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A Tricky, High-Stakes Game

> *Earthquake risk is a game of chance of which we do not know all the rules. It is true that we gamble against our will, but this doesn't make it less of a game.*
>
> Lomnitz (1989)[1]

1.1 Where We Are Today

Natural hazards are the price we pay for living on an active planet. The tectonic plate subduction producing Japan's rugged Tohoku coast gives rise to earthquakes and tsunamis. Florida's warm sunny weather results from the processes in the ocean and atmosphere that cause hurricanes. The volcanoes that produced Hawaii's spectacular islands sometimes threaten people. Rivers that provide the water for the farms that feed us sometimes flood.

Humans have to live with natural hazards. We describe this challenge in terms of *hazards*, the natural occurrence of earthquakes or other phenomena, and the *risks*, or dangers they pose to lives and property. In this formulation, the risk is the product of hazard and *vulnerability*. We want to *assess* the hazards – estimate how significant they are – and develop methods to *mitigate* or reduce the resulting losses.

Hazards are geological facts that are not under human control. All we can do is try to assess them as best we can. In contrast, risks are affected by human actions that increase or decrease vulnerability, such as where people live and

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[1] Lomnitz, 1989. Reproduced with permission of the Seismological Society of America.

Playing against Nature: Integrating Science and Economics to Mitigate Natural Hazards in an Uncertain World, First Edition. Seth Stein and Jerome Stein.

Companion Website: www.wiley.com/go/stein/nature

how they build. We increase vulnerability by building in hazardous areas, and decrease it by making buildings more hazard resistant. Areas with high hazard can have low risk because few people live there. Areas of modest hazard can have high risk due to large population and poor construction. A disaster occurs when – owing to high vulnerability – a natural event has major consequences for society.

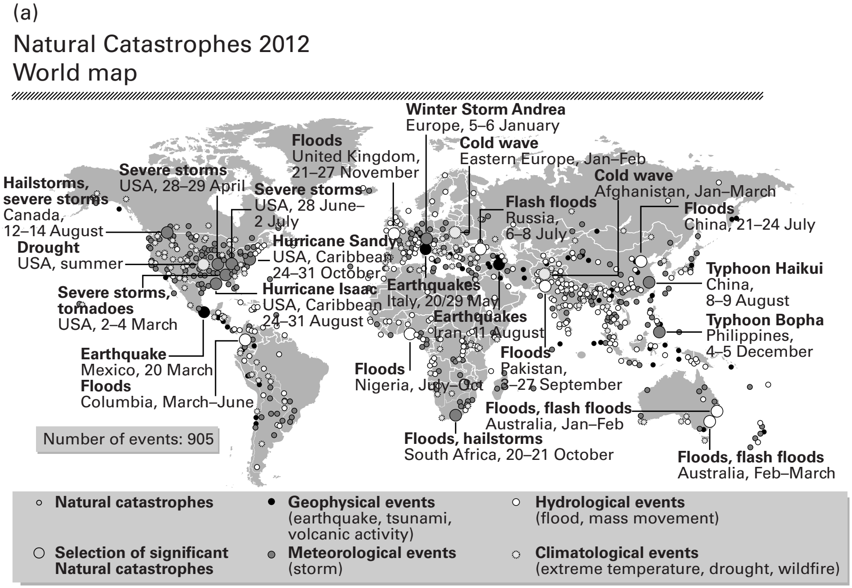
The harm from natural disasters is enormous. On average, about 100,000 people per year are killed by natural disasters, with some disasters – such as the 2004 Indian Ocean tsunami – causing many more deaths. Although the actual numbers of deaths in many events, such as the 2010 Haiti earthquake, are poorly known, they are very large.

Economic impacts are even harder to quantify, and various measures are used to try to do so. Disasters cause *losses*, which are the total negative economic impact. These include direct losses due to destruction of physical assets such as buildings, farmland, forests, etc., and indirect losses that result from the direct losses. Because losses are hard to determine, what is reported is often the *cost*, which refers to payouts by insurers (called *insured losses*) or governments to reimburse some of the losses. Thus the reported cost does not reflect the losses to people who do not receive such payments. Losses due to natural disasters in 2012 worldwide are estimated as exceeding $170 billion (Figure 1.1). Damages within the US alone cost insurers about $58 billion. Disaster losses are on an increasing trend, because more people live in hazardous areas. For example, the population of hurricane-prone Florida has grown from 3 million in 1950 to 19 million today.

Society can thus be viewed as playing a high-stakes game of chance against nature. We know that we will lose, in two ways. If disaster strikes, direct and indirect losses result. In addition, the resources used for measures that we hope will mitigate the hazards and thus reduce losses in the future are also lost to society, because they cannot be used for other purposes.

Thus the challenge is deciding *how much mitigation is enough*. More mitigation can reduce losses in possible future disasters, at increased cost. To take it to the extreme, too much mitigation could cost more than the problem we want to mitigate. On the other side, less mitigation reduces costs, but can increase potential losses. Hence too little mitigation can cause losses that it would make more sense to avoid. We want to hit a “sweet spot” – a sensible balance. This means being careful, thoughtful gamblers.

We want to help society to come up with strategies to minimize the combined losses from disasters themselves and from efforts to mitigate them. This involves developing methods to better assess future hazards and mitigate their effects. Because both of these are difficult, our record is mixed. Sometimes we do well, and sometimes not.


(a)

Natural Catastrophes 2012
World map

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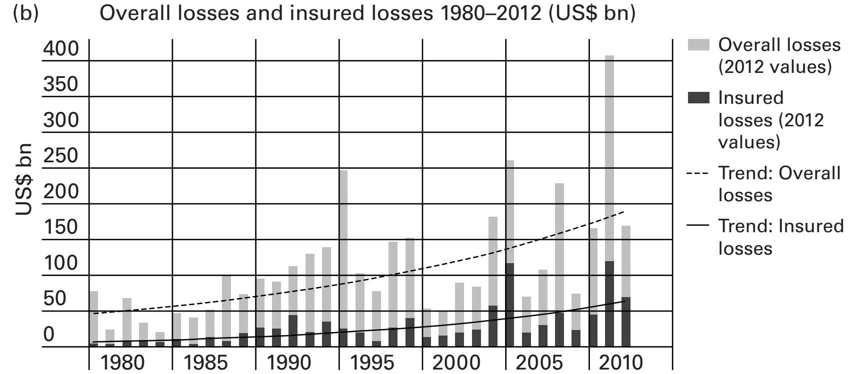

(b) Overall losses and insured losses 1980–2012 (US$ bn)

Figure 1.1 (a) Natural disasters in 2012. (Munich Re, 2013a. Reproduced with permission from Munich Reinsurance Company AG.) (b) Overall and insured losses since 1980 due to natural disasters. (Munich Re, 2013b. Reproduced with permission from Munich Reinsurance Company AG.)

On the hazard assessment side, the problem is that we lack full information. Geoscience tells us a lot about the natural processes that cause hazards, but not everything. We are learning more by using new ideas and methods that generate new data, but still we have a long way to go. For example, meteorologists are steadily improving forecasts of the tracks of hurricanes, but forecasting their strength is harder. We know a reasonable amount about why and where earthquakes will happen, have some idea about how big they will be, but much less about when they will happen. We thus need to decide what to do given these uncertainties.

This situation is like playing the card game of blackjack, also called “21.” Unlike most other card games, blackjack is considered more a game of skill than a game of chance. As mathematician Edward Thorp showed, despite the randomness in the cards drawn, skilled players can on average win by a small fraction using a strategy based on the history of the cards that have already been played. MIT student blackjack teams using these winning strategies formed the basis of the fictionalized 2008 film “21.” A key aspect of the game is that players see only some of the casino dealer’s cards. Dealing with natural hazards has the further complication that we do not fully understand the rules of the game, and are trying to figure them out while playing it.

On the mitigation side, methods are getting better and cheaper. Still, choosing strategies is constrained because society has finite resources. There’s no free lunch – resources used for mitigating hazards are not available for other purposes. Funds spent by hospitals to strengthen buildings to resist earthquake shaking cannot be used to treat patients. Money spent putting more steel in school buildings does not get used to hire teachers. Spending on seawalls and levees comes at the expense of other needs. Choosing priorities is always hard, but it is especially difficult when dealing with natural hazards, because of our limited ability to forecast the future.

When natural hazard planning works well, hazards are successfully assessed and mitigated, and damage is minor. Conversely, if a hazard is inadequately mitigated, sometimes because it was not assessed adequately, disasters happen. Disasters thus regularly remind us of how hard it is to assess natural hazards and make effective mitigation policies. The earth is complicated, and often surprises or outsmarts us. Thus although hindsight is always easier than foresight, examining what went wrong points out what we should try to do better.

The effects of Hurricane Katrina, which struck the US Gulf coast in August 2005, had been anticipated. Since 1722, the region had been stuck by 45 hurricanes. As a result, the hazard due to both high winds and flooding of low-lying areas including much of New Orleans was recognized. Mitigation measures including levees and flood walls were in place, but recognized to be inadequate to withstand a major hurricane. It was also recognized that many New Orleans residents who did not have cars would likely not be able to evacuate unless procedures were established. Thus despite accurate and timely warning by the National Weather Service as the storm approached, about 1,800 people died. The total cost of the damage caused by the disaster is estimated at $108 billion, making Katrina the costliest hurricane in US history.

Japan has a major earthquake problem, illustrated by the 1923 Kanto earthquake that caused more than 100,000 deaths in the Tokyo region. Hence

Figure 1.2 More than a dozen ships were washed inland by the Tohoku tsunami in Kesennuma City, Miyagi Prefecture. The fishing trawler Kyotoku-maru came to rest on a giant debris pile on one of the main roads to City Hall. (Courtesy of Hermann M. Fritz.)

scientists have studied the Japanese subduction zone extensively for many years using sophisticated equipment and methods, and engineers have used the results to develop expensive mitigation measures. But the great earthquake that struck Japan's Tohoku coast on March 11, 2011 was much larger than predicted even by sophisticated hazard models, and so caused a tsunami that overtopped giant seawalls (Figure 1.2). Although some of the mitigation measures significantly reduced losses of life and property, the earthquake caused more than 15,000 deaths and damage costs of $210 billion.

After the Tohoku earthquake the immediate question that arose was if and how coastal defenses should be rebuilt: the defences had fared poorly and building mitigation measures to withstand tsunamis as large as the one on March 2011 is too expensive. A similar issue soon arose along the Nankai Trough to the south, where new estimates warning of giant tsunamis 2–5 times higher than in previous models (Figure 1.3) raised the question of what to do, given that the timescale on which such events may occur is unknown and likely to be of order 1000 years. In one commentator's words, "the question is whether the bureaucratic instinct to avoid any risk of future criticism by presenting the worst case scenario is really helpful . . . What can (or should be) done? Thirty meter seawalls do not seem to be the answer."

The policy question, in the words of Japanese economist H. Hori, is:

> What should we do in face of uncertainty? Some say we should spend our resources on present problems instead of wasting them on things whose results

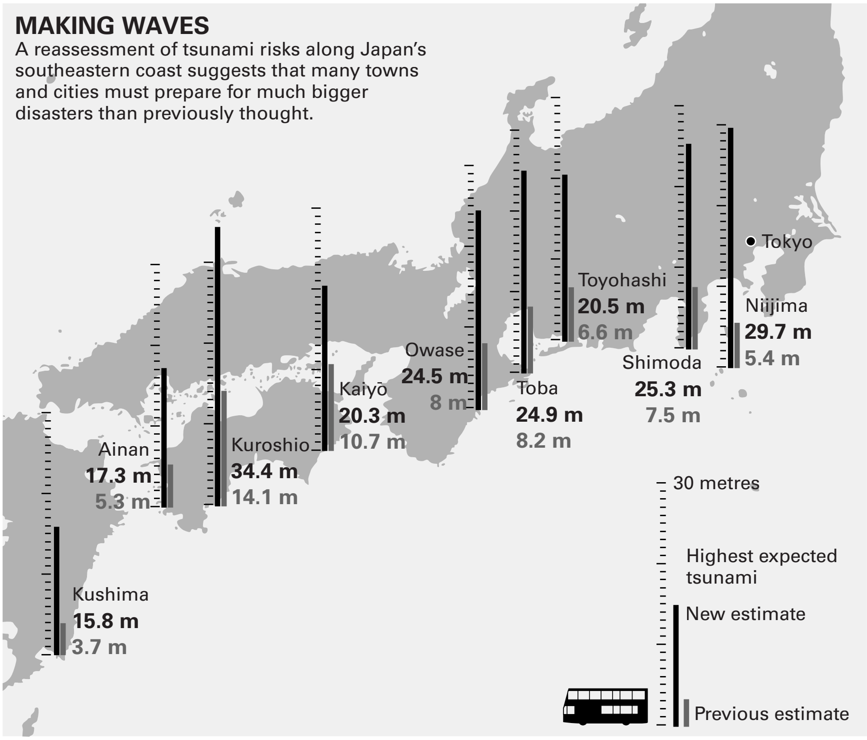


Figure 1.3 Comparison of earlier and revised estimates of possible tsunami heights from a giant Nankai Trough earthquake (Cyranoski, 2012a. Reproduced with permission from *Nature*.)

are uncertain. Others say we should prepare for future unknown disasters precisely because they are uncertain.

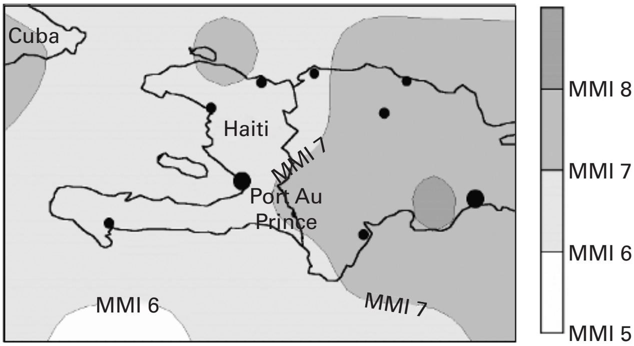
1.2 What We Need to Do Better

The Tohoku earthquake was the "perfect storm," illustrating the limits of both hazard assessment and mitigation, and bringing out two challenges that are the heart of this book. We discuss them using earthquakes as examples, but they arise for all natural hazards.

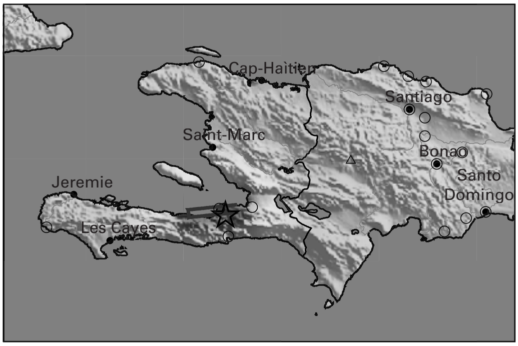
The first challenge is improving our ability to assess future hazards. It was already becoming clear that the methods currently used for earthquakes often fail. Tohoku was not unusual in this regard – highly destructive earthquakes, like the one in Wenchuan, China, in 2008, often occur in areas predicted by hazard maps to be relatively safe.

Another example is the devastating magnitude 7.1 earthquake that struck Haiti in 2010. As shown in Figure 1.4, the earthquake occurred where a hazard map made in 2001 predicted that the maximum ground shaking expected to

(a) 2001 hazard map



(b) 2010 earthquake shaking



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	***<0.17***	***0.17–1.4***	***1.4–3.9***	***3.9–9.2***	***9.2–18***	18–34	34–65	65–124	>124
PEAK VEL.(cm/s)	<0.1	0.1–1.1	1.1–3.4	3.4–8.1	***8.1–16***	***16–31***	***31–60***	***60–116***	***>116***
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1.4 (a) Seismic hazard map for Haiti produced prior to the 2010 earthquake showing maximum shaking expected to have a 10% chance of being exceeded once in 50 years, or on average once about every 500 years. (b) Map of the shaking in the 2010 earthquake. (Stein et al., 2012. Reproduced with permission of Elsevier B.V.) See also color plate 1.4.

have a 10% chance of being exceeded once in 50 years, or on average once about every 500 (= 50/0.1) years, was intensity VI. Intensity is a descriptive scale of shaking, usually described by roman numerals, which we will discuss in Chapter 11. Intensity VI corresponds to strong shaking and light damage. Shaking is more precisely described by the acceleration of the ground, often as a fraction of "g," the acceleration of gravity ($9.8\,m/s^2$). Within ten years, much stronger shaking than expected – intensity IX, with violent shaking and heavy damage – occurred. Great loss of life also resulted, although estimates of the actual numbers of deaths vary widely.

The fundamental problem is that there is much we still do not know about where and when earthquakes are going to happen. A great deal of effort is being put into learning more – a major research task – but major advances will probably come slowly, given how complicated the earthquake process is and how much we do not yet understand. We keep learning the hard way to maintain humility before the complexity of nature. In particular, we are regularly reminded that where and when large earthquakes happen is more variable than we expected. Given the short geological history we have, it is not clear how to tell how often the biggest, rarest, and potentially most destructive earthquakes like the 2011 Tohoku one will happen. There are things we may never figure out, notably how to predict when big earthquakes will happen on any time scale shorter than decades.

Given this situation and the limitations of what we know, how can we assess hazards better today? The traditional approach to this problem is to make new hazard maps after large earthquakes occur in places where the map previously showed little hazard (Figure 1.5). This is an example of what statisticians call "Texas sharpshooting," because it is like first shooting at the barn and then drawing a target around the bullet holes.

To make things worse, sometimes the new map does not predict future earthquake shaking well and soon requires further updating. In Italy, for example, the national earthquake hazard map, which is supposed to forecast hazards over the next 500 years, has required remaking every few years (Figure 1.6).

Earthquake hazard mapping has become an accepted and widely used tool to help make major decisions. The problem is that although it seemed like a sensible approach, governments started using it enthusiastically before any careful assessment of the uncertainties in these maps or objective testing of how well they predict future earthquake shaking had been undertaken. Now that major problems are surfacing, we need to do better. One important task is to assess the uncertainties in hazard map predictions and communicate them to potential users, so that they can decide how much credence to place in the maps, and thus make them more useful. We also need to develop methods to

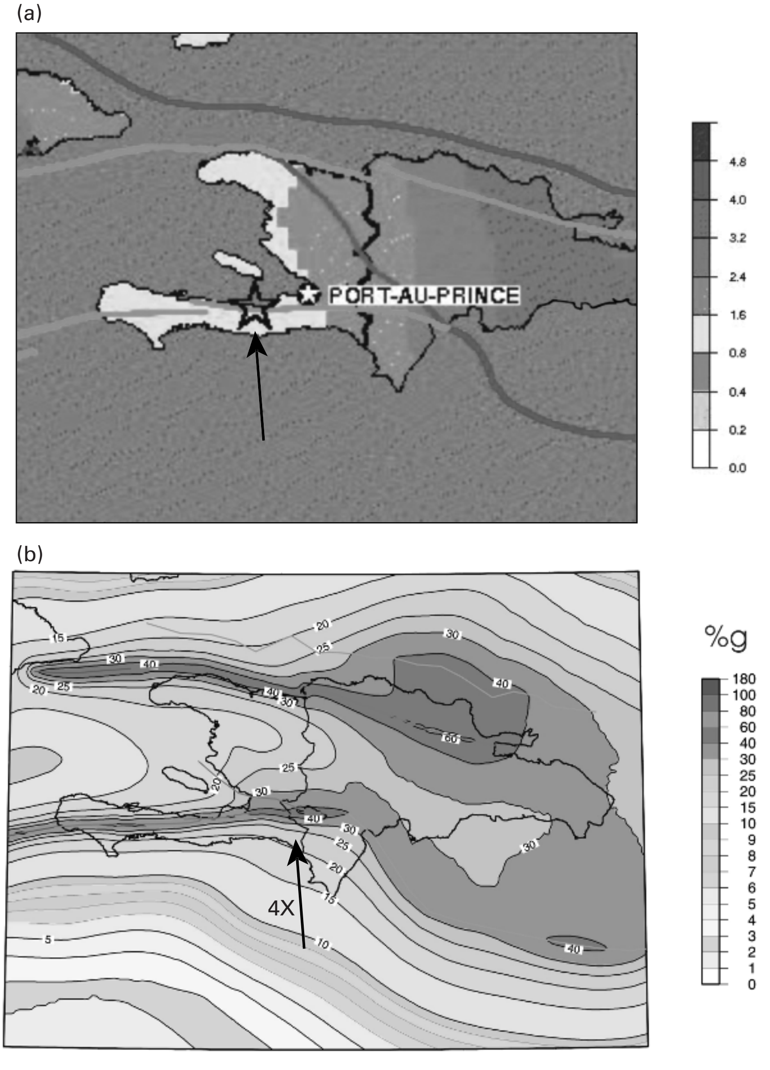


Figure 1.5 Comparison of seismic hazard maps for Haiti made before (a) and shortly after (b) the 2010 earthquake. The newer map shows a factor of four higher hazard on the fault that had recently broken in the earthquake. (Stein et al., 2012. Reproduced with permission of Elsevier B.V.) See also color plate 1.5.

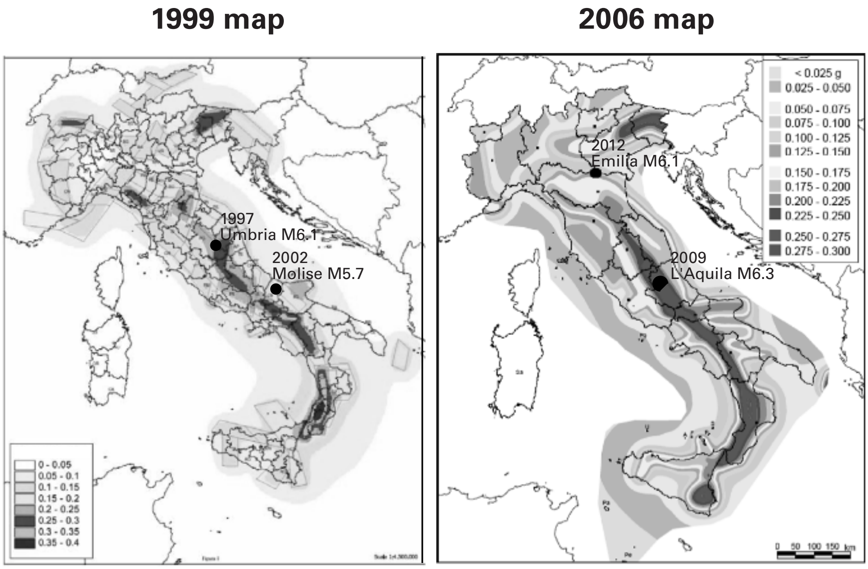


Figure 1.6 Comparison of successive Italian hazard maps, which forecast some earthquake locations well and others poorly. The 1999 map was updated after the missed 2002 Molise quake and the 2006 map will presumably be updated because it missed the 2012 Emilia earthquake. (Stein et al., 2013. Reproduced with permission of Elsevier B.V.) See also color plate 1.6.

objectively test these maps, to assess how well maps made with different methods describe what actually happens, and to improve future maps.

The second challenge is learning how to use what we know about hazards to develop mitigation policies. We need to develop sensible approaches to evaluate alternative strategies. In addition to science, this process involves complicated economic, societal, and political factors.

Typically, more extensive mitigation measures cost more, but are expected to further reduce losses in future events. For example, after Hurricane Katrina breached coastal defenses in 2005 and flooded much of New Orleans, choosing to what level these defenses should be rebuilt became an issue. Should they be rebuilt to withstand only a similar hurricane, or stronger ones? Similarly, given the damage to New York City by the storm surge from Hurricane Sandy in 2012, options under consideration range from doing little, through intermediate strategies such as providing doors to keep water out of vulnerable tunnels, to building up coastlines or installing barriers to keep the storm surge out of rivers.

Although our first instinct might be to protect ourselves as well as possible, reality sets in quickly, because resources used for hazard mitigation are not available for other societal needs. For example, does it make sense to spend billions of dollars making buildings in the central US as earthquake-resistant as in California, or would these funds do more good if used otherwise? Should all hospitals in California be made earthquake-resistant, or would it be wiser to use these resources caring for millions of people without health insurance? As a doctor mused, "we could treat a lot of people for $50 billion." In the same spirit, a European Union official charged with hazard mitigation pointed out that plans for higher levees to reduce river flood damage compete for funds with plans to improve kindergartens.

These difficult issues are discussed in an editorial "Quake work needs limits and balance" in the *New Zealand Herald* after the 2011 Christchurch earthquake that caused 158 deaths and considerable damage. In the newspaper's view,

> Mandatory quake-proofing of all New Zealand buildings would, however, be hugely expensive. Proponents say this would be worthwhile if even one life is saved, let alone the hundreds lost in Christchurch. But the need for preparedness must be balanced so as not to be out of all proportion to the degree of risk. In the aftermath of such an event, there can be a heightened sense of alarm, which triggers a desire to do whatever is required to prevent a repeat, no matter how extreme or costly. A lesson of Christchurch Cathedral is that whatever the precautions, a set of circumstances can render them ineffective. On balance, therefore, it seems reasonable to retain the status quo on older buildings, and insist on earthquake strengthening only when they are being modified. It would, however, be very useful if homeowners were advised individually how earthquake-resistant their houses were. They could then decide whether to strengthen or sit tight. It would also be helpful, as the United Future leader, Peter Dunne, suggests, if earthquake-prone buildings were publicly listed. People should know the status of buildings they live in, work in or use often.

Unfortunately – as the Tohoku sea walls showed – mitigation policies are often developed without careful consideration of their benefits and costs. Communities are often unclear about what they are buying and how much they are paying. Because they are playing against nature without a clear strategy, it is not surprising that they sometimes do badly. Doing better requires selecting strategies to best use their limited resources. This is not easy, because the benefits of various strategies cannot be estimated precisely, given our limited ability to estimate the occurrence and effects of future events. However, even simple estimates of the costs and benefits of different strategies often show that some make much more sense than others.

Table 1.1 US deaths from various causes in 1996

Cause of death	*No. of deaths*
Heart attack	733,834
Cancer	544,278
Motor vehicles	43,300
AIDS	32,655
Suicide	30,862
Liver disease/Cirrhosis	25,135
Homicide	20,738
Falls	14,100
Poison (accidents)	10,400
Drowning	3,900
Fire	3,200
Bicycle accidents	695
Severe weather	514
Animals	191
In-line skating	25
Football	18
Skateboards	10

Stein and Wysession, 2003. Reproduced with permission of John Wiley & Sons.

A key point in allocating resources is that natural hazards are only one of the many problems society faces. Comparing the numbers of deaths per year in the US from various causes (Table 1.1) brings out this point.

US earthquakes have caused an average of about twenty deaths per year since 1812. The precise number depends mostly on how many died in the 1906 earthquake that destroyed much of San Francisco, which is not known well. This analysis starts after 1812 because it is not known if anyone was killed in that year's big (about magnitude 7) New Madrid earthquakes in the Midwest.

These numbers vary from year to year and have uncertainties because of the way they are reported, but give useful insights into risks. For example, because there are about 300 million people in the US, the odds of being killed by an animal are about 200/300,000,000 or 1 in 1.5 million.

As you would expect, these numbers show that earthquakes are not a major cause of deaths in the US Although earthquakes are dramatic and can cause major problems, many more deaths result from causes like drowning or fires. Severe weather is about 25 times more dangerous than earthquakes. Earthquakes rank at the level of in-line skating or football, and severe weather is

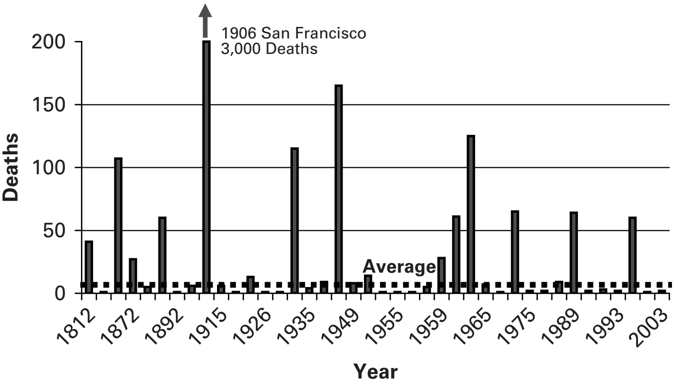


Figure 1.7 Annual deaths in the United States from earthquakes, 1812–2003.

at the level of bicycle accidents. Hence during the 1950s and 1960s seismologist Charles Richter was an early advocate for earthquake-resistant construction in California while pointing out, "I don't know why people in California or anywhere worry so much about earthquakes. They are such a small hazard compared to things like traffic."

This relatively low earthquake danger arises because most US earthquakes do little harm. Even those felt in populated areas are commonly more of a nuisance than a catastrophe. In most years, no one is killed by an earthquake (Figure 1.7). About every 40 years an earthquake kills more than 100 people, and the 1906 San Francisco earthquake is thought to have killed about 3000 people. This pattern arises because big earthquakes are much less common than small ones, and large numbers of deaths occur when a rare big earthquake takes place where many people live, such as happened with the San Francisco earthquake. Other natural disasters like hurricanes behave the same way, with rare large events doing the most damage. Because people remember dramatic events and do not think about how rare they are, it is easy to forget that more common hazards are much more dangerous.

Earthquakes can also cause major property damage. Although the 1994 Northridge earthquake was not that big – magnitude 6.7 – it happened under the heavily populated Los Angeles metropolitan area, and caused 58 deaths and $20 billion in property damage. Still, this damage is only equivalent to about 10% of the US annual loss due to automobile accidents.

Earthquakes are only a secondary hazard in the US because large earthquakes are relatively rare in heavily populated areas, and buildings in the most active areas such as California are built to reduce earthquake damage. Earthquakes are a bigger problem in some other countries where many people live near plate boundaries. Although the statistics are sometimes imprecise, major earthquakes can be very destructive, as the Tohoku earthquake shows. The highest property losses occur in developed nations where more property is at risk, whereas fatalities are highest in developing nations.

Over the past century, earthquakes worldwide have caused about 11,500 deaths per year. This number is increasing over time as populations at risk grow, and averaged about 20,000 deaths per year from 2000–2009. Still, it is a much lower figure than the number of deaths caused by diseases. For example, AIDS and malaria cause about 1.8 million and 655,000 deaths per year, respectively.

Similarly, other natural hazards cause infrequent, but occasionally major, disasters involving higher numbers of fatalities and greater damage. As a result, society needs to think carefully about what to do. We want to mitigate natural hazards, but not focus on them to the extent that we unduly divert resources from other needs.

1.3 How Can We Do Better?

A frequent limitation of current approaches is that of treating the relevant geoscience, engineering, economics, and policy formulation separately. Geoscientists generally focus on using science to assess hazards; engineers and planners focus on mitigation approaches; and economists focus on costs and benefits. Each group often focuses on its aspect of the problem, does not fully appreciate how the others think, what they know, and what they do not.

This situation often leads to policies that make little scientific or economic sense. Hazard assessments often underestimate the limits of scientific knowledge. Mitigation policies are often developed without considering their costs and benefits. The net result is that communities often overprepare for some hazards and underprepare for others.

For example, since 1978 the Japanese government has followed a law called the Large-Scale Earthquake Countermeasures Act that requires operating a monitoring system to detect precursors – i.e., changes in properties of the earth – which are supposed to allow a large earthquake along part of the Japan Trench (Figure 1.3) to be predicted. In theory what should happen is that a panel of five geophysicists will review the data and determine that a large earthquake is imminent, the director of the Japan Meterological Agency will inform the prime minister, and the cabinet will then declare a state of emergency, which will stop almost all activity in the nearby area. The problem is that, as we will discuss, such precursors have never been reliably observed, so at present there is no way to accurately predict earthquakes.

Another good example is the way the US government treats different hazards. It wants buildings built for the maximum wind speed expected on average once every 50 years, the typical life of a building, which there's a 2% (1/50) chance of having in any one year. However, it tells communities to plan for the maximum flooding expected on average once every 100 years, or that there's a 1% chance of having in any one year. It wants even higher standards for earthquakes. California should plan for the maximum shaking expected on average once in 500 years, and Midwestern states for the maximum shaking expected on average once in 2500 years. This pattern is the opposite of what one might expect, because wind and flooding – often due to the same storm – cause much more damage than earthquakes. None of these time periods come from careful analysis, and it is not clear which if any should be different. It might better to prepare a 500-year plan for both floods and earthquakes. We will see that using 2500 years is likely to overprepare for earthquakes. Conversely, it seems that in many areas planning only for the 100-year flood gives too low a level of protection, so it would be wise to prepare for larger floods.

This book explores ways of taking a broader view that can help in developing more sensible policies. Policy-making can be viewed as the intersection of the different approaches (Figure 1.8).

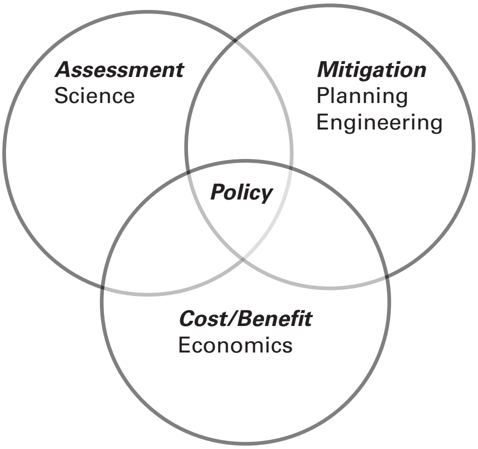


Figure 1.8 Schematic illustrating how formulating hazard policy involves integrating assessment, mitigation, and economics.

One attempt to take a broad view came from the Copenhagen Consensus, a group that evaluated ways to spend an additional $75 billion worldwide (about 15% of global aid spending) to best improve public health. Their top priorities came out as:

1. Nutrition supplements
2. Malaria treatment
3. Childhood immunization
4. Deworming school children
5. Tuberculosis treatment
6. Research to enhance crop yields
7. Natural hazard warning systems
8. Improving surgery
9. Hepatitis B immunization
10. Low cost drugs to prevent heart attacks

Hence in their view natural hazards emerge as a major, but not absolute top, priority.

More effective natural hazards policy can be developed both by advancing each of the relevant disciplines and integrating their knowledge and methods. Fortunately there is an increasing awareness of the need for both, especially among young researchers who would like to do a better job of mitigating hazards.

This book is an overview of some aspects of this challenge. It is written assuming readers have diverse backgrounds in geoscience, engineering, economics, and policy studies. We use the Tohoku earthquake to illustrate some key issues, and then introduce some basic concepts to help readers appreciate the value of the other disciplines and their interrelations, and develop the background to explore more advanced treatments of these topics. We explore aspects of what we know, what we do not know, what mitigation approaches are available, and how we can choose between them. Although we primarily use earthquakes and tsunamis as examples, most of the discussion in this book applies to other natural hazards.

Beyond the scientific and economic issues, the mitigation policies a community chooses reflect sociocultural factors. Because societies overrate some risks and underrate others, what they will spend to mitigate them often has little relation to the actual risk. The policies chosen also reflect interest groups and political influence. For example, the billions of dollars spent on seawalls in Japan is a cost to the nation as a whole, but a benefit to politically connected contractors. In North Carolina, political policy prohibits state coastal planning officials considering the possibility that the warming climate will accelerate the rate of sea level rise, as anticipated from melting ice caps. These factors are beyond our scope here.

For these and other reasons, neither we nor anyone else can offer the "right" way of solving these problems, because no unique or right answers exist for a particular community, much less all communities. However, the approaches we discuss can help communities make more informed and better decisions.

Our view of how to use science in a careful and open process for formulating policy is summarized in an eloquent statement by Nobel Prize winning physicist Richard Feynman. In 1986, after the explosion of the space shuttle *Challenger*, the US government followed its usual practice of appointing a nominally "independent" commission to study the accident. The commissioners who, other than Feynman, were insiders from NASA, government, and the aerospace industry, wanted to support NASA rather than ask hard questions. Their supportive report was instantly forgotten. However, Feynman's dissenting assessment, explaining what went wrong and why, become a classic example of objective outside analysis. It is remembered especially for its conclusion:

> NASA owes it to the citizens from whom it asks support to be frank, honest, and informative, so these citizens can make the wisest decisions for the use of their limited resources. For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.

Questions

1.1. Although the losses from natural disasters are very large, they can be viewed in various ways. How large are these losses per person on earth? How do they compare to the world's total military budget?

1.2. Comparing California and Alaska, which would you expect to have the higher earthquake hazard? Which should have the higher risk?

1.3. Of the approximately 50 people killed each year in the US by lightning, about 80% are male. Analyze the difference between male and female deaths in terms of hazard, vulnerability, and risk. Suggest possible causes for the difference and how to test these hypotheses. For example, what would your hypotheses predict for the geographic distribution?

1.4. In thinking about hazards, it is useful to get a sense of the order of magnitudes involved. This approach is sometimes called "Fermi estimation" after Nobel Prize winning physicist Enrico Fermi, who used to ask students in qualifying exams questions like "How many piano tuners are in Chicago?" Estimate the order of magnitude – 1, 10, 100, or 1000 – of the number of deaths per year in the US caused by bears, sharks, bees, snakes, deer, horses, and dogs. A good way to tackle this is to put them in the relative order you expect, and then try to estimate numerical values.

1.5. A useful way to get insight into risks is to compare them. For example, because about 700 people a year in the US are killed in bicycle accidents and the US population is about 300 million people, the odds of being killed in a bicycle accident are about 700/300,000,000 or 1 in about 430,000. What are the odds of being killed in an earthquake in the US? Because such estimates depend somewhat on whether a disastrous earthquake has occurred recently, estimate the odds both with the data given in this chapter and assuming another earthquake as disastrous as the 1906 one had occurred recently.

1.6. An interesting comparison with natural hazards is the odds of winning a state lottery. If the lottery involves matching six numbers drawn from a field of 1 to 49, the odds can be found as follows: The first number drawn can be any of the 49 numbers, and you need one of the six numbers on your ticket to match it. The second number is one of the 48 numbers left, and you need one of the remaining five numbers on your ticket to match it, and so on. Thus your odds of winning are $6/49 \times 5/48 \times 4/47 \times 3/46 \times 2/45 \times 1/44$. Calculate this number and compare it to the odds of being killed in an earthquake or a bicycle accident.

1.7. The US's National Center for Missing and Exploited Children has said, "Every day 2000 children are reported missing." Use this number to estimate the fraction of the nation's children that would be missing each year. How does this prediction compare to your experience during the years you spent in school? From your experience, estimate a realistic upper bound for this fraction. How might the much larger 2000 per day number have arisen?

1.8. The enormous destruction to New Orleans by hurricane Katrina in 2005 had been predicted for years, because about half of the city is below sea level and human actions caused land subsidence along the coast that increased the destructive power of hurricanes. Some argued that the city should not be rebuilt at its present site, because it would be at risk of a similar disaster. Others argued that the site is too important culturally, economically, and historically to abandon, and that it could be made safe. How would you decide between options of not rebuilding the coastal defenses that failed, rebuilding them to deal with a similar storm, or building ones to deal with larger storms?

1.9. How do you respond to the *New Zealand Herald* editorial quoted in section 1.2? Do you agree or disagree, and why?

1.10. Almost 2000 years ago, Pompeii and other cities near present Naples, Italy were destroyed by an eruption of the volcano Vesuvius. Since the last eruption in 1944, the Bay of Naples region has been a hotbed of construction – much of it unplanned and illegal – that has hugely increased the number of people living in the danger zone of the volcano. Millions of people may be affected by the next eruption, with those in the "red zone" (zona rossa) under the most serious threat. The authorities are considering paying these people to relocate. How would you formulate and evaluate such plans?

1.11. What do you consider to be the five major problems facing your community? Which, if any, involve natural hazards?

Further Reading and Sources

Kieffer (2013) gives an overview of natural disaster science.

Figure 1.1 is taken from "Natural catastrophes 2012" available at *https://www.munichre.com/touch/naturalhazards/en/homepage/default.aspx*

The *Economist* (January 14, 2012; "Counting the cost of calamities", *http://www.economist.com/node/21542755/print*) reviews the cost of natural disasters. Global fatality data are given in Guha-Sapir et al. (2012). Natural disaster loss and cost issues are discussed by Kliesen (1994) and National Research Council, Committee on Assessing the Costs of Natural Disasters (1999).

Thorp's (1966) book presented the winning strategies for blackjack (see also *http://www.edwardothorp.com*). Fictionalized accounts of the MIT blackjack teams given by Mezrich (2003; *http://www.youtube.com/watch?v=QflVqavHHM0*) are the basis of the film "21."

Fritz et al. (2012) discuss the Tohoku tsunami's effects in the area of Figure 1.1. Videos of the tsunami are linked at *http://www.geologyinmotion.com/2011/03/more-videos-of-tsunami-and-situation-in.html*. The resulting losses are summarized by Normile (2012).

Cyranoski (2012a), Harner (2012), and Tabuchi (2012) discuss tsunami policy for the Nankai area. The "worst case" comment is from Harner (2012). O'Connor (2012) reviews the number of earthquake deaths in Haiti. Peresan and Panza (2012) discuss the history of the Italian earthquake hazard map.

The *New Zealand Herald* editorial is dated March 4, 2011. Table 1.1 is from Stein and Wysession (2003). Data in Figure 1.5 are from *http://earthquake.usgs.gov/regional/states/us_deaths.php*. The Richter quotation is from Hough's (2007) biography. Geller (2011) describes the Japanese government prediction policy. The Copenhagen Consensus priorities are from *http://www.copenhagenconsensus.com/projects/copenhagen-consensus-2012/outcome*.

Lee (2012) summarizes the North Carolina sea level issue. Feynman's activities on the Challenger commission are described by Gleick (1992) and his dissent to the commission's report is reprinted in Feynman (1988) and available at *http://science.ksc.nasa.gov/shuttle/missions/51-l/docs/rogers-commission/Appendix-F.txt*.

Weinstein and Adam (2008) explain Fermi estimation with examples including the total length of all the pickles consumed in the US in one year. Ropeik and Gray (2002) and Aldersey-Williams and Briscoe (2008) give general audience discussions of risks. The US National Incidence Studies of Missing, Abducted, Runaway, and Thrownaway Children (Finkelhor et al., 2002; *https://www.ncjrs.gov/html/ojjdp/nismart/03/*) found that in 1999 there were an estimated 115 stereotypical kidnappings, defined as abductions perpetrated by a stranger or slight acquaintance and involving a child who was transported 50 or more miles, detained overnight, held for ransom or with the intent to keep the child permanently, or killed.

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