Nearly 190,000 homes were **destroyed or damaged, killing nearly a quarter of a million people**

1



Introduction to Natural Hazards

Earthquake in Haiti, 2010: A Human-Caused Catastrophe?

One of the primary principles emphasized in this book is that, as a result of increasing human population and poor land-use choices, what were once disasters are now catastrophes in many cases. Haiti has been recognized for many years as an environmental catastrophe waiting to happen. Haiti's population has increased dramatically in recent decades, and about 90 percent of this mountainous country has been deforested (Figure 1.1). The country is extremely vulnerable to hurricanes and other high-intensity storms, causing frequent runoff flooding and landslides on bare slopes. Haiti is also vulnerable to large earthquakes, with three major earthquakes occurring there since 1750.

On January 12, 2010, an earthquake killed more than 200,000 Haitians and injured over 300,000 more. This was an appalling loss of life for an earthquake of magnitude 7.0 (see chapter-opener photograph). For example, the magnitude 7.1 Loma Prieta earthquake that struck the San Francisco area in 1989 caused 63 deaths and injured about 4,000. Why did two earthquakes of about the same magnitude cause such vastly different casualty counts?[1,2]

The poorest country in the Western Hemisphere, Haiti's annual income per person is only a small fraction of that in the United States. Two years before the 2010 earthquake, within a span of about a month, four tropical storms and hurricanes struck in 2008. Land denuded of trees responded quickly to torrential downpours, and hillslopes went crashing into homes. By September 2008 when a hurricane hit, Haiti was devastated. Nearly 800 people had died, and much of the country's harvest of food crops had been destroyed. The situation was grim.

< Collapsed buildings in Port-au-Prince, capital of Haiti, resulting from the January 12, 2010, earthquake that killed more than 200,000 people. The extensive damage and loss of life were in part a result of the high population density in the capital and poorly constructed buildings unable to withstand the earthquake shaking. *(Jorge Silva/Reuters)*

LEARNING Objectives

Natural processes such as volcanic eruptions, earthquakes, floods, and hurricanes become hazards when they threaten human life and property. As population continues to grow, hazards, disasters, and catastrophes become more common. An understanding of natural processes as hazards requires some basic knowledge of earth science.

After reading this chapter, you should be able to:

LO:1 Explain the difference between a disaster and a catastrophe.

LO:2 Discuss the role of history in the understanding of natural hazards.

LO:3 Discuss the components and processes of the geologic cycle.

LO:4 Apply the scientific method to a natural hazard of your choice.

LO:5 Synthesize the basics of risk assessment.

LO:6 Explain how much of the damage caused by natural hazards is often related to decisions people make before, during, and after a hazardous event.

LO:7 Explain why the magnitude of a hazardous event is inversely related to its frequency.

LO:8 Summarize how natural hazards are linked to one another and to the physical environment.

LO:9 Give reasons why increasing population and poor land-use practices compound the effects of natural hazards and can turn disasters into catastrophes.

LO:10 Explain how events we view as hazards provide natural service.

LO:11 Summarize links between climate change and natural hazards.



(a) (b)

FIGURE 1.1 Deforestation in Haiti

(a) Steep mountain slopes in southern Haiti where trees have been removed to burn and make charcoal as a cooking fuel. About 30 million trees were planted in the 1980s at a cost exceeding $20 million, paid for with U.S. aid, but by 2008, nearly all of them had been cut down. Without the trees, soil erosion accelerated, damaging farmland and making slopes more vulnerable to landslides (especially when linked to earthquake shaking) and floods (water runs off more quickly and in greater quantities than from forested land). *(©Getty Images/Robin Moore)* (b) A small shack at the base of a deforested slope in the same area as (a). There are a few banana trees, but agricultural opportunity is severely limited by soil erosion. *(Julio Etchart/Alamy)*

Prior to the earthquake, about 85 percent of the people in the capital of Port-au-Prince lived in slum conditions in concrete buildings that could not withstand intense earthquake shaking. Half the people did not have toilets, and only about 30 percent had access to clean water. When the earthquake struck, nearly 190,000 homes were destroyed or damaged, killing nearly a quarter of a million people and leaving over 2 million more homeless with poor sanitation and water quality. In the immediate aftermath of the quake, about 1.5 million people lived in camps exposed to storms and flooding.[3] The city was covered in 19 million cubic meters (25 million cubic yards) of rubble and other debris (enough to fill about 4 million dump trucks) where homes, government buildings, and schools once stood. The result was a humanitarian disaster with too many untreated injuries, too little food, and a predictable outbreak of infectious diseases, including cholera (causing nearly 6,000 deaths) and diarrhea.

Once the damage from the 2010 earthquake was surveyed, it was found that some buildings that had not collapsed were evidently designed and built to withstand earthquakes and had functioned adequately. If more of the buildings in Haiti had been constructed properly, incorporating earthquake-resistant design and construction, there would have been much less damage. Problems observed ranged from construction of heavy, unsupported block walls to a lack of rebars (thin steel rods that strengthen concrete). Concrete that was poorly compacted and utilized substandard materials, such as marine sands that corroded more easily than river sands, was another problem. Because of these poor construction practices, buildings in Port-au-Prince and other areas could not withstand the shaking from the magnitude 7.0 event.[4]

Thus, the answer to our question of why there were so many deaths from the earthquake is easy to find. A very heavy human footprint can be seen in the catastrophic loss of life. Had the buildings been constructed properly, many more lives would have been spared. If the population of Haiti had not grown so fast, with so many young people (thousands of schools collapsed during the earthquake), there would have been fewer deaths.

During the seven years since the earthquake, Haiti has not recovered, and in October of 2016, Hurricane Matthew hit the island, killing about 1,000 people and causing extensive destruction in many communities in more rural southern Haiti. People killed by the storm had to be buried in mass graves. A cholera outbreak occurred as people consumed contaminated water. The earthquake set the stage for extensive damage and loss of life as many people were living in poorly constructed shelters at risk from high winds and flooding. The land was vulnerable to erosion as a result of deforestation, and the hurricane destroyed crops and damaged the ability of the land to produce food. Thus, the catastrophic earthquake and lack of recovery rendered the

country more liable to damage from the hurricane in a cascade of declining conditions.

As Haiti rebuilds with international support, ways must be found to cost-effectively build the next generation of structures to better withstand seismic shaking and the high winds of storms. The consequences of another damaging earthquake or hurricane is painful to contemplate. Haiti must be assisted to take appropriate steps and be proactive in hazard preparation.[4]

1.1 Why Studying Natural Hazards Is Important

Since 1995, the world has experienced the deadliest tsunami in recorded history, caused by a massive Indian Ocean earthquake; another devastating tsunami in Japan caused by one of the largest and costliest earthquakes in recorded history; catastrophic flooding in Pakistan, Venezuela, Bangladesh, Thailand, and central Europe; a volcanic eruption that shut down international airports for more than a week; and deadly earthquakes around the world. At the same time, North America has experienced catastrophic hurricanes on the Gulf Coast, along the Atlantic Coast, and in Guatemala and Honduras; record-setting wildfires in western Canada, Arizona, Colorado, Utah, California, and the high plains of Kansas and Texas; the worst outbreak of tornadoes in U.S. history; a record-matching series of four hurricanes within six weeks in Florida and the Carolinas; a paralyzing ice storm in New England and Quebec; record-setting hail in Nebraska; and a rapid warming of the climate, especially (but not limited to) Alaska, northern Canada, and Arizona. These events are the result of enormous forces that are at work both inside and on the surface of our planet. In this book, we will explain these forces, how they interact with our civilization, and how we can better adjust to their effects. Although we will describe most of these forces as *natural hazards*, we can at the same time be in awe of and fascinated by their effects.

PROCESSES: INTERNAL AND EXTERNAL

In our discussion of these natural hazards, we will use the term *process* to mean the physical, chemical, and biological ways by which events, such as volcanic eruptions, earthquakes, landslides, and floods affect Earth's surface. Some of these processes, such as volcanic eruptions and earthquakes, are the result of internal forces deep within Earth. Most of these internal processes are explained by the theory of plate tectonics, one of the basic unifying theories in science. In fact, *tectonic plates*, large surface blocks of the solid Earth, are mapped by identifying zones of earthquakes and active volcanism (see Chapter 2).

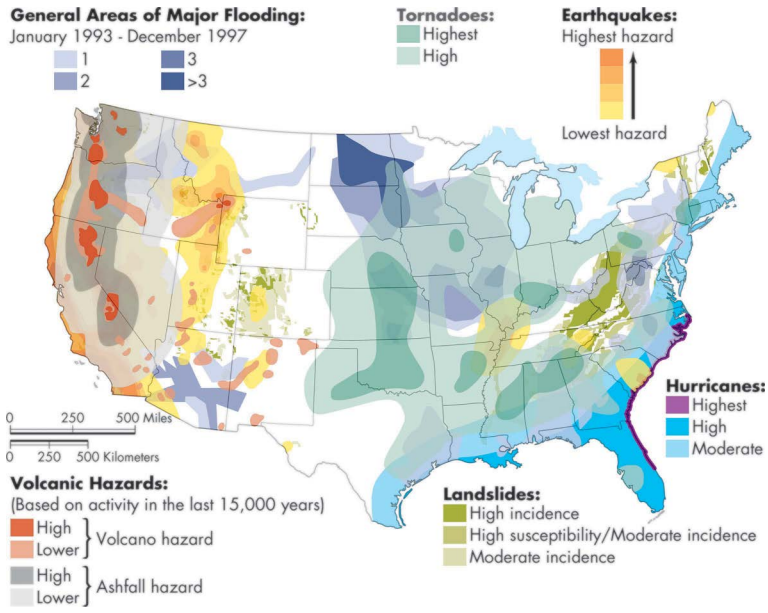
Other processes associated with natural hazards result from external forces that are at or very near Earth's surface. For example, energy from the sun warms Earth's atmosphere and surface, producing winds and evaporating water (see Chapter 9). Wind circulation and water evaporation are responsible for forming Earth's climatic zones and for driving the movement of water in the *hydrologic cycle*. These forces are in turn directly related to hazardous processes, such as violent storms and flooding, as well as coastal erosion. Still other external processes, such as landsliding, are the result of gravity acting on hillslopes and mountains. Gravity is the force of physical attraction to a mass—in this case, the attraction of materials on Earth's surface to the entire mass of Earth. Because of gravitational attraction, objects on hillslopes or along the bed of a river naturally tend to move downslope. Gravity results in water that falls as precipitation on mountain slopes, moving downhill on its way back to the ocean.

Thus, the processes we consider to be hazards result from natural forces such as the internal heating of Earth or external energy from the sun. The energy released by natural processes varies greatly. For example, the average tornado expends about 1,000 times as much energy as a lightning bolt, whereas the volcanic eruption of Mount St. Helens in May 1980 expended approximately a million times as much energy as a lightning bolt. The amount of solar energy Earth receives each day is about a trillion times that of a lightning bolt. However, it is important to keep in mind that a lightning bolt may strike a tree, igniting a tremendous release of energy in a forest fire, whereas solar energy is spread around the entire globe.

Events such as earthquakes, volcanoes, floods, and fires are natural processes that have been occurring on Earth's surface since long before it was populated by humans. These natural processes become hazardous when human beings live or work in their path. We often use the terms *hazard*, *disaster*, and *catastrophe* to describe our interaction with these natural processes.

HAZARD, DISASTER, OR CATASTROPHE

A **natural hazard** is a natural process and event that is a potential threat to human life and property. The process and the events themselves are not a hazard but become so because of human use of the land. A **disaster** is a hazardous event that occurs over a limited time span within a defined area. Criteria for a natural disaster are (1) 10 or more people are killed, (2) 100 or more people are affected, (3) a state of emergency is declared, and (4) international assistance is requested. If any one of these



< FIGURE 1.2 Major Hazards in the United States

Areas of the United States at risk for earthquakes, volcanoes, landslides, flooding, hurricanes, and tornadoes. Almost every part of the country is at risk for one of the six hazards considered here. A similar map or set of maps is available for Canada. *(From the U.S. Geological Survey)*

applies, an event is considered a *natural disaster*.[5,6] A **catastrophe** is a massive disaster that requires significant expenditure of money and a long time (often years) for recovery to take place. Hurricane Katrina, which flooded the city of New Orleans and damaged much of the coastline of Mississippi in 2005, was the most damaging, most costly catastrophe in the history of the United States. Recovery from this enormous catastrophe has taken years and still continues in parts of New Orleans.

Natural hazards affect the lives of millions of people, and all areas of the United States are at risk from more than one hazardous Earth process (Figure 1.2). Not shown in Figure 1.2 are the areas prone to blizzards and ice storms; the coastlines that have experienced tsunamis during the past century; the areas regularly affected by wildfires; the regions that have experienced drought, subsidence, or coastal erosion; or the craters made by the impacts of asteroids and comets. No area is considered hazard-free.

From 1996 to 2015, natural disasters such as earthquakes, floods, and hurricanes have killed about 1.3 million people worldwide, an average of about 65,000 people per year. Earthquakes and tsunamis accounted for 57 percent of the deaths, storms 18 percent, extreme temperature (hot or cold) 12 percent, and floods 11 percent.[7] Financial loss from natural disasters now exceeds $50 billion per year, with individual years capable of being much higher, and that figure does not include social losses such as loss of employment, mental anguish, and reduced productivity. Two individual disasters, a hurricane accompanied by flooding in Bangladesh in 1970 and an earthquake in China in 1976, each claimed well over 300,000 lives. The Indian Ocean tsunami in 2004 resulted in at least 230,000 deaths, and another hurricane that struck Bangladesh in 1991 claimed 145,000 lives (Figure 1.3). Hurricane Katrina in 2005 destroyed much of the coastal development in Mississippi and Louisiana and caused the flooding of New Orleans. Katrina killed more than 1,600 people and inflicted about $250 billion in damages, making the storm the largest financial catastrophe from a natural hazard in U.S. history. An earthquake in Pakistan in 2005 claimed more than 80,000 lives, destroyed many thousands of buildings, and caused extreme property damage (Figure 1.4). These catastrophes, along with the Haiti earthquake introduced in the chapter opener, were



^ FIGURE 1.3 Killer Hurricane

Flooded fields and villages adjacent to a river in Bangladesh the day after the 1991 hurricane struck the country, killing approximately 145,000 people. *(Defence Visual Information Center)*



FIGURE 1.4 Devastating Earthquake
People searching for victims in a 10-story building that collapsed in a major earthquake in Islamabad, Pakistan, in 2005. By the onset of winter, more than 87,000 people had died and more than 3 million were homeless. *(©Getty Images/FAROOQ NAEEM/Stringer)*

caused by natural processes and forces that have always existed. Hurricanes are caused by atmospheric disturbance, and Earth's internal heat drives the movement of tectonic plates, which causes earthquakes and, sometimes, tsunamis. The impact of these events is directly connected to human population density and land-use patterns.

During the last few decades, there has been a significant increase in the number of catastrophes and disasters worldwide (Figure 1.5: Disasters and catastrophes from 1980 to 2015; also shown are the events, by name and location, with the largest economic damage). Although there are several hundred disasters from natural hazardous events each year, only a few are classified as a great catastrophe—one that results in deaths or losses so great that outside assistance is required.[8] Of disasters since the 1990s, flooding and storms caused about 61 percent of disasters and about 56 percent of the total number of people affected by disasters, while earthquakes caused about 57 percent of the deaths, and, over the same period, countries with medium to low income suffered most from floods and storms. High-income countries suffered some of the greatest economic losses but the lowest number of deaths. The losses could have been even greater were it not for improvements in warning systems, disaster preparedness, and sanitation following disasters.[8–12] Nevertheless, economic losses have increased at a faster rate than have the number of deaths. Figure 1.6 shows the disasters in 2015. Notice that about half of the total disasters (44 percent) occurred in Asia where about two-thirds of the people (4.44 billion) on Earth live. By contrast, the United States, with about 0.33 billion people, experienced about 6 percent of the disasters.[8–12]

DEATH AND DAMAGE CAUSED BY NATURAL HAZARDS

When we compare the effects of various natural hazards, we find that those that cause the greatest loss of

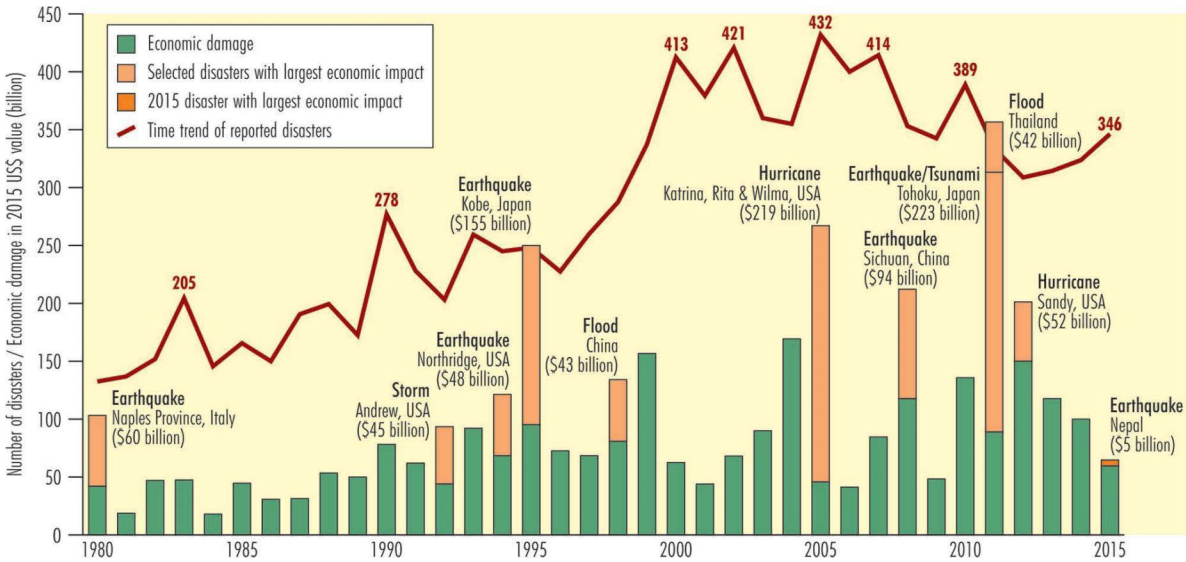


FIGURE 1.5 Disasters and Catastrophes 1980 to 2015 by Number of Events and Economic Losses
Several examples of events with very large economic costs are listed by date, type of hazard, and location.
(Center for Research on the Epidemiology, 2016. Disaster data: A balanced perspective. Cred Crunch Issue No. 41)

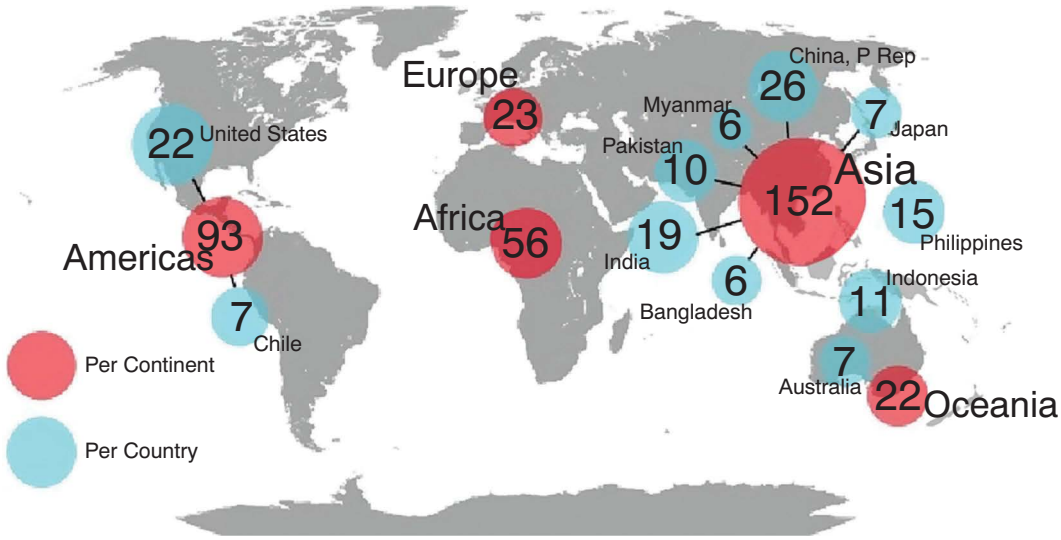


FIGURE 1.6 Number and Locations, by Continent and Country, of Natural Disasters in 2015
Notice that about half are in Asia. *(Center for Research on the Epidemiology, 2016. Disaster data: A balanced perspective. Cred Crunch Issue No. 41)*

human life are not necessarily the same as those that cause the most extensive property damage. The largest number of deaths each year is associated with tornadoes and windstorms, although heat waves, lightning, floods, and hurricanes also take a heavy toll. Loss of life from earthquakes can vary considerably from one year to the next because a single great quake can cause tremendous human loss. For example, in 1994, the large, but not great, Northridge earthquake in the Los Angeles area killed some 60 people and inflicted at least $20 billion in property damage. The next great earthquake in a densely populated part of California could inflict $100 billion in damages while killing several thousand people.[11]

Natural disasters cost the United States multibillion dollars annually; the average cost of a single major disaster may exceed $500 million. The cost in 2104 was about $25 billion. About 200 weather-related disasters and catastrophes have occurred in the United States since 1980. The total economic losses were about $1.1 trillion (an average of about $33 million per year). Hurricane Katrina cost about $250 billion (damages and other economic losses). Table 1.1 lists deaths (476) and economic loss (about $4 billion) from U.S. weather-related disasters in 2015. Floods claimed the most lives (176), but other hazards, including several types of storms, extreme temperature, and coastal beach rip currents, all were consistent killers. Because the population is steadily increasing in high-risk areas, such as along coastlines, we can expect this number to continue to increase significantly.[12]

TABLE 1.1 Deaths and Damages from Weather-related Natural Disasters in the United States for 2015

Event	Deaths	Total Damages (millions of dollars)
Lightning	27	16
Tornado	36	320
Thunderstorm (wind)	41	268
Extreme cold	53	3
Extreme heat	45	0
Flood	176	2,748
Rip current (coastal)	56	0
Hurricane	14	52
Winter storm	20	530
Ice	0	59
Avalanche	8	0

Source: www.nws.noaa.gov.

An important aspect of all natural hazards is their potential to produce a catastrophe, which has been defined as any situation in which the damages to people, property, or society in general are sufficient that recovery and/or rehabilitation is a long, involved process. Natural hazards vary greatly in their potential to cause a catastrophe (see Table 1.2). Floods, hurricanes, tornadoes,

TABLE 1.2 Potential for Humans to Influence Selected Natural Hazards in the United States

Hazard	Occurrence Influenced by Human Use	Potential to Produce a Catastrophe
Flood	Yes	High
Earthquake	Yes	High
Tsunami	No	High
Landslide	Yes	Moderate
Volcano	No	High
Coastal erosion	Yes	Low
Expansive soils	No	Low
Hurricane	Perhaps[a]	High
Tornado and windstorm	Perhaps[a]	High
Lightning	Perhaps[a]	Low
Drought	Perhaps[a]	Moderate
Frost and freeze	Perhaps[a]	Low
Heat wave	Perhaps[a]	High
Wildfire	Yes	High
Extraterrestrial[b] impact	No	Low

[a] Weather-related hazards are listed as perhaps being influenced by human processes because the role of climate change is not well understood.

[b] Extraterrestrial impact is in a separate class because small impacts are frequent, and a rare large impact may produce the largest catastrophes possible on Earth.

Source: Based on White, G. F., and Haas, J. E., *Assessment of Research on Natural Hazards*. Cambridge, MA: MIT Press, 1975.

earthquakes, volcanic eruptions, large wildfires, and heat waves are the hazards most likely to have a high potential to create catastrophes. Landslides, because they generally affect a smaller area, have only a moderate potential to produce a catastrophe. Drought also has a moderate potential to produce a catastrophe because, although drought may cover a wide area, there is usually plenty of warning time before its worst effects are felt. Hazards with a low potential to produce a catastrophe include coastal erosion, frost, lightning, and expansive soils.[13]

The effects of natural hazards change with time because of changes in patterns of human land use, as well as climate change. Urban growth can influence people to develop on marginal lands, such as steep hillsides and floodplains. This trend is a particular problem in areas surrounding major cities in developing nations where urbanization is proceeding rapidly. In addition to increasing population density, urbanization can also change the physical properties of earth materials by influencing drainage, altering the steepness of hillslopes, and removing vegetation. Changes in farming, forestry, and mining practices can affect rates of erosion and sedimentation, the steepness of hillslopes, and the nature of vegetative cover. Climate change in the United States and the world is affecting natural hazards. As the world warms, warming oceans feed more energy into storms, causing an increase in storm intensity. Rising sea levels and larger waves from more intense storms associated with global warming are flooding land and increasing coastal erosion. Climate change is also causing drought to become more common and more extreme in the arid and semiarid regions of Earth (see Chapter 12). Overall, damage from most natural hazards in the United States is increasing, but the number of deaths from many hazards is decreasing because of better prediction, forecasting, and warning.

1.1 CHECK your understanding

1. Differentiate between natural hazards, disasters, and catastrophes.
2. Which natural hazards in the United States take the most lives each year, and which are most costly from an economic perspective?
3. Which hazards have taken the most of the lives worldwide and in the United States in the past two decades?
4. How and why are land-use change and global warming influencing natural hazards?

1.2 The Role of History in Understanding Hazards

A fundamental principle for understanding natural hazards is that they are repetitive events, and, therefore, the study of their history provides much-needed information for any hazard reduction plan. You read in the chapter opener that poor building practices in Haiti led to the great loss of life when the earthquake struck. Whether we are studying earthquakes, floods, landslides, or volcanic eruptions, knowledge of historic events and the recent geologic history of an area is vital to our understanding and assessment of the hazard. For example, if we wish to evaluate the flooding history of a particular river, one of the first tasks is to identify floods that have occurred in the historic and recent prehistoric past. Useful information can be obtained by studying aerial photographs and maps as far back as the record allows. In our reconstruction of previous events, we can look for evidence of past floods in stream deposits. Commonly, these deposits contain organic material

such as wood or shells that may be radiocarbon dated to provide a chronology of ancient flood events. This chronology can then be linked with the historic record of high flows to provide an overall perspective of how often the river floods and how extensive the floods may be. Similarly, if we are studying landslides in a particular area, an investigation of both historic and prehistoric landslides is necessary to better predict future landslides. Geologists have the tools and training to "read the landscape" and evaluate prehistoric evidence for natural hazards. Linking the prehistoric and historic records extends our perspective of time when we study repetitive natural events.

In summary, before we can truly appreciate the nature and extent of a natural hazard, we must study in detail its historic occurrence, as well as any geologic features that it may produce or affect. These geologic features may be landforms, such as channels, hills, or beaches; structures, such as geologic faults, cracks, or folded rock; or earth materials, such as lava flows, meteorites, or soil. Any prediction of the future occurrence and effects of a hazard will be more accurate if we can combine information about historic and prehistoric behavior with a knowledge of present conditions and recent past events, including land-use changes.

To fully understand the natural processes we call hazards, some background knowledge of the geologic cycle processes that produce and modify earth materials, such as rocks, minerals, and water, is necessary. In the next few sections, we will discuss the geologic cycle and then introduce five concepts that are fundamental to understanding natural processes as hazards.

1.2 CHECK your understanding

1. Why is recent geologic history as well as human history important in the study of natural hazards?

1.3 The Geologic Cycle

Geologic conditions and materials largely govern the type, location, and intensity of natural processes. For example, earthquakes and volcanoes do not occur at random across Earth's surface; rather, most of them mark the boundaries of tectonic plates. The location of landslides, too, is governed by geologic conditions. Slopes composed of a weak rock, such as shale, are much more likely to slip than those made of a strong rock, such as granite. Hurricanes, although not themselves governed specifically by geology, will have differing effects, depending on the geology of the area they strike. An understanding of the components and dynamics of the geologic cycle will explain these relationships.

Throughout much of the 4.6 billion years of Earth's history, the materials on or near Earth's surface have been created, maintained, and destroyed by numerous physical, chemical, and biological processes. Continuously operating processes produce the earth materials, land, water, and atmosphere necessary for our survival. Collectively, these processes are referred to as the **geologic cycle**, which is really a group of subcycles that includes:

- the tectonic cycle
- the rock cycle
- the hydrologic cycle
- biogeochemical cycles.

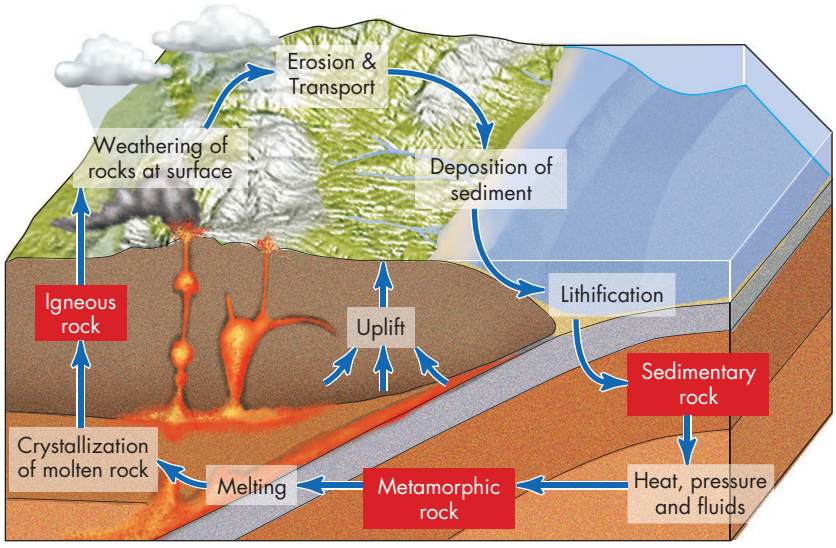
THE TECTONIC CYCLE

The term *tectonic* refers to the large-scale geologic processes that deform Earth's crust and produce landforms such as ocean basins, continents, and mountains. Tectonic processes are driven by forces deep within Earth. To describe these processes, we must use information about the composition and layering of Earth's interior and about the large blocks of the solid Earth that we call *tectonic plates*. The *tectonic cycle* involves the creation, movement, and destruction of tectonic plates. It is responsible for the production and distribution of rock and mineral resources invaluable to modern civilization, as well as hazards such as volcanoes and earthquakes. The tectonic cycle and its linkages to hazards is the subject of Chapter 2.

THE ROCK CYCLE

Rocks are aggregates of one or more *minerals*. A mineral is a naturally occurring, crystalline substance with defined properties (see Appendix A for a discussion of minerals). The *rock cycle* is the largest of the geologic subcycles, and it is linked to all the other subcycles. It depends on the tectonic cycle for heat and energy, the biogeochemical cycle for materials, and the hydrologic cycle for water. Water is then used in the processes of weathering, erosion, transportation, deposition, and lithification of sediment.

Although rocks vary greatly in their composition and properties, they can be classified into three general types, or families, according to how they were formed in the rock cycle (Figure 1.7); rocks and their properties are discussed in Appendix B. We may think of the rock cycle as a worldwide rock recycling process driven by Earth's internal heat, which melts the rocks



< FIGURE 1.7 The Rock Cycle
Idealized rock cycle showing the three types of rocks and important processes that form them. See text for discussion of processes.

subducted in the tectonic cycle (see Chapter 2). *Crystallization* of molten rock produces *igneous rocks* beneath and on Earth's surface. Rocks at or near the surface break down chemically and physically by *weathering* to form particles known as *sediment*. These particles vary in size from fine clay to very large pieces of boulder-sized gravel. Sediment formed by weathering is then transported by wind, water, ice, and gravity to depositional basins, such as the ocean. When wind or water currents slow down, ice melts, or when material moving downward due to gravity reaches a flat surface, the sediment settles and accumulates by a process known as *deposition*. The accumulated layers of sediment eventually undergo *lithification* (conversion to solid rock), forming *sedimentary rocks*. Lithification takes place by cementation and compaction as sediment is buried beneath other sediment.

With deep burial, sedimentary rocks may be metamorphosed (altered in form) by heat, pressure, or chemically active fluids to produce *metamorphic rocks*. Metamorphic rocks may be buried to depths where pressure and temperature conditions cause them to melt, beginning the entire rock cycle again. As with any other Earth cycle, there are many exceptions or variations from the idealized sequence. For example, an igneous or metamorphic rock may be altered into a new metamorphic rock without undergoing weathering or erosion, or sedimentary and metamorphic rocks may be uplifted and weathered before they can continue on to the next stage in the cycle. Finally, there are other sources of sediment that have a biological or chemical origin and types of metamorphism that do not involve deep burial. Overall, the type of rock formed in the rock cycle depends on the rock's environment.

The rock cycle has many links to natural hazards. Different rock types have different composition, and the different composition is often linked to specific processes. For example, limestone is composed of calcite ($CaCO_3$) which dissolves in weak soil and carbonic acid to form collapse pits known as sink holes (see Chapter 8). Shales are very common sedimentary rocks composed of fine particles. Shales are a red flag to those working with landslide hazards (see Chapter 7).

THE HYDROLOGIC CYCLE

The movement of water from the oceans to the atmosphere and back again is called the *hydrologic cycle* (Figure 1.8). Driven by solar energy, the cycle operates by way of evaporation, precipitation, surface runoff, and subsurface flow, and water is stored in different compartments along the way. These compartments include the oceans, atmosphere, rivers and streams, groundwater, lakes, and ice caps and glaciers (Table 1.3). The *residence time*, or estimated average amount of time that a drop of water spends in any one compartment, ranges from tens of thousands of years or more in glaciers to nine days in the atmosphere.

As you can see from studying Table 1.3, only a very small amount of the total water in the cycle is active near Earth's surface at any one time. Although the combined percentage of water in the atmosphere, rivers, and shallow subsurface environments is only about

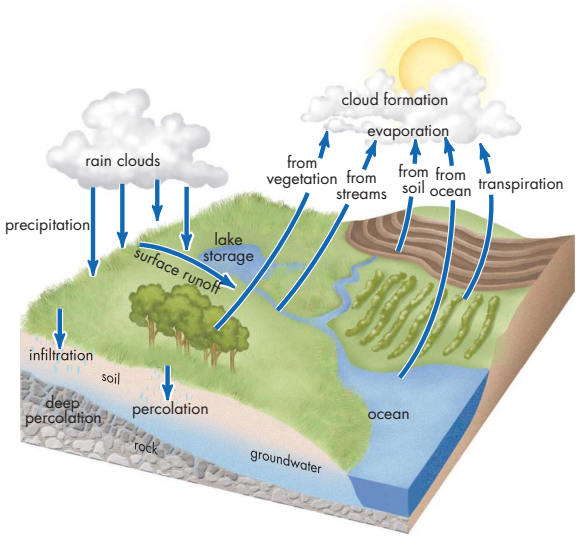


FIGURE 1.8 Hydrologic Cycle
Idealized diagram showing the hydrologic cycle's important processes and transfer of water. *(Based on the Council on Environmental Quality and Department of State.* The Global 2000 Report to the President, *Vol. 2., 1980)*

0.3 percent of the total, this water is tremendously important for life on Earth and for the rock and biogeochemical cycles. This surface or near-surface water helps move and sort chemical elements in solution, sculpt the landscape, weather rocks, transport and deposit sediments, and provide our water resources.

The hydrologic cycle is closely related to most natural hazards:

- Surface runoff is the primary factor in river flooding (see Chapter 6)
- Groundwater is one of the most important factors in landslides and subsidence (see Chapters 7 and 8)
- Water is important in volcanic processes (see Chapter 5)
- Water injected with other materials is an important factor in human-induced earthquakes (see Chapter 3)
- Water in motion in the oceans and atmosphere is an important factor in coastal erosion and violent storms (see Chapters 9–11)
- Water vapor is an important factor in atmospheric processes that produce storms. As a result, it is a significant factor in climate change and changes in hazardous events (see Chapter 12).

BIOGEOCHEMICAL CYCLES

A *biogeochemical cycle* is the transfer or cycling of a chemical element or elements through the atmosphere (the layer of gases surrounding Earth), lithosphere (Earth's rocky outer layer), hydrosphere (oceans, lakes, rivers, and groundwater), and biosphere (the part of the Earth where life exists). It follows from this definition that biogeochemical cycles are intimately related to the tectonic, rock, and hydrologic cycles. The tectonic cycle provides water from volcanic processes, as well as the heat and energy required to form and change the earth materials transferred in biogeochemical cycles. The rock and hydrologic cycles are involved in many processes that transfer and store chemical elements in water, soil, and rock.

Biogeochemical cycles can most easily be described as the transfer of chemical elements through a series of storage compartments or reservoirs (e.g., air, soil, groundwater, vegetation). For example, carbon (in the

TABLE 1.3 The World's Water Supply (Selected Examples)

Location	Surface Area (km^2)	Water Volume (km^2)	Percentage of Total Water	Estimated Average Residence Time
Oceans	361,000,000 (139,000,000 $mi.^2$)	1,230,000,000 (295,000,000 $mi.^3$)	97.2	Thousands of years
Atmosphere	510,000,000 (197,000,000 $mi.^2$)	12,700 (3047 $mi.^3$)	0.001	9 days
Rivers and streams	–	1,200 (288 $mi.^3$)	0.0001	2 weeks
Groundwater; shallow	130,000,000 (50,000,000 $mi.^2$)	4,000,000 (960,000 $mi.^3$)	0.31	Hundreds to many thousands of years to a depth of 0.8 km
Lakes (freshwater)	855,000 (330,000 $mi.^2$)	123,000 (29,500 $mi.^3$)	0.009	Tens of years
Ice caps and glaciers	28,200,000 (10,900,000 $mi.^2$)	28,600,000 (6,860 $mi.^3$)	2.15	Up to tens of thousands of years and longer

Source: Data from U.S. Geological Survey.

form of CO_2) is exhaled by animals, enters the atmosphere, and is then taken up by plants. When a biogeochemical cycle is well understood, the rate of transfer, or *flux*, among all the compartments is known. However, determining these rates on a global basis is a very difficult task. The amounts of such important elements as carbon, nitrogen, and phosphorus in each compartment, and their rates of transfer among compartments, can be only approximately known. The carbon cycle (CO_2) is of particular importance to hazards as it is associated with global warming, which is changing climate and the nature and intensity of weather-driven processes, such as intense storms.

1.3 CHECK your understanding

1. Define the geologic cycle and describe its subcycles.
2. Why is the geologic cycle pertinent to understanding natural hazards?

1.4 Fundamental Concepts for Understanding Natural Processes as Hazards

The five concepts described next are basic to an understanding of natural hazards. These fundamental concepts serve as a conceptual framework for our discussion of each natural hazard in subsequent chapters of this book. Most chapters begin and end with a case study that evaluates a natural hazard with respect to each of the five fundamental concepts described below.

1

Science helps us predict hazards.

SCIENCE AND NATURAL HAZARDS

Science is a body of knowledge that has accumulated from investigations and experiments, the results of which are subject to verification. The method of science, often referred to as the scientific method, has a series of steps. The first step is the formulation of a question. With respect to a hazardous event, geologists may ask: Why did a landslide occur that destroyed three homes? In order to explore and answer this question, geologists will spend time examining the slope that failed. They may notice that a great deal of water is emerging from the base of the slope and landslide. If the geologists also know that a water line is buried in the slope, they may refine the question to ask specifically: Did the water in the slope cause the landslide? This question is the basis for a hypothesis that may be stated as follows: The landslide occurred because a buried water main within the slope broke, causing a large amount of water to enter the slope, reducing the strength of the slope materials and causing the landslide. Often, a series of questions or multiple hypotheses are tested.

The hypothesis is, thus, a possible answer to our question and is an idea that can be tested. In our example, we may test the hypothesis that a broken water main caused a landslide by excavating the slope to determine the source of the water. In science, we test hypotheses in an attempt to disprove them. That is, if we found that there were no leaking water pipes in the slope on which the landslide occurred, we would reject the hypothesis and develop and test another hypothesis. Use of the scientific method has improved our understanding of many natural earth processes, including flooding, volcanic eruptions, earthquakes, hurricanes, and coastal erosion. In our scientific study of natural processes, we have identified where most of these processes take place, their range of magnitude, and how frequently they occur. We have also mapped the nature and extent of hazards. Coupled with knowledge of the frequency of past events, we can use such maps to predict when and where processes such as floods, landslides, and earthquakes will occur in the future. We have also evaluated patterns and types of precursor events. For example, prior to large earthquakes, there may be foreshocks and, prior to volcanic eruptions, patterns of gas emissions may signal an imminent eruption.

HAZARDS ARE NATURAL PROCESSES

Since the dawn of human existence, we have been obligated to adjust to processes that make our lives more difficult. We humans apparently are a product of the Pleistocene ice ages, which started about 2 million years ago (Table 1.4). The Pleistocene epoch and Holocene epoch (last 11,000 years) experienced rapid climatic changes—from relatively cold, harsh glacial conditions as recently as a few thousand years ago to the relatively warm interglacial conditions we enjoy today. Learning to adjust to harsh and changing climatic conditions has been necessary for our survival from the very beginning.

It has recently been suggested that we may be in a new epoch known as the Anthropocene epoch. The idea for an Anthropocene epoch is that humans have so

profoundly changed Earth that a new unit of geologic time is necessary to define it. To be a new unit of geologic time there needs to be a strong signal in earth materials (sometimes called a "golden spike") that is present in the Earth's rock record, such as the dinosaur extinction 65 million years ago (Table 1.4). The signal for the Anthropocene must be a geologic marker in the distant future. The concept is controversial, and there is no agreement on when (or if) a Holocene-Anthropocene boundary should be defined. Candidates for the boundary, include the Industrial Revolution (mid-eighteenth century), the extensive use of plastics (plastic pollution) starting in the early twentieth century, or about 1950 when radioactive elements were dispersed across the globe by nuclear bomb experiments. Geologic time is so long that it is difficult, perhaps impossible, to define a new unit of time that just started.

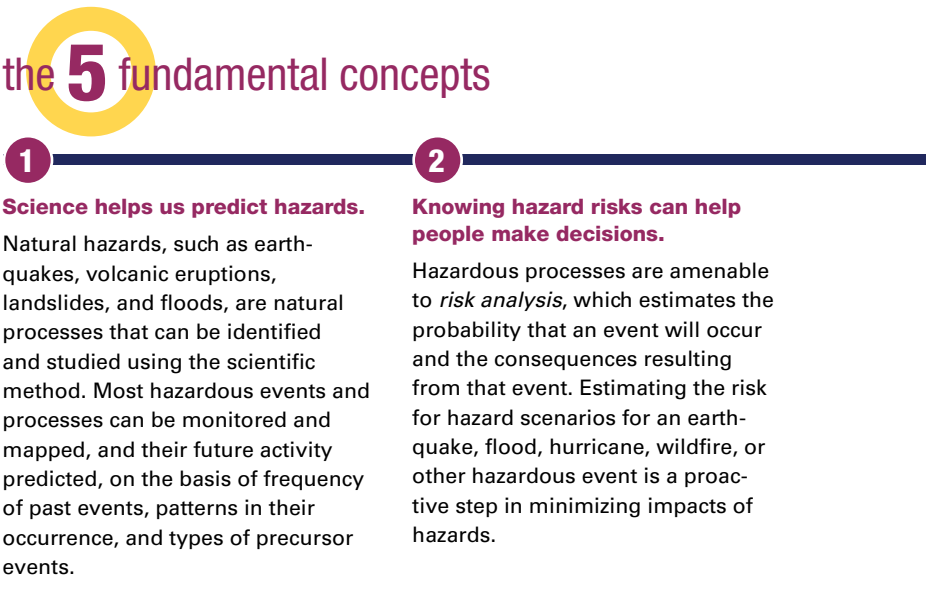
Events we call natural hazards are natural Earth processes. They become hazardous when people live or work near these processes and when land-use changes such as urbanization or deforestation amplify their effect. To reduce damage and loss of life, it is imperative to identify potentially hazardous processes and make this information available to planners and decision makers. However, because the hazards that we face are natural and not the result of human activities, we encounter a philosophical barrier whenever we try to minimize their adverse effects. For example, when we realize that flooding is a natural part of river dynamics, we must ask ourselves if it is wiser to attempt to control floods or to simply make sure that people and property are out of harm's way when they occur.

Although it is possible to control some natural hazards to a certain degree, many are completely beyond our control. For example, although we may have some success in temporarily preventing damage from forest fires by using controlled burns and advanced firefighting techniques, we will never be able to prevent earthquakes. In fact, we may actually worsen the effects of natural processes simply by labeling them as hazardous. Rivers will always flood. Because we choose to live and work on floodplains, we have labeled floods as hazardous processes. This label has led to attempts to control floods. Unfortunately, as we will discuss later, some flood control measures actually intensify the effects of flooding, thereby increasing the very hazard we are trying to prevent (see Chapter 6). The best approach to hazard reduction is to identify hazardous processes and delineate the geographic areas where they occur. Every effort should be made to avoid putting people and property in harm's way, especially for those hazards, such as earthquakes, that we cannot control.

FORECAST, PREDICTION, AND WARNING OF HAZARDOUS EVENTS

Predicting Changes in the Earth System The idea that "the present is the key to the past," called **uniformitarianism**, was popularized in 1785 by James Hutton (referred to by some scholars as the father of geology) and is heralded today as a fundamental concept of Earth sciences. As the name suggests, uniformitarianism holds that processes we observe today also operated in the past (flow of water in rivers, formation and movement of glaciers, landslides, waves on beaches, uplift of the land from earthquakes, and so on). Uniformitarianism does not demand or even suggest that the magnitude (amount of energy expended) and frequency (how often a particular process occurs) of natural processes remain constant with time. We can infer that for as long as Earth has had an atmosphere, oceans, and continents similar to those of today, the present processes were operating.

In making inferences about geologic events, we must consider the effects of human activity on the Earth system and what effect these changes to the system as a whole may have on natural Earth processes. For example, small streams with drainage areas of a few to several tens of square kilometers will flood, regardless of human activities, but human activities, such as



paving the ground in cities, increase runoff and therefore increase the magnitude and frequency of flooding. That is, floods of a particular size are more frequent following the paving, and a particular rainstorm can produce a larger flood than before the paving. Therefore, to predict the long-range effects of flooding, we must be able to determine how future human activities will change the size and frequency of floods. In this case, *the present is the key to the future.* For example, when environmental geologists examine recent landslide deposits (Figure 1.9) in an area designated to become a housing development, they must use uniformitarianism to infer where there will be future landslides, as well as to predict what effects urbanization will have on the magnitude and frequency of future landslides. We will now consider linkages between processes in what is called environmental unity or "you can't do just one thing."

The principle of **environmental unity** states that one action causes others in a chain of actions and events. For example, if we remove the native vegetation from a steep slope or build a large structure on top of the slope, a landslide may occur. The slide mass may move into a canyon and dam a stream, which will cause the stream flow to back up, forming a lake. The dam of landslide material could be overtopped and quickly eroded, causing a flood. Alternatively, the dam may become saturated and collapse, producing a muddy flow of water and debris downstream as a destructive debris flow. Either event could destroy homes and perhaps kill people down the valley. Thus, modifying and destabilizing the slope set off a chain or series of events that changes the environment where people live. Therefore, when we consider the potential effects of a particular event, we need to think about what other events could happen and take appropriate precautions.

A **prediction** of a hazardous event such as an earthquake involves specifying the date, time, and size of the event. This is different from predicting where or how often a particular event such as a flood will occur. A **forecast**, on the other hand, has ranges of certainty. The weather forecast for tomorrow may state there is a 40 percent chance of showers. Learning how to predict hazardous events so we can minimize human loss and property damage is an important endeavor. For some natural hazards, we have enough information to predict or forecast events accurately. When there is insufficient information available, the best we can do is locate areas where hazardous events have occurred and infer where and when similar future events might take place. If we know both the probability and the possible consequences of an event occurring at a particular location, we can assess the risk that the event poses to people and property, even if we cannot accurately predict when it will next occur.

The effects of a hazardous event can be reduced if we can forecast or predict it and if we can issue a warning. Attempting to do this involves most or all of the following elements:

- Identifying the location where a hazardous event is likely to occur
- Determining the probability that an event of a given magnitude will occur
- Observing any precursor events
- Forecasting or predicting the event
- Warning the public.

3

Linkages exist between natural hazards.

Hazardous processes are linked in many ways. For example, earthquakes can produce landslides, and giant sea waves (called tsunamis) and hurricanes often cause flooding and coastal erosion.

4

Humans can turn disastrous events into catastrophes.

The magnitude, or size, of a hazardous event, as well as its frequency or how often it occurs, may be influenced by human activity. As a result of increasing human population and poor land-use practices, events that used to cause disasters are now often causing catastrophes.

5

Consequences of hazards can be minimized.

Minimizing the potential adverse consequences and effects of natural hazards requires an integrated approach that includes scientific understanding, land-use planning, and regulation, engineering, and proactive disaster preparedness.

TABLE 1.4 Geologic Time with Important Events

Era	Period	Epoch	Million Years before Present	Events: Life	Events: Earth	Million Years before Present	True Scale (Million Years before Present)
Cenozoic	Neogene / Quaternary	Holocene	0.0114	• Extinction event • Modern humans	Ice age		
		Pleistocene		• Early humans	Formation of Transverse Ranges, CA		
			1.8			1.8	
	Neogene / Tertiary	Pliocene	5.3		Formation of Andes Mountains		
		Miocene	23	• Grasses • Whales	Collision of India with Asia forming Himalayan Mountains and Tibetan Plateau		
	Paleogene / Tertiary	Oligocene	34	• Extinction event			
		Eocene	56	• Mammals expand			
		Paleocene	65		Rocky Mountains form	65	
Mesozoic	Cretaceous			• Dinosaur extinction[1], extinction event • Flowering plants	Emplacement of Sierra Nevada granites (Yosemite National Park)		
			146				
	Jurassic			• Birds			
			200	• Extinction event • Mammals	• Supercontinent Pangaea begins to break up		
	Triassic			• Dinosaurs			
			251			251	
Paleozoic	Permian			• Extinction event • Reptiles	• Ice age		
			299				
	Carboniferous			• Coal swamps			
			359	• Extinction event • Trees	Appalachian Mountains form		
	Devonian			• Land plants			
			416	• Extinction event			
	Silurian						
			444	• Fish			
	Ordovician						
			488	• Explosion of organisms with shells			
	Cambrian						
			542	• Multicelled organisms	• Ice age	542	
Precambrian time			2500	• Free oxygen in atmosphere and ozone layer in stratosphere	• Ice age		
			3500	• Primitive life (first fossils)			
			4000		• Oldest rocks		
			4600		• Age of Earth	4600	4600

[1]Many scientists believe that not all dinosaurs became extinct but that some dinosaurs evolved into birds.

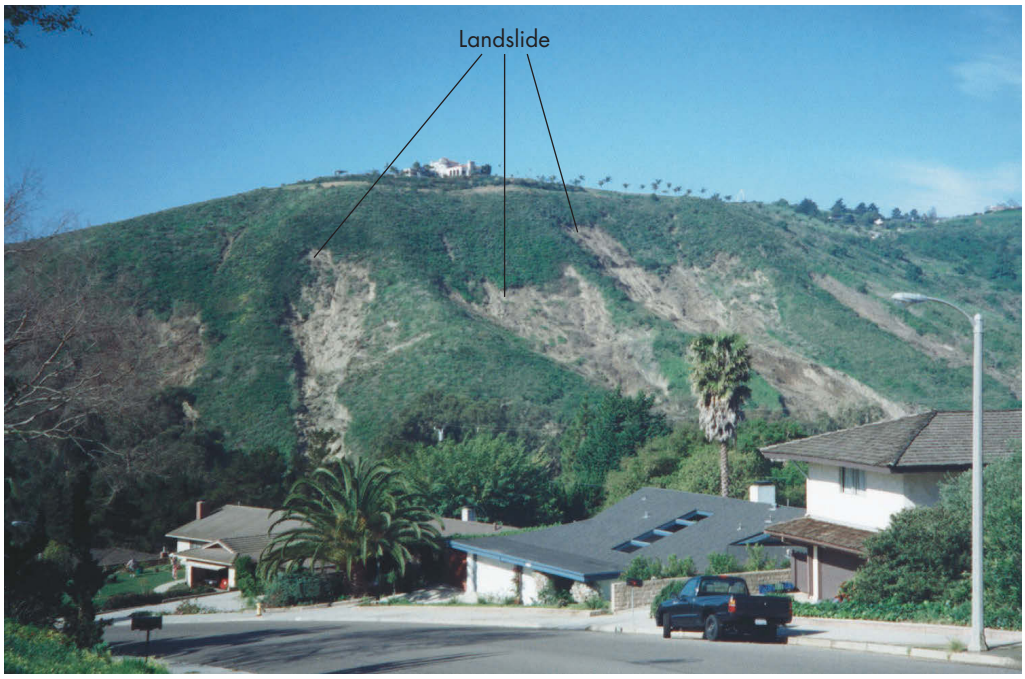


FIGURE 1.9 Urban Development
The presence of a landslide on this slope suggests that the slope is not stable, and that further movement may occur in the future. This is a "red flag" for future development in the area. *(Edward A. Keller)*

Location For the most part, we know where a particular kind of event is likely to occur, and we can accurately map where such events have occurred (see Appendix C for a discussion of maps and images useful in hazard analysis). On a global scale, the major zones for earthquakes and volcanic eruptions have been delineated by mapping (1) where earthquakes have occurred, (2) the extent of recently formed volcanic rocks, and (3) the locations of recently active volcanoes. On a regional scale, we can use past eruptions to identify areas that are likely to be threatened in future eruptions. This risk has been delineated for several Cascade Range volcanoes such as Mt. Rainier in the Pacific Northwest, as well as for several volcanoes in Japan, Italy, Colombia, and elsewhere. On a local scale, detailed mapping of soils, rocks, groundwater conditions, and surface drainage may identify slopes that are likely to fail or where expansive soils exist. In most cases, we can predict where flooding is likely to occur from the location of the floodplain and from mapping the extent of recent floods.

Probability of Occurrence Determining the probability of a particular event occurring at a particular location within a particular time span is an essential part of a hazard prediction (see Appendix D for a discussion of how geologists determine the all-important chronology necessary to evaluate the time element of hazard evaluation and probability of occurrence). For many rivers, we have sufficiently long records of flow to develop probability models that can reasonably predict the average number of floods of a given magnitude that will occur in a decade. Likewise, droughts may be assigned a probability on the basis of past rainfall in the region. However, these probabilities are similar to the chances of throwing a particular number on a die or drawing an inside straight in poker—the element of chance is always present. Although the 10-year flood may occur on average only once every 10 years, it is possible to have several floods of this magnitude in any one year, just as it is possible to throw two straight sixes with a die.

Precursor Events Many hazardous events are preceded by *precursor events*. For example, the surface of the ground may creep (i.e., move slowly for a long period of time) prior to an actual landslide. Often, the rate of creep increases up to the final failure and landslide. Volcanoes sometimes swell or bulge before an eruption and, often, earthquake activity increases significantly in the area. Foreshocks or unusual uplift of the land may precede earthquakes.

Identification of precursor events helps scientists predict when and where a major event is likely to happen. Thus, measurements of landslide creep or swelling

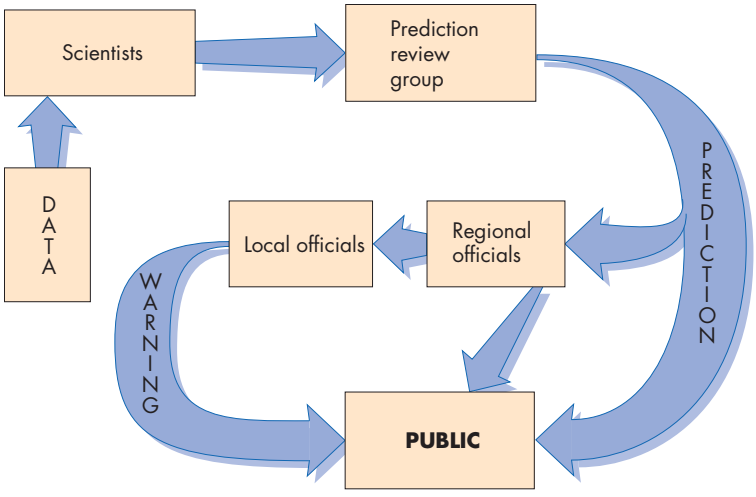
of a volcano may lead authorities to issue a warning and evacuate people from a hazardous area.

Forecasting and Prediction When a forecast of an event is issued, the certainty of the event is given, usually as the percent chance of something happening. When we hear a forecast of a hazardous event, it means we should be prepared for the event.

It is sometimes possible to accurately predict when certain natural events will occur. Flooding of the Mississippi River, which occurs in the spring in response to snowmelt or large regional storm systems, is fairly common. Hydrologists with the National Weather Service usually can predict when the river will reach a particular flood stage or water level. When a hurricane is spotted far out to sea and tracked toward the shore, we can predict when and where it will likely strike land. Large ocean waves, called tsunamis, that are generated by undersea earthquakes, landslides, and other disturbances, may also be predicted once they form. In the past several decades, the prediction of the arrival time for tsunamis in the Pacific Ocean has been fairly successful. Even a short-notice prediction of a hazardous event, such as a tornado, motivates us to act to reduce potential consequences before the event happens.

Warning After a hazardous event has been predicted or a forecast has been made, the public must be warned. The flow of information leading to the **warning** of a possible disaster—such as a large earthquake or flood—should move along a predefined path (Figure 1.10). People do not always welcome such warnings, especially when the predicted event does not come to pass. In 1982 geologists advised that a volcanic eruption near Mammoth Lakes, California, was quite likely. The eruption did not occur, and the advisory was eventually lifted, but this advisory caused loss of tourist business and apprehension for the residents. In July 1986, a series of earthquakes occurred over a four-day period near Bishop, California. The quakes began with minor magnitude 3.0 tremors and culminated in a damaging magnitude 6.1 shock. Investigators concluded that there was a high probability of a larger quake in the vicinity in the near future and issued a warning. Local business owners, who feared the loss of summer tourism, thought that the warning was irresponsible; in fact, the predicted quake never materialized.

Incidents of this kind have led some people to conclude that scientific predictions are worthless, and that advisory warnings should not be issued. Part of the problem is poor communication between the investigating scientists and the news media. Newspaper, television, Internet, and radio reports may fail to explain the evidence or the probabilistic nature of natural hazard prediction, leading the public to expect completely certain statements about what will happen. Although scientists are not yet able to predict volcanic eruptions and earthquakes accurately, it would seem that they have a responsibility to publicize their informed judgments. An informed public is better able to act responsibly than an uninformed public, even if the subject makes people uncomfortable. Ship captains, who depend on weather advisories and warnings of changing conditions, do not suggest that they would be better off not knowing about an impending storm, even though the storm might veer and miss the ship. Just as weather warnings have proved useful for planning, official warnings of hazards such as earthquakes, landslides, and floods are also useful to people deciding where to live, work, and travel.



< FIGURE 1.10 Hazard Prediction or Warning
Possible flow path for issuance of a prediction or warning for a natural disaster.

Consider once more the prediction of a volcanic eruption in the Mammoth Lakes area of California. The location and depth of earthquakes suggested to scientists that molten rock was moving toward the surface. In light of the high probability that the volcano would erupt and of the possible loss of life if it did, it would have been irresponsible for scientists not to issue an advisory. Although the predicted eruption did not occur, the warning led the community to develop evacuation routes and consider disaster preparedness. This planning may prove useful, for it is likely that a volcanic eruption will occur in the Mammoth Lakes area in the future. The most recent event occurred only 600 years ago! As a result of the prediction, the community is better informed than it was before and, thus, better able to deal with an eruption when it does occur.

2

Knowing hazard risks can help people make decisions.

Before rational people can discuss and consider adjustments to hazards, they must have a good idea of the risk that they face in various circumstances. The field of risk assessment is rapidly growing, and its application in the analysis of natural hazards probably should be expanded.

RISK AS A CONCEPT

The **risk** of a particular event may be simply defined as the product of the probability of that event occurring multiplied by the consequences should it occur.[14] Consequences (damages to people, property, economic activity, public service, and so on) can be expressed on a variety of scales. If, for example, we are considering the risk of earthquake damage to a nuclear reactor, we may evaluate the consequences in terms of radiation released, which then can be related to damages to people and other living things. In any such assessment, it is important to calculate the risks for various possible events (scenarios), for example, for earthquakes of various magnitudes. A large event has a lower probability than does a small one, but its consequences are likely to be greater.

Thinking deeper about risk (Figure 1.11), we have come to realize that the hazard and the probability of occurrence of hazards includes both the natural process (earthquake, flood, etc.) and the human processes that can change the probability. For example, urbanization can change the magnitude and frequency of flooding, and human-induced climate change is increasing the intensity of storms. Likewise, consequences are

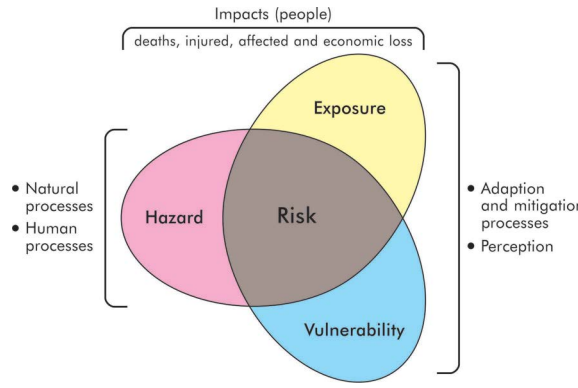


FIGURE 1.11 Risk
Defined as the intersection of hazard, exposure, and vulnerability. *(Modified after IPCC, 2014. Climate change 2014: Impacts, summary, and vulnerability. Technical Summary)*

complex, including the concepts of resiliency, exposure, vulnerability, adaption, mitigation, hazard perception, and social media. Thus, risk can be thought of as the product of hazard, exposure, and vulnerability.[15] Resiliency is the ability to absorb damage and recover from a hazardous event. Exposure refers to elements (people and property) at risk from a natural hazard. Vulnerability is the degree of loss due to exposure to a hazardous event such as a flood or storm (the inverse of resiliency). Vulnerability may vary. For example, a person living in an landslide-prone home who seldom leaves home is more vulnerable to the landslide hazard than other family members who attend school or leave the home each day to work in a nearby town or city. Adaption refers to options that may be taken to reduce exposure and vulnerability, such as insurance, evacuation, engineering to strengthen infrastructure and protect people, and land-use planning to avoid hazardous areas. Mitigation means to reduce the effects of something and is often used by scientists, planners, and policy makers in describing disaster preparedness efforts. For example, after earthquakes and floods, water supplies may be contaminated by bacteria, increasing the spread of diseases. To mitigate the effects of this contamination, a relief agency or government may deploy portable water treatment plants, disinfect water wells, and distribute bottled water.

Vulnerability and exposure can also be reduced by using online resources and social media. For example, during changing conditions of a hazardous event such as a flood, people may use their smartphones to alert friends and family of what is going on (when floodwater will arrive and how deep the flooding is likely to be) and how to respond, such as when to evacuate or how to protect property. Many people have smartphones, and warnings can be issued by emergency agencies and

others that a tsunami may arrive soon from a distant earthquake at beaches and coastal communities. Warnings may also be used to alert people to landslides or storms that have closed roads or where emergency help is needed. Possibilities are numerous. During the disastrous 2011 Bangkok flood, social media is thought to have helped reduce damage to property by as much as 37 percent by providing real-time flood conditions of flood location and depth that allowed people to move some possessions out of harm's way.[16]

Determining *acceptable risk* is also complicated, for the risk that society or individuals are willing to take depends on the situation. Driving an automobile is fairly risky, but most of us accept that risk as part of living in a modern world. On the other hand, for many people the acceptable risk from a nuclear power plant is very low because they consider almost any risk of radiation poisoning unacceptable. Nuclear power plants are controversial because many people perceive them as high-risk facilities. Even though the probability of an accident owing to a geologic hazard such as an earthquake may be quite low for most power plants, the consequences could be devastating, resulting in a relatively high risk.

Institutions, such as the government and banks, approach the topic of acceptable risk from an economic point of view rather than from a personal perception of the risk. For example, a bank will consider how much risk it can tolerate with respect to flooding. The federal government may require that any property receiving a government loan cannot have a flood hazard risk that exceeds 1 percent per year; that is, the property must be protected up to and including the 100-year flood.

On an individual level, it is important to recognize that you have some degree of choice regarding the level of risk you are willing to live with. For the most part, you can choose where you are willing to live. If you move to the North Carolina coast, you should realize you are putting yourself in the path of potentially deadly hurricanes. If you choose to live in Los Angeles, it is highly likely that in your lifetime you will experience an earthquake. So why do people live in hazardous areas? Perhaps you were offered an excellent job in North Carolina, or the allure of warm weather, mountains, and the ocean drew you to Los Angeles. Whatever the case, we as individuals must learn to weigh the pros and cons of living in a given area and decide whether or not it is worth the risk. This assessment should consider factors such as the level of potential devastation caused by an event, the frequency of the event, and the extent of the geographic area at risk, and it should compare these factors to the potential benefits of living in the high-risk area. In this way, we determine our own acceptable risk, which may vary from person to person.

A frequent problem of risk analysis is a lack of reliable data for analyzing either the probability or the consequences of an event. It can be difficult to assign probabilities to geologic events such as earthquakes and volcanic eruptions because the known record of past events is often inadequate.[13] Similarly, it may be difficult to determine the consequences of an event or series of events. For example, if we are concerned with the consequences of releasing radiation into the environment, we need a lot of information about the local biology, geology, hydrology, and meteorology, all of which may be complex and difficult to analyze. Despite these limitations, risk analysis is a step in the right direction. As we learn more about determining the probability and consequences of a hazardous event, we should be able to provide the more reliable analyses necessary for decision making.

RISK MANAGEMENT

Management of risk from natural hazards is part of the broader field of land-use planning and hazard management programs for cities, counties, states, and the United States. The national agency is the Federal Emergency Management Agency (FEMA). Natural hazard plans for cities and counties have names such as Emergency Management Plan, and they include discussions of hazard assessment for specific events, such as earthquake, flood, and wildfire; hazard mitigation, which includes specific actions to reduce exposure and vulnerability to natural hazards; and action taken for recovery following a natural hazard event.

Hazard management is becoming more complex because increasing human population has resulted in more people in cities and rural localities living in areas where natural hazards occur (although no place is completely free from exposure to natural hazards), and global change is altering the intensity and occurrence of violent storms and heat waves linked to other hazards, such as wildfire and landslides. Complex natural hazard problems are often resistant to clear problem definitions and easily identified solutions. Some natural hazard management issues involve social, political, and cultural issues that make problem solutions difficult if not impossible to resolve. Such problems are sometimes labeled as a **wicked problem**.[17] Here, the term "wicked" is not used in the familiar and historic sense of something immoral or evil or in the more modern usage of the term to indicate something pleasurable or desirable. Rather, it is used to indicate resistance to a solution. Wicked problems do not have simple solutions. Not all complex natural hazard management problems are wicked, but those with strong social or political implications may be. Science alone is not able

to mitigate wicked problems. Progress (positive change) on wicked problems requires the use of science, politics, economics, and social justice. Approaches to wicked problems include:[17] decision making at regional to local levels, including government and non-government organizations and private ownership; decision making across several administrative levels in regard to water, land, and air; balancing differences in economic, social, political, and scientific norms and values of the various stakeholders; and, perhaps most important, use of adaptive management.

Adaptive management is a science-based active process that recognizes the uncertainty of future outcomes; the limited usefulness of predictions; and the importance of learning through field experience, monitoring, reevaluating, and being flexible.[17]

Examples of wicked problems associated with natural hazards include natural hazards such as coastal erosion. Coastal erosion is a complex problem with a difficult solution because those living near or visiting beaches often have competing values. Property owners wish to protect their private property, often at the expense of the beach. People visiting the beach for recreation such as swimming or walking wish to protect the beach, even at the expense of property owners. If there is a beach park with grass, picnic tables and areas designated for social gatherings merging with the beach, people using these areas may well value the grass more than the beach itself. The agencies responsible for managing a beach may belong to the city, county, or state, and the issues involved may include water and air quality as well. There are no easy answers to this wicked problem. Therefore, best management is often incremental management (including adaptive management) that needs to be flexible, monitored, reevaluated, and, possibly, changed over time.

3

Linkages exist between natural hazards.

Many of the hazards are linked. For example, hurricanes are often associated with flooding, and intense precipitation associated with hurricanes can cause erosion along a coast and landslides on inland slopes. Volcanic eruptions on land are linked to mudflows and floods, and eruptions in the ocean are linked to tsunamis. Wildfire that denudes vegetation is often linked to soil erosion, landslides, and flooding as runoff from burned slopes increases (see Chapter 13). Climate change with warming oceans and rising sea levels are linked to more intense storms such as hurricanes, as well as to accelerated coastal erosion (see Chapter 12).

One disaster can influence others as a cascade of conditions. One disaster can impact another disaster that soon follows after the first. For example, an earthquake or flood that causes significant loss of life and property damage can lead to pollution of water supplies, resulting in an outbreak of water-borne disease. Consider a severe storm, such as a tropical cyclone with high winds and torrential rain that damages or destroys homes in an area with little resiliency. People are forced into temporary shelter (perhaps tents). If another severe storm occurs before repairs and new housing is made available, then the loss of life may well be worse than in the first storm.

4

Humans can turn disastrous events into catastrophes.

Early in the history of our species, our struggle with earth processes was probably a day-to-day experience. However, our numbers were neither great nor concentrated, so losses from hazardous earth processes were not very significant. As people learned to produce and maintain a larger and, in most years, more abundant food supply, the population increased and became concentrated near sources of food. The concentration of population and resources also increased the effect of periodic earthquakes, floods, and other potentially hazardous natural processes. This trend has continued, so that many people today live in areas that are likely to be damaged by hazardous earth processes or are susceptible to the effect of such processes in adjacent areas. An increase in population puts a greater number of people at risk and also forces more people to settle in hazardous areas, therefore increasing the need for planning in order to minimize losses from natural disasters.

EXAMPLES OF DISASTERS IN DENSELY POPULATED AREAS

Mexico City is the center of North America's largest and the world's third most populous metropolitan area. Approximately 22 million people are concentrated in an area of about 2300 km^2 (~890 $mi.^2$). Families in this area average five members, and an estimated one-third of the families live in a single room. The city is built on ancient lakebeds that amplify the shaking in an earthquake, and parts of the city have been sinking several centimeters per year due to pumping of groundwater. The subsidence has not been uniform, so the buildings tilt and are thus even more vulnerable to earthquake shaking.[18] In September 1985, Mexico endured a

magnitude 8.0 earthquake that killed about 10,000 people in Mexico City.

Another example comes from the Izmit, Turkey, earthquakes in 1999. These quakes killed more than 17,000 people because they took place near a heavily populated area where many buildings were poorly constructed.

One reason that the Mexico City and Izmit earthquakes caused such great loss of life was that so many people were living in the affected areas. If either of these quakes had occurred in less densely populated areas, fewer deaths would have resulted.

POPULATION GROWTH AS A FACTOR IN HAZARDS

The world's population has more than tripled in the past 70 years. Between 1830 and 1930, the world's population doubled from 1 to 2 billion people. By 1970, it had nearly doubled again, and as of 2016, there were about 7.4 billion people on Earth. How did we get to be 7+ billion strong?

The increase in the number of people on our planet can be related to various stages of human development. When we were hunter-gatherers, our numbers were small, population growth rates were low, and population density was far less than 1 person per km^2 (~0.39 mi^2). With the development of agriculture, population growth rates increased by several hundred times and population density increased about 30 times as the result of a stable food supply but still was considerably less than one person per km^2. During the early industrial period (A.D. 1600 to 1800), growth rates increased again by about 10 times, and density of persons increased to about seven persons per km^2. Since the Industrial Revolution, with modern sanitation and medicine, the growth rates increased another 10 times. Human population reached 6 billion in 2000, and by 2016 it exceeded 7.4 billion. That is 1.5 billion new people in only 16 years. By comparison, total human population reached 1 billion only about A.D. 1800, after more than 40,000 years of human history! Today, the density of the human population is much better known and is tremendously variable (it probably always was very variable, but we do not have the data to know). For example, according to the World Bank (2012), in Australia human population density or persons per km^2 (~0.39 mi^2) is about 3, United States 34, Spain 93, China 140, United Kingdom 260, Haiti 360, and India 410. For the entire world, the density is about 50 persons per km^2. The main conclusion is that very recently (in the past 100 years), human population and density has increased dramatically.

Future Population Growth Because Earth's population is increasing exponentially, many scientists are concerned that in the twenty-first century it will be impossible to supply resources and a high-quality environment for the billions of people added to the world population. Increasing population at local, regional, and global levels compounds nearly all hazards, including floods, landslides, volcanic eruptions, and earthquakes.

In the future, we may be able to mass-produce enough food from nearly landless agriculture or to use artificial growing situations. However, enough food does not solve the problems of the space available to people and maintaining or improving their quality of life. Some studies suggest that the present population is already above a comfortable carrying capacity for the planet. *Carrying capacity* is the maximum number of people Earth can hold without causing environmental degradation that reduces the ability of the planet to support the population.[19]

The news regarding population growth is not all bad—for the first time in the past 50 years, the rate of growth is decreasing. Growth may have peaked at 85 million people per year in the late 1980s, but by 2012, the increase was still about 85 million new people per year.[20,21] Every second, about 4.5 people are born somewhere on Earth, and 1.8 people die. Thus, twice as many people are born than die. We are experiencing what is known as *population momentum* as more people are living longer as a result of improved sanitation, nourishment, water quality, and medicine. Eventually, death rates will increase as the population ages and fall more in line with birth rates. From an optimistic point of view, it is possible that our global population of 6 billion persons in 2000 may not double again. Although population growth is difficult to project because of variables such as agriculture, sanitation, medicine, culture, and education, by the year 2050, human population is forecast to be about 10 billion. Most of the population growth in the twenty-first century will be in developing nations. India will likely have the greatest population of all countries by 2050, which will be about 18 percent of the total world population; China will have about 15 percent. By 2050, these two countries will have more than a third of the total world population![21]

The explosive increase in population during the twentieth century was due to *exponential growth* of the number of people on Earth, which means that the population does not grow each year by the addition of a constant number of people; rather, it grows by the addition of a constant percentage of the current population. Exponential population growth results in higher population densities (people per square kilometer),

more exposure of people to hazardous natural processes, increased pollution, reduced availability of food and clean drinking water, and a greater need for waste disposal and energy resources. A significant question is: How many people can Earth support?

There is no easy answer to the population problem, but the role of education is paramount. As people (particularly women) worldwide become more educated, the population growth rate tends to decrease. As the rate of literacy increases, population growth is reduced. Given the variety of cultures, values, and norms in the world today, it appears that our greatest hope for population control is, in fact, through education.[19] However, until the growth rate is zero, population will continue to grow. If the rate of growth is reduced to 0.7 percent per year, which is about two-thirds the current rate of 1.1 percent, human population will still double in 100 years. Having discussed the link between human population and hazards, we will now turn to an important link between how often hazardous processes occur and how big these hazardous events are.

MAGNITUDE AND FREQUENCY OF HAZARDOUS EVENTS

The *impact* of a hazardous event is in part a function of the amount of energy released, that is, its *magnitude*, and the interval between occurrences, that is, its *frequency*. Its impact is also influenced by many other factors, including climate, geology, vegetation, population, and land use. In general, the frequency of an event is inversely related to the magnitude. This is the **magnitude–frequency concept**. Small earthquakes, for example, are more common than large ones. A large event, such as a massive forest fire, will do far more damage than a small, contained burn. However, such events are much less frequent than smaller burns. Therefore, although planners need to be prepared for large, devastating events, the majority of fires suppressed will be smaller ones.

As an analogy to the magnitude–frequency concept, consider the work of logging a forest done by resident termites, human loggers, and elephants. The termites are numerous and work quite steadily, but they are so small that they can never do enough work to destroy all the trees. The people are fewer and work less often, but being stronger than termites, they can accomplish more work in a given time. Unlike the termites, the people can eventually fell most of the trees (Figure 1.12). The elephants are stronger still and can knock down many trees in a short time, but there are only a few of them and they rarely visit the forest. In the long run, the elephants do less work than the people and bring about less change. In our analogy, it is humans who, with a moderate expenditure of energy and time, do the most work and change the forest most drastically. Similarly, natural events with a moderate energy expenditure and moderate frequency are often the most important shapers of the landscape. For example, most of the sediment carried by rivers in regions with a subhumid climate, like most of the eastern United States, is transported by flows of moderate magnitude and frequency. However, there are many exceptions. In arid regions, for example, much of the sediment in normally dry channels may be transported by rare high-magnitude flows produced by intense but infrequent rainstorms. Along the barrier island coasts of the eastern United States, high-magnitude storms cause the most change to the beaches.



▲ FIGURE 1.12 Human Scale of Change
Human beings, with our high technology, are able to down even the largest trees in our old-growth forests. The lumberjack shown here is working in a national forest in the Pacific Northwest. *(Inga Spence/Alamy)*

Land use may directly affect the magnitude and frequency of events. Four deadly catastrophes resulting from natural hazards were Hurricane Mitch and the flooding of the Yangtze River in China, both in 1998; the Indonesian tsunami in 2004 that killed about 230,000 people; and Hurricane Katrina in 2005 that killed at least 1,600 Americans. Hurricane Mitch, which devastated Central America, caused approximately 11,000 deaths, whereas the floods in the Yangtze River resulted in nearly 4,000 deaths. Land-use changes made the damage from these events particularly severe. For example, Honduras has lost nearly one-half of its forests, and an 11,000 km^2 (~4200 $mi.^2$) fire occurred in the region prior to the hurricane, destroying vegetation cover. As a result of deforestation and the fire, hillsides washed away, and with them went farms, homes, roads, and bridges. In central China, the story is much the same; in recent years, the Yangtze River basin has lost about 85 percent of its forest as a result of timber

harvesting and conversion of land to agriculture. These land-use changes have probably made flooding on the Yangtze River much more common than it was previously.[22]

5

Consequences of hazards can be minimized.

The ways in which we deal with hazards are too often primarily *reactive*—following a disaster, we engage in search and rescue, firefighting, and providing emergency food, water, and shelter. There is no denying that these activities reduce loss of life and property and need to be continued. However, a move to a higher level of hazard reduction will require increased efforts to *anticipate* disasters and their effects. Land-use planning that limits construction in hazardous locations, hazard-resistant construction, and hazard modification or control (such as flood control channels) are some of the adjustments that anticipate future disastrous events and may reduce our vulnerability to them.[23]

Consequences of hazards obviously include damage directly from a hazard event such as a flood, landslide, or earthquake, and these costs in property and lives may be very significant—but they may not result in the greatest losses. Often it is what happens before, during, and after a hazardous event occurs that determines most of the losses. Consider total losses A + B = C, where C is the total loss; A represents the direct losses from the event; and B consists of losses related to human actions including, for example, inadequate engineering of dikes or not building homes, schools, and other buildings to withstand earthquake shaking; not wanting to or unable to spend funds for disaster planning that result in supplies, water, food, and medicine being quickly delivered after an earthquake or other disastrous event has occurred; not having public safety plans ready to be implemented; or incompetency, greed, or just being lazy and not doing the right thing or even knowing what to do (see Case Study 1.1: Professional Profile).[24]

REACTIVE RESPONSE: IMPACT OF AND RECOVERY FROM DISASTERS

The effect of a disaster on a population may be either direct or indirect. *Direct effects* include people killed, injured, dislocated, or otherwise damaged by a particular event. *Indirect effects* are generally responses to the disaster. They include emotional distress, donation of money or goods, and payment of taxes levied to finance the recovery. Direct effects are felt by fewer individuals, whereas indirect effects affect many more people.[25,26]

The stages of recovery following a disaster are emergency work, restoration of services and communication lines, and reconstruction (Figure 1.13). We can see these stages in recovery activities following the 1994 Northridge earthquake in the Los Angeles area. Restoration began almost immediately with the repair of roads and utilities, using funds from federal programs, insurance companies, and other sources that arrived in the first few weeks and months after the earthquake. The damaged areas then moved quickly from the restoration phase to what is known as the reconstruction stage, which lasted until 2000. The recovery time from a disaster can vary from a few to many years. Northridge has recovered in less than a decade, while in Haiti the recovery following the 2010 was delayed by the 2016 hurricane, and the country remains still early in the recovery process which will take decades and require massive international aid.

As we move through the reconstruction stage, it is important to remember lessons from two disasters: the 1964 Anchorage, Alaska, earthquake and the flash flood that devastated Rapid City, South Dakota, in 1972. Restoration following the Anchorage earthquake began almost immediately in response to a tremendous influx of dollars from federal programs, insurance companies, and other sources approximately one month after the earthquake. Reconstruction moved rapidly as everyone tried to obtain as much of the available funds as possible. In Rapid City, the restoration did not peak until approximately 10 weeks after the flood, and the community took time to carefully think through the best alternatives. As a result, Rapid City today uses land on the floodplain in an entirely different way—it is now a greenbelt with golf courses and other such facilities—and the flood hazard is much reduced.[13,25,26] Conversely, in Anchorage, the rapid restoration and reconstruction were accompanied by little land-use planning. Apartments and other buildings were hurriedly constructed across areas that had suffered ground rupture; the ground was prepared for rebuilding by simply filling in the cracks and regrading the land surface. By ignoring the potential benefits of careful land-use planning, Anchorage has made itself vulnerable to the same type of earthquake that struck in 1964.

In the Northridge case, the effects of the earthquake on highway overpasses and bridges, buildings, and other structures have been carefully evaluated. The goal has been to determine how more vigorous engineering standards for construction of new structures or strengthening of older structures can be implemented

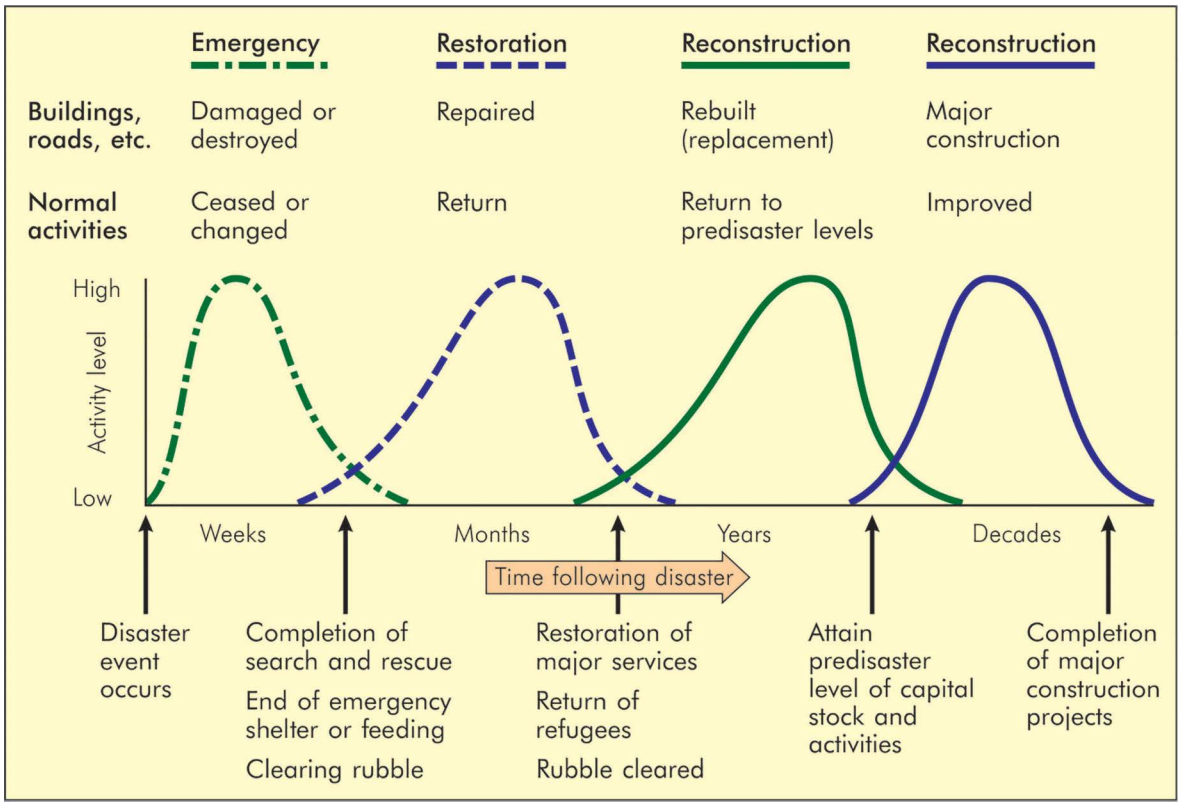


FIGURE 1.13 Recovery from Disaster

Generalized model of four stages of recovery following a disaster. The first stage after a disaster is a state of emergency, in which normal activities cease or are changed. The next stage in the restoration is a return to normal activities, although probably not at predisaster levels. This is followed by the stages of reconstruction and improvement. Finally, major construction and development are underway, and normal activities have returned. Lengths of the various stages are highly variable, depending on the nature of the disaster and available funding. The entire process may take a decade or longer. *(Modified from Kates, R. W., and Pijawka, D. 1977. From rubble to monument: The pace of reconstruction. In* Disaster and Reconstruction*, ed. J. E. Haas, R. W. Kates, and M. J. Bowden, pp. 1–23. Cambridge, MA: MIT Press)*

during the reconstruction stage (Figure 1.13). Future moderate to large earthquakes are certain to occur again in the Los Angeles area. Therefore, we need to continue efforts to reduce earthquake hazards.

ANTICIPATORY RESPONSE: AVOIDING AND ADJUSTING TO HAZARDS

The options we choose, individually and as a society, for avoiding or minimizing the effects of disasters depend in part on our perception of hazards. A good deal of work has been done in recent years to try to understand how people perceive various natural hazards. This understanding is important because the success of hazard reduction programs depends on the attitudes of the people likely to be affected by the hazard. Although there may be adequate perception of a hazard at the institutional level, this perception may not filter down to the general population. This lack of awareness is particularly true for events that occur infrequently; people are more aware of situations such as brush or forest fires that may occur every few years. Standard procedures, as well as local ordinances, may already be in place to control damage from these events. For example, homes in some areas of southern California are roofed with shingles that do not burn readily, they may have sprinkler systems, and their lots are frequently cleared of brush. Such safety measures are commonly noticeable during the rebuilding phase following a fire.

CASE study

1.1 Professional Profile

Professor Robert Bea, University of California, Berkeley

Professor Robert Bea (Figure 1.1.A) is widely recognized as perhaps the most influential, and sometimes controversial, contributor to our understanding of disasters. Professor Bea has an interesting background in civil engineering and has spent time in both industry and academia. He has published literally hundreds of papers and is a recognized expert in risk management. Much of his research has been focused on industrial catastrophes, such as oil blowouts and exploding oil platforms. However, he has also commented extensively on natural hazards, giving particular attention to what happens before, during, and after events such as hurricanes and floods.

Professor Bea has stated that, following the Occidental oil drilling platform explosion in 1988 that killed over 160 people, he realized that catastrophes and disasters have complex parts related to the poor decisions people make. Sometimes the event is natural and sometimes an engineering failure, but why it occurs, how it occurs, and the role of humans in the event are points he constantly hammers home. For example, a volcanic eruption in a remote part of the world is a big event, and, if there are not many people around, it will more or less be considered a large damaging event perhaps to ecosystems but not in terms of financial losses to people. On the other hand, should a large volcanic eruption occur near a large city, it would be considered a disaster or catastrophe, and then taking steps to better understand volcanoes and having emergency plans in place become paramount to minimizing total effects of the eruption. Bea has pointed out that often 20 percent of the financial losses in a disaster may be directly related to the event itself, but the majority of the cost of catastrophes could be greatly reduced by improving human systems that include warnings and better understanding of the hazard.[24]

Bea understands that we have some really big cities in harm's

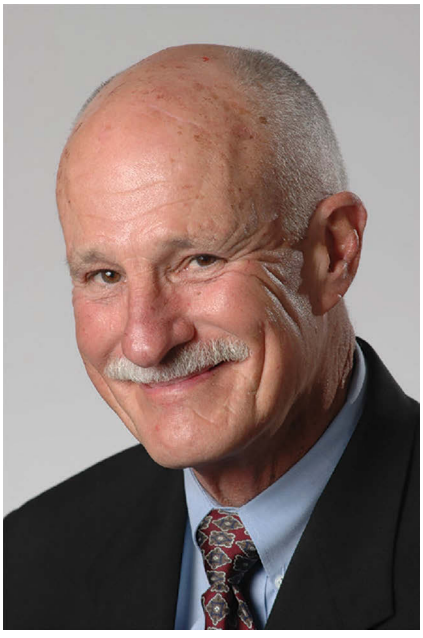


FIGURE 1.1.A
Professor Robert Bea, University of California, Berkeley is an expert on disasters and their causes. *(Courtesy of Robert Bea)*

way of natural processes, such as flooding and hurricanes, but the decisions we make prior to events and other decisions made afterward can reduce the ultimate consequences of the events by many times. He points out that we need to pick carefully the areas we wish to defend, but be prepared in other instances to move out of harm's way or spend the necessary funds for proper engineering structures that really might protect a city such as New York or New Orleans. With respect to New Orleans, Bea has a personal history there. He states that he and his family lost everything in Hurricane Betsy in 1965, including all of his memorabilia such as wedding photographs, marriage license, and so forth. He points out that 40 years later, following Katrina, he went back to the same place and, while there was a new home built on the site, people were again digging out from the hurricane. That affected him emotionally, as he realized that we could do much more to prevent disasters and catastrophes through better planning, management, and just plain fortitude in doing what is necessary to save money down the road. He points out that you can fix an environment of a big city now, or you can do it later when the cost may be 100 times as much.

Bea also raised early the possibility of an unusual storm that would hit New York, and eventually Superstorm Sandy devastated the coastline. He had indicated earlier that the city of New York could build offshore barriers to protect the city from storm surge, and that storm doors could cover openings to underground systems and bridges. In other words, he proposed floodproofing the city. If that had been done, it probably would have cost $15–20 billion, but the damages from Superstorm Sandy total several times that amount, and the city remains vulnerable.

On the West Coast of the United States, there is the large delta system of the Sacramento River. Levees are old and in poor repair, but these levees protect the ninth-largest economy in the world. Should these fail, then millions of people will be without power or fresh water, perhaps for months. Bea and other scientists have pointed out that this could happen at any time from a megaflood, the likes of which last occurred about 1860, or an earthquake, or a combination of events. California planners at the highest levels are aware of the research that points to a potential catastrophe, and still nothing has been done. Is this because the state simply doesn't have the money? Perhaps it's because people just don't believe that such events will occur because they have never seen them in their lifetime. It seems as if California is saying, "Yes, this could happen, and we're simply going to bear the loss." According to Bea and others, this is not an acceptable solution. Solving the delta problem would cost billions of dollars but nowhere near the estimated cost should the system fail. And rest assured that, without some sort of maintenance and a program to reestablish the integrity of the system, it will eventually fail, and the losses could be hundreds of times the cost of doing a fix now.[24]

Professor Bea has pointed out that some of the major problems are related to people, institutions, companies, and government. Often people and institutions take the easy road, putting maintenance or solving a problem of a critical area on the back burner until an event happens—and then everyone acts really surprised. It may be a surprise to some, but not to people like Bea, who study natural disasters and their occurrence. Bea points out that it is not natural events or engineering failures that are the chief culprits producing the catastrophes; rather, it is the failure of human and organizational systems along with, in some cases, inadequate science, complicated by conflicting egos and people being too lazy to do the things they know they should. The key to reducing catastrophic events is not only to better understand their occurrence and the science behind the event but also to greatly improve our institutions, safety protocols, and disaster preparedness that should take place before, during, and after events. For large cities and critical facilities such as power plants, more attention must go toward providing fixes for potential catastrophes that, while costly now, will save that cost many times over when the unexpected event occurs. Of course, these events are not really surprising or unusual, only perhaps rare, but they should be expected and planned for.

One of the most environmentally sound adjustments to hazards involves **land-use planning**. That is, people can avoid building on floodplains, in areas where there are active landslides, and in places where coastal erosion is likely to occur. In many cities, floodplains have been delineated and zoned for a particular land use. With respect to landslides, legal requirements for soil engineering and engineering geology studies at building sites may greatly reduce potential damages. Damages from coastal erosion can

be minimized by requiring adequate setback of buildings from the shoreline or sea cliff. Although it may be possible to control physical processes in specific instances, land-use planning to accommodate natural processes is often preferable to a technological fix that may or may not work.

Insurance is another option that people may exercise in dealing with natural hazards. Flood insurance is common in many areas, and earthquake insurance is also available. Just because insurance is available, however, doesn't mean it is practical (or ethical) to build in an earthquake-prone area without careful engineering, knowing that you will most likely have to use your insurance at some point. In fact, because of large losses following the Northridge earthquake, several insurance companies announced they would no longer offer the insurance.

Evacuation is an important option or adjustment to the hurricane hazard in the states along the Gulf of Mexico and along the eastern coast of the United States. Often, there is sufficient time for people to evacuate, provided they heed the predictions and warnings. However, some people refuse to leave their homes, and if people do not react quickly and the affected area is a large urban region, then evacuation routes may be blocked by residents leaving in a last-minute panic.

Disaster preparedness is an option that individuals, families, cities, states, or even entire nations can implement. Of particular importance is the training of individuals and institutions to handle large numbers of injured people or people attempting to evacuate an area after a warning is issued.

Attempts at *artificial control of natural processes* such as landslides, floods, and lava flows have had mixed success. Seawalls constructed to control coastal erosion may protect property to some extent, but over a period of decades, they tend to narrow or even eliminate the beach (see Chapter 11). Even the best-designed artificial structures cannot be expected to adequately defend against an extreme event, although retaining walls and other structures to defend slopes from landslides have generally been successful when well designed. Even the casual observer has probably noticed the variety of such structures along highways and urban land in hilly areas. Structures to defend slopes have a limited effect on the environment and are necessary where artificial cuts must be excavated or where unstable slopes impinge on human structures. Common methods of flood control are channelization and construction of dams and levees. Unfortunately, flood control projects tend to provide floodplain residents with a false sense of security; no method can completely protect people and their property from high-magnitude floods (see Chapter 6).

An option chosen all too often is simply bearing the loss caused by a natural disaster. Many people are optimistic about their chances of making it through any sort of disaster and, therefore, will take little action in their own defense. This response is particularly true for those hazards—such as volcanic eruptions and earthquakes—that are rare in a given area. Regardless of the strategy we use to minimize or avoid hazards, it is imperative that we understand and anticipate them and their physical, biological, economic, and social effects.

1.4 CHECK your understanding

1. Describe the five fundamental concepts.
2. How is risk from natural hazards evaluated?
3. What is uniformitarianism, and how does it help us understand natural hazards?
4. Differentiate among precursor events, forecasting, predictions, and warnings.
5. Explain what is meant by the magnitude–frequency concept.
6. Why are population growth and land use important in understanding consequences of natural hazards?
7. Differentiate between reactionary responses and anticipatory responses.
8. When we say consequences of hazards are as simple as A + B = C, what do we mean?
9. Explain Robert Bea's message in his Professional Profile.
10. Define what is meant by a wicked problem.

1.5 Many Hazards Provide a Natural Service Function

It is ironic that the same natural events that take human life and destroy property also provide us with important benefits, sometimes referred to as *natural service functions*. For example, periodic flooding of the Mississippi River supplies nutrients to the floodplain and creates the fertile soils needed for agriculture. Flooding, which causes erosion on mountain slopes, also delivers sediment to beaches and flushes pollutants from estuaries in the coastal environment. Landslides may bring benefits to people when the debris forms dams, creating lakes in mountainous areas. Although some landslide dams will collapse and cause hazardous downstream flooding, if a dam remains stable, it can

provide valuable water storage and an important aesthetic resource.

Volcanic eruptions have the potential to produce real catastrophes but also provide us with numerous benefits. They often create new land, as in the case of the Hawaiian Islands, which are completely volcanic in origin (Figure 1.14). Nutrient-rich volcanic ash may settle on existing soils and quickly become incorporated, creating fertile soil suitable for both crops and native plants. Earthquakes can also provide us with valuable services. When rocks are pulverized during an earthquake, they may form an impervious clay zone known as *fault gouge* along a geological fault. In many places, fault gouge has formed natural subsurface barriers to groundwater flow; these barriers then pool water or create springs that are important sources of water. In addition, most of the hydrocarbon traps that contain the world's petroleum resources are produced by deformation along faults that create large zones where oil and gas accumulate, without which the Industrial Revolution would never have happened (Figure 1.15). Finally, earthquakes are important in mountain building and, thus, are directly responsible for many of the scenic landscapes of the western United States.

1.5 CHECK your understanding

1. What is meant by the phrase *natural service functions*?
2. List some examples of natural service functions of hazards such as floods, earthquakes, landslides, and volcanic eruptions.



(a)



(b)

FIGURE 1.14 New Land from Volcanic Eruption
New land being added to the island of Hawaii. (a) The cloud of steam and acidic gases in the central part of the photograph is where hot lava is entering the sea. *(Edward A. Keller)* (b) Close-up of an advancing lava front near the gas cloud. *(Edward A. Keller)*

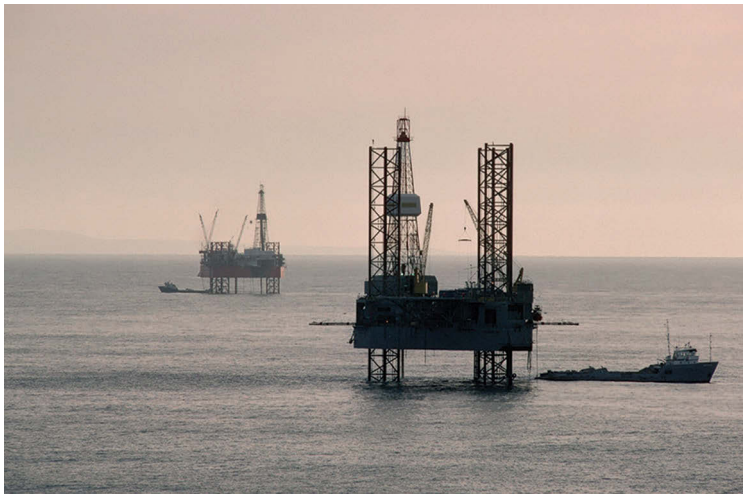


FIGURE 1.15 Hydrocarbon Trap
Faulting in the Santa Barbara Channel has produced a linear fault trap, along which oil rigs at the surface are situated above. *(Nik Wheeler/ Corbis)*

1.6 Global Climate Change and Hazards

Global change in climate is one of the defining science and social issues of the twenty-first century. The science issues are largely settled; human processes (especially burning fossil fuel) is adversely impacting the global climate system (see Chapter 12). In recent years, we have seen the mass movement of people from agriculture areas of Syria suffering from serious drought that lowers food production for cities. Apart from social problems incurred by the mass immigration of people to other regions, such as Western Europe and the Americas, this has led to civil war.[27]

Global warming, a symptom of climate change, is likely affecting the incidence of hazardous natural events such as storms, landslides, drought, and fires (see Chapter 12). How might climatic change affect the magnitude and frequency of these events? With global warming, sea level is rising as the heating of seawater expands the volume of the ocean, and glacial ice is melting. As a result, coastal erosion will increase. Climate change may shift food production areas, as some places receive more precipitation and others receive less. Deserts and semiarid areas will likely expand, and warmer northern latitudes could become more productive. Such changes could lead to global population shifts, which might bring about wars or major social and political upheavals.

Global warming is feeding more energy from warmer ocean water into the atmosphere; this energy is likely to increase the severity and frequency of hazardous weather, such as thunderstorms and tornadoes, and increase the intensity of hurricanes. In fact, this trend may already be underway—an analysis of global extreme-weather events by a United Nations panel indicates that since the 1950s there has been an increase in heavy precipitation events in midlatitude regions and, since the 1970s, a likely increase in the intensity of hurricanes.[28]

1.6 CHECK your understanding

1. In what ways might global climate change influence the occurrence of natural hazards such as coastal erosion, extreme weather events, and droughts?

CONCEPTS in review

1.1 Why Studying Natural Hazards Is Important

LO:1 Explain the difference between a disaster and a catastrophe.

- Natural hazards are responsible for causing significant death and damage worldwide each year. Processes that cause hazardous events include those internal to the Earth, such as volcanic eruptions and earthquakes that result from Earth's internal heat, and those external to the Earth, such as hurricanes and global warming, which are driven by energy from the sun.
- Natural processes may become hazards, disasters, or catastrophes when they interact with human processes.
- Central to an understanding of natural hazards is awareness that hazardous events result from natural processes that have been in operation for millions and possibly billions of years before humans experienced them. These processes become hazards when they threaten human life or property and should be recognized and avoided.



KEY WORDS

catastrophe (p. 5), **disaster** (p. 5), **natural hazard** (p. 5)

1.2 The Role of History in Understanding Hazards

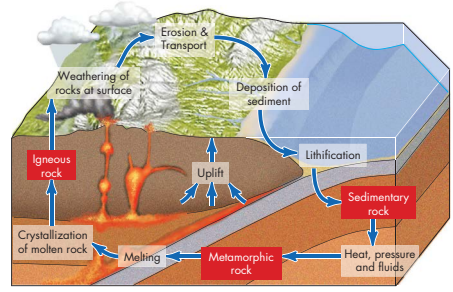
LO:2 Discuss the role of history in the understanding of natural hazards.

- Hazards involve repetitive events. Thus, a study of the history of these events provides much-needed information for hazard reduction. A better understanding and more accurate predictions of natural hazards comes from integrating historic and prehistoric information, present conditions, and recent past events, including land-use changes.

1.3 The Geologic Cycle

LO:3 Discuss the components and processes of the geologic cycle.

- Geologic conditions and materials largely govern the type, location, and intensity of natural processes. The geologic cycle creates, maintains, and destroys earth materials by physical, chemical, and biological processes.
- Subcycles of the geologic cycle are the tectonic cycle, rock cycle, hydrologic cycle, and various biogeochemical cycles. The tectonic cycle describes large-scale geologic processes that deform Earth's crust, producing landforms such as ocean basins, continents, and mountains. The rock cycle may be considered a worldwide Earth material recycling process driven by Earth's internal heat, which melts the rocks subducted in the tectonic cycle. Driven by solar energy, the hydrologic cycle operates by way of evaporation, precipitation, surface runoff, and subsurface flow of water. Biogeochemical cycles can most easily be described as the transfer of chemical elements through a series of storage compartments or reservoirs, such as air or vegetation.



KEY WORD

geologic cycle (p. 10)

1.4 Fundamental Concepts for Understanding Natural Processes as Hazards

LO:4 Apply the scientific method to a natural hazard of your choice.

LO:5 Synthesize the basics of risk assessment.

LO:6 Explain how much of the damage caused by natural hazards is often related to decisions people make before, during, and after a hazardous event.

LO:7 Explain why the magnitude of a hazardous event is inversely related to its frequency.

LO:8 Summarize how natural hazards are linked to one another and to the physical environment.

LO:9 Give reasons why increasing population and poor land-use practices compound the effects of natural hazards and can turn disasters into catastrophes.



KEY WORDS

environmental unity (p. 15), **forecast** (p. 15), **land-use planning** (p. 27), **magnitude–frequency concept** (p. 23), **prediction** (p. 15), **risk** (p. 19), **uniformitarianism** (p. 14), **warning** (p. 18)

- Five fundamental concepts establish a philosophical framework for studying natural hazards:
  1. Hazards are predictable from scientific evaluation.
  2. Risk analysis is an important component in our understanding of the effects of hazardous processes.
  3. Linkages exist between different natural hazards, as well as between hazards and the physical environment.
  4. Hazardous events that previously produced disasters are now producing catastrophes.
  5. Consequences of hazards can be minimized.
- Environmental unity states that one action often leads to others in a sequence (you can't do just one thing).
- Human population growth and poor land-use decisions are turning former disasters into catastrophes.
- The magnitude–frequency concept states that the larger the magnitude of a natural process, the less frequently it occurs.
- Consequences of a natural hazard event such as a flood, hurricane, or earthquake can produce loss of life and property. Human decisions and actions before, during, and after a hazardous event can greatly increase or decrease the consequences.

1.5 Many Hazards Provide a Natural Service Function

LO:10 Explain how events we view as hazards provide natural service.

- Natural service functions refer to benefits provided by a particular process; for example, flooding provides fertile floodplain soil, and volcanic eruption produces new land.



1.6 Global Climate Change and Hazards

LO:11 Summarize links between climate change and natural hazards.

- Global climate change with global warming will likely affect the frequency and intensity of thunderstorms and tornadoes and the intensity of hurricanes. Rising sea level will increase coastal erosion.
- With global warming, deserts and semiarid regions will expand, and droughts will be more common.
- With warming, the frequency and intensity of wildfire will both likely increase.

CRITICAL thinking questions

1. How would you use the scientific method to test the hypothesis that sand on the beach comes from the nearby mountains?
2. It has been argued that we must control human population because otherwise we won't be able to feed everyone. Even if we could feed 10 to 15 billion people, would we still want a smaller population? Why or why not?
3. Considering that events we call natural hazards are natural processes that have been occurring on Earth for millions of years, how do you think we should go about trying to prevent loss of life from these events? Think about the choices society has in terms of attempting to control and prevent hazards or attempting to keep people out of harm's way.
4. Provide an example or two that support the hypothesis that human processes and the appropriate and inappropriate decisions that people make are potentially more important to total losses from a hazardous event than the natural event itself.
5. Global warming is a major concern today. Discuss how global warming might influence the magnitude or frequency of hazardous events, disasters, or catastrophes caused by natural hazards.
6. What was the role of science in understanding the 2010 Haiti earthquake? Could this event have been expected?
7. What other hazards are linked to the 2010 earthquake? Will the effect of these hazards increase or decrease in the future? What do you need to know to determine the likelihood of such an increase or decrease?
8. Human processes are part of the equation of determining the consequences of future large earthquakes in Haiti. What human processes could be implemented in order to reduce the impact of future earthquakes?
9. What do we mean when we say the risk from a natural hazard event is the product of the probability, exposure, and, vulnerability? Provide a hypothetical example to illustrate your answer.

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