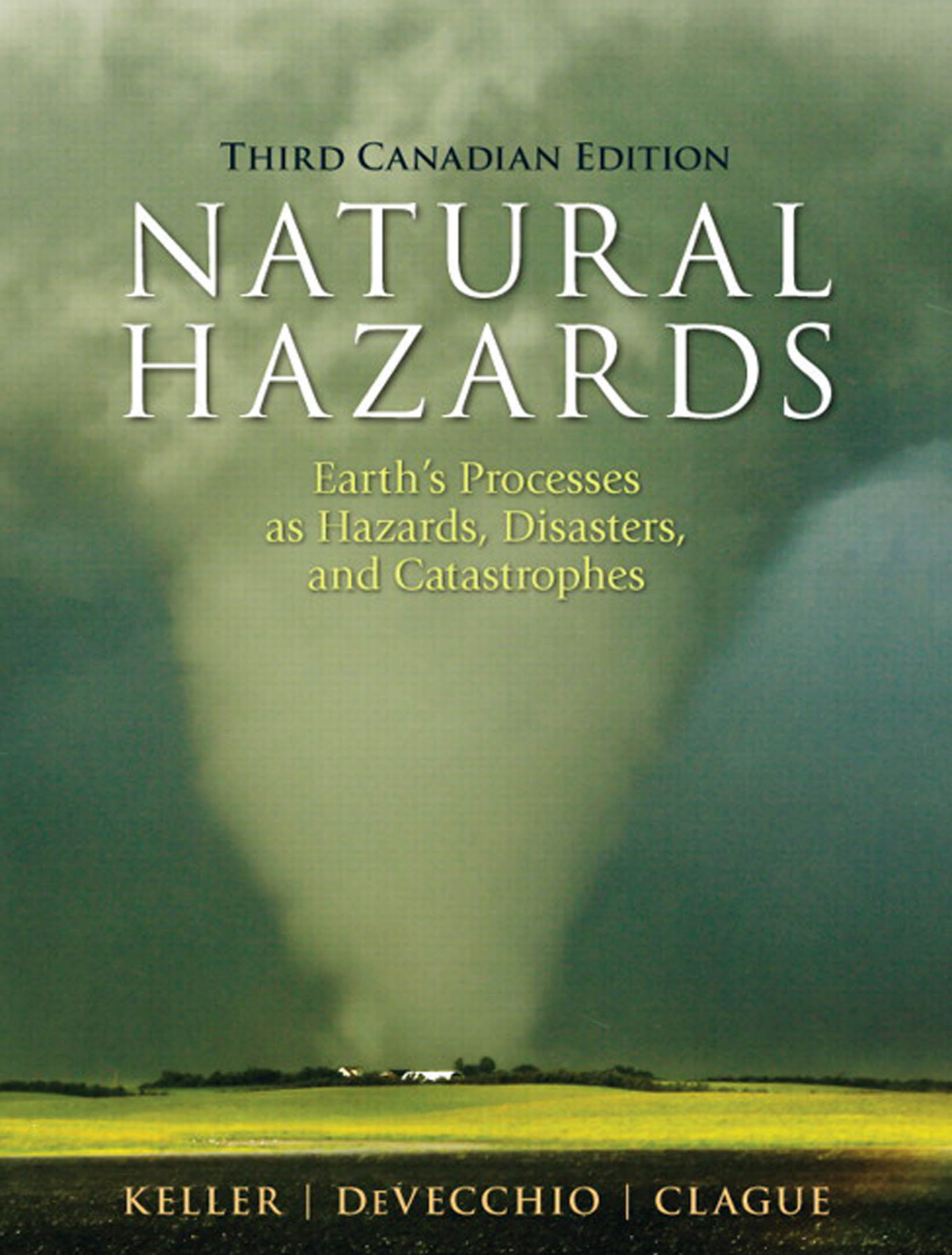
THIRD CANADIAN EDITION

NATURAL HAZARDS

Earth's Processes as Hazards, Disasters, and Catastrophes



KELLER | DEVECCHIO | CLAGUE

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Earth's Processes as Hazards, Disasters, and Catastrophes

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About the Authors

Edward A. Keller

Edward A. Keller is a professor, researcher, and writer, and, most importantly, a mentor and teacher to undergraduate and graduate students. Ed's students are currently working on earthquake hazards, how waves of sediment move through a river system following a disturbance, and on geologic controls on the habitat of endangered southern steelhead trout.

Ed was born and raised in California. He received bachelor's degrees in geology and mathematics from California State University at Fresno, and a master's degree in geology from the University of California at Davis. It was while pursuing his Ph.D. in geology from Purdue University in 1973 that Ed wrote the first edition of *Environmental Geology*, a text that became the foundation of an environmental geology curriculum in many colleges and universities. He joined the faculty of the University of California at Santa Barbara in 1976 and has been there ever since, serving multiple times as chair of both the Environmental Studies and Hydrologic Science programs. In that time he has authored more than 100 articles, including seminal works on fluvial processes and tectonic geomorphology.

Ed's academic honours include the Don J. Easterbrook Distinguished Scientist Award, Geological Society of America (2004); the Quatercentenary Fellowship from Cambridge University, England (2000); two Outstanding Alumnus Awards from Purdue University (1994, 1996); a Distinguished Alumnus Award from California State University at Fresno (1998); and the Outstanding Outreach Award from the Southern California Earthquake Center (1999).

Ed and his wife, Valery, who brings clarity to his writing, love walks on the beach at sunset and when the night herons guard moonlit sand at Arroyo Burro Beach in Santa Barbara.

Duane DeVecchio

Duane DeVecchio is currently a researcher and adjunct professor at the University of California at Santa Barbara, where he earned his Ph.D. in geology. Since starting his graduate education, Duane has devoted a significant amount of time to becoming an effective communicator of science. He is a passionate teacher and feels strongly that students need to develop critical thinking skills, which will enable them to evaluate for themselves data presented in graphs and tables from various sources. This is particularly important today, when the Internet and cable television offer accessibility to vast amounts of information, yet the validity of this information is often questionable or misleading. Integrating data from current and relevant research into core curriculum to illustrate the methodology and rigour of scientific investigations is essential to his teaching strategy.

Duane has a broad field-based background in the geological sciences and likes to share stories about his many months living alone in mobile trailers in the mountains and deserts so he could study rocks and landforms for his research. For his master's degree and post-master's research he conducted structural and stratigraphic analysis, as well as numerical dating of volcanic and volcaniclastic rocks in southeast Idaho and the central Mojave Desert of California, which record the Miocene depositional and extensional histories of these regions. His Ph.D. research was aimed at resolving fault slip rates and quantifying the earthquake hazard presented by several active fault-related folds growing beneath urbanized Southern California. Duane's current research interests focus on the timing and rates of change of Earth's surface due to depositional and erosional processes that result from climate change and tectonics.

When Duane is not teaching or conducting research, he enjoys whitewater rafting, rock climbing, snowboarding, and camping with his partner, Christy.

John J. Clague

John Clague is a professor of earth sciences at Simon Fraser University (SFU) in Burnaby, British Columbia, and an emeritus scientist with the Geological Survey of Canada. John was employed as a research scientist with the Geological Survey of Canada for 24 years, specializing in natural hazards, climate change, and ice age geology of western Canada. In 1998, he accepted a faculty position in the Department of Earth Sciences at SFU, where he is currently based. John became a Canada Research Chair in natural hazards research in 2003 and is currently director of the Centre for Natural Hazard Research. John is the author of 300 scientific papers on subjects as diverse as earthquakes, geochemistry, and archaeology. He has written popular books on Canadian earth science issues and on earthquakes and tsunamis in the Pacific Northwest. He is a fellow of the Royal Society of Canada, former president of the Geological Association of Canada, former president of the International Union for Quaternary Research, and a recipient of numerous awards and honours.

John is a strong proponent of the philosophy captured so eloquently by Margaret Mead: "Never doubt that a small group of committed people can change the world. Indeed, it is the only thing that has."

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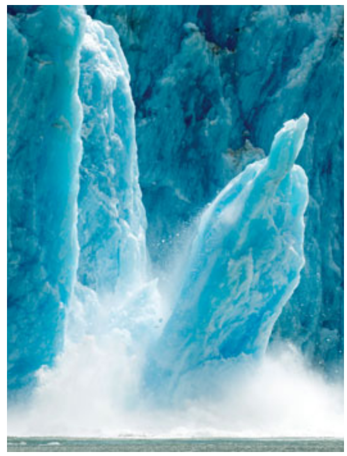
Brief Contents

Contents



Preface

Natural Hazards: Earth's Processes as Hazards, Disasters, and Catastrophes, Third Canadian Edition is an introductory university-level, non-technical survey of natural processes that have direct, often sudden, and violent impacts on humanity. The book integrates principles of geology, geography, hydrology, meteorology, climatology, oceanography, soil science, ecology, and solar system astronomy. It has been designed for a course for non-science majors and will help instructors guide students who may have little background in science through the geologic underpinnings and societal repercussions of hazardous Earth processes. It is also suitable for topical introductory courses in physical geology, physical geography, and Earth science.

In preparing the third edition of this book, we took advantage of the growing amount of information about natural hazards, disasters, and catastrophes. Since the second edition was published, many natural disasters and catastrophes have occurred. In 2010, drought, heat wave, and air pollution from wildfires killed several thousand people in Moscow; in 2011, great earthquakes and tsunamis struck Chile and Japan; and in 2012, a superstorm caused over $65 billion damage on the Atlantic coast of the United States. In 2013, destructive floods happened in southwest Alberta and Colorado, and wildfires destroyed more than 200 homes in New South Wales, Australia. These events are the result of enormous forces that are at work both inside and on the surface of our planet.

Climate change is causing glaciers to melt, permafrost to thaw, the atmosphere and oceans to warm, and sea level to rise more rapidly than had originally been forecast. These changes are caused in part by human activities, primarily the burning of fossil fuels, which releases vast amounts of carbon dioxide and other gases into the atmosphere. The interaction between humans and Earth processes has never been clearer, and the need for understanding these processes as hazards for our economy and society has never been greater.

This edition of *Natural Hazards* seeks to explain destructive Earth processes in an understandable way, illustrate how they affect us, and discuss how we can better prepare for, and adjust to, inevitable natural disasters.

An important point, central to both the text and course, is that Earth processes are not, in and of themselves "hazards," even though we describe them as such. Earthquakes, tsunamis, volcanic eruptions, landslides, floods, tornadoes, hurricanes, and wildfires are natural processes and have occurred for hundreds of millions of years. They are hazards only when they impact people. Ironically, human behaviour can turn hazardous events into disasters or, worse, catastrophes. The text strives to present these phenomena as natural geologic processes that have human impacts.

A course in natural hazards offers many benefits besides satisfying students' natural curiosity about such events. An informed citizenry is our best guarantee of a prosperous future. Armed with insights into the complex relations between people and the geologic environment, we will ask better questions and make better choices. On a local level, we will be better prepared to make decisions about where we live and how best to invest our time and resources. On national and global levels, we will be better able to advise our leaders on important issues related to natural hazards that impact our lives.

Distinguishing Features of the Third Edition

With these objectives in mind, we have incorporated into this edition of *Natural Hazards* a number of features designed to support the student and instructor.

A Balanced Approach

Many readers will naturally focus on natural hazards that threaten their community, province, or country, but globalization of our economy, near-universal information access, and the effects of humans on our planet require a broader, more balanced approach to the study of natural hazards and risk. A major earthquake in Tokyo or San Francisco would affect trade in the ports of Vancouver and Seattle, the economy of Silicon Valley in California, and the price of computers in Toronto and Halifax. The authors have tried to provide balanced coverage of natural hazards, with examples from Canada, the United States, and other countries. Topics covered in this edition include earthquakes and tsunamis on the British Columbia coast; the 1929 Grand Banks earthquake and tsunami; disastrous historic floods on the Fraser and Red rivers; a discussion of how Canada deals with floods; large landslides at Frank, Alberta, in 1903, near Hope, British Columbia, in 1965, and north of Pemberton, British Columbia, in 2010; the disastrous ice storm in Ontario and Quebec in 1998; the 1983 Edmonton tornado; Hurricanes Katrina, Hazel, and Juan; Superstorm Sandy in 2012; destructive wildfires in Kelowna, British Columbia, in 2003 and Slave Lake, Alberta, in 2011; recent killer earthquakes in southwest China, Haiti, New Zealand, and Japan; and an expanded treatment of climate change and its impacts in Canada. This edition also includes a new chapter on plate tectonics.

This book treats each topic as both a natural phenomenon and a human hazard. For example, the discussion of tsunamis includes a description not only of their characteristics, causes, global distribution, frequency, and effects, but also of engineering and nonstructural approaches that can be taken to reduce tsunami risk.

Five Fundamental Concepts

Five key concepts provide a conceptual framework of understanding that guide the reader:

1. **Hazards can be understood through scientific investigation and analysis.**

   Most hazardous events and processes can be monitored and mapped and their future occurrence and magnitude forecast based on the frequency of past events, patterns in their occurrence, and types of precursor events.

2. **An understanding of hazardous processes is vital to evaluating risk.**

   Hazardous processes are amenable to risk analysis because the probability and consequences of an event can be determined or estimated.

3. **Hazards are commonly linked to each other and to the environment in which they occur.**

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

4. **Population growth and socio-economic changes increase risk from natural hazards.**

   As a result of increasing human population, larger concentrations of economic wealth, and poor land-use practices, events that previously caused disasters are now causing catastrophes.

5. **Damage and loss of life from natural disasters can be reduced.**

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

These five concepts are introduced in Chapter 1 and revisited throughout the text. They provide a framework for understanding that can extend beyond the course into everyday life.

Survivor Stories and Professional Profiles

Many chapters contain the personal story of someone who has had a brush with disaster, as well as a profile of a scientist or other professional who has worked with a particular hazard. Although most of us will never experience a volcanic eruption, tsunami, or major hurricane, we are naturally curious about what we would see, hear, and feel if we did. For example, a scientific description of a volcanic eruption does not convey the amazement and terror that Canadian volcanologist Catherine Hickson experienced on the morning of May 18, 1980, when Mount St. Helens exploded (see her professional profile on page 145). Likewise, the story of the tsunami in the Indian Ocean in 2003 does not give us the real sense of what Christine Lang felt when she was caught up in and nearly killed in the tsunami (see Survivor Story in Chapter 4). To fully understand and appreciate natural hazards, we need both scientific knowledge and human experience. As you read the survivor stories, ask yourself what you would do in a similar situation. This knowledge could save your life someday, as it did for Tilly Smith and her family on the beach in Phuket, Thailand, in December 2003 (see Chapter 4).

People study and work with natural hazards for many reasons—curiosity, monetary reward, excitement, or the desire to help others prepare for events that might threaten their lives and property. As you read each professional profile, think about the person's motivation, the type of work he or she does, and how that work contributes to increasing human knowledge or reducing risk. For example, Grant Statham, who works for Parks Canada, has studied snow avalanches in western Canada for nearly three decades (see his professional profile in Chapter 7). For him, this study is both a vocation and an avocation. He has had a lifelong interest in avalanches and is striving to reduce avalanche injuries and deaths by promoting scientific study, educational programs, and heightened awareness of the hazard. Most of the survivor stories and professional profiles are based on interviews conducted exclusively for *Natural Hazards*.

Major New Material in the Third Edition

The third edition benefited greatly from feedback from instructors who used the previous edition, and many of the changes reflect their thoughtful reviews. New material for the third edition includes the following:

- NEW! A chapter on plate tectonics that reflects its overarching importance in Earth science.
- NEW! Revisiting the Fundamental Concepts, which reminds students of the unifying theme of the five fundamental concepts introduced in the first chapter. This feature identifies how the five fundamental concepts relate to each hazard.
- NEW! "A Closer Look" uses real-life events and data to enhance understanding and comprehension not only of the hazard, but also its mitigation.
- NEW! "Did You Learn" questions at the end of each chapter allow students to track their comprehension of the learning goals stated at the beginning of the chapter.
- Coverage of the most recent disasters on Earth, such as recent earthquakes in Haiti, Italy, New Zealand, Chile, Italy, and Japan; the Icelandic volcanic eruptions in 2010; wildfires in Alberta in 2011; the superstorm on the Atlantic coast of the United States in 2012; the flooding in Alberta in 2013; and more.
- Revised design throughout the book includes changes to the chapter openers, which feature new photos and content.
- Updated art with new figures, illustrations, and photos throughout the book. Each image has been reviewed for accuracy, relevance, and its educational impact.

Features of the Text

This text is sensitive to the study needs of students. Each chapter is clearly structured to help students understand the material and effectively review the major concepts. Each chapter is organized with the following study aids:

- Learning Objectives on the first page of each chapter clearly state what students should have achieved after completing their study of the topic.
- Selected features, including Case Studies, Closer Look boxes, Survivor Stories, and Professional Profiles, are added where appropriate to help students understand natural hazards through real-world examples.
- A discussion of the five fundamental concepts as they apply to the specific hazard at hand is followed by a summary. The summaries reinforce the major points of each chapter and help students focus on important concepts.
- References are included with each chapter to provide additional sources of information and give credit to the scholars who did the research reported in the chapter.
- Key terms are highlighted in **bold** where they are first introduced in detail in the text. These terms are listed at the end of each chapter. Other important technical terms that may be new to students are indicated in *italics*. All **key terms** and *useful terms* are defined in a glossary at the end of the book.
- Review questions at the end of each chapter will help students focus on the important subject matter.
- Critical thinking questions at the end of each chapter have been designed to stimulate students to think about important issues and to apply the information to both their lives and society.
- Appendices, which are included in the online resources, provide additional information useful for understanding some of the more applied aspects of geology that relate to natural hazards. This information may be helpful in supplementing laboratory and field exercises.

The Teaching and Learning Package

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  See www.masteringgeology.com.

Hazard City: Assignments in Applied Geology is now part of MasteringGeology. In Hazard City, students will assume the role of a practising geologist and be assigned a variety of tasks: gathering and analyzing real data, evaluating risk, and making assessments and recommendations. Topics include:

Ground Water Contamination: Students use field and laboratory data to prepare a contour map of the water table, determine the direction of ground water flow, and map a contaminated area.

Volcanic Hazard Assessment: Students research volcanic hazards, collect field information, and use decision making to determine the potential impact of a volcanic eruption on different parts of Hazard City.

Landslide Hazard Assessment: Students research the factors that determine the landslide hazard at five construction sites and make recommendations for development.

Earthquake Damage Assessment: Students research the effects of earthquakes on buildings, explore Hazard City, and determine the number of people needing emergency housing given an earthquake of specific intensity.

Flood Insurance Rate Maps: Students estimate flood insurance premiums using a flood insurance rate map, insurance tables, and site characteristics.

Snowpack Monitoring: Students use climatic data to estimate variables that are key to flood control and water supply management.

Coal Property Evaluation: Students estimate what the potential value of a mineral property is by learning about mining and property evaluation and applying that knowledge in a resource calculation.

Landfill Siting: Students use maps and geological data to determine if any of five proposed sites meet the requirements of the State Administrative Code for landfill siting.

Shoreline Property Assessment: Students visit four related waterfront building sites—some developed and some not—and analyze the risk each faces due to shoreline erosion processes.

Tsunamis/Storm Surges: Students research the causes and effects of tsunamis and storm surges and then prepare a risk assessment report for a small oceanside village near Hazard City.

Map Reading: In order to identify the source of water contamination in a local stream, students learn how to read topographic maps and use their knowledge to plan their field work.

For the Instructor

Instruction Resource Centre

Everything you need, where you want it. Pearson Canada has assembled a first-rate package for *Natural Hazards*. The following instructor supplements are available for download from a password-protected section of Pearson Canada's online catalogue (www.pearsoncanada.ca/highered). Navigate to your book's catalogue page to view a list of available supplements. See your local sales representative for details and access.

- **Instructor's Manual.** The Instructor's Manual provides chapter outlines and objectives, classroom discussion topics, and answers to the end-of-chapter questions in the text.
- **Test Generator.** The TestGen provides more than 500 questions in multiple-choice, true/false, short-answer, and essay formats. It also tests recall, understanding, and application of the main data and concepts presented in the text.
- **PowerPoint® Presentation.** PowerPoint presentations are provided for each chapter and include all the figures and many photos from the text.
- **The Prentice Hall Geoscience Animation Library (ISBN 978-0-321-71684-2).** The Prentice Hall Geoscience Animation Library arose from a survey of instructors. We asked them to identify the concepts most difficult to teach using traditional, static resources. Then we animated them. Created through a unique collaboration of five of Prentice Hall's leading geoscience authors, the animations represent a significant advance in lecture presentation. Each animation is mapped to the corresponding chapter in *Natural Hazards* and is available on the Instructor's Resource site. They are provided as Flash files and, for convenience, are pre-loaded into PowerPoint slides.
- **CourseSmart for Instructors.** CourseSmart goes beyond traditional expectations—providing instant, online access to the textbooks and course materials you need at a lower cost for students. And even as students save money, you can save time and hassle with a digital eTextbook that allows you to search for the most relevant content at the moment you need it. Whether it's evaluating textbooks or creating lecture notes to help students with difficult concepts, CourseSmart can make life a little easier. See how when you visit www.coursesmart.com/instructors.
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Edward A. Keller
Duane E. DeVecchio
Santa Barbara, California
John J. Clague
Burnaby, British Columbia

Monster on the Prairie (Saskatchewan)
Winner of Canadian Geographic's Whatever the Weather Photo Contest
Photographer Craig Hilts is a stock broker and storm chaser who gives talks to local schools on storm safety and preparedness. To see more of Craig's work visit: http://www.prairiefirephoto.com/

CHAPTER 1

▶ **CATASTROPHE IN HAITI** A building in Port-au-Prince, Haiti, destroyed by the devastating earthquake on January 12, 2010. Buildings such as this were not constructed to withstand the ground shaking from a strong earthquake. *(Getty Images, Design Pics /Rey old Mainse)*

Introduction to Natural Hazards

Learning Objectives

Natural processes, such as volcanic eruptions, earthquakes, landslides, tsunamis, floods, and hurricanes, threaten human life and property throughout the world. As the world's population continues to grow, disasters and catastrophes will become more common. An understanding of natural processes as hazards requires some basic knowledge of earth science. Your goals in reading this chapter should be to

- Recognize that natural disasters and catastrophes are high-energy events caused by natural Earth processes
- Understand that natural hazards have social, economic, and political dimensions that are just as important as the hazards themselves
- Understand the differences among hazard, risk, acceptable risk, disaster, and catastrophe
- Understand the concept that the magnitude of a hazardous event is inversely related to its frequency
- Recognize that many natural hazards are linked to one another
- Recognize that population growth, concentration of infrastructure and wealth in hazardous areas, and land-use decisions are increasing our vulnerability to natural disasters
- Understand that hazardous natural processes can also provide benefits

Earthquake in Haiti, 2010: Lessons Learned

One of the fundamental realities in the study of natural hazards is that people and governments are poorly prepared for rare natural disasters; they commonly behave as if a disaster will never happen. This unfortunate reality is well illustrated by five recent catastrophes: the tsunami in the Indian Ocean in December 2004, Hurricane Katrina on the U.S. Gulf Coast in August 2004, the Haiti earthquake in January 2010, the Tohoku (Japan) earthquake and tsunami in April 2011, and superstorm Sandy in October 2012. Each of these events provides hard lessons that can help us reduce the toll of future disasters. Here, we illustrate these lessons using the Haiti earthquake as an example.

The massive earthquake struck southern Haiti without warning in the late afternoon (local time) of January 12, 2010. The *epicentre* was near the town of Léogâne, about 25 km west of Port-au-Prince, Haiti's capital. After several tens of seconds of strong shaking, close to 240 000 people had lost their lives, an estimated 300 000 were injured, and more than a million had been rendered homeless (Figure 1.1).[1] Equally devastating was the loss of Haiti's infrastructure, including most of the significant buildings and other engineered structures in Port-au-Prince (Figure 1.2).

The earthquake had a *magnitude* of 7.0 and was much smaller than many recent catastrophic earthquakes, such as those in Sumatra, Indonesia, in 2004, China in 2008, Chile in 2010, and Japan in 2011. Yet it was one of the worst natural disasters in history, with a loss of life comparable to the quake that levelled the city of Tangshan, China, in 1976, killing more than 250 000 people. The loss of life for an earthquake of this size was appalling. In comparison, the magnitude 7.1 earthquake that struck the San Francisco area in 1989 caused only 63 deaths and about 4000 injuries.[2]

The built environments in Port-au-Prince, Jacmel, Jerémie, Les Cayes, and other urban areas in southern Haiti suffered grievous damage. The destruction and loss of life were exacerbated by poor building materials and construction practices stemming from a lack of official building codes and insufficient attention to planning.[3] Some of the problems included construction of heavy unsupported block walls; failure to use steel rods to reinforce concrete columns, walls, and floors; and use

◄ **FIGURE 1.1 EARTHQUAKE DEVASTATION IN HAITI** Unreinforced and poorly reinforced masonry and concrete slab buildings in Canapé Vert, a shanty town in the hills around Port-au-Prince, collapsed during the January 12, 2010, earthquake *(Eduardo Munoz/Landov)*

of marine sand in cement. Salt in the marine sand led to the corrosion and weakening of concrete. Buildings of all types failed—poured concrete, mortared and dry-stacked concrete blocks and stone, and scavenged wood and metal. Slums cover the slopes surrounding Port-au-Prince, which have expanded with little control in recent years due to migration of rural Haitians into the capital city. Most buildings on slopes lack proper foundations and, consequently, many slid down hillsides during the quake (Figure 1.1). Several tens of thousands of commercial buildings collapsed or were severely damaged, including Haiti's prized Cathédrale de Port-au-Prince, the National Assembly building, Palace of Justice (Supreme Court building), the headquarters of the United Nations Stabilization Mission, and several ministerial buildings. The prison civile de Port-au-Prince was also destroyed, allowing 4000 inmates to escape. The second floor of the presidential palace completely collapsed, leaving the third floor resting on the first (Figure 1.2).

The seaport ceased to function. Docks and piers slid into the sea, and cargo cranes fell from their footings. Damage was so extensive that vessels providing international relief were forced to dock along adjacent shores. Many roads were covered with rubble from collapsed buildings or were rendered impassable due to cracks caused by ground failure.

◄ **FIGURE 1.2 COLLAPSED BUILDING IN PORT-AU-PRINCE, HAITI** A front-end loader is ready for clean-up work in front of the destroyed National Palace in Port-au-Prince, the capital of Haiti. Poor construction of even important government buildings was largely responsible for the great loss of life from the earthquake in 2010. *(St. Felix Evans)*

Although it had horrific consequences, the Haiti earthquake is not unprecedented. In an average year, about 17 earthquakes with magnitudes equal to or larger than the Haiti quake occur on Earth. Several things made this earthquake different from most quakes of similar magnitude. First, it occurred in a heavily populated area—the population of Port-au-Prince preceding the earthquake was nearly 3 million. Second, buildings in the affected area were not constructed to withstand strong seismic shaking. Access to resources is limited in Haiti, and most of those scant resources are allocated to immediate needs—food and basic shelter—rather than less pressing concerns such as disaster mitigation. Resource availability to all but a small number of Haitians is particularly low. Haiti is the poorest country in the Northern Hemisphere, with an annual income per person of only $1300 in 2012, in comparison to Canada's per capita income of $41 100. This situation has been made worse by Haiti's government bodies, which have long made few resources available for governance issues, including the establishment and enforcement of building standards.

The Haiti earthquake carries a strong message for people living in earthquake zones, including much of the west coast of North America. Port-au-Prince experienced earthquakes even larger than the 2010 quake in 1751 and 1770.[1] However, a disaster that took place hundreds of years ago is commonly a forgotten one. Due to lack of experience, people and governments were complacent and could not conceive of such an event happening; they were thus completely unprepared, as reflected in the poor construction practices prevalent in Haiti. Scientists have argued that an earthquake as large as the 2010 Haiti event could strike Vancouver, Seattle, or Portland, although no one knows precisely when. These cities are much better prepared than Haiti was before January 12, 2010, but how will they cope when it's their turn?

What are the lessons of the Haiti earthquake? We must design buildings to meet the highest seismic standards: doing so clearly saves lives. We also must continue to provide adequate research funding to scientists who are seeking to better understand where earthquakes occur, how large they are likely to be, and when they are likely to happen. New technologies, including satellite-based sensors, offer opportunities to "measure the pulse" of Earth and provide clues that might someday allow us to more accurately forecast or even predict quakes. Communication is also important. We must review and upgrade communication infrastructure and chain-of-command protocols in earthquake-prone areas to ensure that emergency officials receive timely information and respond quickly after an earthquake. People living close to faults must know what to do in the event of an earthquake. Public education programs must teach people about earthquakes and provide instructions on how to prepare, how to act when the shaking starts, and what to do after it stops. One of the most important lessons of the Haiti catastrophe is that wealthy countries must help poorer ones prepare for earthquakes and other natural disasters. Canada and the United States must do more than just respond when disaster strikes—the standard approach to dealing with disasters in developing countries. A better strategy is a long-term proactive one aimed at helping poor countries develop and prepare for disasters before they occur.

The 2010 catastrophe in Haiti was largely human-caused. Had their buildings been constructed properly, the loss of life would have been much less. If Haiti were not impoverished, its buildings might have been more earthquake resistant and the country would have been better able to deal with the terrible aftermath of the earthquake, including an outbreak of cholera ten months after the earthquake.

1.1 Why Studying Natural Hazards Is Important

In the past few decades, earthquakes, floods, and hurricanes have killed several million people around the world; the average annual loss of life has been around 150 000 per year, with more than 300 000 deaths in 2005 alone. Financial loss from natural disasters now exceeds $50 billion per year and can be as high as $200 billion, as happened in 2005 (this figure represents direct property damage and does not include such expenses as loss of employment, mental anguish, and reduced productivity).

Four catastrophes—a cyclone accompanied by flooding in Bangladesh in 1970, earthquakes in China in 1976 and Haiti in 2010, and a tsunami in the Indian Ocean in 2004—claimed more than 230 000 lives each. A cyclone that struck Bangladesh in 1991 killed 145 000 people. Four years later in 1995, an earthquake in Kobe, Japan, claimed more than 5000 lives, destroyed many thousands of buildings, and caused more than $100 billion in property damage. An earthquake in northern Pakistan in 2005 killed 86 000 people (Figure 1.3). In the same year, Hurricane Katrina devastated New Orleans and killed over 1800 people. It was the most destructive natural disaster in United States history and the deadliest hurricane since one in Florida in 1928.[4] In 2011, the tsunami generated by a powerful earthquake off the coast of Japan claimed at least 16 000 lives. The World Bank estimated that the economic cost of this earthquake and tsunami was U.S.$235 billion, making it the most expensive natural disaster in world history. More recently, in October 2012, superstorm Sandy devastated the northeast Atlantic coast of the United States, with damage estimated at U.S.$75 billion.[5] Other notable disasters in the past 20 years include catastrophic flooding in Venezuela, Bangladesh, and central Europe; the strongest El Niño on record; deadly earthquakes

◄ **FIGURE 1.3 DEVASTATING EARTHQUAKE** People search for victims in the rubble of a 10-storey building in Islamabad, Pakistan, that collapsed during a large earthquake in 2005. About 86 000 people died and 3 million more were left homeless. *(Warrick Page/Getty Images)*

in Chile, India, Iran, Italy, New Zealand, and Turkey; a Category 5 hurricane in Central America; record-setting wildfires in British Columbia, Arizona, California, Colorado, and Utah; and a crippling ice storm in Ontario, Quebec, New Brunswick, and New England. During this period, Earth also experienced many of the warmest years of the past century—and probably even of the past millennium.

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 explain these forces and their impacts on people and property. We also discuss how we can better prepare for natural disasters, thus minimizing their impact when they do occur.

All areas of Canada and the United States are at risk from at least one hazardous natural process.[6,7] Parts of western North America are prone to earthquakes and landslides and experience rare volcanic eruptions; the Pacific coast is vulnerable to tsunamis; the Atlantic and Gulf of Mexico coasts are threatened by hurricanes; forested areas of the continent are prone to wildfires; the mid-continent, from Texas to Ontario, is at risk from tornadoes and blizzards; and drought and flooding can occur almost anywhere. No area is considered hazard-free.

Loss of life from natural disasters in Canada has been decreasing in recent decades, although economic losses have increased. The current low loss of life is due, in part, to land-use planning, education, and high engineering standards. Canada also has been fortunate in having experienced few large natural disasters of the scope of Hurricane Katrina in the United States, the 2011 earthquake and tsunami in Japan, and the flood in Pakistan in 2010.

Hazardous Natural Processes and Energy Sources

In our discussion of natural hazards, we will use the word *process* to mean the ways in which events, such as volcanic eruptions, earthquakes, landslides, and floods, affect Earth's surface. All of these processes are driven by energy, and this energy is derived from three sources.

The first source of energy is Earth's internal heat, which produces slow convection in the solid but plastic mantle. The hazardous processes associated with this source of energy are earthquakes and volcanic eruptions. As we will see, earthquakes and volcanic eruptions are explained by the theory of *plate tectonics*, one of the basic unifying theories of science. Most earthquakes and active volcanoes occur at boundaries of tectonic plates, which are large blocks of Earth's crust.

The second source of energy is the sun. Energy from the sun warms Earth's atmosphere and surface, producing winds and causing evaporation of water. Circulation of the atmosphere and oceans and evaporation of water determine Earth's climate and drive the hydrologic cycle. These forces are, in turn, directly related to hazardous processes such as violent storms, floods, and coastal erosion. Solar energy is also ultimately responsible for wildfires and lightning.

The third source of energy is the gravitational attraction of Earth. Gravity is the force that attracts one body to another—in this case, the attraction of surface materials toward the centre of Earth. Because of gravitational attraction, rocks, soils, and snow on mountainsides and the water that falls as precipitation move downslope. Earth's gravitational field also attracts objects from space that can enter the atmosphere and explode or strike the surface of the planet.

The amount of energy released by natural processes differs greatly. The average tornado expends about 1000 times as much energy as a single lightning bolt, and Earth receives nearly a trillion times more solar energy each day than it receives from a lightning bolt. However, keep in mind that a lightning bolt's energy is focused at a point—a tree, for example—whereas solar energy is spread over the entire globe.

Events such as earthquakes, tsunamis, volcanic eruptions, floods, and fires are natural processes that have been occurring on Earth's surface for billions of years. They become hazardous only when they threaten human beings.

We use the terms *hazard*, *risk*, *disaster*, and *catastrophe* to describe our interaction with these natural processes.

Of course, not all hazards are natural. Many hazards are caused by people; examples include pandemics, warfare, and technological disasters such as regional power failures. The early 2009 outbreak in humans of a new strain of influenza that is endemic in pigs (H1N1 or "swine flu") is an example of a non-natural hazard. The virus rapidly spread around the world and was labelled a pandemic by the World Health Organization in June 2008. The Chernobyl nuclear accident in 1986, which resulted in the release of large quantities of radioactive particles into the atmosphere that spread over much of western Russia and Europe, is an example of a technological disaster.

Over the past century, the distinction between natural and human-induced hazards has become blurred, and technological disasters are increasing as the world's population grows and state economies become increasingly connected and interdependent. Social and technological hazards are important and interesting in their own right, but are beyond the scope of this book. Our focus is on hazardous solid Earth and atmospheric processes.

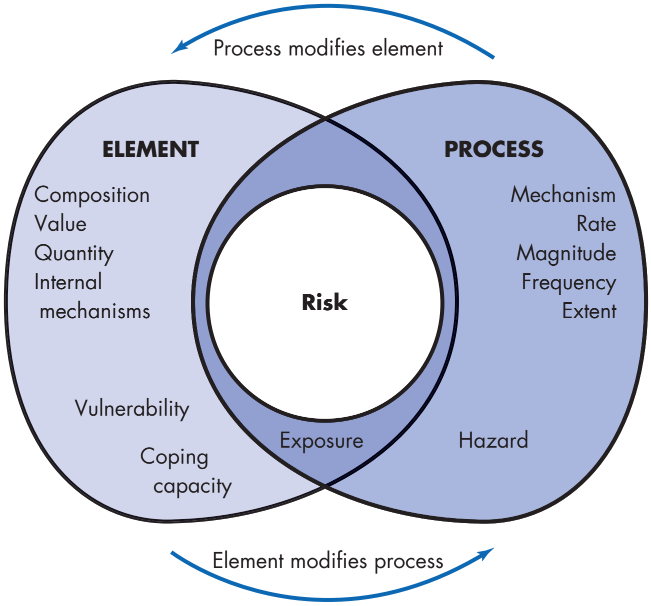
Hazard, Risk, Disaster, and Catastrophe

This book considers hazards within the human context: it focuses on the science of natural hazards and explores the social, economic, and political issues that hazards pose. The text recognizes that the human response to threats posed by natural hazards is just as important as hazard science itself.

Before discussing specific natural hazards, we need to define several key terms. **Hazard** is the probability that a specific damaging event will happen within a particular period of time.[8] This definition is common to both the natural and social sciences. **Risk**, on the other hand, is commonly a subject of social sciences because it is rooted not only in hazard but in vulnerability and coping capacity (Figure 1.4).[9,10,11] Definitions of risk are legion, but for our purposes, risk can be expressed by the following function:

Risk = *f* (hazard, exposure, vulnerability, coping capacity)

Although risk can be conceptualized as a function of these four factors, their interrelationships cannot be described in mathematical terms or even fully understood. *Vulnerability* and *coping capacity* are latent states of the people and property that are at risk and are only manifested through the occurrence of a hazardous event. Vulnerability is the susceptibility of people and property to a hazardous event and is commonly thought of as having technological and human dimensions. Technological aspects are studied by engineers and geoscientists and include primary damage and life loss. Human aspects relate to a wide range of social issues, including loss of livelihood, physical displacement, and psychological and environmental impacts of hazardous events. Coping capacity is the ability of a population to respond to and reduce the negative effects of a hazardous event. *Exposure* is the overlap in space and time of a hazardous process and infrastructure or population.

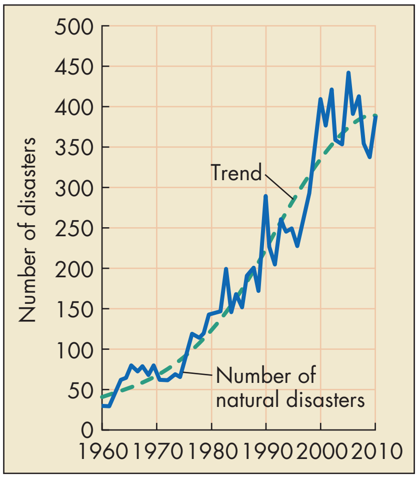


▲ **FIGURE 1.4 CONCEPTUAL MODEL OF RISK** Risk is a function of four factors—hazard, vulnerability, coping capacity, and exposure. *(From Clague, J. J., and N. J. Roberts. 2012. "Landslide hazard and risk." In* Landslides: Types, Mechanisms and Modeling, *eds. J. J. Clague and D. Stead, pp. 1–9. Cambridge, UK: Cambridge University Press. Reprinted with permission.)*

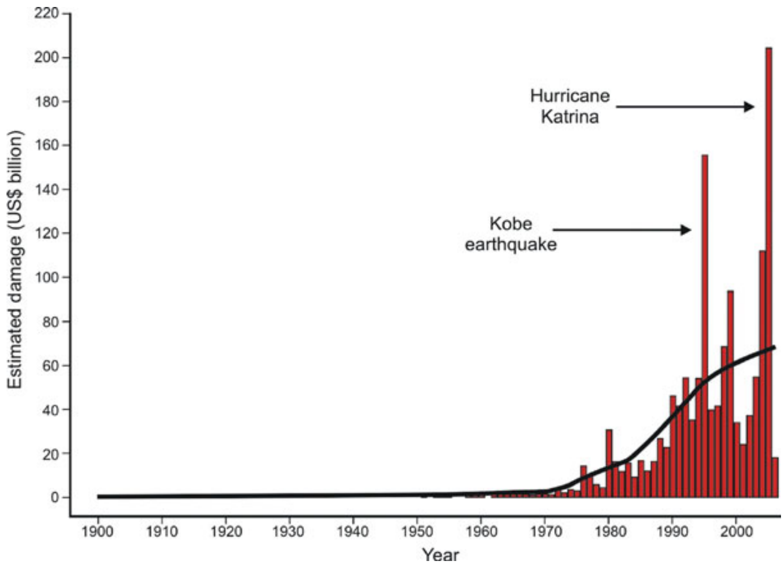
The terms **disaster**, or *natural disaster*, and **catastrophe** refer to events that cause serious injury, loss of life, and property damage over a limited time and within a specific geographic area. Although the distinction between disaster and catastrophe is somewhat vague, the latter is more massive and affects a larger number of people and more infrastructure. Disasters may be regional or even national in scope, whereas catastrophes commonly have consequences far beyond the area that is directly affected and require huge expenditures of time and money for recovery. Examples of catastrophes are the Indian Ocean tsunami in December 2004, Hurricane Katrina in August 2004, and the Haiti earthquake in January 2010.

The United Nations (UN) designated the 1990s as the International Decade for Natural Hazards Reduction. The objectives of the UN program were to minimize loss of life and property damage from natural disasters, but the objectives were not met; rather, losses from disasters increased dramatically in the 1990s (Figure 1.5), along with similar economic losses (Figure 1.6). Achieving the UN objectives will require education and large expenditures of money to mitigate specific hazards and contain diseases that accompany disasters and catastrophes.[12]

The term **mitigation** is used by scientists, planners, and policymakers when describing efforts to prepare for disasters and to minimize their harmful effects. Mitigation can be defined as actions taken to reduce or eliminate the long-term risk to human life and property from natural hazards. For example, buildings in an earthquake-prone area can be retrofitted to better withstand seismic ground motions and thus reduce the risk to occupants during a future quake.



◀ **FIGURE 1.5 INCREASE IN THE NUMBER OF NATURAL DISASTERS** The number of natural disasters is increasing. Here, an event is considered a natural disaster if one of the following four criteria is met: 10 or more people are killed; 100 or more people are affected; a state of emergency is declared; or international assistance is requested. *(Based on Guha-Sapir, D., and P. Hoyola. 2012. Measuring the Human and Economic Impact of Disasters. UK: Government Office for Science)*



◀ **FIGURE 1.6 THE RISING COST OF NATURAL DISASTERS** Estimated damage (in billions of U.S. dollars) caused by natural disasters between 1900 and 2007. *(Data from EM-DAT, the OFDA/CRED International Disaster Database)*

Death and Damage Caused by Natural Hazards

Worldwide, flooding is the largest killer of people, followed by earthquakes, volcanic eruptions, and windstorms. Since 1974, about 2.5 million people have died in natural disasters. Most deaths were in developing countries. Asia has suffered the greatest losses, with about three-quarters of the total deaths and nearly one-half of the economic losses. Loss of life and economic loss could have even been worse were it not for improvements in warning systems, disaster preparedness, and emergency response.[13,14]

Natural hazards that cause the greatest loss of life in North America are not the same as those that cause the most property damage. Tornadoes and windstorms cause the largest number of deaths in most years, although lightning, floods, and hurricanes also take a heavy toll (Table 1.1). Loss of life from earthquakes in North America is surprisingly low, largely because buildings are constructed to a high standard. However a single large earthquake can cause tremendous property damage. For example, the Northridge earthquake in Los Angeles in 1994 caused U.S.$20–30 billion in property damage but killed only 60 people. The next great earthquake in a densely populated part of California could cause more than U.S.$100 billion in damage.[12]

Natural disasters cost Canada and the United States tens of billions of dollars annually. Because populations are increasing in high-risk areas of North America, we can expect losses to increase significantly in the future. Floods, landslides, expansive soils that shrink and swell, and frost each cause in excess of U.S.$1.5 billion in damage each year in the United States alone.

TABLE 1.1 Effects of Selected Hazards in Canada and the United States

Hazard	Deaths per Year	Catastrophe Potential
Flood	100	High
Earthquake[a]	>50	High
Landslide	30	Low
Snow avalanche	20	Low
Volcanic eruption[a]	<1	High
Coastal erosion	0	Low
Soil expansion	0	Very low
Hurricane	60	High
Tornado and windstorm	220	High
Lightning	125	Very low
Drought	0	Medium
Heat wave	100s	High
Wildfire[b]	<10	High
Freezing and frozen rain	<10	Medium
Permafrost thaw	0	High
Extraterrestrial impact	0	Very high

[a] Estimates based on recent or predicted loss over a 150-year period. Actual losses differ considerably from year to year and could be much greater in a given year.

[b] Most deaths are firefighters.

Source: Adapted from White, G. F., and J. E. Haas. 1975. Assessment of Research on Natural Hazards. *Cambridge, MA: MIT Press. Reprinted with permission.*

Note that the relations between loss of life and property damage discussed above apply only to the developed world—mainly North America, Europe, Japan, Australia, and New Zealand. Natural disasters in most developing countries claim far more lives than comparable events in North America. For example, the tsunami in the Indian Ocean in December 2004 killed nearly 230 000 people. In comparison, the tsunami in the North Pacific in 1964, although equal in size, killed 119 people. A notable characteristic of North American disasters, however, is their very large toll on the economy. Category 4 and 5 hurricanes typically cause billions of dollars in damage in southern U.S. states; the direct damage from Hurricane Katrina, the worst storm in U.S. history, was more than U.S.$80 billion, and indirect damage, including lost economic activity and employment, was several times that amount.[4]

Natural hazards differ greatly in their potential to create a catastrophe, mainly because of differences in the size of the area each affects (Table 1.1). Three processes—climate change, eruptions of super volcanoes, and large meteorite impacts—can have global repercussions. Large tsunamis, earthquakes, major volcanic eruptions, hurricanes, monsoon floods, and floods on large rivers have regional effects and may result in catastrophes. Landslides, snow avalanches, floods on small rivers, most wildfires, and tornadoes generally affect small areas and thus are rarely catastrophic. Coastal erosion, lightning, expansive soils, and permafrost thaw do not create catastrophes, but still cause much damage.[15]

Risks associated with natural hazards change with time because of changes in population and land use. As cities grow, neighbourhoods may extend onto hazardous land, such as steep hillsides and floodplains. Such expansion is a serious problem in many large, rapidly growing cities in developing nations. Urbanization alters drainage, increases the steepness of some slopes, and removes vegetation. Agriculture, forestry, and mining also remove natural vegetation and can increase erosion and sedimentation. Overall, damage from most hazardous natural processes in Canada is increasing, but the number of deaths from many hazards is decreasing because of better planning, forecasting, warning, and engineering.

1.2 Magnitude and Frequency of Hazardous Events

The *impact* of a hazardous event is partly a function of its magnitude—the size of an event or the amount of energy released—and partly a function of frequency. The *magnitude–frequency concept* asserts that an inverse exponential relationship exists between the magnitude of an event and its frequency (Figure 1.7). Large floods or earthquakes, for example, are infrequent, whereas small floods or earthquakes are common. The *recurrence interval*, also known as the return period, is the average time separating two events of the same magnitude. The magnitude–frequency relation for many natural phenomena can be approximated by an exponential equation of the type $M = Fe^{-x}$, where M is the magnitude of the event, F is the frequency, e is the base of the natural logarithm, and x is a constant.