U.S. Department of Interior

U.S. Geological Survey

Scaling Laws for Natural Disaster Fatalities

by

Stuart P. Nishenko[1] and Christopher C. Barton[2]

Open File Report 95-67

1. U.S. Geological Survey, National Earthquake Information Center, Denver, CO 80225

2. U.S. Geological Survey, Denver, CO 80225

1995

Abstract

Global comparisons of earthquake fatalities during the 19th and 20th centuries and comparisons of fatalities from different types of disasters occurring in the United States during the 20th century demonstrate that earthquakes and other natural disasters can be described with fractal or power-law fatality-frequency distributions. The introduction of a scaling exponent, D, provides an index to describe and compare losses associated with earthquakes and other natural disasters in space and time. The self-similar nature of these distributions permits the probability of infrequent, catastrophic events to be directly estimated from the rate of occurrence of smaller, more frequent disasters. Probabilistic estimates for the occurrence of catastrophic events provides a quantitative basis for prioritizing global disaster relief and mitigation programs and developing multidisaster mitigation programs at the national level.

Introduction

Earthquakes, hurricanes, tornadoes, and floods are complex natural phenomena that can be characterized by power-law size-frequency distributions (Gutenberg and Richter, 1944; Barton et al., 1994; Mandelbrot, 1983; Turcotte and Greene, 1993). Natural disasters, as defined by the loss of life and property, also exhibit power-law or fractal size-frequency distributions in which small disasters occur more frequently than large disasters. An understanding of how a particular disaster scales to other disasters caused by the same phenomenon and to disasters caused by other phenomena is fundamental to the development and evaluation of natural disaster mitigation and hazard reduction programs.

A scaling law is termed self-similar where the frequency-size distribution has no characteristic size or length scale. The power-law distribution is such a scale-invariant distribution. In addition, any power-law frequency-size distribution with a scaling exponent that is non-integer is considered to be fractal. A power, Pareto, or fractal distribution of random variables is self-similar and scaling in that the same distribution is obtained under truncation (Mandelbrot, 1983). Earthquakes exhibit self-similar scaling behavior in space, time, and magnitude (Kagan and Knopoff, 1980; Smalley et al., 1987;

Pacheco et al., 1992). The Gutenberg-Richter (G-R) frequency-magnitude or b-value relationship,

$$\log N_c = a - bM \qquad [1]$$

where Nc is the cumulative number of events greater than or equal to a particular magnitude, M [where M is proportional to $\log_{10}$ (seismic wave amplitude)], is one such example of power-law scaling in seismology (Turcotte, 1989). The constants a and b in the G-R relationship are determined from the rates of occurrence of smaller magnitude earthquakes and are used to extrapolate the rates of occurrence of infrequent larger magnitude events.

In this study, we investigate the utility of using the distribution of losses from past disasters to estimate future risk. Catalogs or inventories of natural disaster losses contain the integrated effects of fluctuations in the frequency of occurrence, slow vs. rapid onset time, small vs. large damage areas, and variations in damage intensity. This study presents three perspectives on losses due to natural disasters. The first is a global comparison of earthquake fatalities that have occurred during the 20th century. The second is a comparison of earthquake fatalities in the same country during the 19th and 20th centuries. The third comparison is of losses from different types of disasters that occurred in the United States during the 20th century. We find that losses associated with earthquakes, hurricanes, floods, and tornadoes all exhibit power-law frequency-size distributions. This commonality provides a framework for the comparison of losses resulting from different types of disasters and allows use of the rate of occurrence of small disasters to infer the frequency of larger disasters.

I. Global Earthquake Fatalities

Records of earthquake fatalities in China, Japan, Italy, Iran, Peru, Turkey, Chile, and India were examined to establish the equations that describe the frequency-size distribution or scaling behavior of earthquake disasters. These countries experienced the majority of earthquake fatalities during the 20th century (Coburn et al., 1989), and provide a rich sample of geographic and tectonic regimes, types and sizes of earthquakes, construction techniques and population densities. Estimates of both direct and indirect fatalities from individual earthquakes have been combined in our analysis (Dunbar et al., 1992). Direct fatalities are those caused by the collapse of buildings and other structures during the earthquake itself. Indirect fatalities are those caused by secondary effects (e.g., landslides and tsunamis triggered by the earthquake) as well as fires, exposure to cold, epidemics, etc. In many cases it is impossible to distinguish the number of direct and indirect fatalities from available reports. For those events with more than one fatality estimate, we have bracketed the loss with both maximum and minimum estimates.

In the same way that earthquake magnitudes are proportional to $\log_{10}$(seismic wave amplitude) (Ishimoto and Iida, 1938; Richter, 1958) or that the magnitude of a war or deadly quarrel can be defined as $\log_{10}$(number of fatalities) (Richardson, 1960), we define the magnitude of the loss associated with a particular earthquake (or other natural disaster) as

$$F = \log_{10} \text{(number of fatalities)} \qquad [2a]$$

where F is the fatality magnitude. Variations in overall population size and rates of growth from country to country can be accounted for by dividing the number of fatalities for a given event by the population of the country at the time of the event. The normalized fatality magnitude, F', is then

$$F' = \log_{10} \text{(number of fatalities/population)} \qquad [2b]$$

Earthquake fatality-frequency distributions for China, Japan, Italy, Iran, Peru, Turkey, Chile, and India are presented in Figure 1. These data have been normalized by the population of country at the time of the earthquake (McEvedy and Jones, 1979). Once differences in population size are accounted for, 6 out of 8 countries [China, Japan, Italy, Chile, Peru, and India] exhibit linear fatality-frequency behavior in log-log space that extends over 3 to 5 orders of magnitude in loss. A least-squares fit to the central linear segment of the cumulative fatality-frequency distribution in Figure 1 is used to determine the power-law equation,

$$\log N_F = a - D F' \qquad [3]$$

where N_F is the number of events with normalized fatalities greater than or equal to F', the normalized fatality magnitude, D is the slope of the distribution or scaling exponent, and a is a constant. Both the cumulative and interval forms of the fatality-frequency distributions are plotted in Figure 1. While the cumulative form of equation 3 is commonly used in the literature, the interval form allows testing of the data for completeness in various size ranges or intervals. Various fits to these data including cumulative least-squares and interval least-squares were calculated to help constrain the value of D, the scaling exponent. The cumulative least-squares fits to both maximum and minimum sets of normalized earthquake fatality data are summarized in Table 1.

While the overall fatality-frequency behavior of the majority of countries is similar, there are some important differences. The departure from linearity (break in slope or roll-over) at the low fatality (left) end of the cumulative fatality-frequency plot for Chinese and Peruvian earthquakes is interpreted to represent a deficit in the reporting of small fatality events. For earthquake magnitude-frequency distributions, this break in slope is related to the detection threshold of seismograph networks. Similarly the deficit in Figure 1 is related to the selection and reporting criteria (ten or more fatalities) of the earthquake fatality catalogs used on our analysis (Dunbar et al., 1992). In contrast to China and Peru, fatality data from Japan, Italy, Chile, and India show little or no roll-over at the low-fatality end during this same time period. Both the cumulative and interval forms of the frequency-size distribution are useful in determining where the threshold of complete reporting occurs. Knowledge of where this threshold occurs is critical when comparing data from different time periods or different regions. All of data sets in Figure 1 appear to be complete above an absolute threshold value of 10 fatalities per event.

In contrast to the majority of countries in Figure 1, both Iran and Turkey exhibit a different type of cumulative fatality-frequency behavior. Fatalities from both countries appear to terminate abruptly at normalized fatalities of 10^{-4} - 10^{-3} [between 10,000 and 100,000 fatalities per event (F = 4 - 5)]. We suggest that this abrupt or non-linear decay of the cumulative number of events is related to the size of the maximum disaster in Turkey or Iran. It has been long recognized that earthquakes have an inherent finite size or maximum magnitude (Knopoff and Kagan, 1977). The Gutenberg-

Richter recurrence relationship does not extend to infinitely large magnitudes but has a limiting size, which is dictated by the local tectonics. Similarly, it can be argued that there are a maximum number of fatalities that can be caused by a single natural disaster. At the extreme, this would be the entire population of the region at risk. The 1968 M 7.1 Dasht-i Biyaz, Iran earthquake, for example, totally destroyed all of the buildings in the village of Dasht-i Bayaz, killing 74% of the inhabitants (Ambraseys and Melville, 1982). Both Iran and Turkey have long histories of catastrophic earthquakes involving large numbers of fatalities. Typical construction materials used in these countries [mud wall/adobe brick, rubble masonry] are very vulnerable to earthquake damage and highly lethal (Ambraseys and Melville, 1982). The fatality distributions in Figure 1 indicate that poor construction has pushed societal fragility to the maximum limit in Iran and Turkey during this century.

II. Temporal Variations of Earthquake Fatalities

Historic (pre-20th century) fatality data provide a long-term perspective on the impact of natural disasters on society. This earlier time period predates the development of "modern" hazard mitigation programs, and provides a basis for comparison with later 20th century disasters.

Exactly how the scaling of fatalities changes as a function of time varies by region. Earthquake disaster histories for China, Japan, and Italy illustrate three types of behavior (Figure 2). In Japan the scaling exponent, D, appears to have remained constant from the 19th to the 20th century (0.31 vs 0.34, respectively). With the exception of the 1923 Kanto earthquake, the largest fatality earthquakes decreased in size from the 19th to the 20th century. In contrast to the 19th century data, 20th century fatality estimates show no sign of incomplete reporting at low fatality levels (i.e there is no roll-over for low fatalities). Note that the 20th century minimum and maximum fatality estimates in Figure 2 (solid circles and squares) are also in better agreement than 19th century estimates (solid triangles and diamonds). The scaling exponent, D, decreased from the 19th to the 20th century for both China and Italy (Figure 2). For Italy, the decrease in slope (0.42-0.36 to 0.27-0.25) reflects a decrease in the number of small fatality events during the 20th century. For more catastrophic earthquakes with normalized fatalities greater than 10^{-5}, both the 19th and 20th century distributions of Italian earthquake fatalities are essentially identical. For China, 19th century minimum and maximum fatality estimates are essentially identical, and only one set is shown for comparison. Overall, the decrease in D for China from the 19th to the 20th century (0.42 to 0.28) is caused by an increase in the number of high-fatality earthquakes during the 20th century.

Future Earthquake Fatalities

Projections of the rates of urbanization near earthquake belts indicate that 290 million people worldwide will live in regions of seismic risk by the end of this century. Twice that many people are estimated to be at risk by 2035 (Bilham, 1988). The geographic and temporal stability of the scaling relationships for earthquake fatalities in Figure 1 and 2 suggests the use of these distributions to estimate the size and frequency of future earthquake disasters. For countries with little or no disaster mitigation, these estimates provide projections of future losses for developing disaster relief and mitigation programs. For countries with active natural disaster mitigation programs, these projections can provide a baseline for the evaluation of the effectiveness of current programs at a later date.

Estimates of return periods for catastrophic F>4 (10,000 fatality) earthquakes in each country are based on the cumulative fatality-frequency distributions in Figure 1, and are adjusted to 1990 census values (United Nations, 1987). These return period estimates are similar to those for 100-year floods (i.e., the largest flood that occurs once a century) and do not imply any periodicity in the time intervals between events. Table 2 lists return periods and the Poisson probabilities for the occurrence of an $F \geq 4$ disaster during exposure windows of 1, 10, and 20 years duration in each of the eight countries studied. Not surprisingly, China, Iran, and Turkey have the highest probabilities [and the shortest return times (11-13 years)] for catastrophic F>4 events these during these three time periods. Chile and India have the longest return times (40 years) and the lowest probabilities, followed by Peru, Italy, and Japan (33 to 29 years).

III. Natural Disaster Fatalities in the United States

Fatalities associated with other types of natural disasters can also be characterized by power-law size-frequency distributions. Figure 3 compares the cumulative distribution of earthquake, flood, hurricane, and tornado fatalities in the United States during the 20th century. Reports for specific types of disasters span different time periods, and these data have been normalized by the length of the reporting period to reflect the annual rate of occurrence (Stover and Coffman, 1993; Snugg and Carrodus, 1969; Grazulis, 1993; Hebert and Case, 1990; US Army Corps of Engineers, 1986-1993). As in the case of the earthquake fatalities, the roll-off at the low fatality (left) end of the cumulative flood data clearly illustrates the effects of incomplete or partial reporting. Annual reports of U.S. floods since 1986 itemize only those fatalities associated with major events, whereas fatalities associated with smaller events are reported only as part of the annual total (US Army Corps of Engineers, 1986-1993). In contrast, the sharp termination of the tornado frequency-fatality distribution at 10 fatalities per event reflects the minimum number of fatalities per event in our data base (Grazulis, 1993).

The cumulative fatality-frequency curves in Figure 3 are linear over 2 to 4 orders of magnitude in loss and define two groups or families of fatal disasters. The first group, which includes both earthquakes and hurricanes, is characterized by a relatively flat slope (D = 0.4-0.6) and a number of large (>100) fatality events during the 20th century. At this scale, the primary difference between earthquake and hurricane fatalities during this time is the annual rate of activity. Fatal hurricanes occur more frequently than fatal earthquakes, however; the proportion of large to small events is similar in both cases. Flood and tornado disasters comprise the second type of fatality-frequency distribution, with steep slopes (D = 1.3 - 1.4), relatively few large fatality events, and higher annual rates of activity.

The integrated effects of slow- vs. rapid-onset times, small- vs. large-damage areas, and variations in damage density contained in the size-frequency distributions of this suite of disasters indicates that not all disasters have the same impact. Differences in the slope or scaling exponent of these distributions translate into significant differences in their impact at different fatality levels. On an annual basis, small fatality (F=1) floods and tornadoes are 3 to 4 times more frequent than F=1 hurricanes, and 20 to 30 times more frequent than

F=1 earthquakes. Large fatality events (i.e., F=2 and larger) on the other hand, are less frequent and were predominantly related to hurricanes during the 20th century. The crossover point where fatalities from individual hurricanes exceed those caused by floods and tornadoes occurs at approximately F =2 (i.e., 100 fatalities per event). Based on the data in Figure 3, we have computed probabilities for the occurrence of natural disasters in the United States with F =1 (10 fatalities per event) and F=3 (1000 fatalities per event) during exposure windows of 1, 10, and 20 years duration. These estimates are presented in Table 3.

Summary

Natural disasters are the product of complex interactions between nature and society. We have provided three different perspectives of life loss due to natural disasters to demonstrate how individual disasters scale with respect to other disasters caused by the same phenomena and to disasters caused by other phenomena.

The first, a global comparison of earthquake fatalities, illustrates the basic similarity of fatality-frequency distributions among a number of geologically and societally diverse regions. Fatalities associated with earthquakes are described well by power-law size-frequency distributions. The introduction of a scaling exponent, D, provides a index to describe and compare losses associated with either earthquakes or other types of natural disasters in space and time. Regional variations of fatality-frequency distributions provide a measure of societal fragility. Linear behavior over many orders of magnitude in loss is indicative of a society that is much more resilient to natural disasters than one which exhibits a truncated fatality-frequency distribution. Truncated fatality-frequency distributions indicate the frequent occurrence of maximum fatality events and saturation in the degree of earthquake related damage for a region.

The second perspective compared changes in earthquake fatality-frequency distributions as a function of time for Italy, Japan, and China. Japan experienced a roll-back in the number and size of maximum fatality events in the 20th century, while maintaining a relatively constant slope or D value. Italy and China, on the other hand, both experienced decreases in D during the 20th century due to fewer small fatality events in Italy, and more large fatality events in China.

The third perspective examined natural disasters in the United States and identified two groups or families of disasters based on differences in scaling behavior. Earthquakes and hurricanes are typified by low frequency, high maximum fatality events; while floods and tornadoes are characterized as high frequency, low maximum fatality events.

In terms of future disasters, the self-similar scaling behavior of past losses can be used to anticipate and plan for those rare catastrophic events that incur the largest losses and place the most stress on society. Probabilistic estimates for the occurrence of catastrophic events in Table 2 provide a quantitative basis for prioritizing global disaster relief and mitigation programs. The probabilistic estimates in Table 3 provide the foundation for developing multidisaster mitigation programs at a national level. In both cases, these fatality-frequency distributions provide a framework to visualize disaster mitigation strategies. Should disaster mitigation programs attempt to decrease the slope of the fataility-frequency curve by minimizing the number of small fatality events or increase the slope by trying to minimize the number and size of large fatality events? An alternate strategy would be to reduce the number of events in all fatality size classes, keeping the slope D constant.

Acknowledgements

We thank R. Bilham, C. Bufe, J. Dewey, P. Dunbar, D. Morton, D. Perkins, S. Tebbens, L. Whiteside for data, stimulating conversations, and valuable reviews. Both S. P. N. and C. C. B. were supported by the United States Geological Survey G.K. Gilbert Fellowship Program for 1993-1994.

Table 1

Cumulative least-square fits to the 20th century earthquake fatality-frequency data in Figure 1.

Country	Minimum Fatality	Maximum Fatality
China	$\log N = 0.15\ F^{-0.32}$	$\log N = 0.29\ F^{-0.28}$
Japan	$\log N = 0.10\ F^{-0.36}$	$\log N = 0.14\ F^{-0.34}$
Italy	$\log N = 0.25\ F^{-0.27}$	$\log N = 0.34\ F^{-0.25}$
Chile:	$\log N = 0.34\ F^{-0.26}$	$\log N = 0.41\ F^{-0.25}$
Peru	$\log N = 0.04\ F^{-0.46}$	$\log N = 0.06\ F^{-0.44}$
India	$\log N = 0.12\ F^{-0.27}$	$\log N = 0.14\ F^{-0.26}$
Iran	$\log N = 0.73\ F^{-0.29}$	$\log N = 0.88\ F^{-0.28}$
Turkey	$\log N = 0.44\ F^{-0.32}$	$\log N = 0.63\ F^{-0.30}$

Table 2

Poisson probability estimates for the occurrence of an earthquake with greater than 10,000 fatalities (i.e., F >4, where F =log [fatalities per event] during 1, 10, and 20 year exposure times. Return period estimates listed in the last column are based the normalized fatality-frequency distributions of earthquakes in each country during the 20th century and are indexed to 1990 census values [12].

Exposure Time Country	1 year	10 years	20 years	Return Period, yrs
China	0.08	0.55	0.80	13
Japan	0.03	0.29	0.49	29
Italy	0.03	0.26	0.45	33
Iran	0.09	0.60	0.84	11
Peru	0.03	0.26	0.45	33
Turkey	0.08	0.57	0.81	12
Chile	0.02	0.22	0.39	40
India	0.02	0.22	0.39	40

Table 3

Poisson probability estimates for the occurrence of earthquake, hurricane, flood, and tornado disasters with fatality magnitudes of F = 1 and 3 (i.e., 10 and 1000 fatalities) in the United States during 1, 10, and 20 year exposure times, and estimates of the mean return period. Note the reversal in recurrence periods for F =1 and F=3 events. Floods and tornadoes have relatively shorter return periods for F =1 events, whereas earthquakes and hurricanes have relatively short return times for F =3 events.

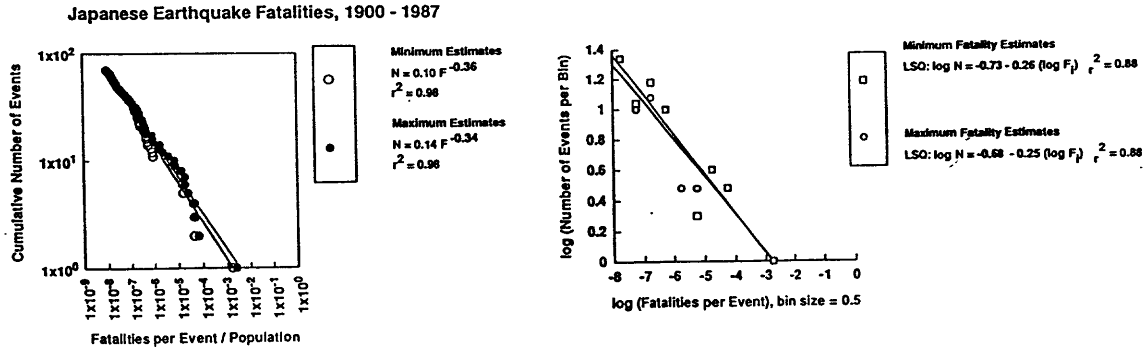
Exposure Time / Disaster	F =1 (10 fatalities/event)			
	1 yr	10 yrs	20 yrs	Return Period, yrs
Earthquakes	0.11	0.67	0.89	9
Hurricanes	0.39	0.99	> 0.99	2
Floods	0.86	> 0.99	> 0.99	0.5
Tornadoes	0.96	> 0.99	> 0.99	0.3

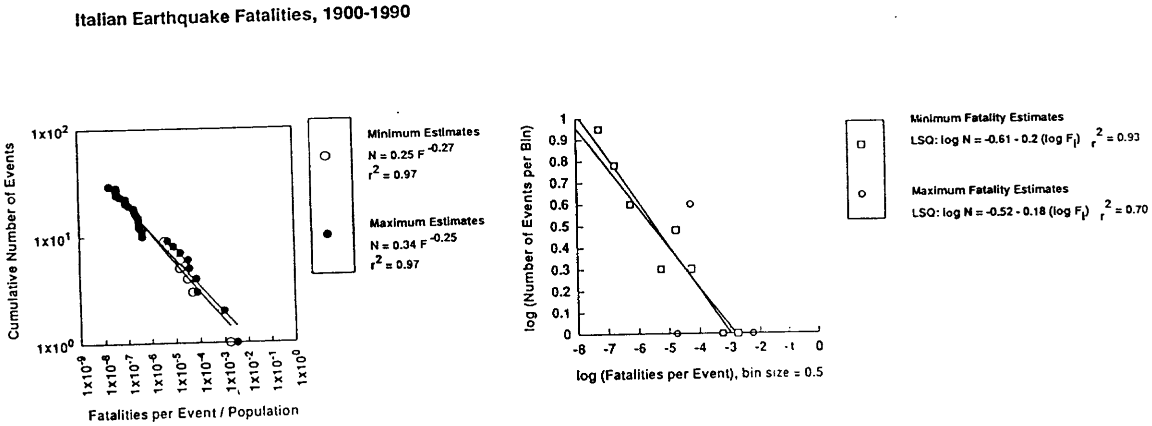
Exposure Time / Disaster	F =3 (1000 fatalities/event)			
	1 yr	10 yrs	20 yrs	Return Period, yrs
Earthquakes	0.01	0.14	0.26	67
Hurricanes	0.06	0.46	0.71	16
Floods	0.004	0.04	0.08	250
Tornadoes	0.006	0.06	0.11	167

Figure 1.

20th Century Earthquake Fatality-Frequency Distributions

Cumulative and interval fatality-frequency distributions for Japan, Italy, China, India, Peru, Chile, Iran, and Turkey illustrate a number of similarities after differences in population size are accounted for. Cumulative plots in log-log space show the number of events of size F' or greater, where F' is the normalized fatality magnitude. Least-squares fits to the linear portion of the cumulative data (solid symbols) are shown for both minimum (circles) and maximum (squares) fatality estimates. Events with fatalities less than the threshold of completeness are shown as open symbols. Least-squares fits to the interval data are also shown in the right hand column. The linear behavior of these many of these distributions in log-log space over 3 to 5 orders of magnitude in loss illustrates the underlying power-law scaling behavior of earthquake fatalities in these diverse regions. The pronounced curvature or truncation of the fatality-frequency distribution for Iran and Turkey indicates the frequent occurrence of maximum fatality disasters in these two countries.


Japanese Earthquake Fatalities, 1900 - 1987
Cumulative Number of Events
1x10^2
1x10^1
1x10^0
Fatalities per Event / Population
Minimum Estimates
N = 0.10 F^-0.36
r^2 = 0.98
Maximum Estimates
N = 0.14 F^-0.34
r^2 = 0.98
log (Number of Events per Bin)
log (Fatalities per Event), bin size = 0.5
Minimum Fatality Estimates
LSQ: log N = -0.73 - 0.26 (log F_i) r^2 = 0.88
Maximum Fatality Estimates
LSQ: log N = -0.68 - 0.25 (log F_i) r^2 = 0.88


Italian Earthquake Fatalities, 1900-1990
Cumulative Number of Events
1x10^2
1x10^1
1x10^0
Fatalities per Event / Population
Minimum Estimates
N = 0.25 F^-0.27
r^2 = 0.97
Maximum Estimates
N = 0.34 F^-0.25
r^2 = 0.97
log (Number of Events per Bin)
log (Fatalities per Event), bin size = 0.5
Minimum Fatality Estimates
LSQ: log N = -0.61 - 0.2 (log F_i) r^2 = 0.93
Maximum Fatality Estimates
LSQ: log N = -0.52 - 0.18 (log F_i) r^2 = 0.70

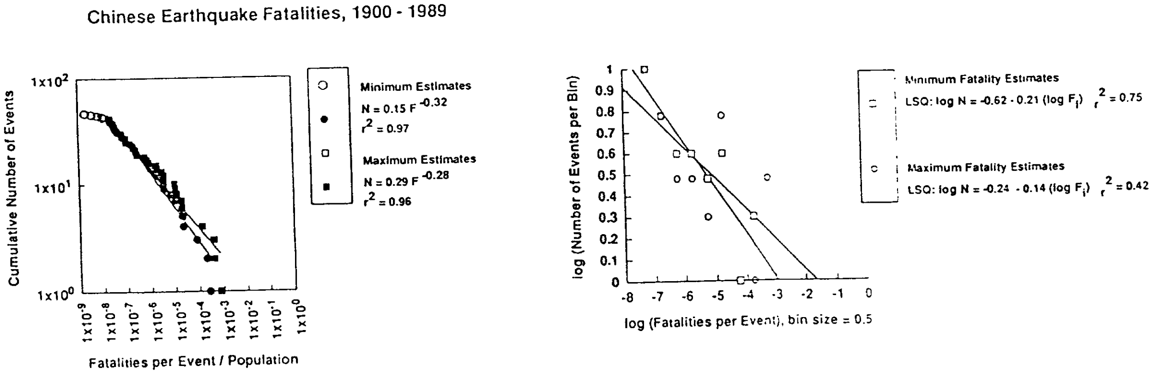
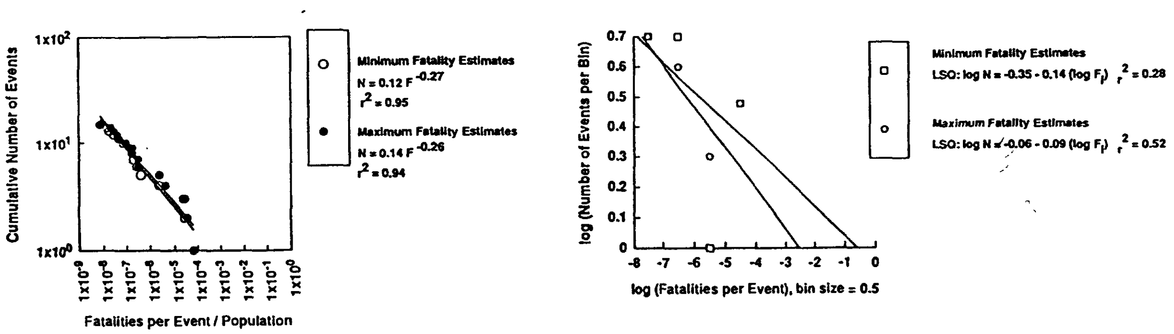
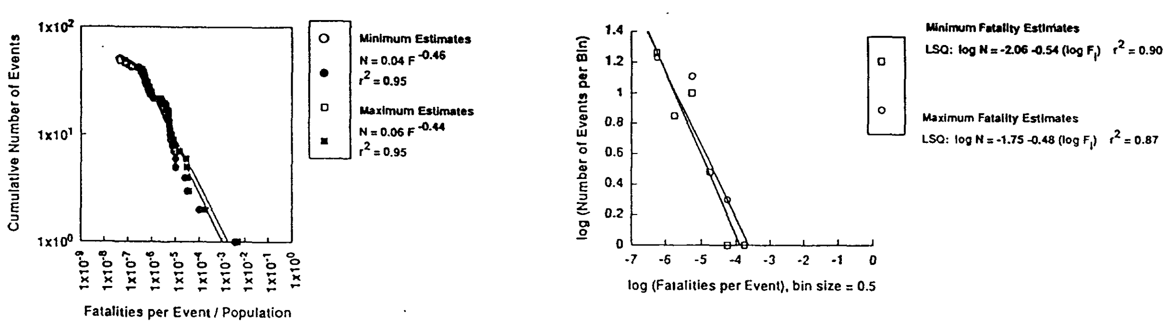

Chinese Earthquake Fatalities, 1900 - 1989
Cumulative Number of Events
1x10^2
1x10^1
1x10^0
Fatalities per Event / Population
Minimum Estimates
N = 0.15 F^-0.32
r^2 = 0.97
Maximum Estimates
N = 0.29 F^-0.28
r^2 = 0.96
log (Number of Events per Bin)
log (Fatalities per Event), bin size = 0.5
Minimum Fatality Estimates
LSQ: log N = -0.62 - 0.21 (log F_i) r^2 = 0.75
Maximum Fatality Estimates
LSQ: log N = -0.24 - 0.14 (log F_i) r^2 = 0.42

Figure 1

Indian Earthquake Fatalities, 1900 - 1993



Peruvian Earthquake Fatalities, 1900 - 1991



Chilean Earthquake Fatalities, 1900 - 1988

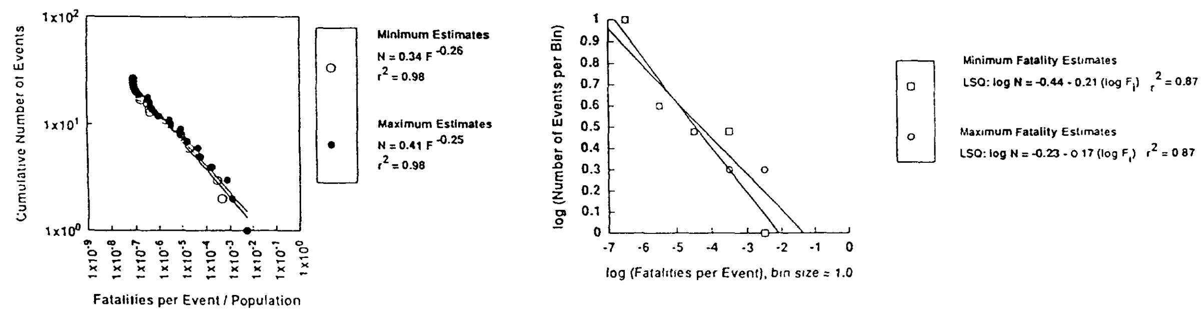
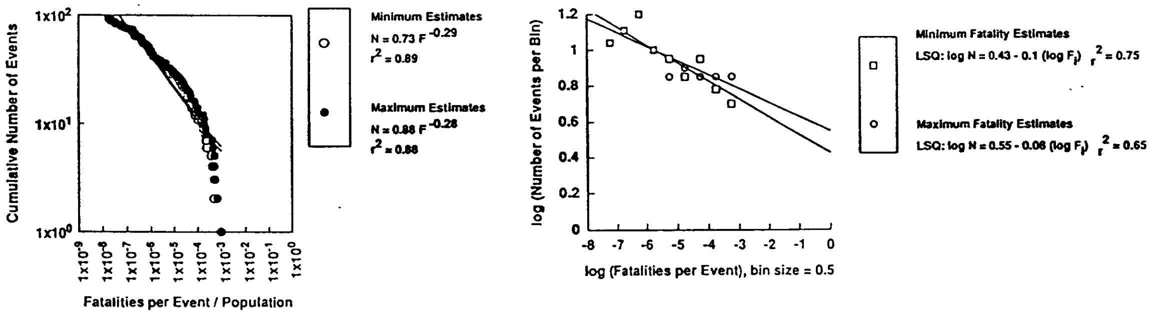


Figure 1 (con't)

Iranian Earthquake Fatalities 1900 - 1990



Turkish Earthquake Fatalities, 1900 - 1991

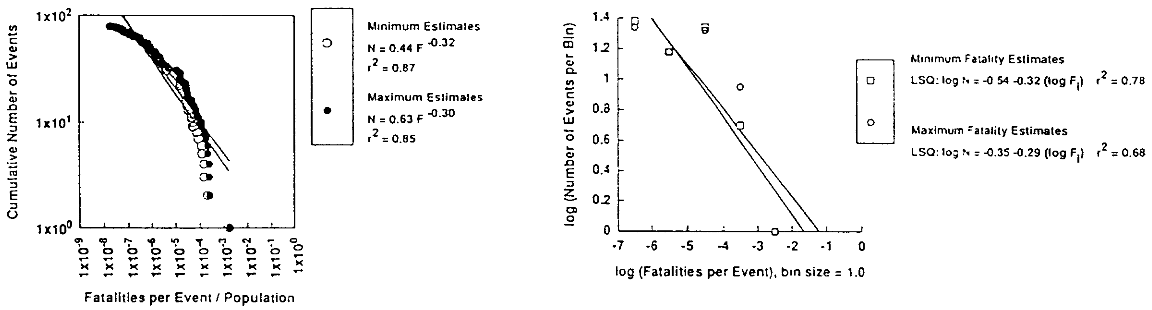
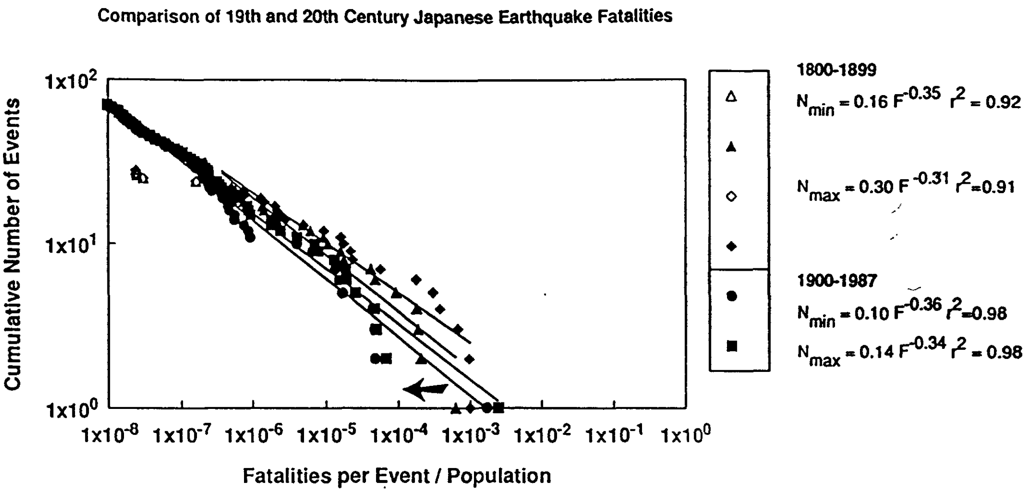


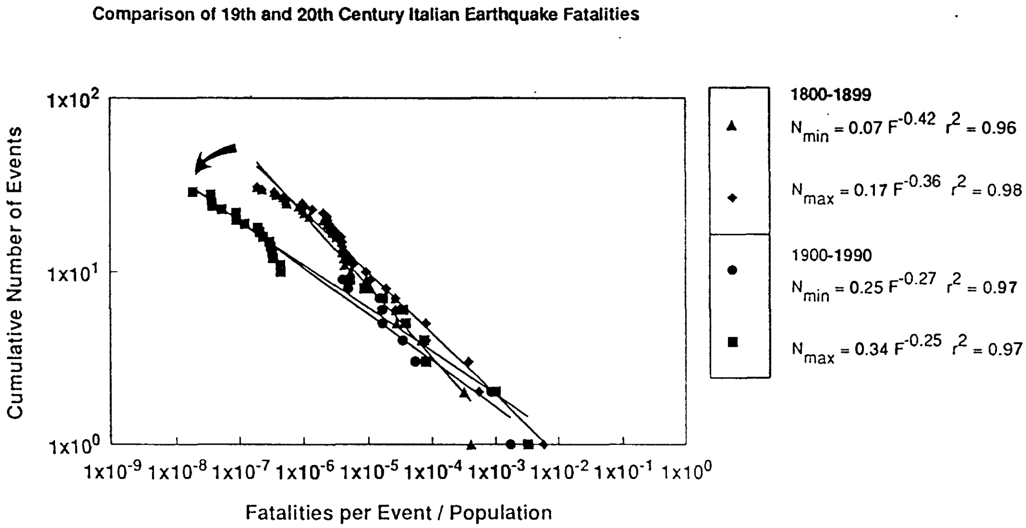
Figure 1 (con't)

Figure 2.

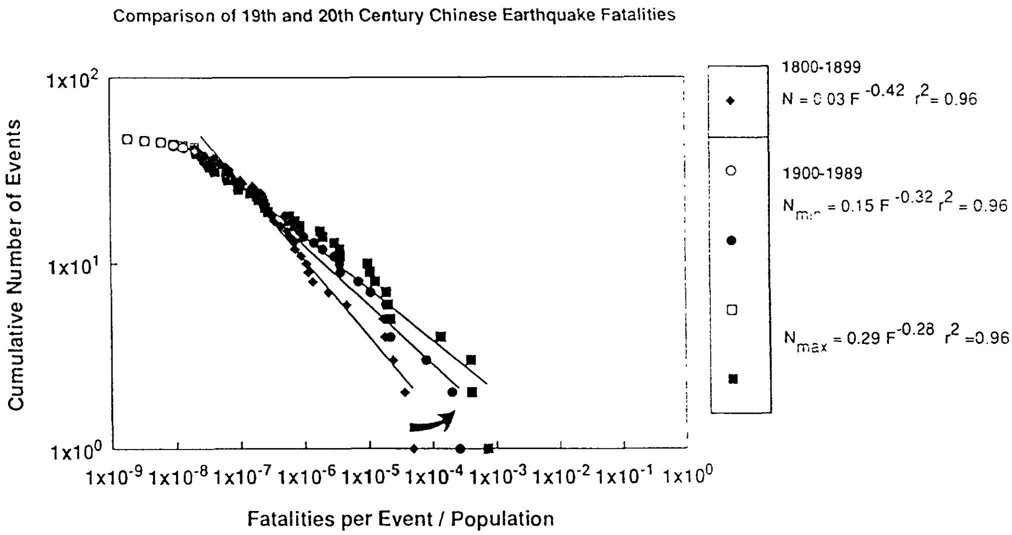
<u>Comparison of 19th and 20th Century Earthquake Fatalities.</u> Earthquake fatality-frequency distributions for 19th and 20th century Japan, Italy, and China demonstrate how losses have changed as a function of time. All data have been corrected for differences in population. 19th century maximum and minimum fatality estimates are shown as diamonds and triangles, 20th century maximum and minimum fatlity estimates are shown as squares and circles. Events with fatalities less than the threshold of completeness are shown as open symbols. While the slope of the Japanese fatality-frequency curve has remained constant with time, the number of fatalities associated with the largest disasters has decreased during the 20th century. In contrast to the 19th century data, both 20th century minimum and maximum fatality estimates show no sign of incomplete reporting at low fatality levels (i.e there is no roll-over for low fatalities). Note that the 20th century minimum and maximum fatality estimates (solid triangles) are also in better agreement than 19th century estimates (solid circles and squares). In Italy, there have been fewer small fatality events during the 20th century, hence a flatter slope and smaller D value. The number of high fatality Italian disasters (>5 10^{-6}), however, has remained approximately constant during these two periods. For China, 19th century minimum and maximum fatality estimates are essentially identical, and only one set is shown for comparison (solid diamonds). Overall, there were more large fatality events during the 20th century in China, and the slope of the fatality-frequency curve decreased from 0.42 to 0.28-0.32.



Comparison of 19th and 20th Century Japanese Earthquake Fatalities
Cumulative Number of Events
1x10^2
1x10^1
1x10^0
1x10^-8 1x10^-7 1x10^-6 1x10^-5 1x10^-4 1x10^-3 1x10^-2 1x10^-1 1x10^0
Fatalities per Event / Population
1800-1899
N_min = 0.16 F^-0.35 r^2 = 0.92
N_max = 0.30 F^-0.31 r^2 = 0.91
1900-1987
N_min = 0.10 F^-0.36 r^2 = 0.98
N_max = 0.14 F^-0.34 r^2 = 0.98



Comparison of 19th and 20th Century Italian Earthquake Fatalities
Cumulative Number of Events
1x10^2
1x10^1
1x10^0
1x10^-9 1x10^-8 1x10^-7 1x10^-6 1x10^-5 1x10^-4 1x10^-3 1x10^-2 1x10^-1 1x10^0
Fatalities per Event / Population
1800-1899
N_min = 0.07 F^-0.42 r^2 = 0.96
N_max = 0.17 F^-0.36 r^2 = 0.98
1900-1990
N_min = 0.25 F^-0.27 r^2 = 0.97
N_max = 0.34 F^-0.25 r^2 = 0.97



Comparison of 19th and 20th Century Chinese Earthquake Fatalities
Cumulative Number of Events
1x10^2
1x10^1
1x10^0
1x10^-9 1x10^-8 1x10^-7 1x10^-6 1x10^-5 1x10^-4 1x10^-3 1x10^-2 1x10^-1 1x10^0
Fatalities per Event / Population
1800-1899
N = 0.03 F^-0.42 r^2 = 0.96
1900-1989
N_min = 0.15 F^-0.32 r^2 = 0.96
N_max = 0.29 F^-0.28 r^2 = 0.96

Figure 2

Figure 3.

Comparison of Natural Disaster Fatalities in the United States, 1900-1990.

Cumulative frequency-size distributions for annualized earthquake (triangle), flood (box), hurricane (circle), and tornado (diamond) fatalities. Solid symbols are those data above the threshold of complete reporting, and are used for the cumulative least-squares fits shown. Open symbols are those data below the threshold of complete reporting. These data group into two families that demonstrate the linear behavior over 2 to 3 orders of magnitude in loss,. Earthquakes and hurricanes are low frequency, high maximum fatality disasters with shallow (D = 0.4-0.6) slopes; floods and tornadoes are high frequency, relatively low maximum fatality events and exhibit steeper (D = 1.4) slopes. The crossover point where fatalities from individual hurricanes dominate fatalities from individual floods and tornadoes occurs at approximately 100 fatalities per event.

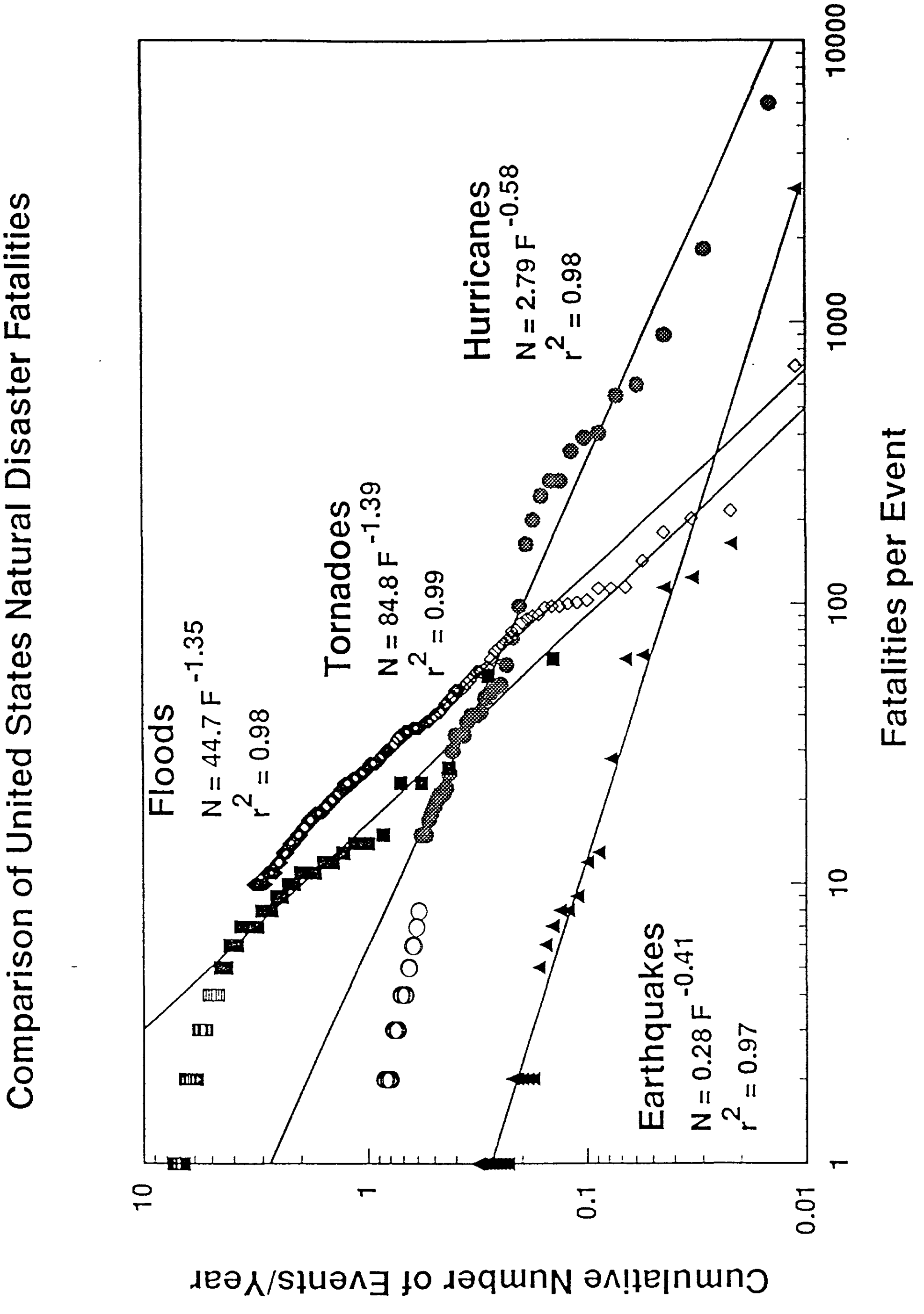

Comparison of United States Natural Disaster Fatalities
Floods
N = 44.7 F -1.35
r 2 = 0.98
Tornadoes
N = 84.8 F -1.39
r 2 = 0.99
Hurricanes
N = 2.79 F -0.58
r 2 = 0.98
Earthquakes
N = 0.28 F -0.41
r 2 = 0.97
Fatalities per Event
Cumulative Number of Events/Year
10
1
0.1
0.01
1
10
100
1000
10000

Figure 3

References

Ambraseys, N.N. and Melville, C.P., A History of Persian Earthquakes, Cambridge Univ. Press, Cambridge, 219 pp (1982)

Barton, C.C., Nishenko, S.P., Tebbens, S.F., and Loeb, W.A., Santa Fe Institute Workshop on Natural Hazards Reduction, Jan 5-9, 1994, Santa Fe, New Mexico

Bilham, R., *Nature*, **336**, 625-626.(1988)

Coburn, A.W., Pomonis, A., and Sakai, S., in Jones, N., et al., eds., International Workshop on Earthquake Injury Epidemiology for Mitigation and Response, John Hopkins Univ., 107-132. (1989)

Dunbar, P.K., P.A. Lockridge, and L.S. Whiteside, 1992, Catalog of Significant Earthquakes 2150BC - 1991AD, US Department of Commerce, Boulder CO, 320 pp.

Grazulis, T., Significant Tornadoes, 1680-1991, Environmental Films, St. Johnsbury, VT, 1326 pp (1993)

Gutenberg, B., and Richter, C.F., *Bull. Seismol. Soc. Amer.*, **34**, 185-188 (1944)

Hebert, P.L., and Case, R.A., *NOAA Tech. Memo. NWS NHC 31*, 33pp. (1990)

Ishimoto, M., and K. Iida, *Bull. Earth. Res. Inst., Tokyo Univ.*, **17**, 443-478. (1938)

Kagan, Y.Y. and Knopoff, L., *Geophys. J. R. Astr. Soc.*, **62**, 303-320 (1980)

Knopoff, L., and Kagan, Y., *Jour. Geophys. Res.*, **82**, 5647-5657 (1977).

Mandelbrot, B., The Fractal Geometry of Nature, W.H. Freeman and Company, New York, 468 pp. (1983)

McEvedy, C. and Jones, R., 1979, Atlas of World Population History, Facts on File, New York, 368 pp.

Pacheco, J.F., Scholz, C.H., and Sykes, L.R., *Nature*, **355**, 71-73 (1992)

Richardson, L. F., Statistics of Deadly Quarrels, Boxwood Press, Pittsburgh, PA, 374 pp. (1960)

Richter, C.F., 1958, Elementary Seismology, W.H. Freeman and Co., New York, 768 pp.

Smalley, R.F., Jr., Chatelain, J.-L., Turcotte, D.L., and Prevot, P., *Bull. Seismol. Soc. Am.*, **77**, 1368-1381 (1987)

Snugg, A.L., and Carrodus, R.L., *US Dept. Commerce, ESSA Tech Memo WBTM SR-42*, 55 pp. (1969)

Stover, C.W.and Coffman, J.L., *U.S. Geol. Survey Prof. Paper 1527*, 418 pp. (1993).

Turcotte, D.L., *Tectonophysics*, **167**, 171-177 (1989)

Turcotte, D.L., and Greene, L., 1993, A scale-invariant approach to flood-frequency analysis, *Stochastic Hydrol. Hydraul.*, **7**, 33-40.

United Nations Department of International Economics and Social Affairs, 1987, The Prospects of World Urbanization, Population Studies No. 101, United Nations, New York, 268 pp.

United States Army Corps of Engineers, Annual Flood Damage Report to Congress (1986-1993)