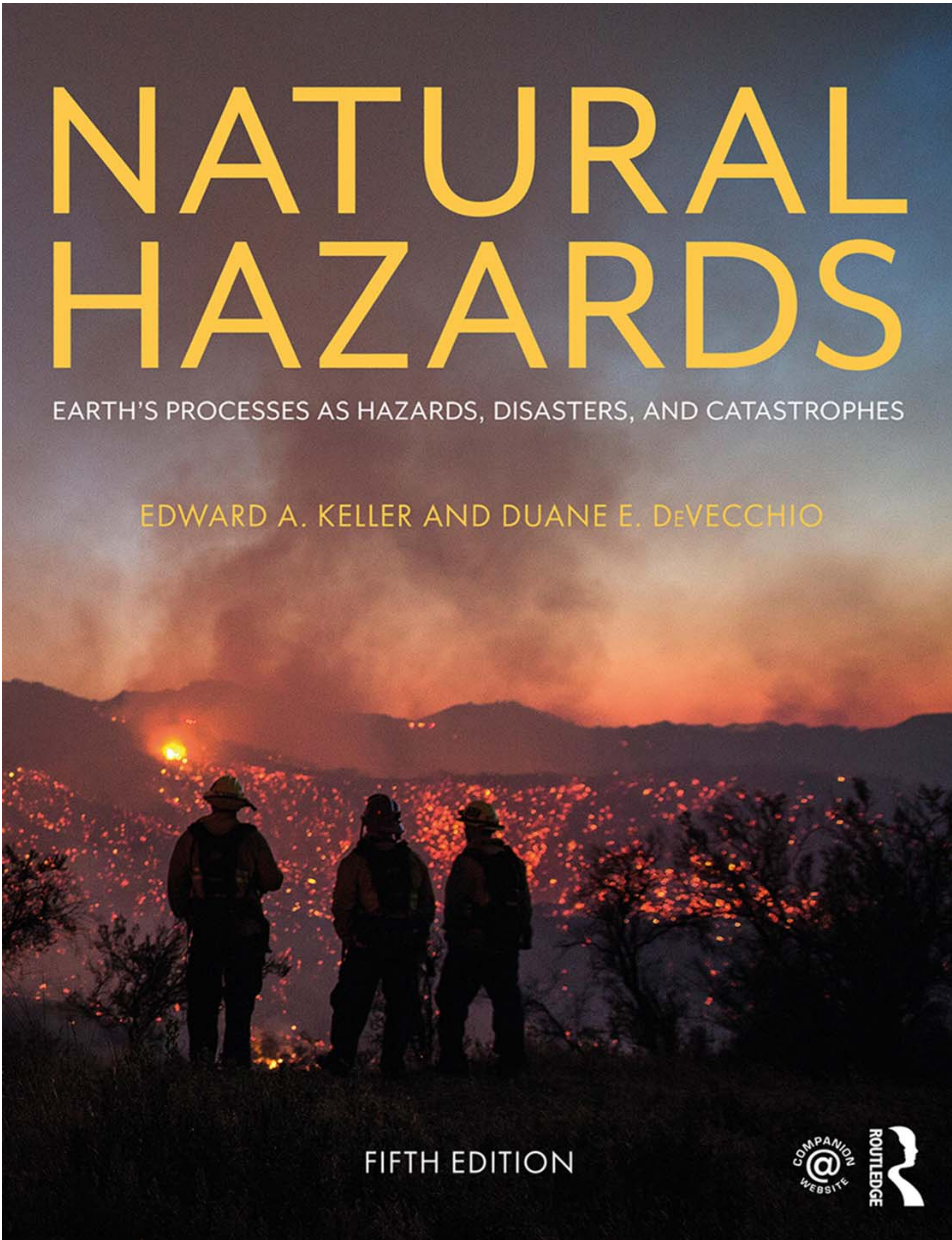
NATURAL HAZARDS

EARTH'S PROCESSES AS HAZARDS, DISASTERS, AND CATASTROPHES

EDWARD A. KELLER AND DUANE E. DeVECCHIO



FIFTH EDITION

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NATURAL HAZARDS

The new revised fifth edition of *Natural Hazards* remains the go-to introductory-level survey intended for university and college courses that are concerned with earth processes that have direct, and often sudden and violent, impacts on human society. The text integrates principles of geology, hydrology, meteorology, climatology, oceanography, soil science, ecology, and solar system astronomy.

The textbook explains the earth processes that drive hazardous events in an understandable way, illustrates how these processes interact with our civilization, and describes how we can better adjust to their effects. Written by leading scholars in the area, the new edition of this book takes advantage of the greatly expanding amount of information regarding natural hazards, disasters, and catastrophes. The text is designed for learning, with chapters broken into small consumable chunks of content for students. Each chapter opens with a list of learning objectives and ends with revision as well as high-level critical thinking questions. A Concepts in Review feature provides an innovative end-of-chapter section that breaks down the chapter content by parts: reviewing the learning objectives, summary points, important visuals, and key terms. New case studies of hazardous events have been integrated into the text, and students are invited to actively apply their understanding of the five fundamental concepts that serve as a conceptual framework for the text. Figures, illustrations, and photos have been updated throughout.

The book is designed for a course in natural hazards for nonscience majors, and a primary goal of the text is to assist instructors in guiding students who may have little background in science to understand physical earth processes as natural hazards and their consequences to society.

Edward A. Keller is a professor in the Environmental Studies and Earth Sciences Departments at University of California at Santa Barbara, USA.

Duane E. DeVecchio is a research professor in the School of Earth and Space Exploration (SESE) at Arizona State University, USA.

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EDWARD A. KELLER AND
DUANE E. DeVECCHIO

WITH ASSISTANCE FROM
ROBERT H. BLODGETT

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Brief Contents

1 Introduction to Natural Hazards 2

2 Internal Structure of Earth and Plate Tectonics 36

3 Earthquakes 64

4 Tsunamis 122

5 Volcanoes 154

6 Flooding 208

7 Mass Wasting 256

8 Subsidence and Soils 298

9 Atmospheric Processes and Severe Weather 344

10 Hurricanes and Extratropical Cyclones 396

11 Coastal Hazards 438

12 Climate Change and Natural Hazards 484

13 Wildfires 528

14 Impacts and Extinctions 558

Contents

About the Authors xvii
Preface xviii

1 Introduction to Natural Hazards 2

1.1 Why Studying Natural Hazards Is Important 5
Processes: Internal and External 5
Hazard, Disaster, or Catastrophe 5
Death and Damage Caused by Natural Hazards 7

1.2 The Role of History in Understanding Hazards 9

1.3 The Geologic Cycle 10
The Tectonic Cycle 10
The Rock Cycle 10
The Hydrologic Cycle 11
Biogeochemical Cycles 12

1.4 Fundamental Concepts for Understanding Natural Processes as Hazards 13

1 Science helps us predict hazards. 13
Science and Natural Hazards 13
Hazards Are Natural Processes 13
Forecast, Prediction, and Warning of Hazardous Events 14

2 Knowing hazard risks can help people make decisions. 19
Risk as a Concept 19
Risk Management 20

3 Linkages exist between natural hazards. 21

4 Humans can turn disastrous events into catastrophes. 21
Examples of Disasters in Densely Populated Areas 21
Population Growth as a Factor in Hazards 22
Magnitude and Frequency of Hazardous Events 23

5 Consequences of hazards can be minimized. 24
Reactive Response: Impact of and Recovery from Disasters 24
Anticipatory Response: Avoiding and Adjusting to Hazards 25

CASE STUDY 1.1 **Professional Profile:** Professor Robert Bea, University of California, Berkeley 26

1.5 Many Hazards Provide a Natural Service Function 28

1.6 Global Climate Change and Hazards 30
Concepts in Review 30
Critical Thinking Questions 33

2 Internal Structure of Earth and Plate Tectonics 36

2.1 Internal Structure of Earth 39

2.2 Plate Tectonics 41

Movement of the Tectonic Plates 41
Types of Plate Boundaries 44
Rates of Plate Motion 48

2.3 A Detailed Look at Seafloor Spreading 48

Paleomagnetism 48
Hot Spots 51

2.4 Pangaea and Present Continents 53

2.5 How Plate Tectonics Works: Putting It Together 56

2.6 Plate Tectonics and Hazards 57

Concepts in Review 59
Critical Thinking Questions 61

3 Earthquakes 64

3.1 Introduction to Earthquakes 66

Faults and Faulting 68

3.2 The Earthquake Processes 70

The Earthquake Cycle 70
Seismic Waves 72
Tectonic Creep and Slow Earthquakes 73
CASE STUDY 3.1 2015 Nepal (Gorkha) Earthquake: Forecasting a Catastrophe 74

3.3 Earthquake Shaking 75

Earthquake Magnitude 75
Earthquake Intensity 77
Depth of Focus 80
Direction of Rupture 80
Distance to the Epicenter 80
Local Geologic Conditions 81
CASE STUDY 3.2 Earthquake Catastrophes: Lessons Learned 83

3.4 Geographic Regions at Risk from Earthquakes 84

Plate Boundary Earthquakes 85
Intraplate Earthquakes 86
CASE STUDY 3.3 Survivor Story: Magnitude 8.8 Earthquake and Tsunami on the Coast of Chile 87

3.5 Effects of Earthquakes and Linkages with Other Natural Hazards 91

Shaking and Ground Rupture 91
CASE STUDY 3.4 The Denali Fault Earthquake: Estimating Potential Ground Rupture Pays Off 92
Liquefaction 93

Regional Changes in Land Elevation 93
Landslides 94
Fires 95
Disease 95

3.6 Natural Service Functions of Earthquakes 96
Groundwater and Energy Resources 96
Mineral Resources 96
Landform Development 96
Future Earthquake Hazard Reduction 96

3.7 Human Interaction with Earthquakes 96
Earthquakes Caused by Human Activity 97

3.8 Minimizing the Earthquake Hazard 98
The National Earthquake Hazard Reduction Program 98
Estimation of Seismic Risk 98
Short-Term Prediction 99
CASE STUDY 3.5 **A Closer Look:** Paleoseismic Earthquake Hazard Evaluation 101
The Future of Earthquake Prediction 104
Earthquake Warning Systems 105

3.9 Perception of and Adjustment to the Earthquake Hazard 106
Perception of the Earthquake Hazard 106
CASE STUDY 3.6 **Professional Profile:** Andrea Donnellan, Earthquake Forecaster 107
Community Adjustments to the Earthquake Hazard 108
Personal Adjustments: Before, During, and After an Earthquake 111
Applying the 5 Fundamental Concepts 112
Concepts in Review 116
Critical Thinking Questions 119

4 Tsunamis 122

4.1 Introduction to Tsunamis 124
How Do Earthquakes Cause a Tsunami? 124
CASE STUDY 4.1 **Survivor Story:** Tsunami in the Lowest Country on Earth 127
How Do Landslides Cause a Tsunami? 128

4.2 Geographic Regions at Risk from Tsunamis 129
CASE STUDY 4.2 Indonesian Tsunami 132
Tsunami Three Centuries Ago 136

4.3 Effects of Tsunamis and Linkages with Other Natural Hazards 137

4.4 Natural Service Functions of Tsunamis 138

4.5 Human Interaction with Tsunamis 138

4.6 Minimizing the Tsunami Hazard 138
Detection and Warning 138
Structural Control 139
Tsunami Runup Maps 139
Land Use 141
Probability Analysis 141
Education 142
Tsunami-Ready Status 142

4.7 Perception and Personal Adjustment to Tsunami Hazard 143
CASE STUDY 4.3 **Professional Profile:** Jose Borrero—Tsunami Scientist 144
Applying the 5 Fundamental Concepts 146
Concepts in Review 149
Critical Thinking Questions 152

5 Volcanoes 154

5.1 Introduction to Volcanism 156
How and Where Magma Forms 157
Magma Properties 159

5.2 Volcano Types, Formation, and Eruptive Behavior 162

5.3 Geographic Regions at Risk from Volcanoes 170

5.4 Effects of Volcanoes 171

Lava Flows 172
Pyroclastic Activity 174

CASE STUDY 5.1 Mount Unzen 177

Volcanic Gases 178
Debris Flows, Mudflows, and Volcanic landslides 180

CASE STUDY 5.2 Volcanic Landslides and Tsunamis 181

CASE STUDY 5.3 Mount St. Helens 1980–2010: From Lateral Blasts to Lava Flows 182

5.5 Linkages between Volcanoes and Other Natural Hazards 186

5.6 Natural Service Functions of Volcanoes 188

Volcanic Soils 188
Geothermal Power 188
Mineral Resources 188
Recreation 188
Creation of New Land 188

5.7 Human Interactions with Volcanoes 189

5.8 Minimizing the Volcanic Hazard 189

Forecasting 189

CASE STUDY 5.4 **Professional Profile:** Chris Eisinger, Student of Active Volcanoes 192

Volcanic Alert or Warning 193

5.9 Perception of and Adjustment to the Volcanic Hazard 194

Perception of Volcanic Hazards 194
Adjustments to Volcanic Hazards 194
Attempts to Control Lava Flows 194

CASE STUDY 5.5 **Survivor Story:** A Close Call with Mount St. Helens 195

Applying the 5 Fundamental Concepts 197
Concepts in Review 202
Critical Thinking Questions 204

6 Flooding 208

6.1 An Introduction to Rivers 211

Earth Material Transported by Rivers 212
River Velocity, Discharge, Erosion, and Sediment Deposition 212
Channel Patterns and Floodplain Formation 213

6.2 Flooding 217

Introduction 217
Magnitude and Frequency of Floods 218
Flash Floods of Zone 1 220
Downstream Floods of Zone 2 220

CASE STUDY 6.1 **Survivor Story:** Flash Flood 221

CASE STUDY 6.2 Mississippi River Floods of 1973–2008: Zone 2 Floods 222

Downstream Floods of Zone 3: Alluvial Fans and Deltas 226

CASE STUDY 6.3 Flooding on the Delta of the Ventura River 227

Megafloods 228

6.3 Geographic Regions at Risk for River Flooding 230

6.4 Effects of Flooding and Linkages between Floods and Other Hazards 232

6.5 Natural Service Functions of Floods 232

Water Resources and Flooding 232
Fertile Lands 233
Riparian and Aquatic Ecosystems 233
Sediment Supply 233

CASE STUDY 6.4 Experimental Floods on the Colorado River 234

6.6 Human Interaction with Flooding 236

Land-Use Changes 236
Dam Construction 236
Urbanization and Flooding 238

6.7 Minimizing the Flood Hazard: Structural Control to Floodplain Management 241

The Structural Approach 241
Social Media and Flood Damage Mediation 245

6.8 Perception of the Flood Hazard 245

Personal Adjustment: What To Do and What Not To Do 246

CASE STUDY 6.5 **Professional Profile:** Nicholas Pinter, Southern Illinois University then U.C. Davis in California 247

Applying the 5 Fundamental Concepts 249
Concepts in Review 251
Critical Thinking Questions 254

7 Mass Wasting 256

7.1 An Introduction to Landslides 258

Slope Processes 259
Types of Landslides 260
Forces on Slopes 263

CASE STUDY 7.1 **A Closer Look:** Forces on Slopes 264

CASE STUDY 7.2 Portuguese Bend, California 270

Snow Avalanches 272

7.2 Geographic Regions at Risk from Landslides 273

7.3 Effects of Landslides and Linkages with Other Natural Hazards 273

Effects of Landslides 273
Linkages between Landslides and Other Natural Hazards 274

CASE STUDY 7.3 2014 Oso Landslide, Washington 275

CASE STUDY 7.4 **Survivor Story:** Landslide in Colorado 277

CASE STUDY 7.5 **Professional Profile:** Bob Rasely, Mass Wasting Specialist 278

7.4 Natural Service Functions of Landslides 279

7.5 Human Interaction with Landslides 279

Timber Harvesting and Landslides 279
Urbanization and Landslides 280

CASE STUDY 7.6 Rio de Janeiro, Brazil 281

7.6 Minimizing the Landslide Hazard 282

Identifying Potential Landslides 282
Preventing Landslides 282
Landslide Warning Systems 285

7.7 Perception of and Adjustment to the Landslide Hazard 286

Perception of the Landslide Hazard 286
Adjustment to the Landslide Hazard 286
Personal Adjustments: What You Can Do to Minimize Your Landslide Hazard 287
Applying the 5 Fundamental Concepts 288
Concepts in Review 292
Critical Thinking Questions 294

8 Subsidence and Soils 298

8.1 Soil and Hazards 300

Soil Horizons 300
Soil Color 301
Soil Texture 302
Relative Soil Profile Development 303
Water in Soils 304
Classifying Soils 305
Soil Erosion as a Hazard 305
CASE STUDY 8.1 Haiti and Soil Erosion 307

8.2 Introduction to Subsidence and Soil Volume Change 309

Karst Formation 309
Thermokarst Formation 313
Sediment and Soil Compaction 313
CASE STUDY 8.2 **Survivor Story:** Sinkhole Drains Lake 314
CASE STUDY 8.3 Mississippi River Delta Subsidence 315
Earthquakes 317
Underground Drainage of Magma 318
Expansive Soils 318
Frost-Susceptible Soils 319

8.3 Geographic Regions at Risk for Subsidence and Soil Volume Change 320

8.4 Effects of Subsidence and Soil Volume Change 321

Sinkhole Damage 321
Changes in Groundwater Conditions 322
Damage Caused by Melting Permafrost 323
Coastal Flooding and Loss of Wetlands 323
Damage Caused by Soil Volume Change 324

8.5 Linkages between Subsidence, Soil Volume Change, and Other Natural Hazards 325

8.6 Natural Service Functions of Subsidence and Soil Volume Change 325

Water Supply 326
Aesthetic and Scientific Resources 326
Unique Ecosystems 326

8.7 Human Interaction with Subsidence and Soil Volume Change 326

Fluid Withdrawal 326
Underground Mining 327
Melting Permafrost 329
Restricting Deltaic Sedimentation 329
Altering Surface Drainage 329
Poor Landscaping Practices 329
CASE STUDY 8.4 **Professional Profile:** Helen Delano, Environmental Geologist 330

8.8 Minimizing Subsidence and Soil Volume Change 331

8.9 Perception of and Adjustment to Subsidence and Soil Volume Change 332

Perception of Subsidence and Soil Volume Change 332
Adjustment to Subsidence and Soil Volume Change 332

Applying the 5 Fundamental Concepts 334
Concepts in Review 337
Critical Thinking Questions 340

9 Atmospheric Processes and Severe Weather 344

9.1 **Energy** 346
Types of Energy 347
Heat Transfer 347

9.2 **Earth's Energy Balance** 348
Electromagnetic Energy 348
Energy Behavior 350

9.3 **The Atmosphere** 350
Composition of the Atmosphere 350
Structure of the Atmosphere 351

9.4 **Weather Processes** 353
Atmospheric Pressure and Circulation 353
Unstable Air 356
CASE STUDY 9.1 **A Closer Look:** Coriolis Effect 357
Fronts 358

9.5 **Hazardous Weather and Geographic Regions at Risk** 358
Thunderstorms 359

CASE STUDY 9.2 **Professional Profile:** Sarah Tessendorf, Severe Storm Meteorologist 363
Tornadoes 366
CASE STUDY 9.3 **Survivor Story:** Struck by Lightning 368
CASE STUDY 9.4 Tri-State Tornado 370
Blizzards and Ice Storms 370
CASE STUDY 9.5 The Great Northeastern Ice Storm of 1998 373
Fog 375
Drought 375
Mountain Windstorms 376
Dust Storms and Sandstorms 376
Heat Waves 377

9.6 **Human Interaction with Weather** 378
CASE STUDY 9.6 Europe's Hottest Summer in More Than 500 Years 379
Lessons Learned 381
Prospects for the Future 382

9.7 **Linkages with Other Hazards** 382

9.8 **Natural Service Functions of Severe Weather** 383

9.9 **Minimizing Severe Weather Hazards** 383
Forecasting and Predicting Weather Hazards 383
Adjustment to the Severe Weather Hazard 384
Applying the 5 Fundamental Concepts 385
Concepts in Review 390
Critical Thinking Questions 393

10 Hurricanes and Extratropical Cyclones 396

10.1 **Introduction to Cyclones** 398
Classifying Cyclones 399
Naming Cyclones 399

10.2 **Cyclone Development and Movement** 401
Tropical Cyclones 401
CASE STUDY 10.1 **A Closer Look:** North Atlantic Oscillation 405
Extratropical Cyclones 406
CASE STUDY 10.2 Hurricane Katrina: "The most anticipated natural disaster in American history" 409

CASE STUDY 10.3 **Survivor Story:** Hurricane Katrina 412

10.3 Geographic Regions at Risk for Cyclones 413

10.4 Effects of Cyclones 415

Storm Surge 415

High Winds 416

Heavy Rains 418

10.5 Linkages between Cyclones and Other Natural Hazards 418

10.6 Natural Service Functions of Cyclones 419

10.7 Human Interaction with Cyclones 419

10.8 Minimizing the Effects of Cyclones 420

Forecasts and Warnings 420

CASE STUDY 10.4 **Professional Profile:** The Hurricane Hunters 423

CASE STUDY 10.5 2017 Atlantic Hurricane Season: Record Breaking 425

10.9 Perception of and Adjustment to Cyclones 426

Perception of Cyclones 426

Adjustment to Hurricanes and Extratropical Cyclones 427

Applying the 5 Fundamental Concepts 428

Concepts in Review 432

Critical Thinking Questions 435

11 Coastal Hazards 438

11.1 Introduction to Coastal Hazards 440

11.2 Coastal Processes 441

Waves 441

Beach Form and Processes 444

11.3 Sea-Level Change 447

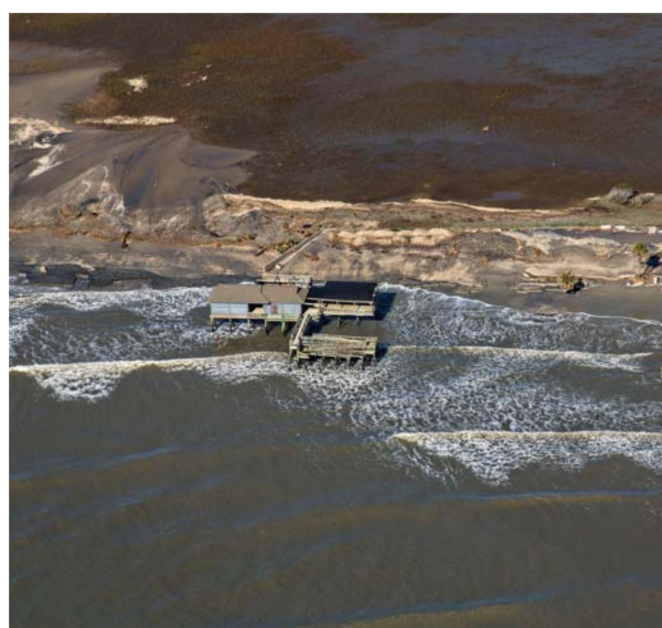
11.4 Geographic Regions at Risk from Coastal Hazards 448

11.5 Effects of Coastal Processes 449

Rip Currents 449

CASE STUDY 11.1 **Survivor Story:** Rip Current: Two Experienced Swimmers Rescued on Florida Beach 451

Coastal Erosion 452



11.6 Linkages between Coastal Processes and Other Natural Hazards 456

11.7 Natural Service Functions of Coastal Processes 457

11.8 Human Interaction with Coastal Processes 459

The Atlantic Coast 459
CASE STUDY 11.2 Maryland Barrier Islands 460
The Gulf Coast 461
The Pacific Coast 461
The Great Lakes 461
Canadian Seacoasts 462

11.9 Minimizing the Effects of Coastal Hazards 462

Hard Stabilization 462
Soft Stabilization 464

11.10 Perception of and Adjustment to Coastal Hazards 467

Perception of Coastal Hazards 467
Adjustment and Management of Coastal Hazards 467
CASE STUDY 11.3 The Cape Hatteras Lighthouse 470
CASE STUDY 11.4 Pointe du Hoc, France 471
Applying the 5 Fundamental Concepts 474
Concepts in Review 478
Critical Thinking Questions 481

12 Climate Change and Natural Hazards 484

12.1 Global Change and Earth System Science: An Overview 486

12.2 Climate and Weather 486

Climate Zones 487

12.3 The Atmosphere and the Cryosphere 488

Atmospheric Composition 488
Hydrosphere and Cryosphere 489

12.4 How We Study Past Climate Change and Make Predictions 490

Global Climate Models 492

12.5 Global Warming 494

The Greenhouse Effect 494
Global Temperature Change 496
Why Does Climate Change? 497
Solar Forcing 500
Volcanic Forcing 501
Anthropogenic Forcing 501

12.6 Effects of Climate Change 502

Glaciers and Sea Ice 502
CASE STUDY 12.1 Loss of Glacial Ice in Antarctica 504
Climate Patterns and Meteorological Hazards 505
Sea-Level Rise 508
CASE STUDY 12.2 Disappearing Islands: Tuvalu, South Pacific 510
Wildfires 512
Landslide Hazard 512
Volcanic, Earthquake, and Tsunami Hazards 513
Changes in the Biosphere 514

12.7 Predicting the Future Climate 516

What Does Our Recent History Tell Us about Potential Consequences of Future Global Warming? 516
Predicting Future Climate Is Problematic 517

12.8 Strategies for Reducing the Impact of Global Warming 517

Abrupt Climate Change 519

Applying the 5 Fundamental Concepts 520
Concepts in Review 522
Critical Thinking Questions 524

13 Wildfires 528

13.1 Introduction to Wildfire 530

CASE STUDY 13.1 Wildfires in the U.S. Southwest, Colorado, Arizona and California **530**

13.2 Wildfire as a Process 531

Fire Environment 533
Types of Fires 535

13.3 Geographic Regions at Risk from Wildfires 536

13.4 Effects of Wildfires and Linkages with Other Natural Hazards 536

Effects on the Geologic Environment 536
Effects on the Atmospheric Environment 541
Linkages with Climate Change 541
Effects on the Biological Environment 543

13.5 Natural Service Functions of Wildfires 544

Benefits to Soil 544
Benefits to Plants and Animals 545

13.6 Minimizing the Wildfire Hazard 546

Fire Management 546

13.7 Perception of and Adjustment to the Wildfire Hazard 547

Perception of the Wildfire Hazard 547
Adjustments to the Wildfire Hazard 548
Personal Adjustment to the Fire Hazard 549

CASE STUDY 13.2 **Survivor Story:** Elderly Couple Survives Wildfire by Jumping into a Neighbor's Swimming Pool 550

Applying the 5 Fundamental Concepts 551
Concepts in Review 553
Critical Thinking Questions 555

14 Impacts and Extinctions 558

14.1 Earth's Place in Space 560

Asteroids, Meteoroids, and Comets 560

14.2 Airbursts and Impacts 564

CASE STUDY 14.1 The Tunguska Event 564

Impact Craters 566
Uniformitarianism, Gradualism, and Catastrophism 570

14.3 Mass Extinctions 571

CASE STUDY 14.2 K-Pg Boundary Mass Extinction 573

CASE STUDY 14.3 Impact and Mass Extinction 12,800 Years Ago 576

CASE STUDY 14.4 **Professional Profile:** Emeritus Professor James Kennett, University of California, Santa Barbara 580

14.4 Linkages with Other Natural Hazards 581

14.5 Minimizing the Impact Hazard 582

Risk Related to Impacts 582
Minimizing the Impact Hazard 582
Applying the 5 Fundamental Concepts 585
Concepts in Review 588
Critical Thinking Questions 590

APPENDIX A **Minerals** 592

APPENDIX B **Rocks** 600

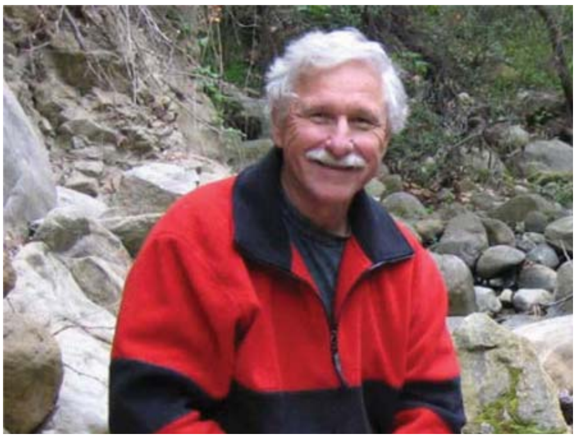
APPENDIX C **Maps and Related Topics** 603

APPENDIX D **How Geologists Determine Geologic Time** 610

Glossary 613

Index 632

About the Authors



EDWARD A. KELLER

Ed Keller is a professor, researcher, writer, and most importantly, 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 geologic controls on habitat to endangered southern steel-head 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 been an author on more than 100 articles, including seminal works on fluvial processes and tectonic geomorphology. Ed's academic honors 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 moonlight sand at Arroyo Burro Beach in Santa Barbara.

DUANE E. DEVECCHIO

Duane DeVecchio is a research professor in the School of Earth and Space Exploration (SESE) at Arizona State University, where he is deeply engaged in undergraduate education and teaches a broad range of courses to students completing degrees in both the geological sciences and environmental studies. Outside of the classroom, Dr. DeVecchio serves on both the SESE undergraduate education committee and the curriculum redesign committee, where he collaborates with coworkers to develop student learning strategies and curriculum designed to develop student critical thinking skills and scientific literacy, which are particularly important today when cable television and the Internet offer accessibility to vast amounts of information, yet the validity of this information is often questionable or misleading.

Duane grew up in California where he completed his Bachelor's degree at San Francisco State University before moving on to Idaho State University where he completed a Master's degree. In 2009 he graduated with his Ph.D. from University of California Santa Barbara where he honed his teaching skills while conducting a wide range of research in the geological sciences. Dr. DeVecchio 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 of the western United States. For his Master's degree and post-Master's research he conducted structural and stratigraphic analyses as well as numerical dating of volcanic and volcaniclastic rocks in southeastern Idaho and the central Mojave Desert of California, which record the Miocene depositional and extensional histories of these regions. His dissertation and current research 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 he is not teaching or conducting research, he's hang gliding, but he also enjoys rock climbing, whitewater rafting, snow boarding, and camping.

Preface

Natural Hazards: Earth Processes as Hazards, Disasters, and Catastrophes, *Fifth Edition*, is an introductory-level survey intended for university and college courses that are concerned with earth processes that have direct, and often sudden and violent, impacts on human society. The text integrates principles of geology, hydrology, meteorology, climatology, oceanography, soil science, ecology, and solar system astronomy. The book is designed for a course in natural hazards for nonscience majors, and a primary goal of the text is to assist instructors in guiding students who may have little background in science to understand physical earth processes as natural hazards and their consequences to society.

In revising the fifth edition of this book we take advantage of the greatly expanding amount of information regarding natural hazards, disasters, and catastrophes. Since the fourth edition was published, many natural disasters and catastrophes have occurred. Becoming the wettest tropical cyclone in U.S. recorded history, Hurricane Harvey in 2017 produced peak accumulations of rainfall of more than 1.5 m (~60 in.) over a three-day period causing catastrophic flooding in the Houston metropolitan area; earthquakes killed more than 8,000 people in Nepal in 2015, and were responsible for widespread destruction in Mexico in 2017; wildfires in northern and southern California in 2017 destroyed more than 7,000 buildings and killed 46 people; and the deadliest U.S. landslide on record killed 43 people in Washington state in 2014. Most of these disasters have a common denominator—they were not unexpected and the effects of these catastrophes could have been minimized had the population been better prepared and the warnings from the scientific community been heeded. In other words, they were largely, in terms of lives lost and property damaged, disasters caused by humans.

On a global scale, climate change is causing glaciers, ice caps, and permafrost to melt; the atmosphere and oceans to warm; and sea levels to rise more rapidly than originally forecast. These changes are caused in part by human activities, primarily the burning of fossil fuels, which releases vast quantities of carbon dioxide and other gases into the atmosphere each day. The interaction between humans and earth processes has never been clearer, nor has the need for understanding these processes as hazards for our economy and society ever been greater. This edition of *Natural Hazards* seeks to explain the earth processes that drive hazardous events in an understandable way, illustrate how these processes interact with our civilization, and describe how we can better adjust to their effects.

A central thesis to this text is that we must first understand that earth processes are not, in and of themselves, hazards. Earthquakes, floods, volcanic eruptions, wildfires, and other processes have occurred for millennia, indifferent to the presence of people. Natural processes become hazards when they impact humanity. Ironically, it is human behavior that often causes the interactions with these processes to become disasters or, worse, catastrophes. Most important is the unprecedented increase in human population in the past 50 years linked to poor land-use decisions.

In addition to satisfying a natural curiosity about hazardous events, there are additional benefits to studying natural hazards. An informed citizenry is one of our best guarantees of a prosperous future. Armed with insights into linkages between people and the geologic environment, we will ask better questions and make

the 5 fundamental concepts

1

Science helps us predict hazards.

Natural hazards, such as earthquakes, volcanic eruptions, landslides, and floods, are natural processes that can be identified and studied using the scientific method. Most hazardous events and processes can be monitored and mapped, and their future activity predicted, on the basis of frequency of past events, patterns in their occurrence, and types of precursor events.

2

Knowing hazard risks can help people make decisions.

Hazardous processes are amenable to *risk analysis*, which estimates the probability that an event will occur and the consequences resulting from that event. For example, if we were to estimate that in any given year, Los Angeles has a 5 percent chance of a moderate earthquake, and if we know the consequence of that earthquake in terms of loss of life and damage, then we can calculate the potential risk to society.

better choices. On a local level we will be better prepared to make decisions concerning where we live and how best to invest our time and resources. On a national and global level we will be better able to advise our leaders on important issues related to natural hazards that impact our lives.

Major New Material in the Fifth Edition

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

- **Active, Modular Learning Path.** The fifth edition of *Natural Hazards* is designed for learning with each chapter broken into smaller, more consumable, chunks of content for students. Each chapter opens with a list of learning objectives and students can check their mastery of these objectives with new **Check Your Understanding** questions at the end of each section. Each chapter concludes with a new **Concepts in Review** section: an innovative end-of-chapter section that breaks down the chapter content by section—reviewing the learning objectives, summary points, important visuals, and key terms. All chapters end with high-level critical thinking questions.
- **Applying the Fundamental Concepts.** Every chapter begins with a captivating hazard story that applies the five fundamental concepts that serve as a conceptual framework for the text. We then close each chapter by recapping this hazard story and, through assessment, invite the students to actively apply their understanding of the five fundamental concepts.
- Current hazard coverage on the Tohoku, Japan earthquake and tsunami in 2011, Hurricane Sandy in New Jersey and New York City in 2012, the tornado in Moore, Oklahoma in 2013, historic flooding in Houston in 2017, and the 2017 fire season in California.
- New in-chapter **case studies** and **chapter openers** that highlight hazardous events have been integrated into the text, providing coverage of the most recent natural disasters on earth.
- Updated art program showcases new figures, illustrations, and photos throughout. Each image has been reviewed for accuracy and relevance, focusing on its educational impact.

Distinguishing Features of the Fifth Edition

We have incorporated a number of features designed to support the student and instructor.

A BALANCED APPROACH

Although the interest of many readers will naturally focus on natural hazards that threaten their community, state, or province, the globalization of our economy, information access, and human effects on our planet require a broader, more balanced approach to the study

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.

of natural hazards. A major earthquake in Taiwan affects trade in the ports of Seattle and Vancouver; the economy of Silicon Valley in California affects the price of computer memory in Valdosta, Georgia, and Halifax, Nova Scotia. Because of these relationships, we provide examples of hazards from throughout the United States as well as throughout the world.

This book discusses each hazardous process as both a natural occurrence and a human hazard. For example, the discussion of earthquakes balances the description of their characteristics, causes, global distribution, estimated frequency, and effects with a description of engineering and nonstructural approaches to reduce their effects on humans, including actions that communities and individuals can take.

The five concepts introduced in Chapter 1 and revisited in every chapter are designed to provide a memorable, transportable, and conceptual framework of understanding that students can carry with them throughout their lives to make informed choices about their interaction with and effect upon earth processes.

CASE STUDIES: SURVIVOR STORIES, PROFESSIONAL PROFILES, AND CLOSER LOOKS

Many of the chapters contain personal stories of someone who has experienced the effects of a hazardous event, such as a flood, earthquake, or wildfire, a profile of a scientist or other professional who has worked with a particular hazard, and Closer Look boxes that use life events and data to enhance the understanding and comprehension of not only the hazard but also the mitigation that coincides with the hazard. Most of us in our lifetimes will experience (directly or indirectly) a flood, wildfire, volcanic eruption, tsunami, or major hurricane, and we are naturally curious as to what we will see, hear, and feel. For example, a scientific description of wildfire does not convey the fear and anxiety when a fire is rushing toward your home. Likewise, the stream gauge records for the Rio Grande River do not give us the sense of excitement and fear felt by Jason Lange and his friends when their spring-break canoe trip in West Texas nearly turned to tragedy (see Case Study 6.1: Survivor Story). To fully 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, especially once you more fully understand the hazard. Knowledge from reading this book could save your life someday, as it did for Tilly Smith and her family on the beach in Phuket, Thailand, during the Indian Ocean tsunami (see Case Study 4.2: Indonesian Tsunami).

People study and work with natural hazards for many reasons—scientific curiosity, monetary reward, excitement, or the desire to help others deal with events that threaten our lives and property. As you read the professional profiles, think about these people's motivation, the type of work that they do, and how that work contributes to increasing human knowledge or to saving people's lives and property. For example, for many years Bob Rasely worked as a geologist with the U.S. Natural Resources Conservation Service studying what happens to hillslopes after wildfires in Utah (see Case Study 7.5: Professional Profile). For Bob, geology had long been both a vocation and an avocation. He maintains an intellectual curiosity as to how Earth works and a practical goal of predicting the likelihood and location of debris flows following a fire. Working with other state and federal scientists, Bob develops plans for hillslope recovery and helps communities downslope from burned land establish warning systems to protect lives and property. Nearly all the survivor stories and professional profiles are based on interviews conducted exclusively for *Natural Hazards* by Kathleen Wong, a science writer from Oakland, California, and Chris Wilson, a former journalism student at the University of Virginia.

For the Instructor

The Instructor Resource Center provides a collection of resources to help teachers make efficient and effective use of their time. All digital resources can be found in one well-organized, easy to access place. The IRC (download only) includes:

- Pre-authored Lecture Outline PowerPoint presentations, which outline the concepts of each chapter with embedded art and can be customized to fit instructors' lecture requirements
- The test bank includes over 1,000 multiple-choice, true/false, and short-answer test questions on the science of natural hazards and their effects on the world and humankind. Questions are correlated against chapter-specific learning outcomes and Bloom's Taxonomy to help teachers better map the assessments against both broad and specific teaching and learning objectives. TestGen software for both PC and Mac.

The Instructor Resource content is available online at www.routledgetextbooks.com/textbooks/ 9781138057227/#instructors.

For the Student

This title has recently been acquired by Taylor & Francis. Due to rights reasons, any multimedia resources will not be available from Taylor & Francis. Mastering Geology incorporating Hazard City will still be available for purchase from Pearson.

Acknowledgments

Many individuals, companies, and agencies have helped make this book a success. In particular, we are indebted to the U.S. Geological Survey and the National Oceanic and Atmospheric Administration for their excellent natural hazard programs and publications.

To authors of papers cited in this book, we offer our thanks and appreciation for their contributions. Without their work, this book could not have been written. We must also thank the thoughtful scholars who dedicated valuable time reviewing chapters of this book. The following reviewers' comments helped us significantly improve the fifth edition:

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Duane would like to offer special thanks to his family and friends, and to all of the students who continue to ask good questions, reinforcing and reminding him of the importance of science today.

Edward A. Keller

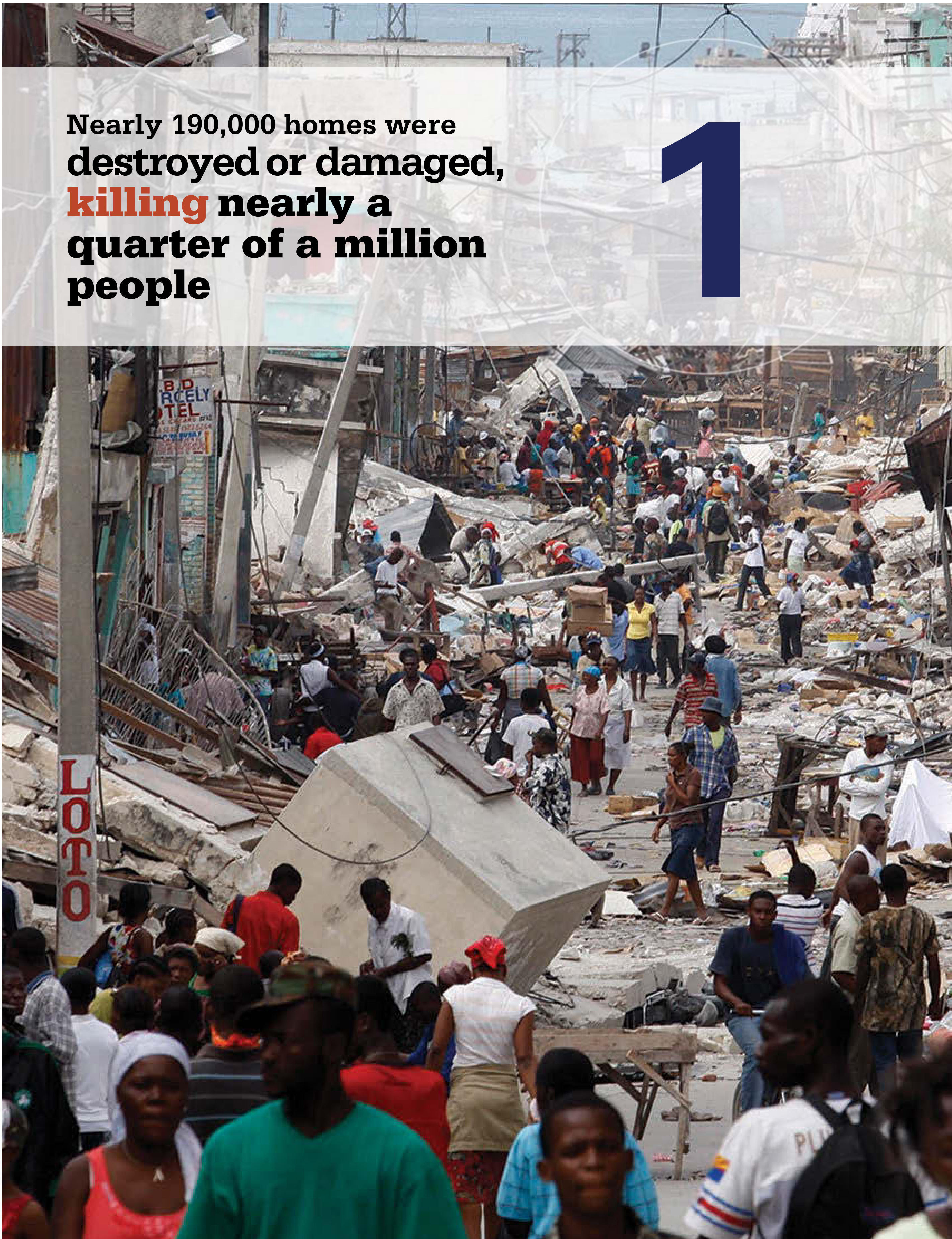
Santa Barbara, California

Duane E. DeVecchio

Tempe, Arizona

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

1



Introduction to Natural Hazards

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.

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)*

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

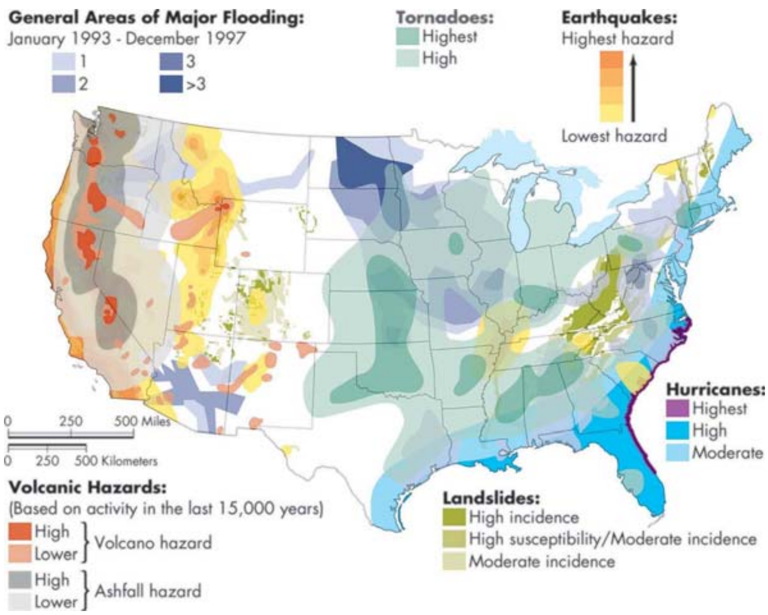


FIGURE 1.2 Major Hazards in the United States
Areas of the United States at risk for earthquakes, volcanoes, landslides, flooding, hurricanes, and tornadoes. Almost every part of the country is at risk for one of the six hazards considered here. A similar map or set of maps is available for Canada. *(From 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

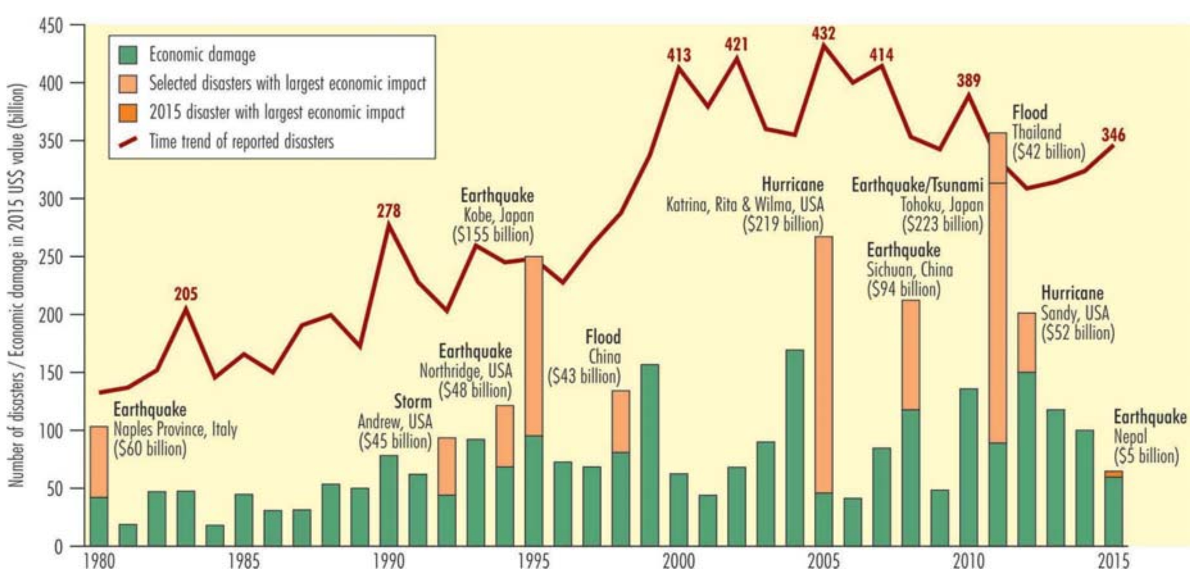


FIGURE 1.5 Disasters and Catastrophes 1980 to 2015 by Number of Events and Economic Losses
Several examples of events with very large economic costs are listed by date, type of hazard, and location.
(Center for Research on the Epidemiology, 2016. Disaster data: A balanced perspective. Cred Crunch Issue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

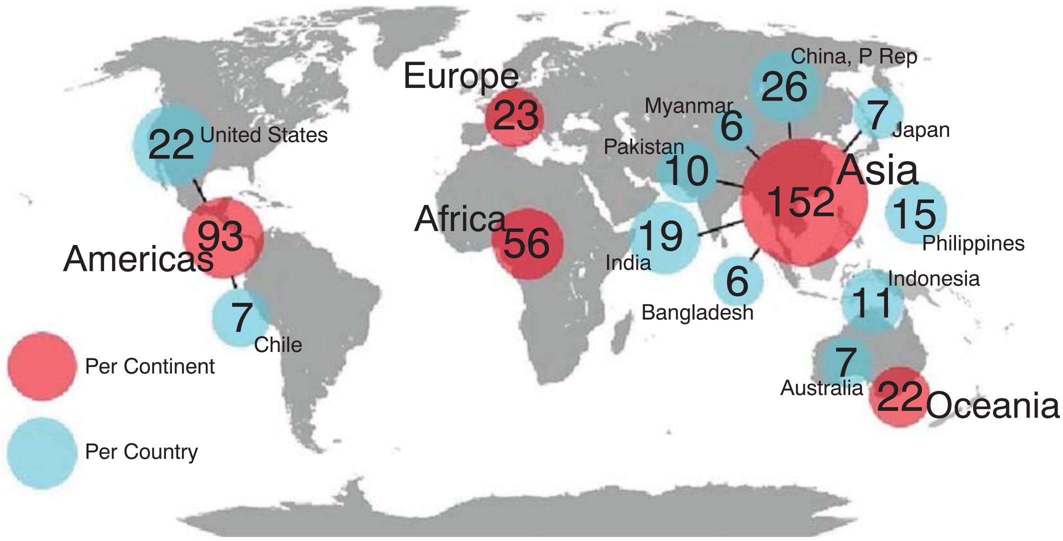


FIGURE 1.6 Number and Locations, by Continent and Country, of Natural Disasters in 2015
Notice that about half are in Asia. *(Center for Research on the Epidemiology, 2016. Disaster data: A balanced perspective. Cred Crunch Issue No. 41)*

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