"\n\nSensitivity to indicator selection.\n");
  fprintf(fpout2,"\n\nSensitivity to indicator selection.\n");
```

```
for(p=0; p<6; p++) {                    /* loop through all factors and EDRI */
for(q=0; q<n[p]; q++) {     /* loop through all indicators in each factor */
        t++;                                     /* increment num. of trials */
                        /* remove indicator by setting its weight to zero */
        w[p][q] = 0;
        normwgts(n[p], w[p]);                        /* renormalize weights */
                            /* calculate factor & EDRI values, & ranks */
        for(i=0; i<6; i++) {
            lincombo(n[i], w[i], xprime[i], F[i]);
            rank(m, F[i], Franks[i]);
            if(i!=5) {
                for(k=0; k<m; k++) {
                    xprime[5][i][k] = F[i][k];
                }
            }
            rs2[i] = calcrs(Franks[i], Forigranks[i]);       /* calculate r_s */
        }
                    /* calculate statistics and print results in SensOut2 */
        fprintf(fpout1, "\nTrial %4d.  Value w[%d][%d] is set to "
            "zero, i.e., indicator[%d][%d] is removed.", t, p, q, p, q);

        updatestats1(min1, max1, mean1, sd1, sum1, sumsq1, F, Forig,
            t, tskip, min1trial, max1trial);

        fprintf(fpout2, "\nT%d\t", t);
        for(k=0; k<m; k++) {
            fprintf(fpout2, "%d     ", k);
        }
        fprintf(fpout2, "rs2");

        for(i=0; i<6; i++) {
            fprintf(fpout2, "\n%3d  ", i);
            for(k=0; k<m; k++) {
                fprintf(fpout2, "%6.3lf", F[i][k]);
            }
                fprintf(fpout2, "%6.3lf", rs2[i]);
            }
            fprintf(fpout2, "\n");

            for(i=0; i<6; i++) {     /* reset weights to their original values */
                for(j=0; j<n[i]; j++) {
                    w[i][j] = worig[i][j];
                }
            }
        }
    }

    /*******************************************************
*****
    * Print statistics set #1 results of sensitivity analysis:
    *   min, max, mean, s.d. over all trials for each factor-city
    * For sensitivity to indicator selection
    *******************************************************
*****/

    fprintf(fpout3,"\n\nSensitivity to indicator selection\n");
    printstats1(min1, max1, mean1, sd1, min1trial, max1trial, fpout3);

    /*******************************************************
*****
    * Initialize statistics set 1 and number of trials t
    *******************************************************
*****/

    for(i=0; i<6; i++) {
        for(k=0; k<m; k++) {
            sum1[i][k] = 0;
            sumsq1[i][k] = 0;
            min1[i][k] = Forig[i][k];
            max1[i][k] = Forig[i][k];
            min1trial[i][k] = 0;
```

```
            max1trial[i][k] = 0;
        }
        tskip[i] = 0;
    }
    t = 0;

    /*****************************************************
*****
    * Perform sensitivity analysis to scaling function
    *****************************************************
*****/

    fprintf(fpout1,"\n\nSensitivity to scaling function.\n");
    fprintf(fpout2,"\n\nSensitivity to scaling function.\n");
    for(s=0; s<4; s++) {                /* loop through four scaling options */
        option = s;
        t++;
        for(i=0; i<5; i++) {                              /* scale all indicators */
            for(j=0; j<n[i]; j++) {
                scale(option, inv[i][j], x[i][j], xprime[i][j], minposs[i][j],
                    maxposs[i][j]);
            }
        }
        for(i=0; i<6; i++) {     /* calculate factor & EDRI values, & ranks */
            lincombo(n[i], w[i], xprime[i], F[i]);
            rank(m, F[i], Franks[i]);
            if(i!=5) {
                for(k=0; k<m; k++) {
                    xprime[5][i][k] = F[i][k];
                }
            }
            rs2[i] = calcrs(Franks[i], Forigranks[i]);          /* calculate r_s */
        }
        if (s==0) {     /* calculate statistics and print results in SensOut2 */
            fprintf(fpout1, "\nTrial %d.  When scaling w.r.t. the "
                "mean minus two standard deviations.", t);
        } else if (s==1) {
            fprintf(fpout1, "\nTrial %d.  When scaling w.r.t. the "
                "min. and max. observed values.", t);
        } else if (s==2) {
            fprintf(fpout1, "\nTrial %d.  When scaling w.r.t. the "
                "min. and max. possible values.", t);
        } else if (s==3) {
            fprintf(fpout1, "\nTrial %d.  When scaling w.r.t. a "
                "base city.", t);
        }
        updatestats1(min1, max1, mean1, sd1, sum1, sumsq1, F, Forig, t,
            tskip, min1trial, max1trial);

        fprintf(fpout2, "\nT%d\t", t);
        for(k=0; k<m; k++) {
            fprintf(fpout2, "%d     ", k);
        }
        fprintf(fpout2, "rs2");

        for(i=0; i<6; i++) {
            fprintf(fpout2, "\n%3d  ", i);
            for(k=0; k<m; k++) {
                fprintf(fpout2, "%6.3lf", F[i][k]);
            }
            fprintf(fpout2, "%6.3lf", rs2[i]);
        }
        fprintf(fpout2, "\n");
    }
    option = 0;

    /*****************************************************
*****
    * Print statistics set #1 results of sensitivity analysis:
    *   min, max, mean, s.d. over all trials for each factor-city
    * For sensitivity to scaling function
```

```
    ******************************************************
*****/

    fprintf(fpout3,"\n\nSensitivity to scaling function.\n");
    printstats1(min1, max1, mean1, sd1, min1trial, max1trial, fpout3);
}

/******************************************************
******
* scale():      Function to scale a vector of values X[i] into a vector
*                       Xprime[i].
*               Four scaling options are possible, and the scaling may be for
*                       an indicator that
*               is directly or inversely related to earthquake disaster risk.
*******************************************************
****/

void scale(
    int option,                         /* indicates which scaling option to use */
    int inv,        /* indicates if ind. is directly or inversely related to EDRI */
    double X[],                                 /* input vector of unscaled values */
    double Xprime[],                            /* output vector of scaled values */
    double minposs,             /* min. and max. possible values for option 2 */
    double maxposs
)
{
    int j;
    double sumx, sumsqx;
    double meanx, sdx;
    double minobs, maxobs;
                                    /* scaling with respect to the mean minus two */
    if (option==0) {
        sumx = 0;
        sumsqx = 0;
        for(j=0; j<m; j++) {
            sumx = sumx + X[j];
            sumsqx = sumsqx + (X[j]*X[j]);
        }

        meanx = sumx/((double) m);
        sdx = sqrt( (((double) m)*sumsqx - sumx*sumx) /
            (((double) m)*((double) (m-1))) );

        for(j=0; j<m; j++) {
            if (inv==0) {
                Xprime[j] = ( X[j] - (meanx - 2.0*sdx) )/sdx;
            } else if (inv==1) {
                Xprime[j] = (-X[j] + (meanx + 2.0*sdx) )/sdx;
            }
        }               /* scaling with respect to the min. and max. observed */
    } else if (option==1) {
        minobs = X[0];
        maxobs = X[0];
        for(j=0; j<m; j++) {
            if (X[j] < minobs) {
                minobs = X[j];
            } else if (maxobs < X[j]) {
                maxobs = X[j];
            }
        }
        for(j=0; j<m; j++) {
            if (inv==0) {
                Xprime[j] = (X[j]-minobs)/(maxobs-minobs);
            } else if (inv==1) {
                Xprime[j] = (maxobs-X[j])/(maxobs-minobs);
            }
        }                       /* scaling with respect to the min. and max. possible */
    } else if (option==2) {
        for(j=0; j<m; j++) {
            if (inv==0) {
                Xprime[j] = (X[j]-minposs)/(maxposs-minposs);
```

```
            } else if (inv==1) {
                Xprime[j] = (maxposs-X[j])/(maxposs-minposs);
            }
        }
    } else if (option==3) {
        for(j=0; j<m; j++) {
            if (inv==0) {
                Xprime[j] = X[j]/X[basecity];
            } else if (inv==1) {
                Xprime[j] = 2.0 - (X[j]/X[basecity]);
            }
        }
    }
}

/***********************************************************
******
* normwgts():    Function to normalize weights so that their sum equals
*                one.
************************************************************
*****/

void normwgts(
    int numwgts,
    double wgts[]
)
{
    int i;
    double sumwgts = 0;

    for(i=0; i<numwgts; i++) {
        sumwgts = sumwgts + wgts[i];
    }
    for(i=0; i<numwgts; i++) {
        wgts[i] = wgts[i]/sumwgts;
    }
}

/***********************************************************
******
* lincombo():  /* scaling with respect to base city */  Function to calculate linear combos. of a matrix of values.
*              Input number of terms in linear combination (numterms),
*                  vector of weights (wgts[]), matrix of values (X[][]).
*              Output vector of linear combination values (combo[]), one
*                  per city.
************************************************************
*****/

void lincombo(
    int numterms,            /* number of terms to be combined */
    double wgts[],           /* weight values */
    double X[][m],           /* matrix of values to be combined */
    double combo[]           /* vector of linear combination values */
)
{
    int j, p;

    for(j=0; j<m; j++) {
        combo[j] = 0;
        for(p=0; p<numterms; p++) {
            combo[j] = combo[j] + (wgts[p]*X[p][j]);
        }
    }
}

/***********************************************************
******
* rank(): Function to take a vector of n values as input arr[], order them from
*         largest to smallest, and output the ranks corresponding to each
*         value in the output vector ranks[].  From Numerical recipes in C.
************************************************************
*****/
```

```
void rank(
	unsigned long n,			/* number of values in arr[] */
	double arr[],				/* input vector of values */
			/* output vector of ranks corresponding to values in arr[] */
	unsigned long ranks[]
)
{
	unsigned long indx[n];
	unsigned long i, indxt, ir=n, itemp, j, k, l=1;
	int jstack=0, *istack;
	double a;
	int p;

	for(p=m-1; p>=0; p--) {
		arr[p+1] = arr[p];
	}

	istack = ivector(1, NSTACK);
	for(j=1; j<=n; j++) indx[j] = j;
	for(;;) {
		if (ir-1 < M) {
			for(j=l+1; j<=ir; j++) {
				indxt = indx[j];
				a = arr[indxt];
				for(i=j-1; i>=l; i--) {
					if (arr[indx[i]] <= a) break;
					indx[i+1] = indx[i];
				}
				indx[i+1] = indxt;
			}
			if (jstack == 0) break;
			ir = istack[jstack--];
			l = istack[jstack--];
	} else {
			k = (l+ir) >> 1;
			SWAP(indx[k], indx[l+1]);
			if (arr[indx[l]] > arr[indx[ir]]) {
				SWAP(indx[l], indx[ir])
			}
			if (arr[indx[l+1]] > arr[indx[ir]]) {
				SWAP(indx[l+1], indx[ir])
			}
			if (arr[indx[l]] > arr[indx[l+1]]) {
				SWAP(indx[l], indx[l+1])
			}
			i = l+1;
			j = ir;
			indxt = indx[l+1];
			a = arr[indxt];
			for(;;) {
				do i++; while (arr[indx[i]] < a);
				do j--; while (arr[indx[j]] > a);
				if (j< i) break;
				SWAP(indx[i], indx[j])
			}
			indx[l+1] = indx[j];
			indx[j] = indxt;
			jstack += 2;
			if (jstack > NSTACK) nrerror("NSTACK too small in	rank()");
			if (ir-i+1 >= j-1) {
				istack[jstack] = ir;
				istack[jstack-1] = i;
				ir = j-1;
			} else {
				istack[jstack] = j-1;
				istack[jstack-1] = l;
				l = i;
			}
		}
	}
	free_ivector(istack, 1, NSTACK);
```

```
        for(j=1; j<=n; j++) ranks[indx[j]] = (n-j+1);
        for(p=0; p<m; p++) {
                arr[p] = arr[p+1];
        }
}

/*********************************************************
******
* updatestats1():        Function to update statistics set 1—min., max., mean,
and
*                        standard deviation of each factor-city value over all
*                        trials.  One value per trial.
*                    Input current values of stats, F, num. trials (t) for updating
*********************************************************
*****/

void updatestats1(
        double min1[][m],
        double max1[][m],
        double mean1[][m],
        double sd1[][m],
        double sum1[][m],
        double sumsq1[][m],
        double F[][m+1],
        double Forig[][m+1],
        int t,
        int tskip[6],
        int min1trial[][m],
        int max1trial[][m]
)
{
        int i, k;
        int trel[6];                    /* num. trials relevant to each factor */
        int skip;             /* skip>0 means don't skip update; skip=0 means do */
        for(i=0; i<6; i++) {
                skip = 0;       /* skip update because the change did not affect the */
                for(k=0; k<m; k++) {              /* value of this factor for any city */
                        if (F[i][k] != Forig[i][k]) {
                                skip++;
                        }
                }
                if (skip == 0) {
                        tskip[i]++;
                } else if (skip != 0) {
                        for(k=0; k<m; k++) {
                                if(F[i][k] < min1[i][k]) {
                                        min1[i][k] = F[i][k];
                                        min1trial[i][k] = t;
                                }
                                if(F[i][k] > max1[i][k]) {
                                        max1[i][k] = F[i][k];
                                        max1trial[i][k] = t;
                                }
                                trel[i] = t-tskip[i];
                                sum1[i][k] = sum1[i][k] + F[i][k];
                                sumsq1[i][k] = sumsq1[i][k] + (F[i][k]*F[i][k]);
                                mean1[i][k] = sum1[i][k]/((double) trel[i]);                    /* upd
                                sd1[i][k] = (sumsq1[i][k] - ( ((double) trel[i])*
                                        (mean1[i][k]*mean1[i][k]) )) / ((double) (trel[i]-1));      /* update sd1
                        }
                }
        }
}

/*********************************************************
******
* printstats1():     Function to print statistics set 1 to output file "SensOut2"
*********************************************************
*****/
```

```
void printstats1(
	double min1[][m],
	double max1[][m],
	double mean1[][m],
	double sd1[][m],
	int min1trial[][m],
	int max1trial[][m],
	FILE *fpout3
)
{
	int i, k;

	fprintf(fpout3, "\nFactor/City      ");
	for(k=0; k<m; k++) {
		fprintf(fpout3, "%d     ", k);
	}
	for(i=0; i<6; i++) {
		fprintf(fpout3,"\n  %d  Min1     ", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%6.3lf", min1[i][k]);
		}
		fprintf(fpout3,"\n  %d  Mean1-sd1", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%6.3lf", (mean1[i][k]-sd1[i][k]));
		}
		fprintf(fpout3,"\n  %d  Mean1    ", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%6.3lf", mean1[i][k]);
		}
		fprintf(fpout3,"\n  %d  Mean1+sd1", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%6.3lf", (mean1[i][k]+sd1[i][k]));
		}
		fprintf(fpout3,"\n  %d  Max1     ", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%6.3lf", max1[i][k]);
		}
		fprintf(fpout3,"\n  %d  sd1      ", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%10.2e", sd1[i][k]);
		}
		fprintf(fpout3,"\n  %d  Min1trial", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%6d", min1trial[i][k]);
		}
		fprintf(fpout3,"\n  %d  Max1trial", i);
		for(k=0; k<m; k++) {
			fprintf(fpout3, "%6d", max1trial[i][k]);
		}
	}
}



/***********************************************************
******
* calcrs():	Function to calculate Spearman's rank correlation coefficient rs
*		for two vectors of ranks U[] and V[].
***********************************************************
*****/

double calcrs(
	unsigned long U[],
	unsigned long V[]
)
{
	int j;
	unsigned long diffsq[m];
	unsigned long sumdiffsq = 0;
	double rs;

	for(j=0; j<m; j++) {
```

```
        diffsq[j] = ( (U[j]-V[j])*(U[j]-V[j]) );
        sumdiffsq = sumdiffsq + diffsq[j];
    }
    rs = 1.0 - ( (6.0*sumdiffsq)/(m*( (m*m)-1 )) );

    return rs;
}
```

Appendix J
Minimum and Maximum Possible Values for Scaling Sensitivity Analysis

Appendix K

Values of Δx_{ij} for Data Uncertainty Sensitivity Analysis

Delta values for data uncertainty sensitivity analysis

Factor	Ind.	Boston	Istanbul	Jakarta	Lima	Manila	Mexico City	San Francisco	Santiago	St. Louis	Tokyo
Hazard	xh1	150	200	100	900	500	100	350	200	150	140
	xh2	1100	1000	250	1500	900	500	1200	600	1500	370
	xh3	5.0%	7.5%	5.0%	10.0%	10.0%	7.5%	5.0%	5.0%	5.0%	5.0%
	xh4	8.0%	10.0%	8.0%	10.0%	10.0%	10.0%	8.0%	8.0%	8.0%	8.0%
	xh5	5.0%	20.0%	10.0%	5.0%	7.5%	5.0%	5.0%	5.0%	5.0%	5.0%
	xh6	27	365	506	296	593	360	32	244	22	265
	xh7	0	0	0	0	0	0	0	0	0	0
Exposure	xe1	28,500	53,000	82,000	64,000	79,000	166,000	31,000	43,000	12,500	177,500
	xe2	768	52	46	17	19	81	759	63	605	775
	xe3	45,417	35,833	61,915	35,989	29,657	101,299	49,144	21,124	20,543	280,920
	xe4	14	56	34	49	40	113	22	24	10	141
	xe5	28,500	53,000	82,000	64,000	79,000	166,000	31,000	43,000	12,500	177,500
	xe6	768	52	46	17	19	81	759	63	605	775
Vulner-ability	xv1	3.5	10.2	2.2	2.5	2.7	10.0	13.2	4.9	2.5	13.2
	xv2	111	13	4	5	5	20	119	10	114	185
	xv3	2.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.1	1.0
	xv4	27	365	506	296	593	360	32	244	22	265
	xv5	5.3	1.0	1.0	1.0	1.0	1.2	1.9	1.6	4.5	1.8
	xv6	0.10%	0.10%	0.30%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
External Context	xc1	1.03E+11	9.83E+09	1.72E+10	2.46E+09	7.68E+09	7.47E+10	1.24E+11	3.38E+09	1.98E+10	1.26E+12
	xc2	0.0002	0.0011	0.0100	0.0100	0.0100	0.0100	0.0003	0.0100	0.0001	0.0100
	xc3	4.62E+09	3.23E+08	8.34E+09	3.65E+08	1.14E+09	6.86E+09	4.75E+09	8.24E+08	1.51E+09	9.57E+10
Emerg. Resp. & Recovery	xr1	1	1	1	1	1	1	0	1	1	0
	xr2	768	52	46	17	19	81	759	63	605	775
	xr3	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%
	xr4	1%	5%	5%	3%	5%	5%	1%	1%	1%	1%
	xr5	0.28	0.24	0.30	0.48	0.33	0.08	0.22	0.27	0.30	0.56
	xr6	23.24	18	3.65	17.2	3.2	13.09	20.93	6.8	17.71	11.48
	xr7	17.70	6.21	1.88	1.20	6.97	1.17	1.56	9.76	18.99	8.35
	xr8	27	365	506	296	593	360	32	244	22	265
	xr9	0	0	0	0	0	0	0	0	0	0

Note: See Figure 4.1 for indicator definitions corresponding to the variables x_i.

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