Donald Hyndman | David Hyndman

Natural Hazards and Disasters

FIFTH EDITION

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***Natural Hazards and Disasters*, Fifth Edition**
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To Shirley and Teresa

for their endless encouragement and patience

About the Authors

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Brief Contents

Appendix 1: Geological Time Scale, and Appendix 2: Mineral and Rock Characteristics Related to Hazards, can be found online at www.cengagebrain.com/shop/isbn/9781305581692

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Preface

The further you are from the last disaster, the closer you are to the next.

Why We Wrote This Book

In teaching large introductory environmental and physical geology courses for many years—and, more recently, natural hazards courses—it has become clear to us that topics involving natural hazards are among the most interesting for students. Thus, we realize that employing this thematic focus can stimulate students to learn basic scientific concepts, to understand how science relates to their everyday lives, and to see how such knowledge can be used to help mitigate both physical and financial harm. For all of these reasons, natural hazards and disasters courses appear to achieve higher enrollments, have more interested students, and be more interesting and engaging than those taught in a traditional environmental or physical geology framework.

A common trend is to emphasize the hazards portions of physical and environmental geology texts while spending less time on subjects that do not engage the students. Students who previously had little interest in science can be awakened with a new curiosity about Earth and the processes that dramatically alter it. Science majors experience a heightened interest, with expanded and clarified understanding of natural processes. In response to years of student feedback and discussions with colleagues, we reshaped our courses to focus on natural hazards.

Students who take a natural hazards course greatly improve their knowledge of the dynamic Earth processes that will affect them throughout their lives. They should be able to make educated choices about where to live and work, how to better recognize natural hazards, and to deal with those around them. Perhaps some who take this course will become government officials or policy makers who can change some of the current culture that contributes to major losses from natural disasters.

Undergraduate college students, including nonscience majors, should find the writing clear and stimulating. Our emphasis is to provide them a basis for understanding important hazard-related processes and concepts. This book encourages students to grasp the fundamentals while still appreciating that most issues have complexities that are beyond the current state of scientific knowledge and involve societal aspects beyond the realm of science. Students not majoring in the geosciences may find motivation to continue studies in related areas and to share these experiences with others.

Natural hazards and disasters can be fascinating and even exciting for those who study them. Just don't be on the receiving end!

Living with Nature

Natural hazards, and the disasters that accompany many of them, are an ongoing societal problem. We continue to put ourselves in harm's way, through ignorance or a naïve belief that a looming hazard may affect others but not us. We choose to live in locations that are inherently unsafe.

The expectation that we can control nature through technological change stands in contrast to the fact that natural processes will ultimately prevail. We can choose to live *with* nature or we can try to fight it. Unfortunately, people who choose to live in hazardous locations tend to blame either "nature on the rampage" or others for permitting them to live there. People do not often make such poor choices willfully, but rather through their lack of awareness and understanding of natural processes. Even when they are aware of an extraordinary event that has affected someone else, they somehow believe "it won't happen to me." These themes are revisited throughout the book, as we relate principles to societal behavior and attitudes.

People often decide on their residence or business location based on a desire to live and work in scenic environments without understanding the hazards around them. Once they realize the risks, they often compound the hazards by attempting to modify the environment. Students who read this book should be able to avoid such errors. Toward the end of the course, our students sometimes ask, "So where is a safe place to live?" We often reply that you can choose hazards that you are willing to deal with and live in a specific site or building that you know will minimize impact of that hazard.

It is our hope that by the time students have finished reading this textbook, they should have the basic knowledge to critically evaluate the risks they take and the decisions they make as voters, homeowners, and world citizens.

Our Approach

This text begins with an overview of the dynamic environment in which we live and the variability of natural processes, emphasizing the fact that most daily events are small and generally inconsequential. Larger events are less frequent, though most people understand that they can happen. Fortunately, giant events are infrequent; regrettably, most people are not even aware that such events can happen. Our focus here is on Earth and atmospheric hazards that appear rapidly, often without significant warning.

The main natural hazards covered in the book are earthquakes and volcanic eruptions; extremes of weather, including hurricanes; and floods, landslides, tsunami, wildfires, and asteroid impacts. For each, we examine the nature and processes that drive the hazard, the dangers associated with it, the methods of forecasting or predicting such events, and approaches to their mitigation. Throughout the book, we emphasize interrelationships between hazards, such as the fact that building dams on rivers often leads to greater coastal erosion. Similarly, wildfires generally make slopes more susceptible to floods, landslides, and mudflows.

The book includes chapters on dangers generated within the Earth, including earthquakes, tsunami, and volcanic eruptions. Society has little control over the occurrence of such events but can mitigate their impacts through a deeper understanding that can afford more enlightened choices. The landslides section addresses hazards influenced by a combination of in-ground factors, human actions, and weather, a topic that forms the basis for many of the following chapters. A chapter on sinkholes, subsidence, and swelling soils addresses other destructive in-ground hazards that we can, to some extent, mitigate and that are often subtle yet highly destructive.

The following hazard topics depend on an understanding of the dynamic variations in weather, thunderstorms and tornadoes, so we begin with a chapter to provide that background. The next two chapters on climate change address the overarching atmospheric changes imposed by increasing carbon dioxide and other greenhouse gases that affect weather and many hazards described in the following chapters. Chapters on streams and floods begin with the characteristics and behavior of streams and how human interaction affects both a stream and the people around it. Chapters follow on wave and beach processes, hurricanes and nor'easters, and wildfires. The final chapter addresses asteroid impacts on Earth.

The book is up-to-date and clearly organized, with most of its content derived from current scientific literature and from our own personal experience. It is packed with relevant content on natural hazards, the processes that control them, and the means of avoiding catastrophes. Numerous excellent and informative color photographs, many of them our own, illustrate scientific concepts associated with natural hazards. Diagrams and graphs are clear, straightforward, and instructive.

Extensive illustrations and Case in Point examples bring reality to the discussion of principles and processes. These cases tie the process-based discussions to individual cases and integrate relationships between them. They emphasize the natural processes and human factors that affect disaster outcomes. Illustrative cases are placed at the chapter end to not interrupt continuity of the discussion. Coverage of natural hazards is balanced with excellent examples across North America and the rest of the world. As our global examples illustrate, although the same fundamental processes lead to natural hazards everywhere, the impact of natural disasters can be profoundly different depending on factors such as economic conditions, security, and disaster preparedness.

End-of-chapter material also includes Critical View photos with paired questions, a list of Key Points, Key Terms, Questions for Review, and Critical Thinking Questions.

New to the Fifth Edition

With such a fast-changing and evolving subject as natural hazards, we have extensively revised and added to the content, with emphasis not only on recent events but also on those that best illustrate important issues. We have endeavored to keep material as up-to-date as possible, both with new Cases in Point and in changes in governmental policy that affect people and their hazardous environments. New to this edition is a Survival Guide feature that highlights risk, preparedness, and safety information related to relevant hazards. To make space for new Cases in Point, some older cases have been moved online, where they can be accessed in the CourseMate available at cengagebrain.com.

In recognition of the rapid advances in understanding of climate change and its increasing importance, we now present this important topic in two separate chapters. That material is thoroughly reorganized, rewritten, and revised, with numerous new graphs and photos. Graphs have been updated with the most recent available information.

In addition to these overall changes, some significant additions to individual chapters include the following:

- **Chapters 3 and 4, Earthquakes**, include new coverage of the giant 2015 Nepal earthquake that killed more than 8600 people, destroyed most of the capital, Kathmandu and surrounding cities, and flattened most of its priceless ancient temples. We have added new insights on earthquakes associated with fracking, the latest way to drill for oil and gas. The moderate-size but destructive 2014 earthquake near Napa, California's iconic wine-growing area provides another wake-up call for this region.
- **Chapters 6 and 7, Volcanoes**, include an update on Hawaii's lava flows, which continued into 2015.
- **Chapter 8, Landslides**, features a new Case in Point on the tragic Oso landslide in western Washington, which occurred in a known hazard area that permitted building of a new subdivision.

- **Chapter 10, Weather, Thunderstorms, and Tornadoes**, has been significantly updated and revised. We have added coverage of the polar vortex, a process that is now better understood and more relevant to the public after millions of people in the northeastern United States lived through the bitterly cold winter of 2014. A new Case in Point focuses on the 2013 EF5 tornado that struck Moore, Oklahoma (the fourth in 14 years), killing many people who had no tornado shelters, in spite of federal support to partially pay for them. Another new Case is devoted to the severe California drought.
- **Chapters 11 and 12, Climate Change**, breaks the existing climate change coverage into two updated and expanded chapters. Chapter 11 focuses on processes related to climate change, whereas Chapter 12 focuses on the impacts of climate change and mitigation strategies. Coverage has been significantly expanded to encompass new data and illustrations from the 5th Intergovernmental Panel on Climate Change (IPCC).
- **Chapters 13 and 14, Streams and Floods**, features a new Case in Point about the disastrous 2013 flash floods in the Rocky Mountain foothills near Denver that provided a reminder of the Big Thompson canyon event almost 40 years before.
- **Chapter 16, Hurricanes and Nor'easters**, includes coverage of Hurricane Sandy in late 2012, which was a major wake-up call for those who view a "weak" hurricane as a minor inconvenience.
- **Chapter 17, Wildfires**, includes new Cases in Point about two large fires near Colorado Springs and the tragic Yarnell Hill fire in Arizona that killed 14 professional firefighters.
- **Chapter 18, Asteroid and Comet Impacts**, includes a new Case on the 2013 Chelyabinsk meteor in Russia, which was a frightening near miss that nearly became a catastrophe.

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We are grateful to a wide range of people for their assistance in preparing and gathering material for this book, far too many to list individually here. However, we particularly appreciate the help we received from the following:

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Donald Hyndman and David Hyndman

During Hurricane Sandy the east end of the Mantoloking Bridge, at left, was submerged, and houses on the barrier island battered. Some like the one in the lower left floated off their foundations.

Mark Olsen, NJ Army National Guard

Natural Hazards and Disasters

1

Living in Harm's Way

> Those who cannot remember the past are condemned to repeat it.
>
> —George Santayana (Spanish philosopher), 1905

Why would people choose to put their lives and property at risk? Large numbers of people around the world live and work in notoriously dangerous places—near volcanoes, in floodplains, or on active fault lines. Some are ignorant of potential disasters, but others even rebuild homes destroyed in previous disasters. Sometimes the reasons are cultural or economic. Because volcanic ash degrades into richly productive soil, the areas around volcanoes make good farmland. Large floodplains attract people because they provide good agricultural soil, inexpensive land, and natural transportation corridors. Some people live in a hazardous area because of their job. For understandable reasons, such people live in the wrong places. Hopefully they recognize the hazards and understand the processes involved so they can minimize their risk.

But people also crowd into dangerous areas for frivolous reasons. They build homes at the bases or tops of large cliffs for scenic views, not realizing that big sections can give way in landslides or rockfalls. They build beside picturesque streams without realizing they have put themselves in a flood zone. Far too many people build houses in the woods because they enjoy the seclusion and scenery of this natural setting without understanding their risk from wildfires. Others choose to live along edges of sea bluffs where they can enjoy ocean views, or on the beach to experience the ocean more intimately. But in these locations they also expose themselves to coastal storms. In October 2012, the devastating effects of Hurricane Sandy, only a Category 1 storm, reminded many people of the hazards of living on the Atlantic coast.

Some natural catastrophe experts say these people have chosen to live in "idiot zones." But people don't usually reside in hazardous areas knowingly—they generally don't understand or recognize the hazards. However, they might as well choose to park their cars on a rarely used railroad track. Trains don't come frequently, but the next one might come any minute.

Catastrophic natural hazards are much harder to avoid than passing freight trains; we may not recognize the signs of imminent catastrophes because these events are infrequent. So many decades or centuries may pass between eruptions of a large volcano that most people forget it is active. Many people live so long on a valley floor without seeing a big flood that they forget it is a floodplain. The great disaster of a century ago is long forgotten, so folks move into the path of a calamity that may not arrive today or tomorrow, but it is just a matter of time.

Catastrophes in Nature

Geologic processes, like erosion, have produced large effects over the course of Earth's vast history, carving out valleys or changing the shape of coastlines. While some processes operate slowly and gradually, infrequent catastrophic events have sudden and major impacts.

Although streams may experience a few days or weeks of flooding each year, major floods occurring once every few decades do far more damage than all of the intervening floods put together. Soil moves slowly downslope by creep, but occasionally a huge part of a slope may slide. Pebbles roll down a rocky slope daily, but every once and a while a giant boulder comes crashing down (**FIGURE 1-1**). Mountains grow higher, sometimes slowly, but more commonly by sudden movements. During an earthquake, a mountain can abruptly rise several meters above an adjacent valley.

Some natural events involve disruption of a temporary *equilibrium*, or balance, between opposing influences. Unstable slopes, for example, may hang precariously for thousands of years, held there by friction along a slip surface until some small perturbation, such as water soaking in from a large rainstorm, sets them loose. Similarly, the opposite sides of a fault may stick until slowly building stress finally tears them loose, triggering an earthquake. A bulge may form on a volcano as molten magma slowly rises into it, then it collapses as the volcano erupts. The behavior of these natural systems is somewhat analogous to a piece of plastic wrap that can stretch up to a point, until it suddenly tears.

Donald Hyndman

Courtesy of the Utah Geological Survey (UGS)

FIGURE 1-1 The Unexpected

On December 12, 2013, a huge mass of sandstone separated from a prominent cliff above homes along Highway 9 in the community of Rockville, Utah, instantly killing the two home owners. This hazardous area of homes was highlighted in a Utah Geological Survey report in 2013. The same home was pictured as in a dangerous location in the previous edition of this textbook printed in late 2012, one year before the disaster.

People watching Earth processes move at their normal and unexciting pace rarely pause to imagine what might happen if that slow pace were suddenly punctuated by a major event. The fisherman enjoying a quiet afternoon trout fishing in a small stream can hardly imagine how a 100-year flood might transform the scene. Someone gazing at a serene, snow-covered mountain can hardly imagine it erupting in an explosive blast of hot ash followed by destructive mudflows racing down its flanks. Large or even gigantic events are a part of nature. Such abrupt events produce large results that can be disastrous if they affect people.

Human Impact of Natural Disasters

When a natural process poses a threat to human life or property, we call it a **natural hazard**. Many geologic processes are potentially hazardous. For example, streams flood as part of their natural process and become a hazard to those living nearby. A hazard is a **natural disaster** when the event causes significant damage to life or property. A moderate flood that spills over a floodplain every few years does not often wreak havoc, but when a major flood strikes, it may lead to a disaster that kills or displaces many people. When a natural event kills or injures large numbers of people or causes extensive property damage, it is called a **catastrophe**.

The potential impact of a natural disaster is related not only to the size of the event but also to its effect on the public. A natural event in a thinly populated area can hardly pose a major hazard. For example, the magnitude 7.6 earthquake that struck the southwest corner of New Zealand on July 15, 2009, was severe but posed little threat because it happened in a region with few people or buildings. In contrast, the much smaller January 12, 2010, magnitude 7.0 earthquake in Haiti killed more than 46,000 (**FIGURE 1-2**). In another example, the eruption of Mt. St. Helens in 1980 caused few fatalities and remarkably little property damage simply because the area surrounding the mountain is sparsely populated. On the other hand, a similar eruption of Vesuvius, in the heavily populated outskirts of Naples, Italy, could kill hundreds of thousands of people and cause property damage beyond reckoning.

You might assume that more fatalities occur as a result of dramatic events, such as large earthquakes, volcanic eruptions, hurricanes, or tornadoes. However, some of the most dramatic natural hazards occur infrequently or in restricted areas, so they cause fewer deaths than more common and less dramatic hazards such as floods or droughts. **FIGURE 1-3** shows the approximate proportions of fatalities caused by typical natural hazards in the United States.

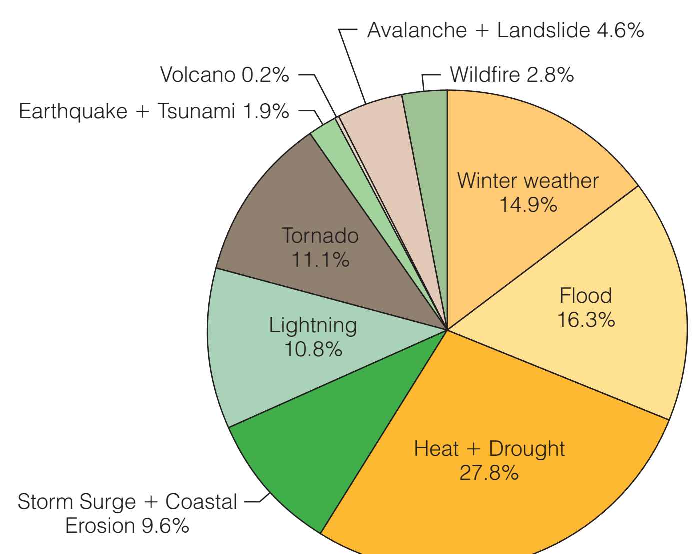
In the United States, heat and drought together account for the largest numbers of deaths. In fact, there were more U.S. deaths from heat waves between 1997 and 2008 than from any other type of natural hazard. In addition to heat stress, summer heat wave fatalities can result from dehydration and other factors; the very young, the very old, and the poor are affected the most. The same populations are vulnerable during winter weather, the third most deadly hazard in the United States. Winter deaths often involve hypothermia, but some surveys include, for example, auto accidents caused by icy roads.

Flooding is the second most deadly hazard in the United States, accounting for 16 percent of fatalities between 1986 and 2008. Fatalities from flooding can result from

Ho new/UN Photo Logan Abassi/Handout/Reuters

FIGURE 1-2 A Disaster Takes a High Toll

Searchers dig for survivors of the Haiti earthquake of January 12, 2010, which killed more than 316,000, mostly in concrete and cinder block buildings with little or no reinforcing steel.



Compiled from many sources, including NOAA-NWS, USGS, USFS, and the NW Avalanche Center

FIGURE 1-3 Hazard-Related Deaths

Approximate percentages of U.S. fatalities due to different groups of natural hazards from 1986 to 2008, when such data are readily available. For hazardous events that are rare or highly variable from year to year (earthquakes and tsunami, volcanic eruptions, and hurricanes), a 69-year record from 1940 to 2008 was used.

hurricane-driven floods; some surveys place them in the hurricane category rather than floods.

The number of deaths from a given hazard can vary significantly from year to year due to rare, major events. For example, there were about 1800 hurricane-related deaths in 2005 when Hurricane Katrina struck, compared with zero in other years. The rate of fatalities can also change over time as a result of safety measures or trends in leisure activities. Lightning deaths were once among the most common hazard-related causes of death, but associated casualties have declined significantly over the past 50 years, due in part to satellite radar and better weather forecasting. In contrast, avalanche deaths have increased significantly over a similar period, a change that seems to be associated with increased snowmobile use and skiing in mountain terrains.

Some natural hazards can cause serious physical damage to land or man-made structures, some are deadly for people, and others are destructive to both. The type of damage sustained as a result of a natural disaster also depends on the economic development of the area where it occurs. In developing countries, there are increasing numbers of deaths from natural disasters, whereas in developed countries, there are typically greater economic losses. This is because developing countries show dramatic increases in populations relegated to marginal and hazardous land on steep slopes and near rivers. Such populations also live in poorly constructed buildings and have less ability to evacuate as hazards loom; many lack transportation and financial ability to survive away from their homes.

For an example of this phenomenon, in 2010, earthquakes of similar sizes (magnitude 7.0) struck Haiti, a poor, developing country, and New Zealand, a prosperous, developed country. In Haiti, between 46,000 and 316,000 people were killed (U.S. government versus Haitian government estimates), mostly in the collapse of poorly built masonry buildings. Total damages were estimated to be about U.S. $7.8 billion. In contrast, only 185 people died in the New Zealand earthquake, which also occurred near a populous area. New Zealand's buildings were generally well constructed. Despite this, damages were still estimated to be about U.S. $6.5 billion.

The average annual cost of natural hazards has increased dramatically over the last several decades (**FIGURE 1-4**). This is due in part to the increase in world population, which doubled in the 40 years between 1959 and 1999. By July 2015, it reached 7.3 billion. It is also a function of the increased value of properties at risk and to human migration to more hazardous areas. Overall losses have increased even faster than population growth. Population increases in urban and coastal settings result in more people crowding into land that is subject to major natural events. In effect, people place themselves in the path of unusual, sometimes catastrophic events. Economic centers of society are increasingly concentrated in larger urban areas that tend to expand into regions previously considered undesirable, including those with greater exposure to natural hazards.

The reality of climate change adds an additional dimension to these problems; it is one of the greatest challenges facing the human race. Scientists agree that global temperatures are rising. As world population grows and large numbers of people become more affluent and use larger amounts of resources, greenhouse gas emissions increase dramatically.

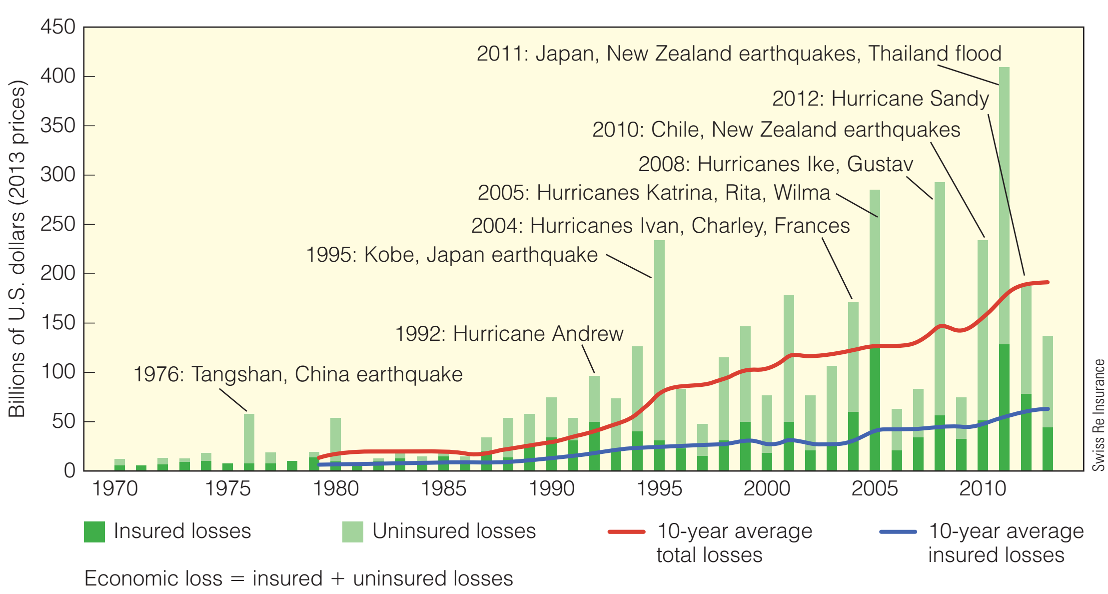


FIGURE 1-4 **Increasing Costs of Natural Hazards**

The cost of natural hazards is increasing worldwide. The 2011 earthquake and tsunami in Japan alone caused losses of about $235 billion.

FIGURE 1-5 Homes at Risk

Homes along channels in the Mekong River delta in southern Vietnam are almost in the water under normal circumstances. They would be washed away in the next major cyclone.

Our generation of greenhouse gases seems likely to cause population collapse in some parts of the world, especially in poor areas most affected by natural hazards. People's living conditions will be severely disrupted. Millions will die from increased incidence of storms and coastal flooding, heat stroke, dehydration, famine, disease, and wars over water, food, heating fuel, and other resources.

Climate change is expected to lead to more rapid erosion of coastlines, along with more extreme weather events that cause landslides, floods, hurricanes, and wildfires. Some small islands in the Indian Ocean, far from the 2004 Sumatra earthquake's epicenter, were completely overwashed by tsunami waves. As sea level continues to rise, such low-lying islands will gradually submerge, even without a catastrophic event. Extensive low-lying coastal regions of major river deltas in Southeast Asia feed and are homes to millions of poor people. Deltas of the Ganges and Brahmaputra Rivers in Bangladesh, the Irrawaddy River in Myanmar, and the Mekong River in Vietnam and Cambodia are subject to 2-m ocean tides more than 200 km upstream (**FIGURE 1-5**). Major storms can submerge most of the deltas, including all of their rice fields and homes, under more than 2 m of water, with storm waves on top of that. Sea-level rise with climate change is expected to worsen those effects, killing thousands in major typhoons. The number of hurricanes has not increased significantly, but since 1990 the annual number of the most intense storms—Categories 4 and 5—nearly doubled to 18 worldwide in 2005 although the future trend remains unclear. Hurricane development and intensity depend on energy provided by higher sea-surface temperatures.

Predicting Catastrophe

A catastrophic natural event is unstoppable, so the best way to avoid it would be to predict its occurrence and get out of the way. Unfortunately, there have been few well-documented cases of accurate prediction, and even the ones on record may have involved luck more than science. Use of the same techniques in similar circumstances has resulted in false alarms and failure to correctly predict disasters.

Many people have sought to find predictable cycles in natural events. Those that occur at predictable intervals are called *cyclic events*. However, most recurrent events are not really cyclic; too many variables control their behavior. Even with cyclic events, overlapping cycles make resultant extremes noncyclic, which affects the predictability of a specific event. So far as anyone can tell, most episodes, large and small, occur at seemingly random and essentially unpredictable intervals.

Although scientists cannot predict exactly when an event will occur, based on past experience they can often **forecast** the chance that a hazardous event will occur in a region within a few decades. For example, they can forecast that there will be a large earthquake in the San Francisco Bay region over the next several decades, or that Mt. Shasta will likely erupt sometime in the next few centuries. In many cases, their advice can greatly reduce the danger to lives and property.

Ask a stockbroker where the market is going, and you will probably hear that it will continue to do what it has done during recent weeks. Ask a scientist to forecast an event, and he or she will probably look to the geologically recent past and forecast more of the same; in other words, *the past is the key to the future*. Most forecasts are based on linear projections of past experience. However, we must be careful to look at a long enough sample of the past to see prospects for the future. Many people lose money in the stock market because *short-term* past experience is not always a good indicator of what will happen in the future.

Similarly, statistical forecasts are simply a refinement of past recorded experiences. They are typically expressed as **recurrence intervals** that relate to the probability that a natural event of a particular size, or **magnitude**, will happen within a certain period of time, or with a certain **frequency**. For example, the history of movement along a fault may indicate that it is likely to produce an earthquake of a certain size once every hundred years on average.

A recurrence interval is not, however, a fixed schedule for events. Recurrence intervals can tell us that a 50-year flood is likely to happen sometime in the next several decades but *not* that such floods occur at intervals of 50 years. Many people do not realize the inherent danger of an unusual occurrence, or they believe that they will not be affected in their lifetimes because such events occur infrequently. That inference often incorrectly assumes that the probability of another severe event is lower for a considerable length of time after a major event. In fact, even if a 50-year flood occurred last year, that does not indicate that there will not be another one this year or for the next ten years.

To understand why this is the case, take a minute to review probabilities. Flip a coin, and the chance that it will come up heads is 50%. Flip it again, and the chance is again 50%. If it comes up heads five times in a row, the next flip still has a 50% chance of coming up heads. So it goes with floods and many other kinds of apparently random natural events. The chance that someone's favorite fishing stream will stage a 50-year flood this year and every year is 1 in 50, regardless of what it may have done during the last few years.

As an example of the limitations of recurrence intervals, consider the case of Tokyo. This enormous city is subject to devastating earthquakes that for more than 500 years came at intervals of close to 70 years. The last major earthquake ravaged Tokyo in 1923, so everyone involved awaited 1993 with considerable apprehension. The risk steadily increased during those years as the strain across the fault zone grew, as did the size of the population at risk. More than 20 years later, no large earthquake has occurred. Obviously, the recurrence interval does not predict events at equal intervals, in spite of the 500-year Japanese historical record. Nonetheless, the knowledge that scientists have of the pattern of occurrences here helps them assess risk and prepare for the eventual earthquake. Experts forecast that there is a 70% chance that a major quake will strike that region in the next 30 years.

To estimate the recurrence interval of a particular kind of natural event, we typically plot a graph of each event size versus the time interval between sequential individual events. Such plots often make curved lines that cannot be reliably extrapolated to larger events that might lurk in the future (**FIGURE 1-6**). Plotting the same data on a logarithmic scale often leads to a straight-line graph that can be extrapolated to values larger than those in the historical record. Whether the extrapolation produces a reliable result is another question.

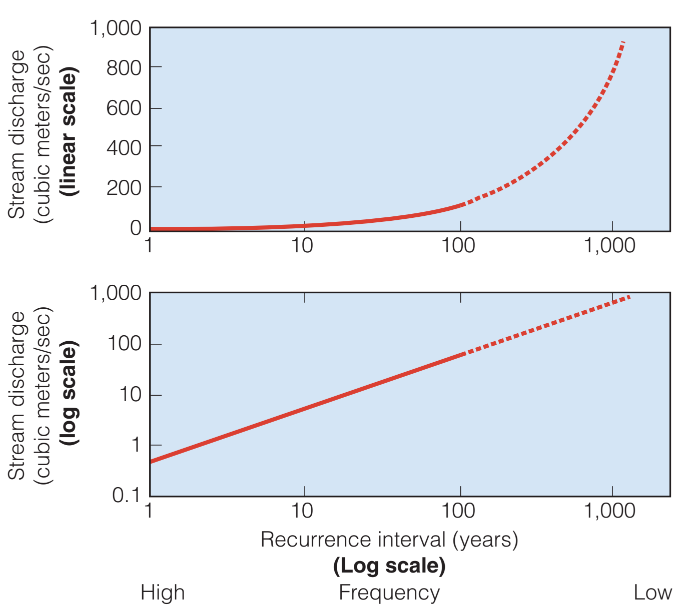


FIGURE 1-6 Recurrence Interval

If major events are plotted on a linear scale (top graph, vertical axis), the results often fall along a curve that cannot be extrapolated to larger possible future events. If the same events are plotted on a logarithmic scale (bottom graph), the results often fall along a straight line that can use historical data to forecast what to expect in future events.

By the Numbers 1-1

Relationship between Frequency and Magnitude

$$M \propto 1/f$$

Magnitude (M) of an event is inversely proportional to **frequency (f)** of the type of event.

The probability of the occurrence of an event is related to the magnitude of the event. We see huge numbers of small events, many fewer large events, and only a rare giant event (**By the Numbers 1-1:** Relationship between Frequency and Magnitude). The infrequent occurrence of giant events means it is hard to study them, but it is often rewarding to study small events because they may well be smaller-scale models of their uncommon larger counterparts that may occur in the future.

Many geologic features look the same regardless of their size, a quality that makes them **fractal**. A broadly generalized map of the United States might show the Mississippi River with no tributaries smaller than the Ohio and Missouri Rivers. A more detailed map shows many smaller tributaries. An even more detailed map shows still more. The number of tributaries depends on the scale of the map, but the general branching pattern looks *similar across a wide range of scales* (**FIGURE 1-7**). Patterns apparent on a small scale quite commonly resemble patterns that exist on much larger scales that cannot be easily perceived. This means that small events may provide insight into huge ones that occurred in the distant past but are larger than any seen in historical time; we may find evidence of these big events if we search. The geologic record provides evidence for massive natural catastrophes in the Earth's distant past, such as the impact of a large asteroid that caused the extinction of the dinosaurs. We need to be aware of the potential for such extreme events in the future.

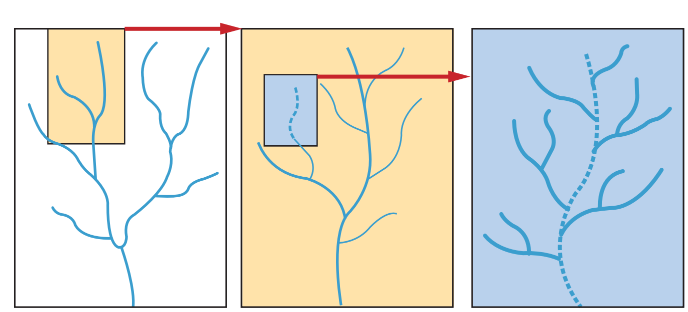


FIGURE 1-7 Fractal Systems

The general *pattern* of a branching stream looks similar regardless of scale—from a less-detailed map on the left to the most detailed map on the right.

It is impossible in our current state of knowledge to predict most natural events, even if we understand in a general way what controls them. The problem of avoiding natural disasters is like the problem drivers face in avoiding collisions with trains. They can do nothing to prevent trains, so they must look and listen. We have no way of knowing how firm the natural restraints on a landslide, fault, or volcano may be. We also do not generally know what changes are occurring at depth. But we can be confident that the landslide or fault will eventually move or that the volcano will erupt. And we can reasonably understand what those events will involve when they finally happen.

Relationships among Events

Although randomness is a factor in forecasting disasters, most natural events do not occur as randomly as tosses of a coin. Some events are directly related to others—formed as a direct consequence of another event (**FIGURE 1-8**). For example, the slow movement of Earth's huge outer layers colliding or sliding past one another clearly explains the driving forces behind volcanic eruptions and earthquakes. Heavy or prolonged rainfall can cause a flood or a landslide. But are some events unrelated? Could any of the arrows in Figure 1-8 be reversed?

Past events can also create a contingency that influences future events. It is certainly true, for example, that sudden movement on a fault causes an earthquake. But the same movement also changes the stress on other parts of the fault and probably on other faults in the region, so the next earthquake will likely differ considerably from the last. What if, after an earthquake movement on a fault, one side of the fault is now across from a very slippery area of rock on the other side of the fault. Might then the fault break more easily and the next movement on the fault come sooner? Similar complex relationships arise with many other types of destructive natural events.

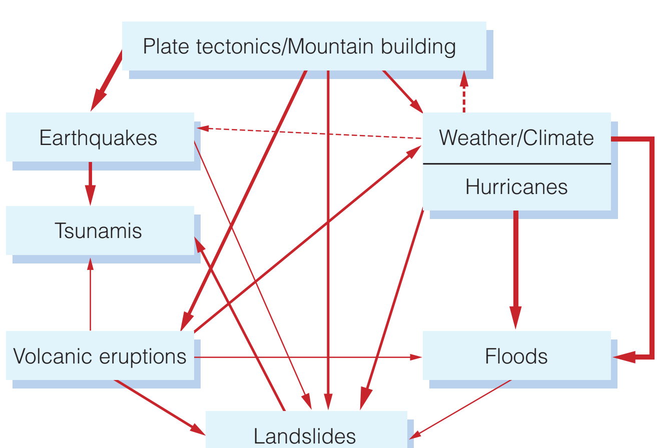


FIGURE 1-8 Interactions among Natural Hazards

Some natural disasters are directly related to others. The bolder arrows in this flowchart indicate stronger influences. Can you come up with words to describe these influences?

Some processes result in still more rapid changes—a **feedback effect**. For example, global warming causes more rapid melting of Arctic sea ice. The resulting darker sea water absorbs more of the Sun's energy than the white ice, which in turn causes even more sea ice melting. Similarly, global warming causes faster melting of the Greenland and Antarctic ice sheets. More meltwater pours through fractures to the base of the ice, where it lubricates movement, accelerating the flow of ice toward the ocean. This leads to more rapid crumbling of the toes of glaciers to form icebergs that melt in the ocean.

In other cases, an increase in one factor may actually lead to a decrease in a related result. Often as costs of a product or service go up, usage goes down. With increased costs of hydrocarbon fuels, people conserve more and thus burn less. A rapid increase in the price of gasoline in 2008 led people to drive less and to trade in large SUVs and trucks for smaller cars. In some places, commuter train, bus, and bicycle use increased dramatically. With the rising cost of electricity, people are switching to compact fluorescent bulbs and using less air conditioning. These changes had a noticeable effect on greenhouse gas emissions and their effect on climate change (discussed in Chapter 12).

Sometimes major natural events are preceded by a series of smaller **precursor events**, which may warn of the impending disaster. Geologists studying the stirrings of Mt. St. Helens, Washington, before its catastrophic eruption in 1980 monitored swarms of earthquakes and decided that most of these recorded the movements of rising magma as it squeezed upward, expanding the volcano. Precursor events alert scientists to the potential for larger events, but events that appear to be precursors are not always followed by a major event.

The relationships among events are not always clear. For example, an earthquake occurred at the instant Mt. St. Helens exploded, and the expanding bulge over the rising magma collapsed in a huge landslide. Neither the landslide nor the earthquake caused the formation of molten magma, but did they trigger the final eruption? If so, which one triggered the other—the earthquake, the landslide, or the eruption? One or more of these possibilities could be true in different cases.

Events can also overlap to amplify an effect. Most natural disasters happen when a number of unrelated variables overlap in such a way that they reinforce each other to amplify an effect. If the high water of a hurricane storm surge happens to arrive at the coast during the daily high tide, the two reinforce each other to produce a much higher storm surge (**FIGURE 1-9**). If this occurs on a section of coast that happens to have a large population, then the situation can become a major disaster. Such a coincidence caused the catastrophic hurricane that killed 8000 people in Galveston, Texas, in 1900.

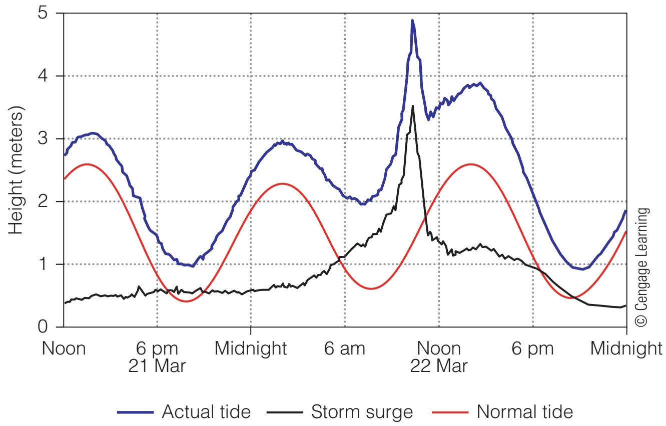


FIGURE 1-9 Amplification of Overlapping Effects

If events overlap, their effects can amplify one another. In this example, a storm surge (black line) can be especially high if it coincides with high tide (red line). The blue line shows the much higher tide that resulted when the tide overlapped with the storm surge.

Mitigating Hazards

Because natural disasters are not easily predicted, it falls to governments and individuals to assess their risk and prepare for and mitigate the effects of disasters. **Mitigation** refers to efforts to prepare for a disaster and reduce its damage. Mitigation can include engineering projects such as levees, as well as government policies and public education efforts. "Soft" solutions for hazardous areas include zoning to prevent building in certain regions and strict building codes, which minimize damage and are much less expensive in the long run. "Hard" alternatives, including levees on rivers and riprap along coasts, are expensive, often short-term, and create other problems. Throughout this book, we examine mitigation strategies related to specific disasters.

Land-Use Planning

One way to reduce losses from natural disasters is to find out where disasters are likely to occur and restrict development there, using **land-use planning**. Ideally, we would prevent development along major active faults by reserving that land for parks and natural areas. We should also limit housing and industrial development on floodplains to minimize flood damage and along the coast to reduce hurricane and coastal erosion losses. Limiting building near active volcanoes and the river valleys that drain them can curtail the hazards associated with eruptions.

It is hard, however, to impose land-use restrictions in many areas because such imposition tends to come too late. Many hazardous areas are already heavily populated, perhaps even saturated with inhabitants. Many people want to live as close as they can to a coast or a river and resent being told that they cannot; they oppose attempts at land-use restrictions because they feel it infringes on their property rights. Almost any attempt to regulate land use in the public interest is likely to ignite intense political and legal opposition.

Developers, companies, and even governments often aggravate hazards by allowing—or even encouraging—people to move into hazardous areas. Many developers and private individuals view restrictive zoning as an infringement on their rights to do as they wish with their land. Developers, real estate agents, and some companies are reluctant to admit the existence of hazards that may affect a property for fear of lessening its value and scaring off potential clients (**FIGURE 1-10**). Most local governments consider news of hazards bad for growth and business. They shun restrictive zoning or minimize possible dangers for fear of inhibiting improvements in their tax base. As in other venues, different groups have different objectives. Some are most concerned with economics, others with safety, still others with the environment.

Should landowners be permitted to do whatever they wish with their property? Property rights advocates often say yes. If a governmental entity permits building on land within its jurisdiction, should the taxpayers in the district shoulder the responsibility if there is a disaster? Should the government inform a buyer that a property is in a hazardous location and what the hazards are? Should a landowner be prevented from developing a piece of property that might be subjected to a disaster? If so, has the government effectively taken the landowner's anticipated value without compensation, a taking characterized in the courts as **reverse condemnation?**

FIGURE 1-10 Risky Development

Some developers seem unconcerned with the hazards that may affect the property they sell. High spring runoff floods this proposed development site in Missoula, Montana.

What about personal responsibility? As adults we like to think that we are responsible for our actions. That assumes, of course, that we know what we are doing and understand the consequences of our actions. If we build in the forest, surrounded by brush and trees, who should be responsible for fighting a forest fire (**FIGURE 1-11**)? Who should pay if we suffer loss? If we decide to build our home close to a stream, do we really understand enough about the natural behavior of streams to safely and responsibly do that? If the government were to restrict us from building on our own property, would they be infringing on our rights? If a future major flood wipes out our investment or causes severe damage to a downstream neighbor who sues us because of our construction, then what? Are we then likely to blame the government for permitting us to build there in the first place? If we demand personal rights, we need to be responsible for the consequences of our actions.

If you buy a property you later decide is at risk of a hazard, what responsibility do you have to a potential buyer? In many aspects of society, property sellers are held responsible if they are aware of some aspect of a property that is dangerous or damaged. Home owners commonly blame—and often sue—others for damages to property they have purchased. However, perhaps they should have remembered the old adage, "Buyer beware."

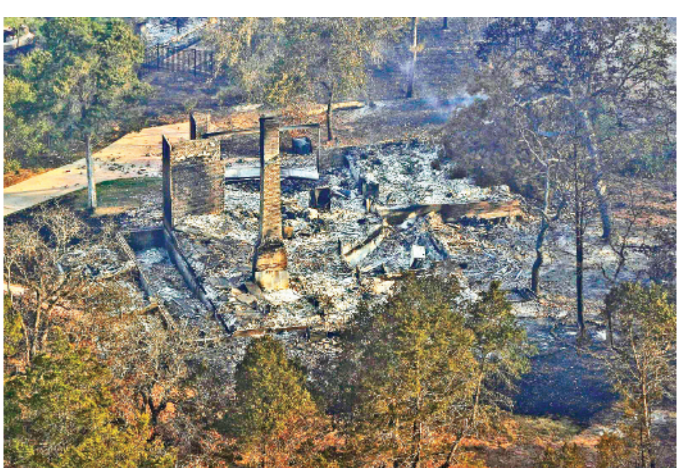
Insurance

Some mitigation strategies are designed to help with recovery once a disaster occurs. **Insurance** is one way to lessen the financial impact of disasters after the fact. People buy property insurance to shield themselves from major losses they cannot afford. Insurance companies use a formula for risk to establish premium rates for policies. **Risk** is essentially a hazard considered in the light of its recurrence interval and expected costs (**By the Numbers 1-2:** Assessing Risk). The greater the hazard and the shorter its recurrence interval, the greater the risk.

In most cases, a company can estimate the cost of a hazard event to a useful degree of accuracy, but they can only guess at its recurrence interval, and therefore the level of risk. The history of experience with a given natural hazard in any area of North America is typically less than 200 years. Large events recur, on average, only every few decades or few hundred years or even more rarely. In some cases, most notably floods, the hazard and its recurrence interval are both firmly enough established to support a rational estimate of risk. But the amount of risk and the potential cost to a company can be so large that a catastrophic event would put the company out of business.

The uncertainties of estimating risk make it impossible for private insurance companies to offer affordable policies that protect against many kinds of natural disasters. As a result, insurance is generally available for events that present relatively little risk, mainly those with more or less dependably long recurrence intervals. In high-risk areas for a particular hazard, for example Florida or Louisiana for hurricanes and sinkholes, insurance companies may either charge very high insurance premiums to cover their risks or refuse to cover damages from such hazards. In those states, nonprofit state programs have been formed to provide insurance that is not otherwise available. In California, where the risks and expected costs of earthquake damages are very high, insurance companies are required by law to provide earthquake coverage. As a result, companies now make insurance available through the California Earthquake Authority, a consortium of companies, in order to spread out their risks.

Insurance for some natural hazards is simply not available. Landslides, most mudflows, and ground settling or swelling are too risky for companies, and each potential hazard area would have to be individually studied by a scientist or engineer who specialized in such a hazard. The large number of variables makes the risk too difficult to quantify; it is too expensive to estimate the different risks for the relatively small areas involved.



Texas Parks and Wildlife

FIGURE 1-11 Who Should Pay?
Remains of a home surrounded by brush and trees that was destroyed by the Bastrop fire in Texas, 2011.

By the Numbers 1-2

Assessing Risk

Insurance costs are actuarial: They are based on past experience. For insurance, a "hazard" is a condition that increases the severity or frequency of a loss.

Risk is proportional to [probability of occurrence] × [cost of the probable loss from the event].