MULTI HAZARD *Identification and Risk Assessment*

A Cornerstone of the National Mitigation Strategy

Prepared in support of the International Decade for Natural Disaster Reduction

First edition published 1997
Printed in the United States of America

Includes bibliographical references and index

MULTI HAZARD

Identification and Risk Assessment

The Cornerstone of the National Mitigation Strategy

Mitigation

Prepared in Support of the International Decade for Natural Disaster Reduction

A MESSAGE FROM THE DIRECTOR

During a presentation before the U.S. Congress in 1993, I indicated that the United States cannot afford the continuing high costs of natural and technological disasters. We cannot afford the economic costs to the American taxpayer, nor can we afford the social costs inflicted on our communities and citizens.

The Federal Emergency Management Agency (FEMA) has embarked on a full-scale effort to help build safer communities. Our goals include increasing public awareness of hazards and loss reduction (mitigation) measures, reducing the risk of loss of life and property, and protecting our nation's communities and the economy from all types of natural and technological hazards.

FEMA's role in this effort is to provide leadership and programmatic, technical, and financial support to our partners: Federal, State, and local agencies; national and State legislative bodies; colleges and universities; private-sector organizations; volunteer organizations; and individuals. Our partnerships are accomplished through a comprehensive, risk-based, all-hazards program of mitigation, preparedness, response, and recovery.

FEMA has been busy. In addition to responding to numerous disasters, we have made significant progress in developing mitigation programs. Among many accomplishments, in 1995 we developed a national strategy for mitigation after meeting with our partners across the United States. We have started a process that is vital to successful implementation of pre- and post-disaster mitigation. We have also executed performance-based partnership agreements with all 50 States and the U.S. territories.

An integral part of implementing our mitigation strategy is the transfer and sharing of information and knowledge. *Multi-Hazard Identification and Risk Assessment* supports that objective. We look forward to working with our partners to update and expand scientific knowledge and applied technology so that we will be better prepared for the hazards that will affect our families, friends and neighbors in the future.

James Lee Witt

Director

Federal Emergency Management Agency

A MESSAGE FROM THE ASSOCIATE DIRECTOR FOR MITIGATION

Hurricanes, earthquakes, wildfires, and tornadoes cause millions of dollars in damage. They force individuals and families out of their homes and destroy their belongings. Businesses often lose money or even close their doors for good. Public infrastructure such as roads, bridges, water supplies and sewage systems suffer damage, diminishing our quality of life. These losses tear at the very fabric of our communities and our lives.

What is most saddening is that much of the suffering and losses associated with natural disasters is unnecessary. While we cannot keep natural hazards from occurring, we do know how to reduce their effects. By taking actions in our homes, businesses, and our communities to mitigate risks, we can reduce disaster impacts and break the cycle of losses that we have witnessed in recent years. In a nutshell, we can reduce our nation's vulnerability to natural disasters.

Central to our success in breaking the disaster-loss cycle is our ability to identify the hazards that we face and to assess the level of risk they bring to our lives. The report before you is a product of FEMA's efforts to further develop such a capability at the national level. It documents months of research and coordination and provides a baseline of knowledge concerning the identification of hazards and assessment of the risks. The report was created to be a "working" or "living" reference document for State and local specialists. As such, it is FEMA's intention to periodically update or amend the report to ensure that the best and most accurate information is available to those who need it most.

I believe this report provides State and local decision-makers with a better understanding of the types and magnitudes of the natural and technological hazards which their communities face. This, in turn, will help them evaluate exposure of people and property and assess the consequences of hazard events. With these tools, we can make more informed decisions about reducing future disaster losses. I trust you will find this report useful and informative. We look forward to working together to address natural and technological hazards nationwide.

Michael J. Armstrong

Michael J. Armstrong

Associate Director for Mitigation

ACKNOWLEDGEMENTS

This report was prepared by the Federal Emergency Management Agency's (FEMA) Mitigation Directorate, with assistance from Michael Baker Jr., Inc., Arthur D. Little, Inc., of Cambridge, MA, and Mr. John Hilson of Boulder, CO. We wish to acknowledge the valuable contributions of these organizations, the staffs of the FEMA Regional Offices, and the following organizations and individuals:

Atmospheric

- Arthur Mears, Inc., Gunnison, CO
- Carbon Dioxide Information Analysis Center, World Data Center for Atmospheric Trace Gasses, Oak Ridge National Laboratory, Oak Ridge, TN
- Mr. Chris Jones, Earth Tech, Charlottesville, VA
- Mr. Knox Williams, Colorado Avalanche Information Center, Denver, CO
- EOSDIS Distributed Active Archive Center, User Services Office, National Aeronautic and Space Administration, Oak Ridge, TN
- National Climatic Data Center, National Oceanic and Atmospheric Administration, Asheville, NC
- National Hurricane Center, National Weather Service, Coral Gables, FL
- National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, MD

Geologic

- Geologic Division, U.S. Geological Survey: Reston, VA; Golden, CO; Menlo Park, CA; Seattle, WA
- Geology Department, University of Washington, Seattle, WA

Photo: Red Cross

Photo: Red Cross

- J.H. Wiggins Company, Redondo Beach, CA
- National Landslide Information Center, U.S. Geological Survey, Golden, CO
- Oklahoma State University, Stillwater, OK
- Slosson and Associates, Van Nuys, CA
- Water Resources Division, U.S. Geological Survey: Sacramento, CA; Tucson, AZ

Hydrologic

- Institute for Water Resources, U.S. Army Corps of Engineers, Fort Belvoir, VA
- Property Loss Research Bureau, Schaumberg, IA
- TEMCO/Department of Public Safety, Pago Pago, American Samoa
- U.S. Army Corps of Engineers, Headquarters, Division, and District Offices
- University of California, Santa Cruz, CA
- Dr. Robert Dolan, University of Virginia, Charlottesville, VA

Seismic

- Building Seismic Safety Council, Washington, DC
- Geologic Division, U.S. Geological Survey: Golden, CO; Reston, VA; Seattle, WA
- National Earthquake Information Center, U.S. Geological Survey, Golden, CO
- National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, CO
- National Institute of Building Sciences, Washington, DC
- Dr. Edward Bernard, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, WA

Volcanic

- Cascades Volcano Observatory, U.S. Geological Survey, Vancouver, WA
- Geologic Division, U.S. Geological Survey, Menlo Park, CA

Wildfire

- Arapaho/Roosevelt National Forest, U.S. Forest Service, Fort Collins, CO
- Boulder County Land Use Department, Boulder, CO
- Colorado State Forest Service, Fort Collins, CO
- Fire and Aviation, U.S. Forest Service, Washington, DC
- Intermountain Fire Sciences Lab, Missoula, MT
- National Interagency Fire Center, Boise, ID
- State and Private Forestry, Region 2, U.S. Forest Service, Denver, CO

Technological

- Mr. Martin McCann, Jr., Center on the Performance of Dams, Stanford University, Stanford, CA
- Risk Management Solutions, Inc., Menlo Park, CA

Photo: FEMA

Photo: Red Cross

Multiple Hazards

- Department of Geology and Geography, Hunter College of the City University of New York, New York, NY
- Disaster Preparedness Resources Centre, University of British Columbia, Vancouver, British Columbia
- Insurance Institute for Property Loss Reduction, Boston, MA
- Board of Natural Disasters, National Research Council, Washington, DC
- National Fire Protection Association, Quincy, MA
- Ms. Mary Fran Myers, Natural Hazards Research and Applications Center, Institute of Behavioral Sciences, University of Colorado, Boulder, CO

Risk Assessment

- Mr. Hemant Shah and Dr. Scott Lawson, Risk Management Solutions, Inc., Menlo Park, CA

TABLE

OF

CONTENTS

TABLE OF CONTENTS

Page

LIST

OF

ILLUSTRATIONS

LIST OF ILLUSTRATIONS

Tables — Page

Tables **Page**

Maps Page

EXECUTIVE SUMMARY

"Experience is a good teacher, but changes in population patterns, physical characteristics of structures, and economic development during the past century suggest that relying on experiences alone is inadequate for judging vulnerability."

From Reducing Disasters' Toll:
The United States Decade for
Natural Disaster Reduction

EXECUTIVE SUMMARY

For decades, most Americans assumed that they were immune to, or could control, the forces and fury of natural hazards. With each new flood, hurricane, tornado, earthquake, avalanche, landslide, or wildfire, that assumption has proven incorrect. Since 1990, the United States has experienced numerous major disasters, among them were Hurricanes Andrew, Iniki, Marilyn and Opal; the Great Midwest Flood of 1993; the Northridge Earthquake; and wildfires in California.

Recent disasters, regardless of scale, have focused the attention of government officials and citizens alike on the economic, human, and environmental costs. With each new event, it becomes more apparent that a unified, concerted approach to lessening if not eliminating the risks is needed. The United States has the technical skill to reduce loss of life and property. Unfortunately, until recently, the will to do so has been unfocused.

Under the leadership of Director James Lee Witt, the staff of the Federal Emergency Management Agency (FEMA) has developed a national approach to mitigating human and economic loss caused by disasters. As one part of the effort, FEMA initiated a research project to clarify and document previous efforts to identify natural and technological hazards, and to assess associated risks. This report, *Multi-Hazard Identification and Risk Assessment,* is prepared as a reference document to summarize the findings.

For specific natural and technological hazards, the report summarizes the state of scientific and technical knowledge on identification and the risks that have been or can be assigned to each hazard. FEMA's recently developed risk assessment methodology, Hazards United States, known as HAZUS, is introduced. Also summarized are the National Mitigation Strategy and highlights from recent successes in each of the five major elements of the Strategy: (1) hazard identification and risk assessment; (2) applied research and technology transfer; (3) public awareness, training, and education; (4) incentives and resources; and (5) leadership and coordination.

Using Geographic Information System technology and available data, selected maps were generated. Often, the maps illustrate areas that appear to be most susceptible to individual and multiple hazards. Some readers may be surprised at the variety and extent of hazards that may occur in various regions of the United States. The maps do not, and are not intended to, depict a final assessment of where hazards exist or where disasters are likely to occur. Uncertainty about risks will always be present, but assessments can be improved.

Brief summaries of existing programs and initiatives, and plans for future mitigation activities, suggest that while a great deal has been accomplished, much more remains to be done.

Multi-Hazard Identification and Risk Assessment is a reference that is available to assist hazard identification, risk assessment, and mitigation specialists in refining our understanding of hazards and their impacts on people and the built environment. FEMA intends to update this report as identification, assessment, and mitigation approaches are refined.

INTRODUCTION

"Want of foresight, unwillingness to act when action would be simple and effective, lack of clear thinking, confusion of counsel until the emergency comes, until self-preservation strikes its jarring gong - these are the features which constituted the endless repetition of history."

Winston Churchill
Speaking to the House of Commons
Before World War II

INTRODUCTION

BACKGROUND

Since its creation in 1979, the role of the Federal Emergency Management Agency (FEMA) has been to develop, implement, and support policies and programs for emergency management at the national, State, and local levels. Such policies and programs are necessary because periodically throughout its history the United States has been damaged disastrously by natural and technological hazard events. Many events, even if not disastrous in scope or magnitude, take their toll in terms of life and property. Cumulatively, natural and technological hazard events cost millions each year and affect every State (Figure i-1).

Presidential disaster declarations throughout the United States and its territories from 1975 through 1995 are shown on Map i-1.

During the late 1980s and early 1990s, the United States experienced unprecedented devastation from major events, such as earthquakes, hurricanes, tropical storms, floods, landslides, volcanic eruptions, severe winterstorms, and wildfires. Over 500 people lost their lives during these events. Between 1989 and 1994, 291 presidential disaster declarations were issued. Federal disaster assistance made available to affected States, communities, and individuals cost the U.S. Treasury over $34 billion. Figure i-2 presents information provided by the Insurance Research Council and the Property Claims Service, Inc., on insured losses for selected major natural disasters that occurred from 1989 to 1995.

Under the leadership of Director James Lee Witt, FEMA's efforts have been redefined and better focused. FEMA's primary mission is to reduce the risk of loss of life and property in the United States, and to protect U.S. institutions from the disastrous effects of natural and technological hazards. FEMA accomplishes this mission by leading, coordinating with, and supporting specialists at every level of government (Federal, State, and local) and the private sector in the development of a comprehensive, risk-based emergency management program of mitigation, preparedness, response, and recovery.

The importance and necessity of FEMA's efforts are underscored by the following statistics:

- Estimates indicate approximately 9 to 11 million homes are at risk from flooding, approximately 25 million homes are at risk from severe wind hazards, approximately 2 million homes may be at risk from coastal storm surge, and at least 50 million homes may be located in counties with significant earthquake risk;

- More than 36 million people live in the most hurricane-prone counties from Maine to Texas, and the number is expected to grow to 73 million by the year 2010; and

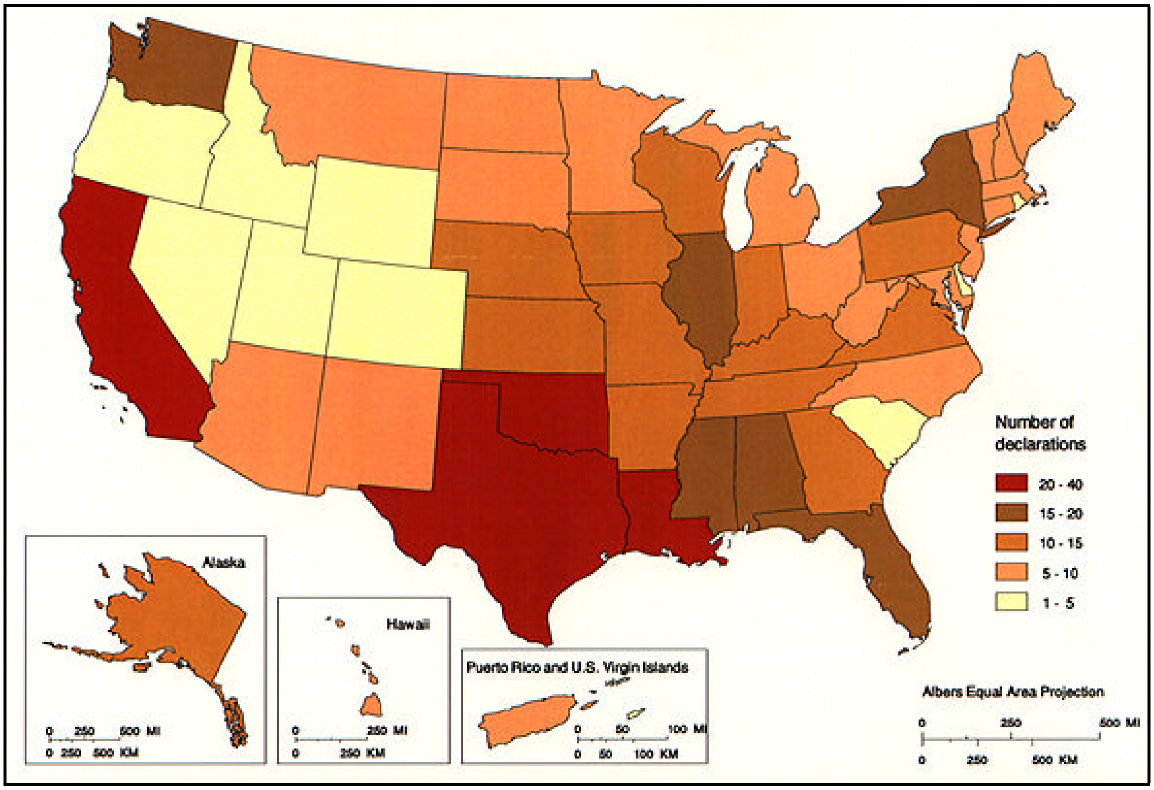
- During the last 5 years alone, combined Federal disaster assistance and insurance industry payments totaled over $67 billion.

Presidents and the U.S. Congress have exhibited strong leadership in raising awareness concerning the United States' exposure to hazard events. They have provided valuable input to FEMA in the development of its policies and programs. Recently, the U.S. Congress stressed the importance of identifying natural and technological hazards and assessing the risks posed to people and property.

In Senate Report 101-128, which accompanied the 1990 FEMA appropriations bill, the Senate Appropriations Committee directed FEMA to ". . . prepare a study on the principal threats facing communities and local emergency management coordinators . . . The study should rank the principal threats to the population according to region and any other factors deemed appropriate."

From 1990 to 1993, FEMA produced reports that summarized the principal natural and technological threats, or hazards, facing communities and emergency management coordinators. However, the limitations of these rankings were acknowledged in the first report, dated April 1990. Some of the limiting factors cited were the wide variation in application of criteria to the same hazards, differences between the State and regional impacts of particular hazards, applicability of threats from region to region, and variances in amounts and types of data collected on particular hazards.

The April 1990 report cited the following as factors that make relative rankings of hazards, even within regions, very difficult: level of community preparedness; degree to which urban or sparsely populated rural areas are affected by disaster events; and emergency managers' perceptions regarding the potential severity, magnitude, or rankings of particular hazards.



Map i-1. Presidential disaster declarations by State for the period of 1975 - 1995. The Pacific Territories have had 35 declarations. Source: *FEMA, 1995.*

As a direct result of the disasters of the early 1990s, in particular the Midwest Floods of 1993, the U.S. Congress directed FEMA to place its highest priority on working with State and local agencies to mitigate the impacts of future natural hazard events. This marked a fundamental shift in policy: rather than placing primary emphasis on response and recovery, FEMA's focus broadened to incorporate mitigation as the foundation of emergency management.

NATIONAL MITIGATION STRATEGY AND GOAL

In keeping with congressional directive, Director Witt and FEMA staff led the development of the National Mitigation Strategy. FEMA derived 10 fundamental principles for the framework and objectives of the National Mitigation Strategy.

1. Risk reduction measures ensure long-term economic success for the community as a whole rather than short-term benefits for special interests.

2. Risk reduction measures for one natural hazard must be compatible with risk reduction measures for other natural hazards.

3. Risk reduction measures must be evaluated to achieve the best mix for a given location.

4. Risk reduction measures for natural hazards must be compatible with risk reduction measures for technological hazards and vice versa.

5. All mitigation is local.

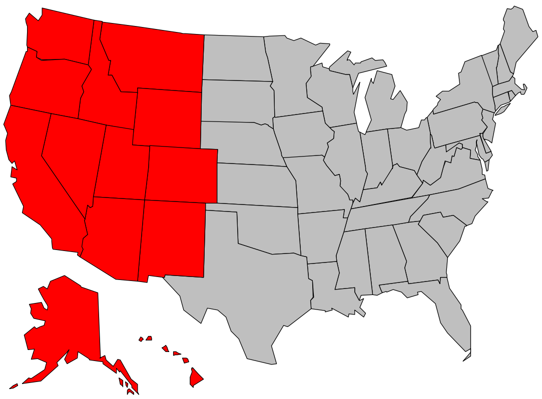
6. Disaster costs and the impacts of natural hazards can be reduced by emphasizing pro-active mitigation before emergency response; both pre-disaster (preventive) and post-disaster (corrective) mitigation is needed.

7. Hazard identification and risk assessment are the cornerstones of mitigation.

8. Building new Federal-State-local partnerships and public-private partnerships is the most effective means of implementing measures to reduce the impacts of natural hazards.

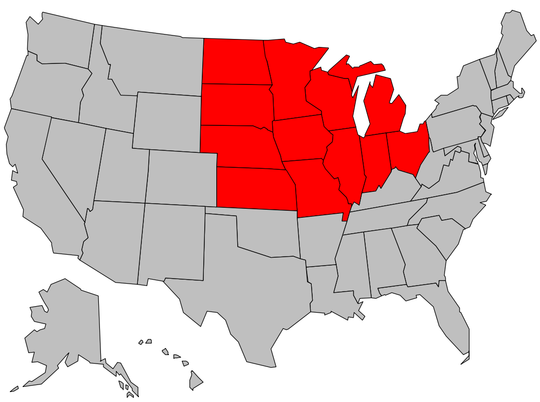
GEOGRAPHY OF NATURAL HAZARDS

Although occasional events of a particular natural hazard can occur in any area of the United States, most tend to occur more frequently in some areas than in others. The following table lists the hazards that are most prevalent in each area.



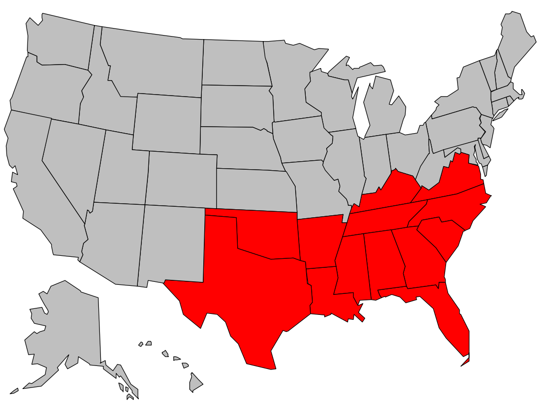
West

Avalanches	Land Subsidence
Droughts	Storm Surges
Earthquakes	Tsunamis
Expansive Soils	Tornadoes
Extreme Heat	Typhoons
Hailstorms	Volcanoes
Floods	Wildfires
Landslides	Windstorms



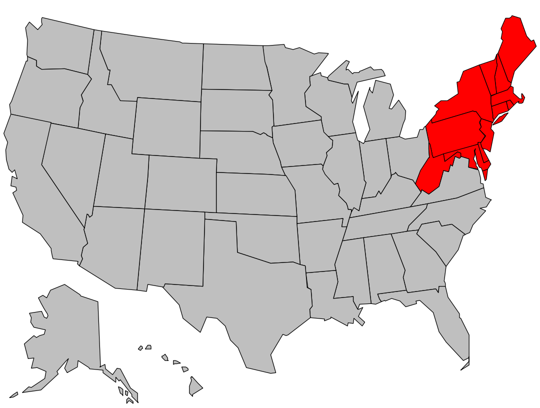
Midwest

Droughts	Hailstorms
Earthquakes	Severe Winter Storms
Expansive Soils	Thunder & Lightning
Extreme Heat	Tornadoes
Floods	Windstorms



South

Coastal Erosion	Hurricanes
Droughts	Land Subsidence
Earthquakes	Storm Surges
Expansive Soil	Thunder & Lightning
Extreme Heat	Tornadoes
Floods	Windstorms



Northeast

Coastal Erosion	Hurricanes
Earthquakes	Landslides
Extreme Heat	Severe Winter Storms
Floods	Storm Surges

FIGURE i-1.

Source: *Compiled by FEMA, 1995*

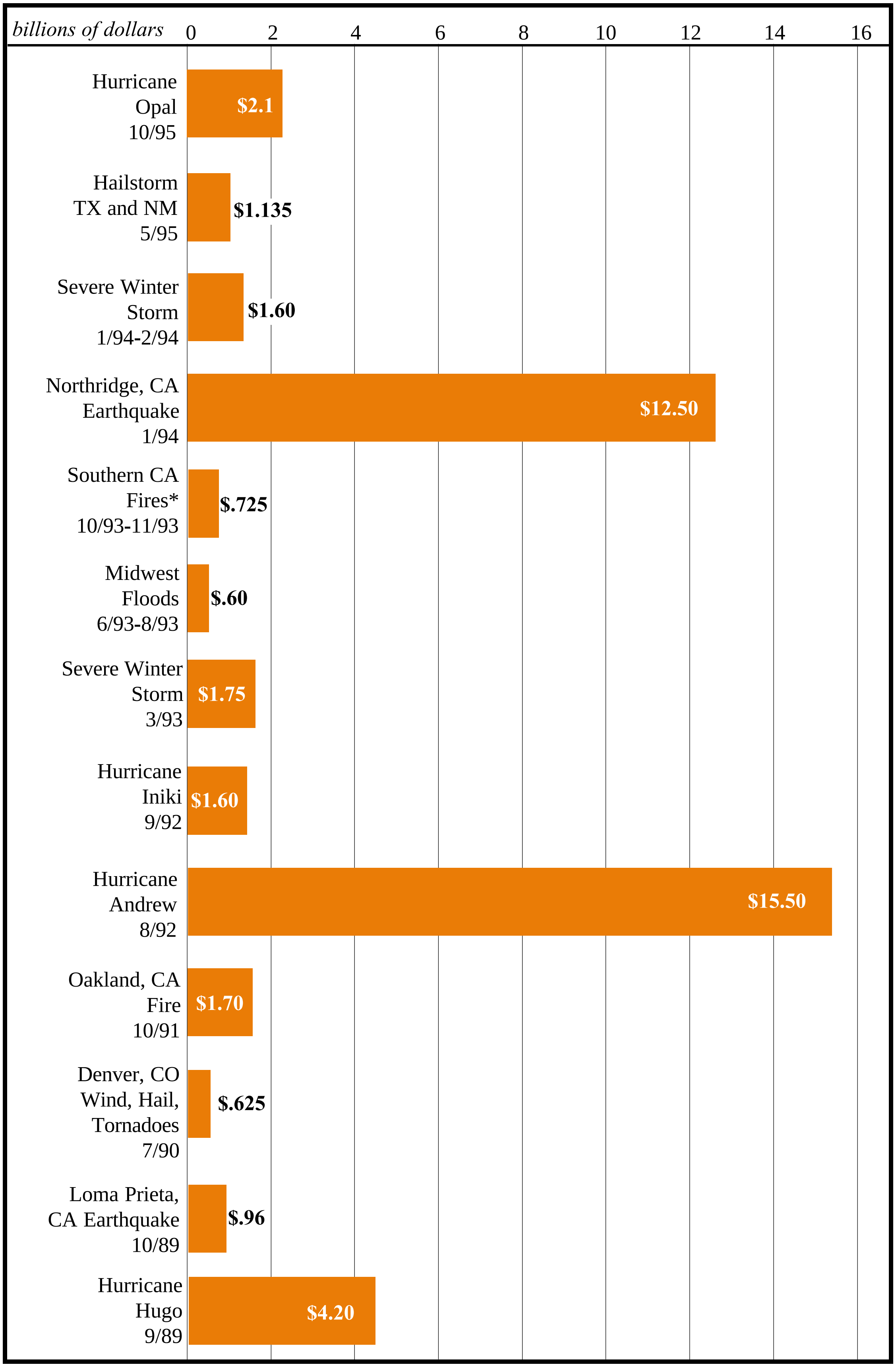


FIGURE i-2.—Total insured losses for major natural disasters: 1989-1995.

Source: *From Property Claim Services, 1997; and Insurance Research Council, 1995*

* *Only 2 of the 27 fires were officially classified by the insurance industry as catastrophes. Costs associated with other fires at the same time may have caused losses to reach $.95 billion.*

9. Those who knowingly choose to assume greater risk must accept responsibility for that choice.

10. Risk reduction measures for natural hazards must be compatible with the protection of natural and cultural resources.

Using these principles as guidance, FEMA established a National Mitigation Goal to be accomplished by the year 2010. The two components of the goal are (1) to substantially increase public awareness of natural hazard risk so that the public demands safer communities in which to live and work, and (2) to significantly reduce the risk of loss of life, injuries, economic costs, and destruction of natural and cultural resources that result from natural hazards.

To meet the National Strategy Goal, FEMA set specific objectives for five major "elements" of the Strategy:

- Hazard identification and risk assessment;
- Applied research and technology transfer;
- Public awareness, training, and education;
- Incentives and resources; and
- Leadership and coordination.

INTENT OF THIS REPORT

This report is intended to serve as a baseline for hazard identification and risk assessment efforts. The research and reviews documented in this report are not intended to be exhaustive evaluations of hazards and the risks they pose throughout the United States. The research, monitoring, mitigation measures, recommendations and federal programs described herein are current as of 1995. The report may be updated as hazard identification and risk assessment techniques are refined and improved, and as Federal, State, and local programs evolve.

FEMA initiated this report to focus primarily on identification of hazards and factors important to risk assessment: probability and frequency, exposure, and consequences. FEMA also began development of a consistent methodology to assess risks posed by natural and technological hazards.

The baseline of knowledge was developed by identifying and contacting Federal and State agencies, research institutes, and universities known to have leading experts in each specialty area. For example, experts from the National Oceanic and Atmospheric Administration were contacted regarding atmospheric hazards; experts from the U.S. Geological Survey were contacted regarding geologic, seismic, and volcanic hazards; and experts at the Natural Hazards Research and Applications Information Center at the University of Colorado were contacted for information on multiple hazards.

KEY TERMS AND DEFINITIONS

Terminology is important because variations in meaning lead to differences in hazard identification and measures of risk. The following key terms and definitions are used in this report:

Hazard means an event or physical condition that has the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, damage to the environment, interruption of business, or other types of harm or loss.

Hazard Identification means the process of defining and describing a hazard, including its physical characteristics, magnitude and severity, probability and frequency, causative factors, and locations/areas affected.

Risk means the potential losses associated with a hazard, defined in terms of expected probability and frequency, exposure, and consequences.

Probability and Frequency means a measure of how often an event is likely to occur. Frequency can be expressed as the average time between occurrences or exceedances (non-exceedances) of an event or the percent chance or probability of the event occurring or being exceeded (not exceeded) in a given year or a longer time period.

Exposure means the number, types, qualities, and monetary values of various types of property or infrastructure and life that may be subject to an undesirable or injurious hazard event.

Consequences mean the damages (full or partial), injuries, and losses of life, property, environment, and business that can be quantified by some unit of measure, often in economic or financial terms.

Risk Assessment means a process or method for evaluating risk associated with a specific hazard and defined in terms of probability and frequency of occurrence, magnitude and severity, exposure, and consequences.

Mitigation means sustained action taken to reduce or eliminate long-term risk to people and property from hazards and their effects. Mitigation distinguishes actions that have a long-term impact from those that are more closely associated with preparedness for, immediate response to, and short-term recovery from a specific event.

PREVIOUS HAZARD IDENTIFICATION AND RISK ASSESSMENT ACTIVITIES

Over the past 12 years, FEMA and State emergency managers have developed a variety of tools to assist with hazard identification and risk assessment. Two such cooperative programs—the Integrated Emergency Management System (IEMS) and the Capability and Hazard Identification Program (CHIP)—have evolved and have contributed significantly to hazard identification program activities.

FEMA instituted IEMS in 1983. Its objective was to develop and maintain a credible emergency management capability nationwide by integrating activities along functional lines at all levels of government and, to the fullest extent possible, across all hazards. Through a 13-step process, IEMS collected basic information from State and local emergency management organizations on which reasonable and justifiable plans could be made and implemented to increase emergency management capabilities nationwide.

The 13 steps in the IEMS process were: (1) hazards analysis, (2) capability assessment, (3) emergency operations plan development, (4) capability maintenance, (5) mitigation efforts, (6) emergency operations, (7) emergency operations evaluation, (8) capability shortfall determination, (9) multi-year development plan development, (10) modification of multi-year development plan for annual increments, (11) estimate of State/local financial resource requirements, (12) estimate of Federal financial resource requirements, and (13) annual review of completed work. Based on the review completed in Step 13 each year, the process was begun again.

Under CHIP, instituted in 1989 to replace IEMS, FEMA established a national database of information on the status of emergency preparedness and the impact of FEMA funds on State and local government operations. Emergency management data were collected for 3,300 communities and maintained in a comprehensive and easily accessible database. However, a drawback of the "self-assessment" was the lack of consistent criteria for reporting, which resulted in incomplete and inaccurate information.

Through regular updates of the CHIP database, local government officials provided information on natural hazards in their areas, including the likelihood and frequency of events and the impacts on local population and property. They also provide information on local emergency management expenditures, including totals expended and the sources of funding. By answering questions separated into five topic areas, local governments provided information to allow assessment of their capability to deal with disasters. The five topic areas are: planning, logistics, training and education, operations, and administration.

On the Federal level, the information from CHIP was used to prepare reports to the U.S. Congress on the status of emergency management capabilities. It also was used to evaluate the effectiveness of FEMA programs in delivery of financial and technical assistance to State and local governments. At the local level, CHIP was used as a planning tool, guiding local jurisdictions through a logical sequence: identify hazards; assess capabilities to address those hazards; set priorities for improving those capabilities; and schedule process activities to improve those capabilities.

REPORT CONTENT AND FORMAT

Two categories of hazards are covered: natural hazards and technological hazards. Natural hazards, the largest single contributor to catastrophic or repetitive damage to communities nationwide, evolve from atmospheric or weather, geologic, hydrologic, and seismic events. They pose threats in all areas of the United States.

The impacts of natural hazards can be local or widespread, predictable or unpredictable. Resulting property and infrastructure damage can range from minor to major, depending on whether hazard events affect major or minor population centers.

Technological or manmade hazards have expanded dramatically throughout the 20th century. Like natural hazards, their effects can be local or widespread. They are frequently unpredictable and have the potential to cause substantial loss of life in addition to property damage. Some technological hazards can be significant threats to infrastructure. For the purposes of this report, the discussions of technological hazards are limited to those that have been or may be triggered by natural events.

To present what is known today with respect to hazard identification and risk assessment, this report is organized to allow location of information on a specific hazard or a group of hazards. It is intended as a reference document for use by emergency management and mitigation specialists in all levels of government and the private sector.

For each hazard, the chief characteristics necessary for hazard identification are described, followed by the factors required in risk assessment: probability and frequency, exposure, and consequences. Each chapter includes brief summaries on previous and on-going research, data collection and monitoring activities, and brief discussions of mitigation measures and recommendations.

The report is divided into five major parts:

- **Part I** "Natural Hazards" presents atmospheric, geologic, hydrologic, seismic, and other hazards.

  Subpart A includes chapters on atmospheric hazards: tropical cyclones, thunderstorms and lightning, tornadoes, windstorms, hailstorms, snow avalanches, severe winterstorms, and extreme summer weather.

  Subpart B includes chapters on geologic hazards: landslides, land subsidence, and expansive soils.

  Subpart C includes chapters on hydrologic hazards: floods, storm surges, coastal erosion, and droughts.

  Subpart D includes chapters on seismic hazards: earthquakes and tsunami events.

  Subpart E includes chapters on two other natural hazards: volcanoes and wildfires.

- **Part II** "Technological Hazards" presents dam failures, fires, hazardous materials events, and nuclear accidents.

- **Part III** "Risk Assessment Approaches" presents risk assessment methodologies. One chapter addresses a method developed by the National Institute of Building Sciences, in cooperation with FEMA. The initial methodology estimates potential losses from earthquake events, but will be modified for other hazards. When completed, FEMA will make it available to State and local agencies along with many inventory databases. Components of other risk assessment methodologies are discussed briefly in a separate chapter.

- **Part IV** "Activities Under the National Mitigation Strategy," summarizes the major elements of the National Mitigation Strategy and provides information on existing programs, recently completed activities, and future initiatives of FEMA, other Federal agencies, State and local agencies, and others.

- **Part V** "Summary and Conclusions" presents an overall summary of the report and some general conclusions drawn from the research.

To illustrate graphically the breadth and extent of both natural and technological hazards, color maps produced using Geographic Information System technology are included in Parts I and II. The source of data used to prepare each map is cited below the map caption for ready reference. A notation is made if information is not available for a particular State, territory, or region.

STATE AND LOCAL PARTICIPATION IN REPORT UPDATE PROCESS

Consistent definitions for, and a comprehensive identification of, natural and technological hazards can best be achieved through Federal-State-local partnerships and through cooperative efforts with private sector organizations, research and academic institutions, and individuals. The information in this report is intended to provide a baseline of knowledge.

Future research on methodology, identification, assessment, and application will prove to be invaluable as risk-based strategies are refined. This report is a living document, and all Federal and State agencies, the scientific community, local government officials, emergency management specialists, and informed and concerned private sector organizations and individuals are encouraged to contribute to its enhancement and expansion in the coming years.

To assist in the effort, comments may be submitted to:

Multi-Hazard Identification and Risk Assessment
Risk Assessment Branch
Mitigation Directorate
Federal Emergency Management Agency
500 C Street SW
Washington, DC 20472

E-mail: anne.flowers@fema.gov

Part I

NATURAL HAZARDS

"Mitigation is about lowering the risk and reducing the effects of disasters, and this ambitious venture has the potential to reap great rewards. To successfully mitigate against disaster will require the combined talents and concerted efforts of all levels of governments, academia, professional and voluntary organizations, the corporate sector, and all Americans."

William J. Clinton
President of the United States
December 6, 1995

Introduction

Natural phenomena that have the potential to cause fatal and costly damage—such as lightning, windstorms, and floods—are natural hazards. When the damage to life and property becomes real, not just potential, the event is commonly called a natural disaster. Risk assessment involves evaluating the probability and frequency, exposure, and consequences of natural hazard events, where:

- Probability and frequency is a measure of how often a natural hazard event is likely to occur at a particular location;
- Exposure defines the number of people and the number, types, qualities, and monetary values of property subject to the natural hazard event at a location; and
- Consequences are the quantifiable impacts to people and property that may result from an event.

PART I—NATURAL HAZARDS are grouped in the following categories:

SUBPART A: Atmospheric Hazards (tropical cyclones, thunderstorms and lightning, tornados, windstorms, hailstorms, snow avalanches, severe winterstorms, and extreme summer weather)

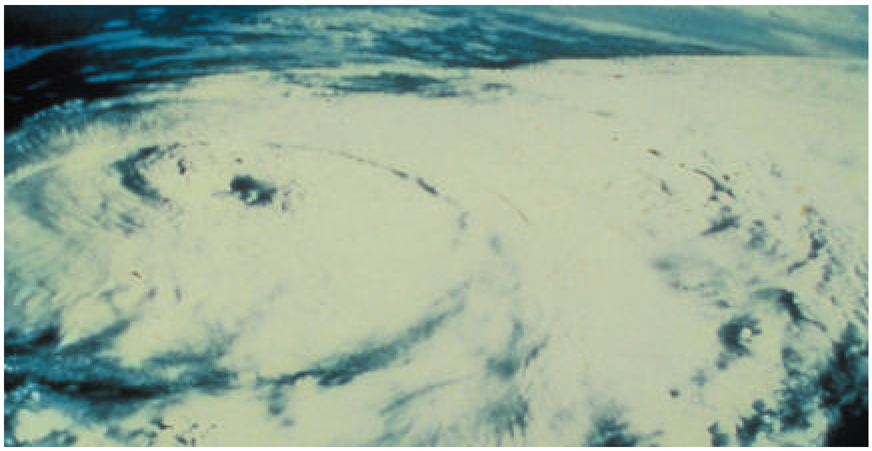
SUBPART B: Geologic Hazards (landslides, land subsidence, and expansive soils)

SUBPART C: Hydrologic Hazards (floods, storm surges, coastal erosion, and droughts)

SUBPART D: Seismic Hazards (earthquakes and tsunami events)

SUBPART E: Other Natural Hazards (volcanoes and wildfires)

Subpart A



ATMOSPHERIC HAZARDS

Introduction

For purposes of this report, phenomena associated with certain weather-generated events are grouped as atmospheric hazards. The individual hazards included are:

Tropical Cyclones

Thunderstorms and Lightning

Tornados

Windstorms

Hailstorms

Snow Avalanches

Severe Winterstorms

Extreme Summer Weather

Each of the atmospheric hazards may have its own natural characteristics, geographic area where it occurs (areal extent), time of year it is most likely to occur, severity, and associated risk. While these characteristics allow identification of each hazard, many atmospheric hazards are interrelated. In most cases, a natural disaster or event involves multiple hazards: severe thunderstorms spawn tornados; wind is a factor in thunderstorms, severe winterstorms, tropical cyclones, and hailstorms; snowfall from a severe winterstorm can prompt avalanches.

Because several atmospheric hazards may occur concurrently, it may be difficult to attribute damage to any one hazard or to assess the risk a particular hazard. On the other hand, mitigation efforts directed at a specific hazard, windstorms for example, often have beneficial effects on related atmospheric hazards.

Although atmospheric hazards are presented separately from geologic, hydrologic, seismic, and other natural hazards, atmospheric hazards may be related to these natural events and often to technological hazards, as well: extreme summer weather contributes to drought; earthquakes cause snow avalanches, landslides, subsidence, and dam failures; and tropical cyclones can exacerbate coastal erosion and flooding.

Photo: Red Cross

CHAPTER

1

TROPICAL CYCLONES

Hurricanes

Tropical Storms

Typhoons

Chapter Summary

Hurricanes, tropical storms, and typhoons, collectively known as tropical cyclones, are among the most devastating naturally occurring hazards in the United States and its territories. Recent events reveal the magnitude of damage that is possible. In 1992, Hurricane Andrew resulted in the highest total damage of any natural disaster in U.S. history, an estimated $25 billion. Tropical Storm Alberto in 1994 caused 30 deaths and $500 million in damage. Puerto Rico and the U.S. Virgin Islands suffered more than $1 billion in damage from Hurricane Hugo in 1989. Hurricane Iniki in 1992 inflicted almost $2 billion in damage to Hawaii. During the past 20 years, more than 75 Federal disaster declarations have involved tropical cyclone activity.

More than 36 million people live in the counties along the Gulf of Mexico and Atlantic Ocean coast, the area of the conterminous United States most susceptible to tropical cyclones. These are also the regions with the highest growth rates and rising property values. The trend of increasing development in coastal zones magnifies the exposure of those areas to catastrophic losses from tropical cyclones. Although the Western States are less prone to landfall by tropical cyclones than the Atlantic and Gulf regions, storms in the eastern North Pacific Ocean have produced damaging rainfalls in California, Nevada, Arizona, and New Mexico. Hawaii and the Pacific territories are at risk from hurricane and typhoon activity year round.

Computer models, improved radar technology, and historical data have enhanced the ability to predict the paths and impacts of tropical cyclones. However, predicting landfall locations with sufficient advance warning remains uncertain. A low-level tropical storm can develop into a hurricane within 6 to 12 hours, yet heavily developed, hurricane-prone areas often require 24 to 36 hours to complete evacuations.

Current mitigation and response efforts rely heavily on public awareness and development of evacuation plans. Adoption and enforcement of strict building codes is one of the more successful long-term mitigation measures for minimizing structural damage. Other efforts include buy-out programs, relocation and/or elevation of structures, improved open-space preservation, and land-use planning in high-risk areas.

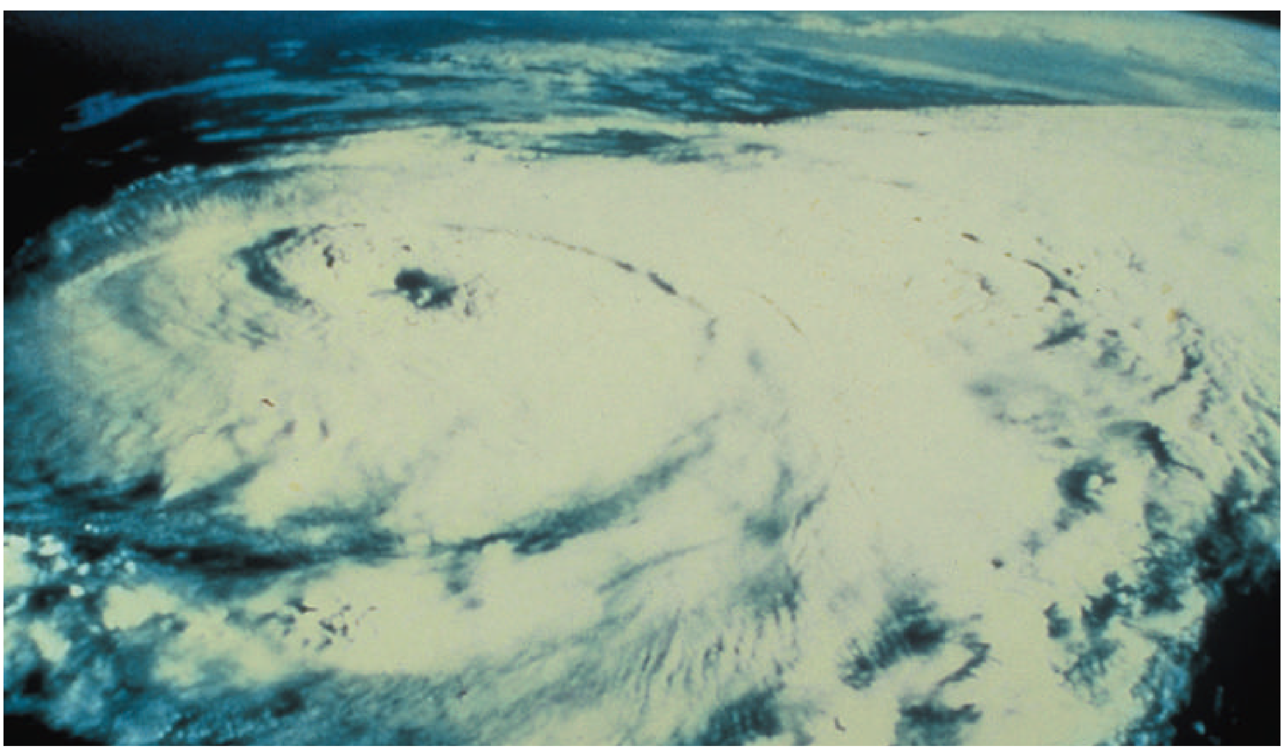


Photo: Red Cross

Photo: Red Cross

HAZARD IDENTIFICATION

A tropical cyclone is defined as a low pressure area of closed circulation winds that originates over tropical waters. Winds rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

A tropical cyclone begins as a tropical depression with wind speeds below 39 mph (18 m/s). As it intensifies, it may develop into a tropical storm, with further development producing a hurricane or typhoon. As a storm travels over land or colder waters, it eventually weakens. Table 1-1 defines the classification criteria for tropical cyclones based on the stage of development, wind speed, and tropical or subtropical environment.

In the North Atlantic and Central and South Pacific basins east of the International Date Line, tropical cyclones with wind speeds between 39 mph (19 m/s) and 74 mph (33 m/s) are commonly known as tropical storms. When wind speeds exceed 74 mph (33 m/s), they are commonly known as hurricanes. In the western North Pacific basin, tropical cyclones are called typhoons. Typhoons that attain maximum sustained wind speeds of 150 mph (67 m/s) or greater are classified as super typhoons.

The distinguishing feature of tropical cyclones is the eye around which winds rotate. The eye, the storm's core, is an area of low barometric pressure that is generally 10 to 30 nautical miles in diameter. The surrounding storm may be 100 to 500 nautical miles in diameter, with intense windfields in the eastern and northern quadrants. The eye can be seen distinctly in satellite and radar imagery.

The Saffir/Simpson Hurricane Scale is used to classify tropical cyclones by numbered categories (Table 1-2) in the North Atlantic Basin, eastern and central North Pacific Basin, and the South Pacific basin. Hurricanes are classified as Categories 1 through 5 based on central pressure, wind speed, storm surge height, and damage potential.

Tropical cyclones involve both atmospheric and hydrologic characteristics. Those commonly associated with tropical cyclones include severe winds, storm surge flooding, high waves, coastal erosion, extreme rainfall, thunderstorms, lightning, and, in some cases, tornadoes. These individual phenomena are addressed separately in separate chapters in this report.

TABLE 1-1.—*Classification criteria for tropical, subtropical, and extratropical cyclones*

Stage of Development	**Criteria**
Tropical depression (development)	The formative stages of a tropical cyclone in which the maximum sustained (1-min mean) surface wind speed is <39 mph (<18m/s).
Tropical storm	A warm core tropical cyclone in which the maximum sustained surface wind speed (1-min mean) ranges from 39 to <74 mph (18 to <33m/s).
Hurricane	A warm core tropical cyclone in which the maximum sustained surface wind speed (1-min mean) is at least 74 mph (33 m/s).
Tropical depression (dissipation)	The decaying stages of a tropical cyclone in which the maximum sustained surface wind speed (1-min mean) has dropped below 39 mph (18 m/s).
Extratropical cyclone	Tropical cyclones modified by interaction with nontropical environment. There are no wind speed criteria, and maximum winds may exceed hurricane force.
Subtropical depression	A subtropical cyclone in which the maximum sustained surface wind speed (1-min mean) is below 39 mph (18 m/s).
Subtropical storm	A subtropical cyclone in which the maximum sustained surface wind speed (1-min mean) is at least 39 mph (18 m/s).

Source: *Modified from Neumann and others, 1993*

TABLE 1-2.—*Saffir/Simpson hurricane scale ranges*

Scale Number (Category)	Central Pressure (mbar)	Central Pressure (in)	Wind Speed (mph)	Storm Surge (ft)	Potential Damage
1	≥ 980	≥ 28.94	74 - 95	4 - 5	Minimal
2	965 - 979	28.50 - 28.91	96 - 110	6 - 8	Moderate
3	945 - 964	27.91 - 28.47	111 - 130	9 - 12	Extensive
4	920 - 944	27.17 - 27.88	131 - 155	13 - 18	Extreme
5	< 920	< 27.17	> 155	> 18	Catastrophic

Source: *Hebert and others, 1995*

ATLANTIC REGION. For the coastline from Texas to Maine, tropical cyclones develop over the warm waters of the Gulf of Mexico, Caribbean Sea, and Atlantic Ocean south of latitude 35 degrees. The cooler waters of the North Atlantic Ocean off the central and northeastern U.S. shorelines usually reduce the strength of storms approaching the shore. The strong steering current of the Gulf Stream, flowing northeasterly from the coast of Florida past the Outer Banks of North Carolina and up to the maritime areas off Nova Scotia, often directs storms on a track away from the coast. There, storms transition into the extratropical phase and dissipate. The primary impact of a tropical cyclone during its rapidly moving extratropical phase is on shipping traffic.

The North Atlantic and northern Pacific Ocean season for hurricanes and typhoons lasts from June through November, when sea and surface temperatures peak. The majority of hurricane activity in the North Atlantic basin occurs during August and September. For the Northern Hemisphere and the North Atlantic basin, Figure 1-1 shows the monthly distribution of landfalling hurricanes striking the U.S. coastline from 1900 to 1994 (Hebert and others, 1995). Table 1-3 lists the most intense hurricanes, categories 4 and 5, to strike the United States between 1900 and 1994.

The peak typhoon season for the Southern Hemisphere and the South Pacific Ocean occurs from October to April. However, the meteorological history of the American Samoa region indicates that major catastrophic tropical cyclones can strike at any time of year.

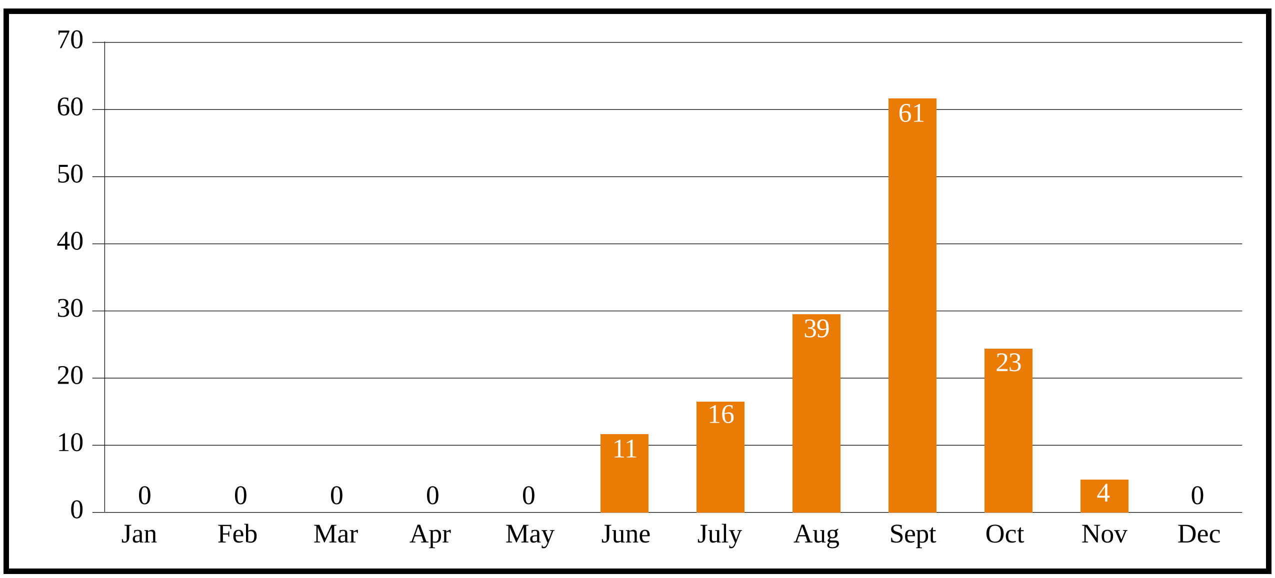


FIGURE 1-1.—Total number of U.S. hurricanes per month: 1900-1994.

Source: *Based on data from Hebert and others 1995*

TABLE 1-3.—*Most intense U.S. hurricanes at time of landfall: 1900 - 1994*

Hurricane	Year	Category	Central Pressure (mbar)	Central Pressure (in)
Florida (Keys)	1935	5	892	26.35
Camille (MS/SE LA/VA)	1969	5	909	26.84
Andrew (SE FL/SE LA)	1992	4	922	27.23
Florida (Keys) /S TX	1919	4	927	27.37
Florida (SE/Lake Okeechobee)	1928	4	929	27.43
Donna (FL/Eastern U.S.)	1960	4	930	27.46
Texas (Galveston)	1900	4	931	27.49
Louisiana (Grand Isle)	1909	4	931	27.49
Louisiana (New Orleans)	1915	4	931	27.49
Carla (N & Central TX)	1961	4	931	27.49
Hugo (SC)	1989	4	934	27.58
Florida (Miami/Pensacola)/MS/AL	1926	4	935	27.61
Hazel (SC/NC)	1954	4	938	27.70
SE FL/SE LA/MS	1947	4	940	27.76
N TX	1932	4	941	27.79

Source: *Hebert and others, 1995*

For the period 1886-1994, an average of five hurricanes a year have occurred in the North Atlantic basin (Hebert and others, 1995). This region is particularly vulnerable because hurricanes occur frequently, the areas are prone to storm surge and coastal riverine flooding, and the population has climbed to an estimated 45 million people. Puerto Rico and the U.S. Virgin Islands are affected by both Atlantic Ocean and Caribbean Sea hurricanes.

PACIFIC REGION. California, Oregon, and Washington are less prone to landfall by tropical cyclones originating in the eastern North Pacific Ocean. From 1952 through 1971, an average of 6 tropical cyclones occurred each year in this area (Bryant, 1991). Storms tend to move away from the coast, heading toward Hawaii and the open ocean of the central North Pacific. The only effects of tropical cyclones felt in the eastern North Pacific Ocean have been in the form of extreme rainfall in California, Nevada, Arizona, and New Mexico.

Tropical systems approaching the western coastal States tend to lose cyclonic characteristics but retain large areas of convection. As remnants of tropical systems move into the southwestern region, voluminous amounts of rainfall may result. Table 1-4 shows the two-day precipitation totals associated with tropical cyclones affecting the Southwestern States from 1900 to 1984 (Smith, 1986).

Hurricanes impact Hawaii more often than the western States. The island of Kauai has been struck recently by two major storms, Iwa (1982) and Iniki (1992). Although the Islands have experienced hurricanes throughout recorded history, significant coastal flood events had previously been caused by tsunami waves, not hurricanes.

Historical information for hurricanes in the Central Pacific region was compiled by U.S. Army Corps of Engineers (USACE), Pacific Ocean Division, for a 1985 hurricane vulnerability study for Honolulu, HI (USACE, 1985). The report cites the activity of Central Pacific hurricanes based on data from 1832-1979 and updated information for the period of 1980-1983. Before Hurricanes Iwa and Iniki struck, the Kohala Cyclone of August 1871 and the Mokapu Cyclone of August 1938 were considered the most significant tropical cyclones in the Central Pacific.

South Pacific hurricane activity has always been significant in the vicinity of the seven islands of American Samoa. The likelihood of impact from a tropical storm or hurricane places these islands at risk each year. The risk increases because of the ancillary hazard effects and damage from stream and river flooding, winds in excess of 125 mph (56 m/s), and landslides.

Annual typhoon activity also is very high in the western North Pacific Ocean in the vicinity of Guam and the 14 islands of the Northern Mariana Islands. The lack of a wide continental shelf typical in the North Atlantic basin and the fringing reefs around islands reduce storm surge elevations and wave impacts. Consequently, the severe winds and wind-driven rainfall have much greater effects on island structures and agricultural industries than storm surges.

RISK ASSESSMENT

The various hazard components and risks associated with tropical cyclones come from storm surge, rainfall, and wind. Associated damage includes:

- Storm surge causes coastal flooding, salinization of land and groundwater, water supply contamination, agricultural losses, coastal erosion, loss of life due to drowning, and structural and infrastructure damage;

- Rainfall causes riverine and flash flooding, landslides, loss of life, and damages including structures, infrastructure, and agriculture; and

- Wind impacts utilities and transportation, results in loss of life due to downbursts and tornadoes, creates tremendous amounts of debris, and causes agricultural losses and building damage (Bryant, 1991).

Probability and Frequency

The measure of probability of occurrence for tropical cyclones is generally derived from the coastal flooding caused by storm surge. The probability or return period used to classify the significance of an event is determined as the percent chance of a flood elevation being equaled or exceeded in any given year. The coastal flood elevation caused by a 1-percent-annual-chance tropical cyclone event is commonly referred to as the 100-year frequency flood. The 1-percent-annual-chance flood event is established through detailed analyses of stage-frequency relationships of measured tide level data or analysis and modeling of specific historical tropical cyclone parameters such as direction, minimum central pressure, forward speed, and radius of maximum winds.

TABLE 1-4.—*Two-day precipitation totals, eastern North Pacific tropical cyclones: 1900-1984*

Station	**Date**	**Precipitation** *(in)*
Carlsbad, NM (unofficial)	September 20-21, 1941	17.00
Workman Creek, AZ	September 4-5, 1970	11.40
Mt. Wilson, CA	September 10-11, 1976	10.74
Mt. Wilson, CA	September 25-26, 1939	10.62
Castle Hot Springs, AZ	August 28-29, 1951	10.46
Crown King, AZ	August 28-29, 1951	10.44
Greenville, NM	September 21-22, 1941	8.79
Lake Arrowhead, CA	September 10-11, 1976	8.71
Sunflower, AZ	September 4-5, 1970	8.30
Camp Hi Hill Opids, CA	September 10-11, 1976	8.22
Gladstone, CO	October 4-5, 1911	8.16
Hereford, AZ	September 26-27, 1926	8.15
Newkirk, NM	September 21-22, 1941	8.15
Alamogordo Dam, NM	September 21-22, 1941	8.05
Yates, NM	September 21-22, 1941	8.00

Source: *Smith, 1986*

Detailed hydraulic analyses include the establishment of the relationship of tide levels, wave heights, and synthetic generation of a storm population data base from hydrodynamic models such as TTSURGE and SURGE. The coastal flood elevation for the 1-percent-chance tropical cyclone will be a function of the combined influences of tidal rise and wave setup, height, and run-up along the coastline. A discussion of storm surge elevations and probability of occurrence due to tropical cyclones and other storms is presented in Chapter 13.

The frequency of occurrence of tropical cyclones can be determined by the number of landfall events over a given time period. The frequencies of landfall events are measured from historical data for specific geographic areas of the United States which have experienced direct or indirect hits by hurricanes or typhoons. In an analysis of hurricanes experienced by coastal county populations from Texas to Maine (Hebert and others, 1984), the direct and indirect hurricane landfalls in each county were tabulated. Storms in which the eye passed directly over a county were considered direct hits. Indirect or fringe hits were defined as the areas on either side of the direct landfall zone and were accounted for by assessing the occurrence of hurricane force winds and/or storm surge tides of 4 to 5 ft (1.2 to 1.5 m) in adjacent counties.

In an update of the 1984 study, the assessment was expanded to include the number of direct hits by landfalling hurricanes in coastal States from Texas to Maine from 1900 to 1994 (Hebert and others, 1995). The assessment was modified further using data from the U.S. Department of Commerce to include indirect hits from 1984 to 1994 (Neumann and others, 1993). As shown in Figure 1-2, Florida had the greatest number of direct hits by hurricanes since 1900, with Texas, Louisiana, North Carolina, South Carolina, and Rhode Island ranked in order behind Florida. Florida also has the highest incidence rate of category 3 or greater landfalls.

Map 1-1 shows the geographic distribution of direct and indirect impacts of landfalling hurricanes affecting coastal counties from Texas to Maine from 1900 to 1994. Map 1-2 depicts the probability of each hurricane category based on events having at least a 5-percent chance of occurring in any given year.

In Hawaii, coastal flood elevations from historic hurricanes have been combined with statistical information on tsunami flood inundation limits and used to establish 1-percent-annual-chance flood elevations and associated wave runup. The combination includes recent significant hurricane events that exhibited tsunami-like wave bore flooding effects.

The most recent information available on Central Pacific hurricanes is the USACE 1985 report. Reliable information about the Hawaiian Islands used was determined to include only the period 1950-1983. For this 34-year period, there was an annual average of two to three tropical cyclones, either tropical storms or hurricanes. The highest number recorded during that period was 10, during the 1982 season. Records show that the month with the highest frequency of occurrence is August, although the devastation of Hurricane Iwa occurred in November, 1982.

USACE found the number of hurricanes peaked during years in which strong El Niño conditions occurred. However, the El Niño, an area of warm surface water in the equatorial region of the eastern Pacific Ocean, is only one of many factors that influence hurricane activity. For 1950 to 1983, USACE identified 20 hurricanes that affected the Hawaiian Islands, but only Hurricane Dot in 1959 made landfall. The next major hurricane to landfall was Iniki in 1992, which also hit Kauai.

According to research in the draft *Survivable Crisis Management Plan for American Samoa* (Department of Public Safety, 1995), the meteorological history of the islands indicates major hurricanes can strike throughout the year. The Joint Typhoon Warning Center (JTWC) reports that from 1981 through 1993, an average of just over 5 tropical cyclones developed each year in the South Pacific basin. However, more than 13 tropical cyclones were recorded in 1992 (JTWC, 1993). The frequency of tropicsl cyclones has not been established in American Samoa.

From 1945 to 1990, 162 tropical cyclones made landfall or came within 180 nautical miles of the island of Guam (JTWC, 1991). In 1994, the JTWC reported that an average of 28 tropical storms developed annually in the western North Pacific from 1960 to 1993. An average of just under 18 of the 28 storms reached typhoon magnitude. Because of the warm tropical waters in the region, typhoons formed during every month of the year during this 33-year period.

In 1993, JTWC reported that the western North Pacific Ocean experienced an above-normal tropical cyclone season, with 30 named storms. In addition, three super typhoons developed, although they did not directly affect the islands. In 1992, five typhoons affected Guam between August 28 and November 24, including Typhoon Omar which passed right over the island.

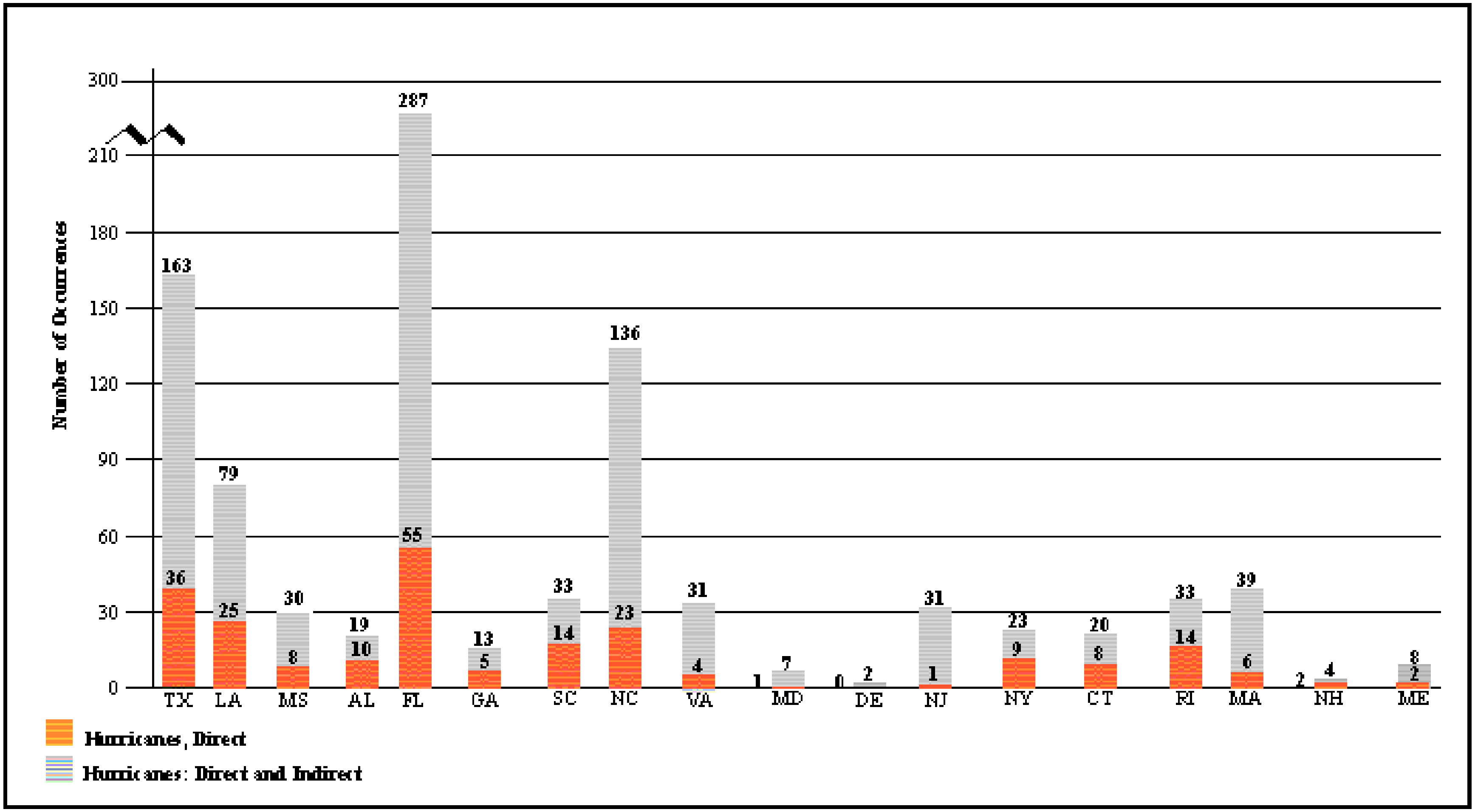
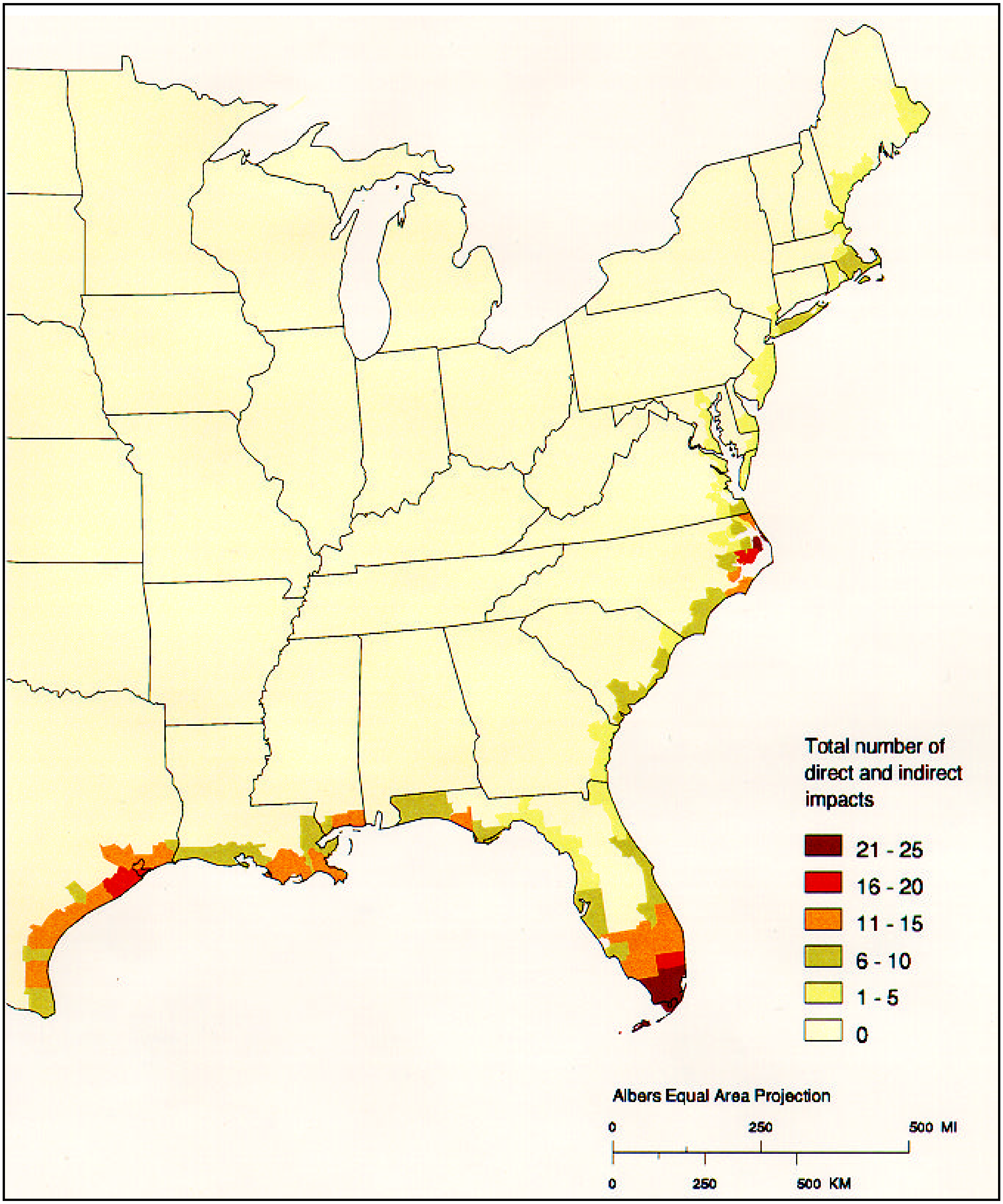
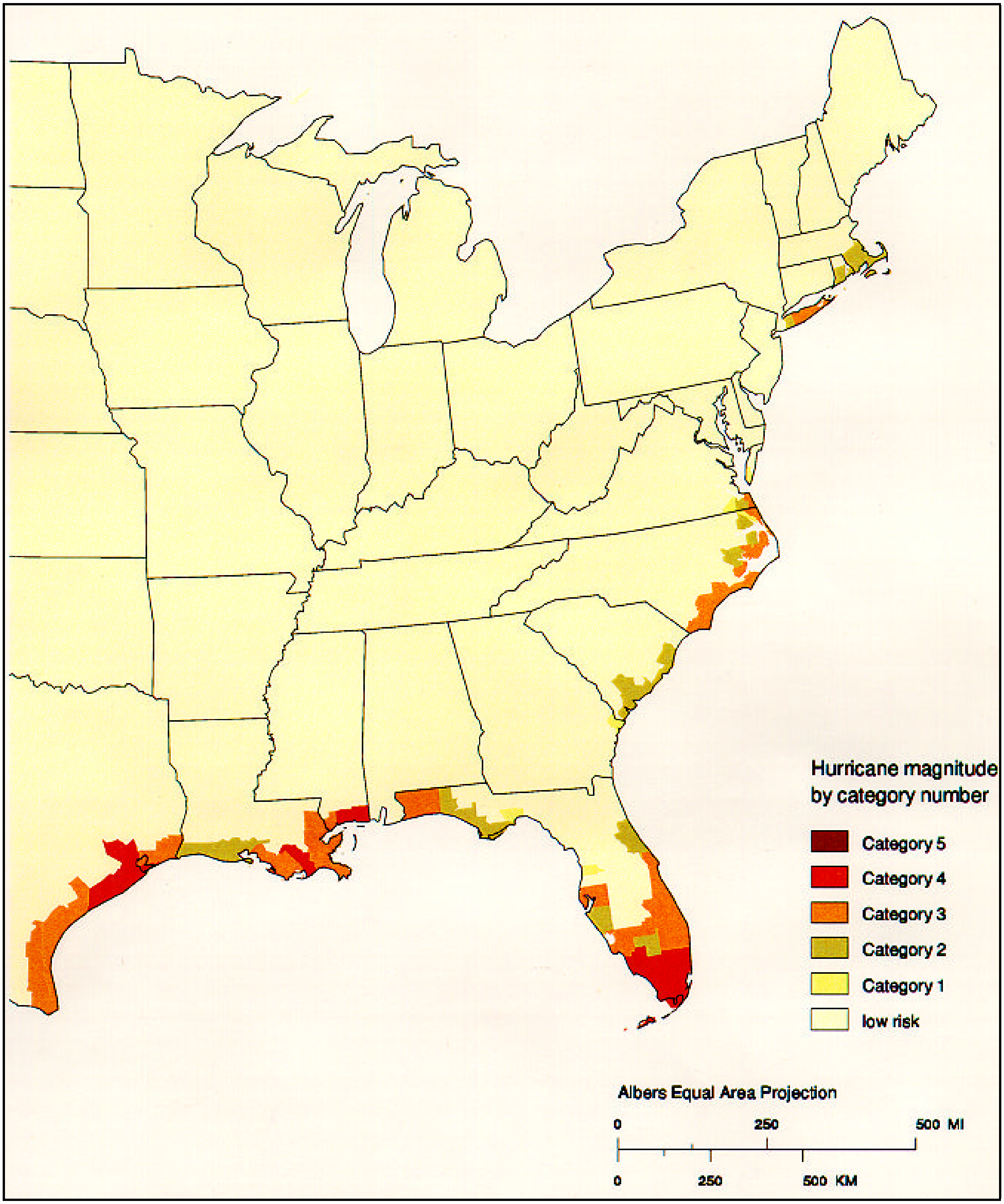


FIGURE 1-2.—U.S. hurricane landfalls (categories 1-5): 1900 - 1994.

Source: *Modified from Hebert and others, 1995*



Map 1-1. Total number of direct and indirect impacts from landfalling hurricanes for coastal counties from Texas to Maine: 1900-1994.
Source: *Data from NOAA, National Weather Service, 1994*



Map 1-2. Coastal counties from Texas to Maine and the 5% chance associated with the occurrence of landfalling hurricane magnitude (by category) being equaled or exceeded in any given year. Source: *Data from NOAA, National Weather Service, 1994*

Exposure

Hurricanes present one of the greatest potentials for substantial loss of life, property damage, and economic impact because more than 36 million U.S. residents live in the coastal counties from Texas to Maine that have the greatest exposure to hurricanes.

More than 85 percent of coastal residents have never experienced the effects of a direct-hit hurricane (Hebert and others, 1995). The period from 1970 to 1995 experienced low hurricane activity and few direct hits occurred. Only about one-fifth (12) of the total number of intense hurricanes (Category 3 or higher) since 1900 occurred during the last 25 years. Of those, only Hurricane Agnes in 1972 caused more than 25 deaths.

The highest population growth rates in the United States have been in Gulf and Atlantic coastal counties. These areas have experienced an estimated 15 percent increase in population, more than 5 million people, from 1980 to 1993. For the period from 1988 to 1990, the value of insured residential and commercial property has increased an estimated 65 percent (Insurance Research Council, 1995). Figure 1-3 shows the 1993 value of insured coastal property exposures by State (IRC, 1995).

The nature of the Hawaiian Islands make the entire island chain vulnerable to damage from tropical cyclones and related hazards, but major tropical cyclones appear to be infrequent. On the whole, more significant damage results from tsunami waves, winter coastal storm waves, riverine flooding, and volcanic activity. Development along the coastline is highly valued, and damage from future tropical storms is likely to have significant social and economic consequences.

American Samoa's draft *Survivable Crisis Management Plan* recognizes that devastation caused by hurricanes can affect all aspects of island life. Coastal flood inundation, severe winds, and wind-driven rain impacts residences, transportation, utilities, and agricultural industries. Hurricanes also trigger other natural hazards, such as riverine flooding and landslides.

Consequences

Statistics on the 10 deadliest U.S. hurricanes are presented in Table 1-5. Half of the most costly hurricanes (more than $500 million in damages) occurred in the past 25 years, with Hurricane Andrew in 1992 the most expensive. The 10 costliest U.S. hurricanes of the 20th century are summarized in Table 1-6.

Two recent tropical cyclonic events reveal consequences in densely populated areas: Hurricane Andrew (1992) and Tropical Storm Alberto (1994). Hurricane Andrew resulted in the highest total damage of any natural disaster in U.S. history, estimated at $25 billion for southeastern Florida and southeastern Louisiana. Tropical Storm Alberto was significant because of the extensive inland flooding that occurred as rain fell over the southeastern United States, primarily in Georgia. Although only a tropical storm, Alberto caused 30 deaths and $500 million in property damage. Deaths from Alberto are the highest total recorded for a tropical cyclone since 1975 (Hebert and others, 1995).

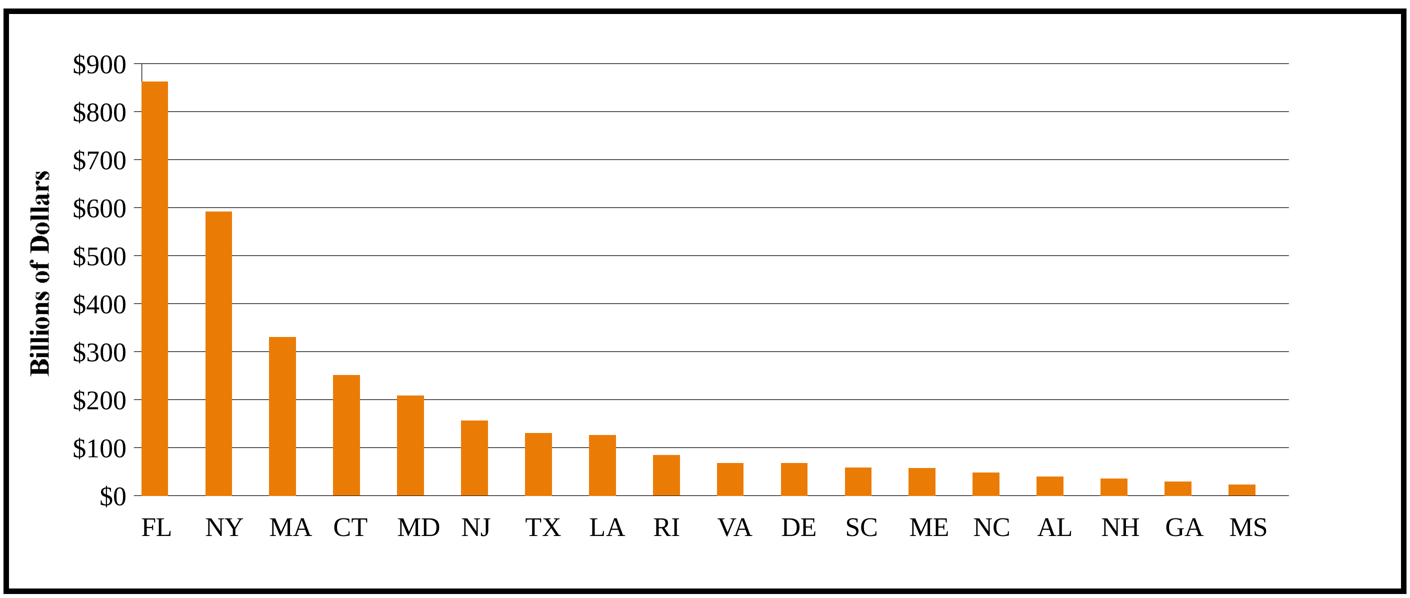


FIGURE 1-3.—Value of insured coastal property exposures by mainland State: 1993.

Source: *Insurance Research Council, 1995, from data provided by Applied Insurance Research.*

TABLE 1-5.—*Deadliest U.S. hurricanes: 1900-1994*

Hurricane	Year	Category	Deaths
Texas (Galveston)	1900	4	8,000+
Florida (SE/Lake Okeechobee)	1928	4	1,836
Florida (Keys/S TX)	1919	4	600[1]
New England	1938	3	600
Florida (Keys)	1935	5	408
Audrey (SW LA/N TX)	1957	4	390
Northeastern U.S.	1944	3	390[2]
Louisiana (Grand Isle)	1909	4	350
Louisiana (New Orleans)	1915	4	275
Texas (Galveston)	1915	4	275

[1] 600-900 estimated deaths, including 500 lost at sea.
[2] Including 344 lost at sea.

Source: *Hebert and others, 1995*

TABLE 1-6.—*Costliest U.S. hurricanes: 1900-1994*

Hurricane	Year	Category	Damage *(1990 dollars)*
Andrew (SE FL/SE LA)	1992	4	$25,000,000,000
Hugo (SC)	1989	4	7,155,120,000
Betsy (SE FL/SE LA)	1965	3	6,461,303,000
Agnes (FL/NE U.S.)	1972	1	6,418,143,000
Camille (MS/SE LA/VA)	1969	5	5,242,380,000
Diane (NE U.S.)	1955	1	4,199,645,000
New England	1938	3	3,593,853,000
Frederic (AL/MS)	1979	3	3,502,942,000
Alicia (N TX)	1983	3	2,391,854,000
Carol (NE U.S.)	1954	3	2,370,215,000

Source: *Based on Hebert and others, 1995*

In Puerto Rico, about a dozen hurricanes have made landfall in the past 100 years, causing damage to buildings and resulting in significant coastal and riverine flooding. Category 5 hurricanes are expected to hit, on average, every 15 years. In the U.S. Virgin Islands, the primary impacts of hurricanes are severe winds and coastal flooding.

The last major hurricane to affect Puerto Rico and the U.S. Virgin Islands was Hurricane Hugo, a category 4 storm when it passed through the islands on September 17-18, 1989. The majority of the more than $1 billion in damage was a result of severe winds, and nearly 5,000 homes were destroyed.

Previous loss of life and damage from tropical cyclones affecting Puerto Rico include: Tropical Storm Eloise in 1975 with 34 fatalities and over $125 million damage; September 1932 San Ciprian hurricane with 300 fatalities and $30–$50 million damage; the September 1928 San Felipe II hurricane with 300 fatalities and $50–$85 million damage; and the August 1899 San Ciriaco hurricane and associated Arecibo River flood event with 2,184 fatalities and $35 million in direct damage (Palm and Hodgson, 1993).

TABLE 1-7.—*Significant Hawaiian hurricanes of the 20th century*

Name	Date	Damage *(1990 dollars)*	Deaths
Mokapu Cyclone	Aug. 19, 1938	Unknown	Unknown
Hiki	Aug. 15, 1950	Unknown	Unknown
Nina	Dec. 2, 1957	$900,000	4
Dot	Aug. 6, 1959	$28,000,000	0
Iwa	Nov. 23, 1982	$394,000,000	1
Iniki	Sept. 11, 1992	$1,800,000,000	4

Source: *Based on Hebert and others, 1995*

Tropical cyclone activity in the Pacific Ocean near the Hawaiian Islands is less severe than in the North Atlantic Ocean or western North Pacific Ocean. Nonetheless, as indicated in Table 1-7, many storms have affected the Hawaiian Islands since 1900 (Hebert and others, 1995). In 1992, Hurricane Iniki's landfall on the south shore of Kauai was by far the most destructive hurricane to hit the islands, causing an estimated $1.8 billion in damage from both coastal flooding and severe winds. The cost of damage along the coast was very high due to high property values and the cost of construction.

Damage from recent devastating hurricanes affecting American Samoa includes:

- Hurricane Esau in 1981 caused $1.5 million in damage to public facilities, $3.2 million in agricultural losses and $0.68 million to private structures;

- Hurricane Tusi in 1987 damaged more than 300 structures;

- Hurricane Ofa in 1990, with waves up to 50 ft (15 m) in the open ocean, caused $7.7 million damage to government facilities, $15 million in damage to Ofu Harbor, and total estimated damage of $32 million, including coastal roads and utilities on Tutuila and Ofu; and

- Hurricane Val in 1991 caused one fatality, 200 injuries, and damage in excess of $50 million to structures, utilities, and agricultural crops.

According to the Joint Typhoon Warning Center, Typhoon Omar in the vicinity of Guam in 1992 had sustained winds of up to 121 mph (54 m/s) and inflicted $457 million in damage (JTWC, 1993). Storm surge levels were estimated to be 10 ft (3 m) above normal high tide, and rainfall of 12 to 19 in (30 to 48 cm) fell over 3 days (Coch, 1995). Typhoon Omar's damages included the destruction of 2,158 structures.

From June 1975 to May 1995, more than 76 Federal disaster declarations resulted from coastal storm surge and severe winds associated with tropical storms, hurricanes, and typhoons. Four declarations were issued for Florida. New York, Texas, and American Samoa each had three. Disaster declarations usually include all associated secondary atmospheric and hydrologic hazard impacts of inland flooding and high winds, tornadoes, heavy rain, thunderstorms, lightning, and coastal erosion.

Secondary economic impacts have been noted in recent hurricane disasters in Florida and Georgia, far beyond the immediately apparent damage. Agriculture and tourism in south Florida were disrupted long after Hurricane Andrew's landfall. It is difficult to estimate the magnitude of losses to these industries. Some businesses relocated from the impacted area to relatively safer locations in the central and northern parts of the State. This left many skilled workers either without employment or faced with relocation, increasing the extent of secondary economic losses.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Key research efforts on tropical cyclone activity, characterization, and evolution have been undertaken by the National Oceanic and Atmospheric Administration (NOAA) and its divisions: National Hurricane Center (NHC), Atlantic Meteorological and Oceanographic Laboratory (AMOL), and National Weather Service (NWS). University researchers have conducted extensive work on, and monitoring of, significant storm events.

NOAA has documented the history and tracks of tropical cyclones occurring since 1871. Cyclone prediction based on available climactic data, atmospheric conditions, remote-sensing data collection, and other monitoring programs and computer models has progressed tremendously since the 1950s. NOAA's ability to predict landfall locations to provide adequate advance warning for evacuation is still maturing. Tropical depressions can develop into hurricanes within 6 to 12 hours, and changes in track may occur quickly. However, some heavily developed hurricane-prone areas require 24 to 36 hours to complete evacuations.

Dr. William Gray, Colorado State University, studies tropical cyclones and accompanying atmospheric and other weather patterns. He has found direct correlations between the level of hurricane activity in the North Atlantic basin and influencing factors, including equatorial upper level wind patterns, El Niño, sea surface temperatures and pressures, and rainfall patterns in the Saheel desert region of Northwest Africa.

Dr. Gray's historical research indicates distinct, 10-year periods of weather and hurricane activity. The number and locations of hurricanes that are category 3 and higher can be attributed to unique combinations of the influencing factors. However, this analysis only serves as a tool to understand a pattern of past weather behavior, it is not a means to make accurate predictions of the severity or location of hurricanes.

The U.S. Army Corps of Engineers and the National Hurricane Center use the Sea Lake Overland Surge from Hurricanes (SLOSH) model to help FEMA and affected States develop specific evacuation plans for urban centers along the Atlantic and Gulf Coast shorelines. SLOSH accounts for different hurricane categories and key combinations of hurricane parameters, including central pressure, forward speed, radius of maximum winds, and angle of approach. The storm surge heights from the models are geographically dependent due to the influence of offshore bathymetry and nearshore topography.

The National Hurricane Center uses other models to predict and forecast the movement and intensity of hurricanes in the North Atlantic basin. The computer models include those prepared by AMOL in Key Biscayne, FL, and a new model developed by the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, NJ. The GFDL model incorporates new mathematical equations of known physical properties of the atmosphere and sea surface and incorporates storm variable parameters for upper level steering currents, windspeed, air and water temperature, and barometric pressure. The GFDL model has improved the forecasting capability of the National Hurricane Center.

For the Pacific Ocean, the Joint Typhoon Warning Center (JTWC) reports that Next Generation Radar (NEXRAD) has been implemented to provide Doppler weather radar capabilities (JTWC, 1993). The JTWC and its U.S. Air Force satellite reconnaissance component are working to improve capabilities in new technology such as the Meteorological Imagery Data Display and Analysis System. The Naval Research Laboratory has begun work on an addition to the Automated Tropical Cyclone Forecast System to improve forecasting capabilities.

MITIGATION APPROACHES

In recent years, loss of life from tropical cyclones has been reduced due to two activities: public awareness campaigns to educate residents about storm preparedness, and development of evacuation plans and actual evacuations of high-risk areas during emergencies.

Regional evacuation planning efforts proved successful in moving residents from the paths of hurricanes in south Florida during Hurricane Andrew (1992) and in South Carolina during Hurricane Hugo (1989). However, continued awareness and public education programs are required to educate new residents who may be unaware of the hurricane threat in high hazard coastal areas.

Mitigation of building damage has been most successful where strict building codes for high-wind influence areas and designated special flood hazard areas have been adopted and enforced by local governments, and complied with by builders. Coastal setback and regulatory programs have helped limit encroachment by some developments near high-risk areas, especially where erosion and wave impacts are anticipated.

During the past 25 years, intense development occurred so rapidly along the many reaches of the coast that building codes and regulatory programs may not have been in place. Without codes, communities did not have adequate mechanism to control the type and nature of structures or construction techniques needed to resist wind and water forces associated with tropical cyclones.

For the most part, buildings constructed prior to adoption of building codes remain more susceptible to damage. Some retrofit projects, for example specially designed shutters and windows for public schools, are expected to reduce future damage. Modification of existing buildings to incorporate hurricane-resistant measures may come about slowly as buildings are substantially improved.

Post-disaster mitigation efforts include buyout programs, relocation, elevation of structures, improved open-space preservation, and land-use planning within high-risk areas. In many areas of the coast, utility lines and critical transportation routes may have to be relocated to protect against damage resulting from tropical cyclones.

RECOMMENDATIONS

In April 1995, the Insurance Research Council (IRC) and Insurance Institute for Property Loss Reduction (IIPLR) published a report entitled *Coastal Exposure and Community Protection: Hurricane Andrew's Legacy* (IRC, 1995). This report summarized a number of global and specific recommendations from the Southern Building Code Congress International (SBCCI) field team investigations in south Florida following Hurricane Andrew's landfall in 1992. An interdisciplinary group agreed on 15 objectives and strategies in a series of symposia in 1993 that would "facilitate mitigation of natural hazards and foster a cooperative approach among groups that can affect change, including government regulators, code officials and code-making bodies, planners, civil engineers, and insurers" (IRC, 1995). The recommendations for improvements were primarily for the south Florida region, but are applicable to all hurricane-prone areas.

BIBLIOGRAPHY AND REFERENCES

Anders, F., S. Kimball, and R. Dolan. 1989. Map. ***Coastal Hazards: National Atlas of the United States.*** Map. U.S. Geological Survey.

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Culliton, T. J., M.A. Warren, T.R. Goodspeed, D.G. Remer, C.M. Blackwell, and J.J. McDonough, III. 1990. ***The Second Report of a Coastal Trends Series: 50 Years of Population Change Along the Nation's Coasts, 1960-2010.*** Rockville, MD: National Oceanic and Atmospheric Administration.

Daniels, R.C., V.N. Gornitz, A.J. Mehta, S.C. Lee, and R.M. Cushman. 1992. ***Adapting to Sea-Level Rise in the U.S. Southeast: The Influence of Built Infrastructure and Biophysical.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3915.

Department of Public Safety, TEMCO. 1995. ***Survivable Crisis Management (SCM) Plan for American Samoa*** (draft). Pago Pago, American Samoa.

Doehring, F., I.W. Duedall, and J.M. Williams. 1994. ***Florida Hurricanes and Tropical Storms 1871—1993: An Historical Survey.*** Technical Paper 71, Florida Sea Grant College Program, University of Florida.

Federal Emergency Management Agency, Federal Insurance Administration. 1994. ***Mitigation of Flood and Erosion Damage to Residential Buildings in Coastal Areas.*** Washington DC.

Federal Emergency Management Agency, Federal Insurance Administration. 1991. ***Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program.***

Finkl, C. W., Jr. (ed.). 1994. ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." ***Reviews of Geophysics.*** American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Good, J.W., and S.S. Ridlington. 1992. ***Coastal Natural Hazards: Science Engineering and Public Policy.*** Oregon Sea Grant. Corvallis, OR: Oregon State University.

Gornitz, V.N., R.C. Daniels, T.W. White and K.R. Birdwell. 1994. "The Development of a Coastal Risk Assessment Database: Vulnerability to Sea-Level Rise in the U.S. Southeast." ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Gornitz, V.M., T.W. White, and R.C. Daniels (ed.). 1994. ***A Coastal Hazards Data Base for the U.S. Gulf Coast.*** Oak Ridge Laboratory, Environmental Sciences Division, Publication No. 4101.

Gornitz, V.M., and T.W. White. 1992. ***A Coastal Hazards Data Base for the U.S. East Coast.*** Oak Ridge Laboratory, Environmental Sciences Division, Publication No. 3913.

Hebert, P.J., J.D. Jerrel, and M. Mayfield. 1995. "The Deadliest, Costliest, and Most Intense United States Hurricanes of This Century (And Other Frequently Requested Hurricane Facts)." ***Proceedings for 17th Annual National Hurricane Conference, April 11-14, 1995, Atlantic City, New Jersey.***

Hebert, P.J., G. Taylor, and R.A. Case. 1984. ***Hurricane Experience Levels of Coastal County Populations—Texas to Maine.*** Technical Memorandum NWS NHC 24. Miami, FL: National Hurricane Center.

Insurance Research Council and Insurance Institute for Property Loss Reduction. 1995. ***Coastal Exposure and Community Protection: Hurricane Andrew's Legacy.*** Wheaton, IL.

Joint Typhoon Warning Center. 1993. ***Annual Tropical Cyclone Report.*** U.S. Naval Oceanography Command Center, Joint Typhoon Warning Center, Guam, Mariana Islands.

Joint Typhoon Warning Center. 1991. ***Tropical Cyclones Affecting Guam (1671-1990).*** U.S. Naval Oceanography Command Center, Joint Typhoon Warning Center, Guam, Mariana Islands. NOAA/JTWC Tech Note 91-2.

National Academy of Sciences. 1994. ***Natural Disaster Studies Volume Six, Hurricane Hugo: Puerto Rico, the U.S. Virgin Islands, and South Carolina—September 17-22, 1989.*** Washington, DC: National Academy of Sciences/National Research Council, Committee on Natural Disasters, Board on Natural Disasters, Commission on Engineering and Technical Systems, Commission on Geosciences, Environment, and Resources.

National Committee on Property Insurance. 1989. ***Surviving the Storm: Building Codes, Compliance, and the Mitigation of Hurricane Damage.*** Oak Brook, IL: All-Industry Research Advisory Council.

NOAA, National Weather Service. 1993. ***Natural Disaster Survey Report: Hurricane Andrew—South Florida and Louisiana—August 23-26, 1992.***

NOAA, National Weather Service. 1993. ***Natural Disaster Survey Report: Hurricane Iniki—September 6-13, 1992.***

NOAA, National Weather Service. 1994. ***Hurricanes...The Greatest Storms on Earth.***

Neumann, C.J., B.R. Jarvinen, C.J. McAdie, and J.D. Elms. 1993. Supplements (1994) to ***Tropical Cyclones of the North Atlantic Ocean—1871 to 1992.*** National Oceanographic and Atmospheric Administration, National Climactic Data Center, Ashville, NC, and National Hurricane Center, Coral Gables, FL.

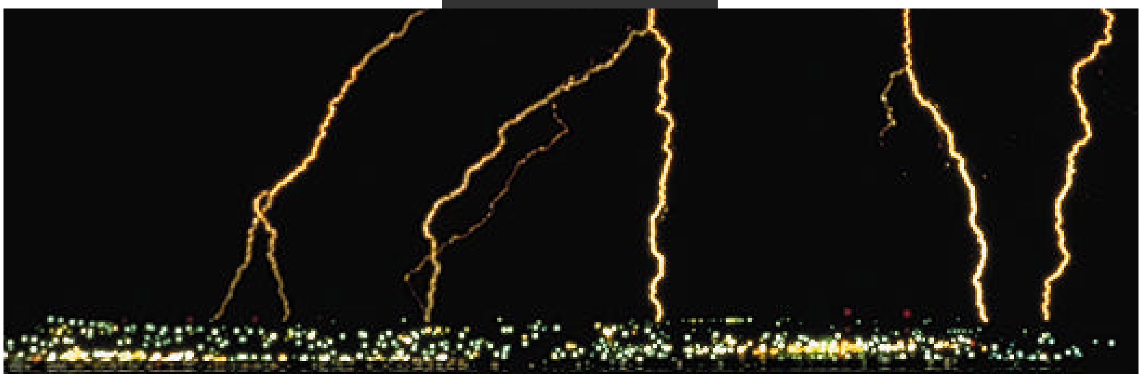
Palm, R.I., and M.E. Hodgson. 1993. ***Natural Hazards in Puerto Rico: Attitudes, Experience, and Behavior of Homeowners.*** Monograph No. 55. Boulder, CO: Institute of Behavioral Science, University of Colorado.

Smith, W. 1986. ***The Effects of Eastern North Pacific Tropical Cyclones on the Southwestern United States.*** NOAA Technical Memorandum NWS WR-197. Tucson, AZ: Department of Atmospheric Sciences, University of Arizona.

U.S. Army Corps of Engineers. 1985. ***Hurricane Vulnerability Study for Honolulu, Hawaii, and Vicinity, Volume 1—Hazard Analysis.*** USACE, Pacific Ocean Division, Floodplain Management Section, Planning Branch.

CHAPTER

2



THUNDERSTORMS AND LIGHTNING

Chapter Summary

The National Weather Service (NWS) estimates that over 100,000 thunderstorms occur each year on the U.S. mainland. Approximately 10 percent are classified as "severe." Thunderstorms can produce deadly and damaging tornadoes, hailstorms, intense downburst and microburst winds, lightning, and flash floods. Thunderstorms spawn as many as 1,000 tornadoes each year. Since 1975, severe thunderstorms were involved in 327 Federal disaster declarations.

During the past decade, more than 15,000 lightning-induced fires resulted in widespread property damage and the loss of 2 million acres of forest. On average, 89 people are killed by lightning each year, and another 300 are injured. Flashloods from thunderstorms, the number one cause of deaths associated with thunderstorms, claim more than 140 lives in the United States each year. In 1993 alone, thunderstorm winds caused 23 fatalities and $348.7 million in property damage, while lightning caused 43 deaths and damage estimated at $32.5 million.

Florida has the greatest number of thunderstorms and the central region of the State has the highest density of lightning strikes in the mainland United States. The Western States, around the junction of Arizona, Utah, and Nevada, experience the longest duration thunderstorms. The lengthier, less frequent thunderstorms in this region can create as great a hazard as the more frequent, but shorter duration storms in Florida.

Mitigation efforts are directed at the components of thunderstorms: tornadoes, hailstorms, windstorms, lightning, and flash floods. The modernization of the NWS weather monitoring systems and computer models should increase the warning time available to alert local emergency officials and citizens.

Thunderstorms and lightning are underrated killer events experienced in nearly every region of the mainland United States. Thunderstorms do not pose a hazard in the U.S. territories in the Pacific Ocean. Data are not available for Alaska, Hawaii, Puerto Rico, or the U.S. Virgin Islands. Although individual storms have only a relatively small impact area, throughout the world as many as 1,800 thunderstorms can occur at a time.

Photo: Red Cross

HAZARD IDENTIFICATION

Thunderstorm and lightning events are generated by atmospheric imbalance and turbulence due to the combination of conditions:

- Unstable warm air rising rapidly into the atmosphere;
- Sufficient moisture to form clouds and rain; and
- Upward lift of air currents caused by colliding weather fronts (cold and warm), sea breezes, or mountains.

Thunderstorms, sometimes referred to as "thunder events," are recorded and observed as soon as a peal of thunder is heard by an observer at a NWS first-order weather station. A thunder event is composed of lightning and rainfall, and can intensify into a severe thunderstorm with damaging hail, high winds, tornadoes, and flash flooding.

The duration of a thunder event is determined by measuring the time between the first peal of thunder and the last. The last peal of thunder is defined to be that which is followed by a period of at least 15 minutes without an additional peal. A "thunder day" is defined as any day in which at least one thunder peal is heard.

Downburst winds are strong, concentrated, straight-line winds created by falling rain and sinking air that can reach speeds of 125 mph (200 km/h). The combination induces a strong downdraft of wind due to aerodynamic drag forces or evaporation processes (Golden and Snow, 1991). Microburst winds are more concentrated than downbursts, with speeds up to 150 mph (240 km/h). Severe damage can result from the spreading out of downbursts and microbursts, which generally last 5 to 7 minutes. Due to wind shear and detection difficulties, they pose the biggest threat to aircraft departures and landings.

Lightning, which occurs during all thunderstorms, can strike anywhere. Generated by the buildup of charged ions in a thundercloud, the discharge of a lightning bolt interacts with the best conducting object or surface on the ground. The air in the channel of a lightning strike reaches temperatures higher than 50,000ºF. The rapid heating and cooling of the air near the channel causes a shock wave which produces thunder (NOAA, 1994).

The NWS classifies a thunderstorm as severe if its winds reach or exceed 58 mph (km/h), produces a tornado, or drops surface hail at least 0.75 in (1.91 cm) in diameter (Golden and Snow, 1991).

Compared with other atmospheric hazards such as tropical cyclones and winter low pressure systems, individual thunderstorms affect relatively small geographic areas. The average thunderstorm system is approximately 15 mi (24 km) in diameter and typically lasts less than 30 minutes at a single location. However, weather monitoring reports indicate that coherent thunderstorm systems can travel intact for distances in excess of 600 mi (1,000 km).

RISK ASSESSMENT

Dangerous and damaging aspects of a severe thunderstorm, other than tornadoes and hail, are lightning strikes, flash flooding, and the winds associated with downbursts and microbursts. Detailed information is presented separately on tornadoes (Chapter 3), hailstorms (Chapter 5), and flash flooding (Chapter 12).

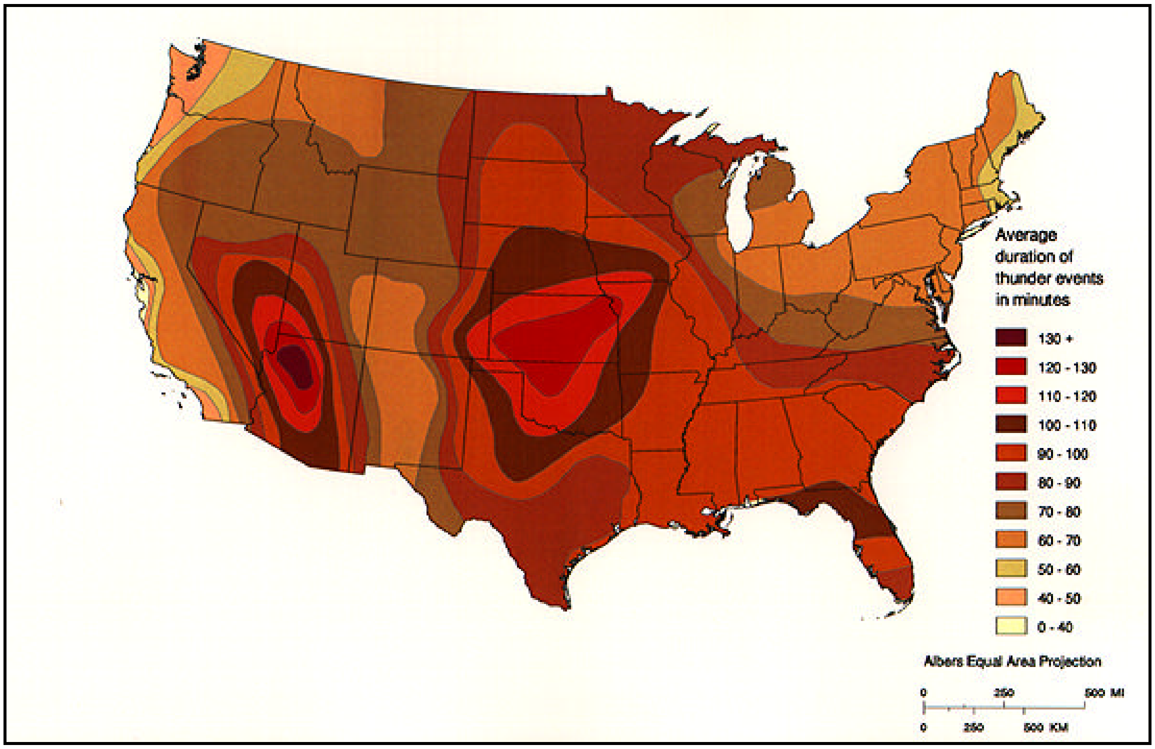
Probability and Frequency

The probability of a severe thunderstorm occurring in a specific region depends on certain atmospheric and climatic conditions. Duration and frequency can be used as indicators of potential severity. Damage from lightning strikes will likely increase with longer duration and more frequent thunderstorm occurrence. Therefore, the geographic areas with a high density of lightning strikes, measured in units of flashes per square kilometer, are at a greater risk for damage or potential loss of life during a thunder event.

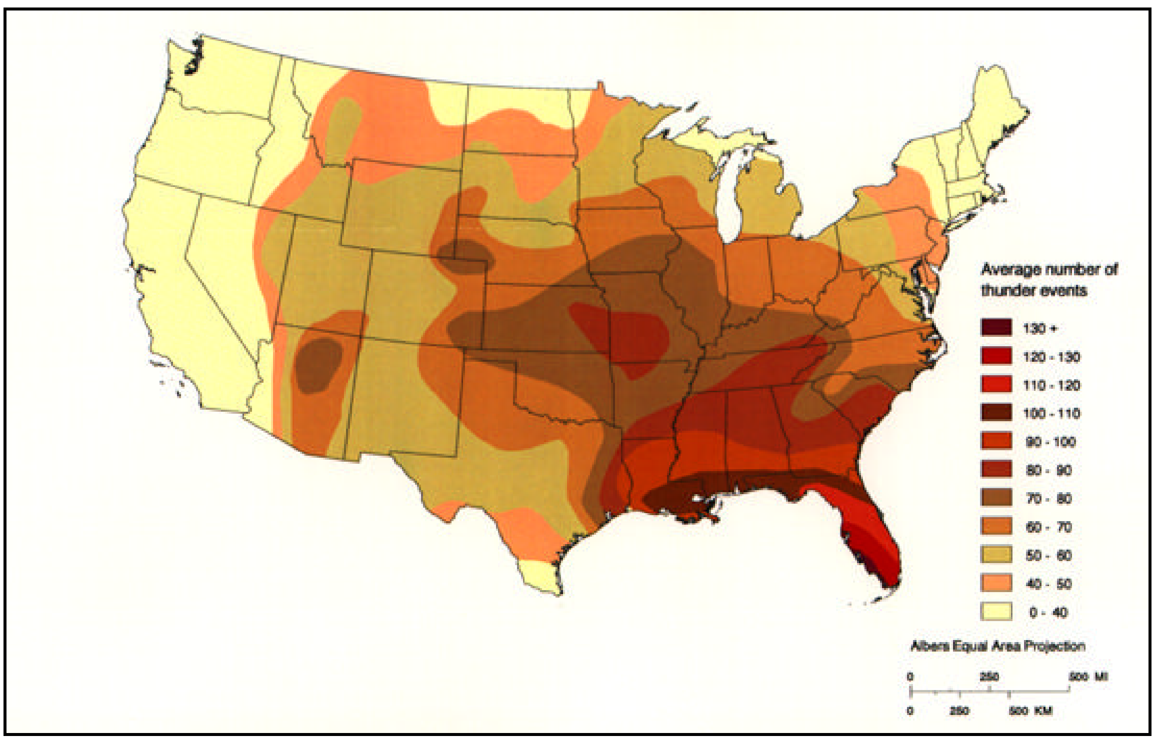
The likelihood of a severe thunderstorm occurring increases as the average duration and number of thunder events increase. Therefore, data collection and combined review of these aspects provide information to assess the areal extent and frequency of the hazard.

NWS collected data for thunder days, number and duration of thunder events, and lightning strike density for the 30-year period from 1948 to 1977. A series of maps was generated showing the annual average thunder event duration (Map 2-1), the annual average number of thunder events (Map 2-2), and the mean annual density of lightning strikes (Map 2-3). Together, these maps indicate the areal extent and frequency of occurrence of thunderstorm and lightning hazards across the mainland United States (Changnon, 1988).

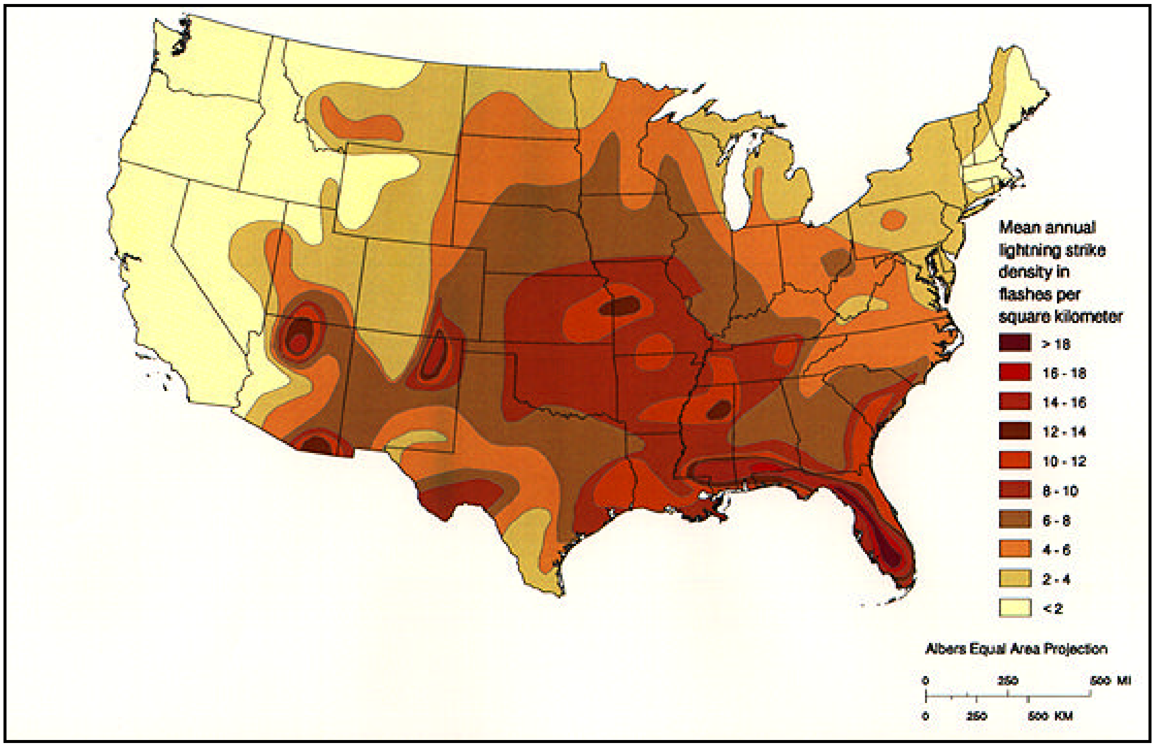
Thunderstorm Frequency. Maps 2-1 and 2-2 indicate that two areas of the United States are subject to the most damaging thunderstorms, but have different influencing characteristics. South Florida has the greatest number of thunderstorms, with an annual average of 100 to 130, and an average duration of 80 to 100 min-



Map 2-1. Thunderstorm hazard severity based on the annual average duration of thunder events from 1949 - 1977. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Changnon, 1988.*



Map 2-2. Thunderstorm hazard severity based on the annual average number of thunder events from 1948 - 1977. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Changnon, 1988.*



Map 2-3. Areal extent and severity of lightning hazard based on mean annual lightning strike density: 1948 - 1977. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from MacGorman and others, 1984.*

utes. The area around the junction of Arizona, Utah, and Nevada has an annual average of 30 to 50 thunder events, and the average duration is 110 to 130 minutes. The longer duration, less frequent thunderstorms in this region can create hazards comparable to those experienced in Florida.

The severity of thunderstorm activity in the desert region is influenced by the fact that the annual peak occurrence takes place during a shorter period of time, 3 months during the late summer. In Florida, the season lasts from early summer to late fall, due to the warmer tropical climate and resulting unstable atmospheric conditions favorable for thunderstorm development.

Although severe thunderstorms occur less frequently in the Midwest, the period of activity is not well-defined. Significant activity occurs during different months, but mostly from spring until early winter (Changnon, 1988). The unstable air masses and collision of developing cold and warm fronts during the summer and fall appear to be the cause of activity throughout the Midwestern States.

Lightning Frequency. The lightning hazard component of thunderstorms has been documented by researchers at the NOAA National Climatic Data Center (NCDC), who record the mean annual ground flash density (flashes per square kilometer). Review of these data shows that the central Florida region has over 18 flashes/km^2, the highest density in the U.S. mainland (Map 2-3). Southern Alabama has the next highest strike density with over 16 flashes/km^2. Northeastern New Mexico and northern Arizona have isolated high density areas with over 14 flashes/km^2.

Florida has a higher lightning strike density and more frequent occurrence of thunderstorms, therefore the risk of damaging impacts and loss of life are expected to be greatest. Data were not available for Alaska, Hawaii, Puerto Rico, or the U.S. Virgin Islands, and the Pacific Territories.

Exposure

People and property in virtually the entire United States are exposed to damage, injury, and loss of life from thunderstorms and related hazards such as lightning, severe windstorms, hail, tornadoes, and flash floods. Everywhere they occur, thunderstorms are responsible for significant structural damage to buildings, forest and wildfires, downed power lines and trees, and loss of life. Damage similar to that caused by tornadoes and other cyclonic windstorms can result from severe thunderstorm downbursts and microburst winds. As many as 1,000 tornadoes each year grow out of thunderstorms (Golden and Snow, 1991).

Consequences

NOAA reports that thunderstorm winds were responsible for 23 fatalities in 1993, and associated lightning strikes caused 43 deaths (NOAA, 1994). For the same year, damage from thunderstorm winds amounted to $348.7 million, while lightning caused $32.5 million in damage.

According to NOAA, from 1963 to 1993, the average loss of life due to lightning was 89 per year, with an additional 300 persons injured each year. Most lightning-related deaths and injuries occurred when people were outdoors during summer afternoons and evenings. The total number of deaths by State from 1959 to 1993 is shown on Map 2-4.

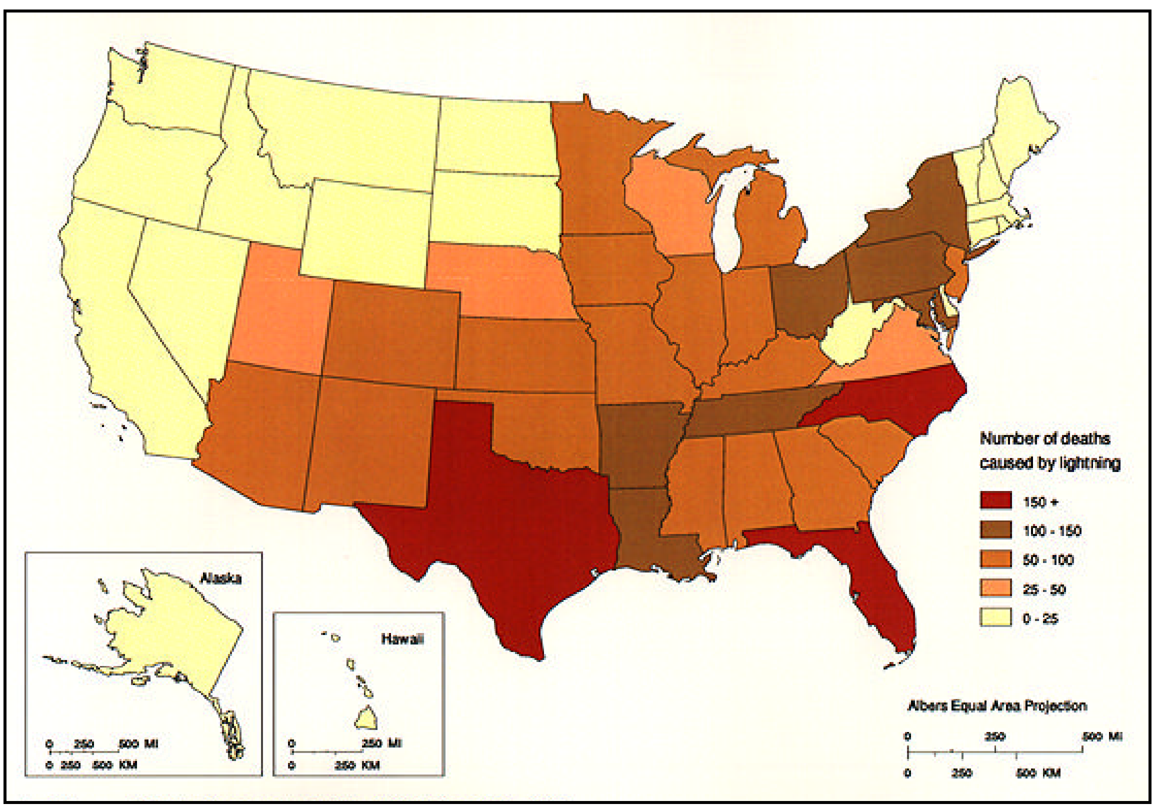
Significant airplane disasters often are associated with thunderstorms and lightning. Crashes in 1982 in Kenner, LA, and in 1985 in Dallas/Ft. Worth, TX, were attributed to thunderstorm downbursts. In 1963, a plane struck by lightning near Elkton, MD, killed 38 people.

Flash flooding from thunderstorms cause more than 140 fatalities each year and is the primary cause of death from thunderstorm events. Most fatalities occur when people become trapped in automobiles (NOAA, 1994). During the past decade, more than 15,000 lightning-induced fires nationwide resulted in widespread property damage and the loss of 2 million acres of forest.

Severe thunderstorms were involved in 327 Federal disaster declarations from 1975 to 1995. Tornadoes spawned from severe thunderstorms accounted for 106, while several declarations cited thunderstorms and associated phenomena: rain (26), high winds (22), and flash flooding (17).

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Thunderstorm wind speeds were included in research conducted by Twisdale and Vickery (1993). The 100-year return period thunderstorm wind speeds were predicted for nine locations in the Central and Southern



Map 2-4. Total deaths caused by lightning: 1959 - 1993.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from U.S. Department of Commerce, NOAA, 1993.*

United States, based on daily peak gust data for each site obtained from the National Climatic Data Center in Asheville, NC. The 100-year return periods for highest wind speeds were derived from stochastic models, which predict thunderstorm wind velocities of 66 to 84 mph (106 km/h to 135 km/h) in the Central United States. Each station analyzed showed the highest wind speed on record to be associated with a thunderstorm event.

The National Weather Service has undertaken modernization of weather observation through implementation of NEXRAD systems. The various climatology monitoring programs that allow forecasting of thunderstorms are fairly well-established in each weather-related agency. The forecast centers have been integrated into warning systems for their respective areas. In conjunction with existing Doppler radar weather stations, NEXRAD will improve forecaster capability to predict the development of, and to detect, severe thunderstorms and associated strong winds, hail, lightning, and tornadoes.

MITIGATION APPROACHES

There are no clearly defined mitigation approaches designed specifically for thunderstorms that are separate from the associated hazard phenomena. Mitigation measures for tornadoes, hailstorms, windstorms, and flash flooding can be expected to achieve a reduction in damage caused by or associated with thunderstorms.

Proven techniques are available to reduce lightning damage by grounding techniques for buildings.

RECOMMENDATIONS

The National Research Council (NRC) report on wind hazards, *Wind and The Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation*, includes recommendations applicable to mitigating damage caused by or associated with thunderstorms and lightning (NRC, 1993).

BIBLIOGRAPHY AND REFERENCES

Byrant, E. 1991. ***Natural Disasters***. New York, NY: Cambridge University Press.

Changnon, Jr, S.A. 1988. "Climatology of Thunder Events in the Conterminous U.S., Part I: Temporal Aspects" and "Part II: Spatial Aspects." ***Journal of Climate***. Vol. 1, No. 4, pp. 389-405.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." ***Reviews of Geophysics.*** American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Kitsmiller, D.H., W.E. McGovern, and R.E. Saffle. 1992. ***The NEXRAD Severe Weather Potential Algorithm***. NOAA Technical Memorandum, NWS TDL 81. Silver Spring, MD: Techniques Development Laboratory.

MacGorman, D.R., M.W. Maier, and W.D. Rust. 1984. ***Lightning Strike Density for the Contiguous United States from Thunderstorm Duration Records***. NOAA, Environmental Research Laboratories, National Severe Storms Laboratory.

National Research Council. 1993. ***Wind and the Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation.*** Washington, D.C.: National Academy Press.

NOAA, National Weather Service. 1994. ***Thunderstorms and Lightning: The Underrated Killers.*** U.S. Department of Commerce, NOAA, NWS.

Twisdale, L.A., and P.J. Vickery. 1993. "Analysis of Thunderstorm Occurrences and Windspeed Statistics." In: ***Proceedings of the 7th U.S. National Conference on Wind Engineering***. Los Angeles, CA: University of California.

CHAPTER

3

TORNADOES

Chapter Summary

Approximately 1,000 tornadoes each year are spawned by severe thunderstorms. Although most tornadoes remain aloft, those that touch ground are forces of destruction. Tornadoes have been known to lift and move huge objects, destroy or move whole buildings long distances, and siphon large volumes from bodies of water. Over the past 20 years, 106 Federal disaster declarations included damage associated with tornadoes.

Tornado Alley, portions of Texas, Oklahoma, Arkansas, Missouri, and Kansas, is the most susceptible area of the United States. Texas alone averaged 128 tornadoes and 11 tornado-related deaths a year over the 40-year period ending in 1993.

Tornadoes follow the path of least resistance. People living in valleys, which normally are the most highly developed areas, have the greatest exposure. When a tornado warning is issued, local officials typically notify residents with radio and television announcements and alarm systems. Many tornado-prone areas have public shelters, and residents often have specially constructed shelter areas in their homes.

Other hazards that accompany weather systems that produce tornadoes include rainstorms, windstorms, large hail, and lightning.

Photo: Severe Storm Lab

HAZARD IDENTIFICATION

A tornado is a rapidly rotating vortex or funnel of air extending groundward from a cumulonimbus cloud. Most of the time, vortices remain suspended in the atmosphere (Golden and Snow, 1991). When the lower tip of a vortex touches earth, the tornado becomes a force of destruction. Approximately 1,000 tornadoes are spawned by severe thunderstorms each year.

Tornado damage severity is measured by the Fujita Tornado Scale. The Fujita Scale assigns numerical values based on wind speeds and categorizes tornadoes from 0 to 5. The letter "F" often precedes the numerical value. Scale values above F5 are not used because wind speeds above 318 mph (513 km/h) are unlikely. Table 3-1 shows the Fujita Scale values, wind speeds, descriptions of damage, and average annual number of tornadoes for the period 1953-1989.

Tornadoes are related to larger vortex formations, and therefore often form in convective cells such as thunderstorms or in the right forward quadrant of a hurricane, far from the hurricane eye. The strength and number of tornadoes are not related to the strength of the hurricane that generates them. Often, the weakest hurricanes produce the most tornadoes (Bryant, 1991). In addition to hurricanes, events such as earthquake-induced fires and fires from atomic bombs or wildfires may produce tornadoes.

TABLE 3-1.—*Fujita tornado scale*

Scale Value	Wind Speed* Range and Description of Damage
F0	**40-72 mph (17.8-32.6 m/s):** Light damage. Some damage to chimneys; tree branches broken off; shallow-rooted trees pushed over; sign boards damaged. Average number per year, 1953-1989: 218 (29 percent).
F1	**73-112 mph (32.7-50.3 m/s):** Moderate damage. The lower limit is the beginning of hurricane wind speed. Roof surfaces peeled off; mobile homes pushed off foundations or overturned; moving autos pushed off roads. Average number per year, 1953-1989: 301 (40 percent).
F2	**113-157 mph (50.4-70.3 m/s):** Considerable damage. Roofs torn off from houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated. Average number per year, 1953-1989: 175 (23 percent).
F3	**158-206 mph (70.4-91.9 m/s):** Severe damage. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off ground and thrown. Average number per year, 1953-1989: 43 (6 percent).
F4	**207-260 mph (92.0-116.6 m/s):** Devastating damage. Well-constructed houses leveled; structures with weak foundations blown off some distance; cars thrown; large missiles generated. Average number per year, 1953-1989: 10 (1 percent).
F5	**261-318 mph (116.7-142.5 m/s):** Incredible damage. Strong frame houses lifted off foundations and carried considerable distances to disintegrate; automobile-sized missiles fly through the air in excess of 100 yards; trees debarked. Average number per year, 1953-1989: 1 (0.002 percent).
	* Wind speeds in the range are defined by Fujita to be “the fastest 1/4-mile wind.”

Sources: *From Golden and Snow, 1991: NOAA, NWS Natural Disaster Survey Report, 1991.*

The path width of a single tornado generally is less than 0.6 mi (l km). The path length of a single tornado can range from a few hundred meters to dozens of kilometers. A tornado typically moves at speeds between 30 and 125 mph (50 and 200 km/h) and can generate internal winds exceeding 300 mph (500 km/h). However, the lifespan of a tornado rarely is longer than 30 minutes.

A tornado event occurs when a single atmospheric condition such as a thunderstorm or hurricane generates more than one tornado. Multiple tornadoes generally are the result of many thunderstorms embedded in one large extratropical cyclone or mesoscale convective complex (Golden and Snow, 1991).

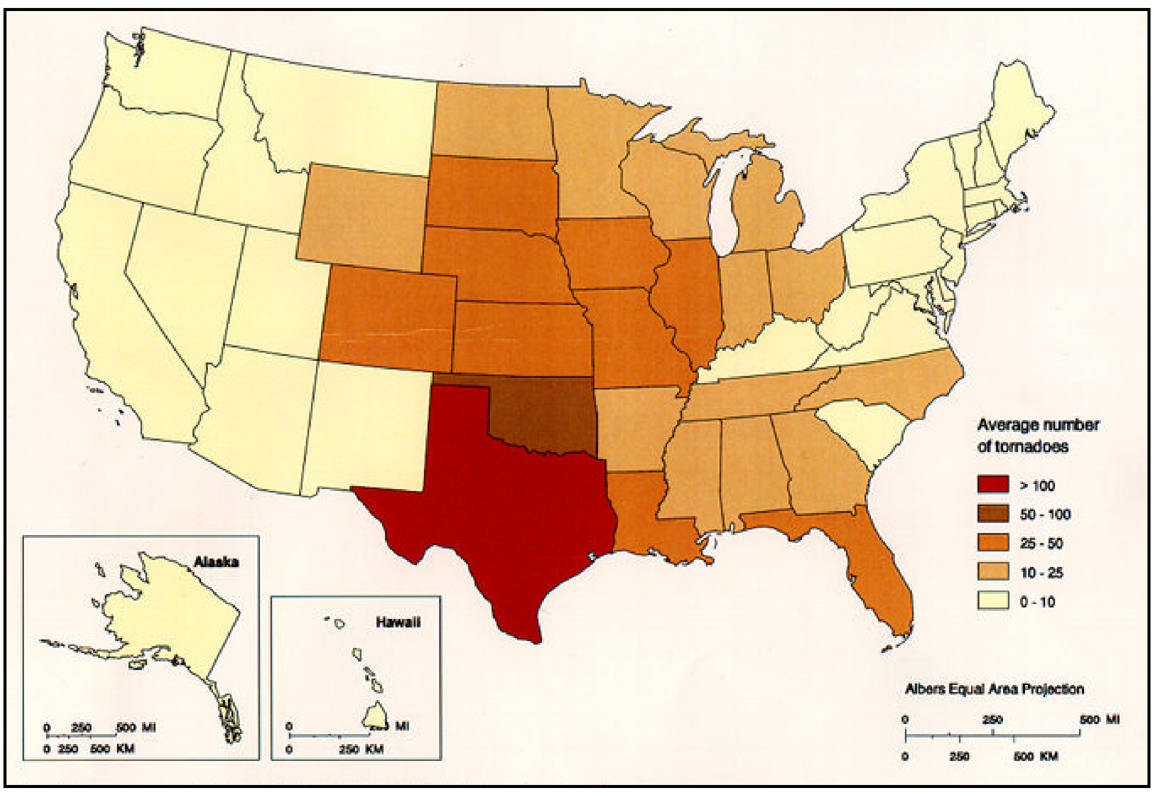
RISK ASSESSMENT

The NWS National Severe Storms Forecast Center in Kansas City, MO, provides information on severe thunderstorms and tornadoes to the general public, news media, emergency managers, and law enforcement personnel. The Center uses the latest Doppler radar, wind profilers, and the networks of automated surface observing systems (ASOS) across the United States to assist in the prediction and identification process for severe thunderstorm and tornado watches and warnings.

A tornado watch is issued for a specific location when thunderstorms capable of producing tornadoes are recognized and arrival is expected in a few hours. A tornado warning is issued when tornadoes are spotted or when Doppler radar identifies a distinctive "hook-shaped" area within a local partition of a thunderstorm line that is likely to form a tornado.

When a tornado watch or warning is issued, local tornado spotters, emergency response organizations, and ham radio operators are placed on alert to assist in identifying and locating possible tornadoes. When a tornado is detected, emergency operations personnel and law enforcement agencies are alerted immediately. Warnings are broadcast to the public on radio, television, and alarm systems. Emergency managers and local law enforcement officials sound sirens to notify those who have not already received the information by television, radio, or visual sighting.

Education about tornado hazards continues to be emphasized for schoolchildren in all grades. Residents in tornado-prone areas such as the Southern and



Map 3-1. Average annual number of tornadoes per State from 1953 - 1993.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from National Oceanographic and Atmospheric Administration, 1993.*

Photo: Red Cross

Midwestern States are aware of the dangers and many have underground or specially constructed shelters in their homes. Employees and occupants of unsafe or unprotected facilities are routinely instructed on procedures for safe evacuation.

Probability and Frequency

Map 3-1 shows the average number of tornadoes that occurred each year from 1953 to 1993. Texas experienced the highest average annual number of tornadoes with 128, followed by Oklahoma (52), Kansas (47), Florida (46), and Nebraska (38). Hurricanes Carla (1960), Beulah (1967), and Gilbert (1980) produced 26, 115, and 40 tornadoes, respectively.

The occurrence of F4 and F5 tornadoes may at times be underestimated by as much as a factor of five in some areas of the United States: F5 tornadoes may be listed as F4 tornadoes, F4 tornadoes may be listed as F3 tornadoes, and so on (Twisdale, 1978). This can occur because F3 tornadoes have an F3 intensity for approximately 35 percent of their duration, and an intensity of less than F3 for the remainder. Similarly, F4 and F5 tornadoes endure at those intensities for 24 percent and 19 percent of their lifespan, respectively (Ramsdell and Andrews, 1986).

There has been considerable research on the relationship between tornado dimensions and tornado intensity: the length, width, and area of the tornado track compared to the probability of being exceeded and strike probability. The arithmetic averages of length, width, area, and strike probability of all tornadoes during the period 1954-1983 have been developed (Ramsdell and Andrews, 1986). These data are available and can been used to assess the risk of tornado hazards.

Exposure

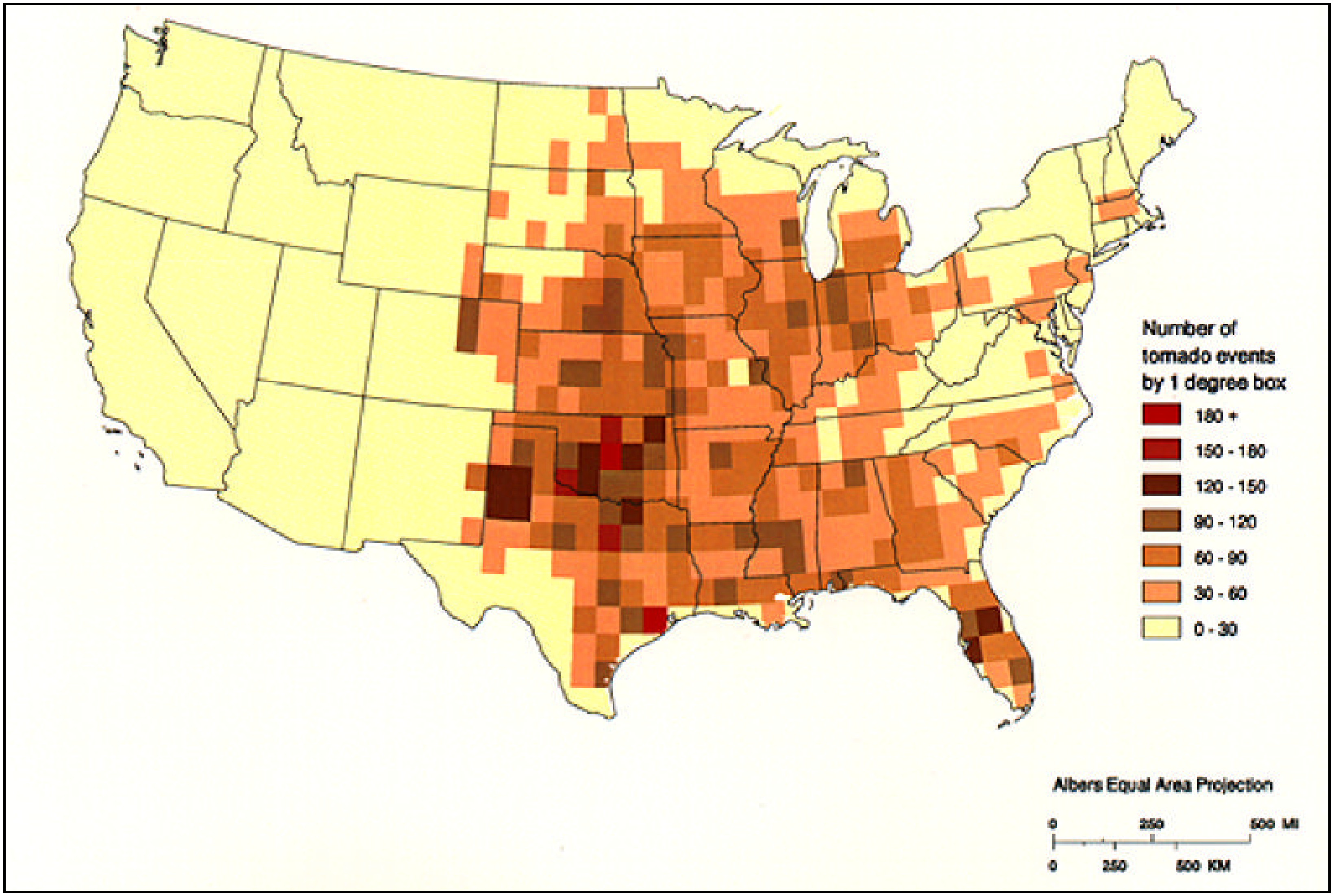
An area covering portions of Texas, Oklahoma, Arkansas, Missouri, and Kansas is known as Tornado Alley, where the average annual number of tornadoes is the highest in the United States. Tornadoes occur in this area for several reasons. Cold air from the north collides with warm air from the Gulf of Mexico, creating a temperature differential on the order of 20–30ºC. The flat terrain enhances rapid movement of air, while the high humidity of the Gulf Stream further induces instability in the atmosphere. Most tornadoes in this area occur during the spring (Bryant 1991). People, buildings, and infrastructure located in Tornado Alley have the highest exposure to this hazard.

People living in manufactured or mobile homes are most exposed to damage from tornadoes. Even if anchored, mobile homes do not withstand high wind speeds as well as some permanent, site-built structures.

Ramsdell and Andrews (NOAA, 1986) placed tornado data for the period of 1954–1983 into 1-degree (longitude and latitude) squares on a map of the United States (Map 3-2). Combining this information with data on the estimated population living within each 1-degree area allows assessment of the relative degree of exposure.

Consequences

Tornadoes have been known to lift and move objects weighing more than 300 tons a distance of 30 ft (10 m), toss homes more than 300 ft (100 m) from their foundations, and siphon millions of tons of water from water bodies. Tornadoes generate a tremendous amount of debris, which often becomes airborne shrapnel that causes additional damage. Tornadoes are almost always accompanied by heavy precipitation (Bryant, 1991).



Map 3-2. Geographic distribution of tornadoes based on total number of tornado events per one degree of latitude and longitude: 1954 -1983. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Ramsdell and Andrews, 1986.*

TABLE 3-2.—*Ten most deadly tornado events: 1870-1979*

Date	Name or Location of Event	Number of Tornadoes	Deaths	Number of States Affected	Estimated Damage *(in millions)*
March 18, 1925	Tri-State	7	740	6	$18
April 5-6, 1936	Tupelo-Gainesville	17	446	5	$18
February 19, 1884	Enigma	60	420	8	$3
March 21-22, 1932	Northern Alabama	33	334	7	$5
April 3-4, 1974	Super	148	315	13	N/A
April 24-25, 1908	Louisiana-Georgia	18	310	5	$1
May 27, 1896	St. Louis, MO	18	306	3	$15
April 11-12, 1965	Palm Sunday	51	256	6	$200
March 21-22, 1952	Dierks, AR	28	204	4	$15
March 23, 1913	Easter Sunday	8	181	3	$4

Source: *J. Galway, Weatherwise Magazine, 1981*

The largest recorded tornado event occurred on April 3–4, 1974, during which 148 tornadoes across 13 States resulted in 315 deaths. Table 3-2 summarizes damage caused by the 10 deadliest tornadoes occurring between 1870 and 1979. Table 3-3 provides similar information for tornado events since 1979.

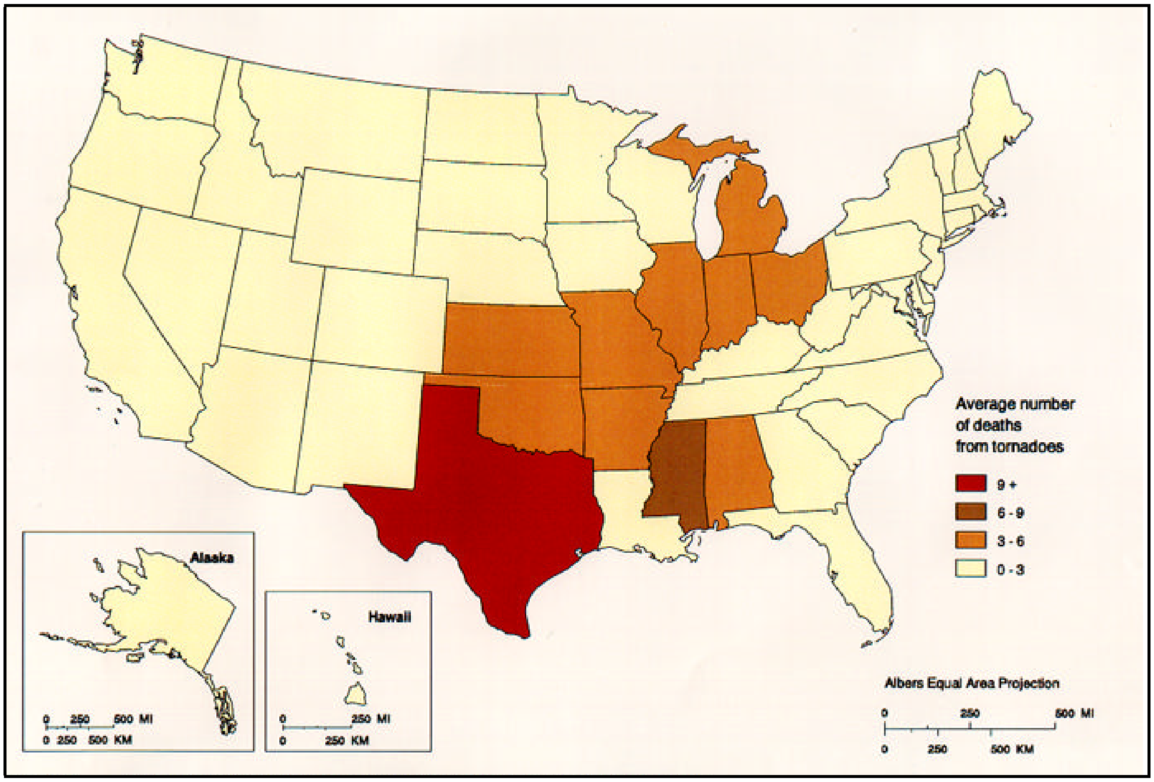
From 1916 to 1950, 5,204 tornadoes occurred in the United States, resulting in the deaths of 7,961 people, an average of 234 deaths per year (Bryant, 1991). From 1953-1989, tornadoes claimed 3,550 lives, an average of 96 deaths per year. From 1961-1990, the highest number of tornado-related deaths occurred in Mississippi, Indiana, Ohio, Alabama, and Arkansas (Golden and Snow, 1991). According to NWS, 39 tornado-related deaths occurred in 1992, and 33 occurred in 1993.

Map 3-3 shows the average annual number of deaths by State from 1953 to 1993. During that period, Texas had

TABLE 3-3.—*Six most deadly recent tornado events: 1980-1994*

Date	Name or Location of Event	Number of Tornadoes	Deaths	Number of States Affected	Estimated Damage *(in millions)*
May 31, 1985	Pennsylvania-Ohio	41	75	3	$450
March 28, 1984	Carolinas	22	57	2	$200
March 27, 1994	Southeastern U.S.	2	42	2	$107
November 21-23, 1992	Houston to Raleigh and Gulf Coast to Ohio Valley	94	26	13	$291
April 26-27, 1991	Wichita/Andover, KS	54	21	6	$277
October 3, 1992	Tampa Bay Area	3	4	1	$100

Source: *From NOAA, NWS Natural Disaster Survey Reports, 1985-1994.*



Map 3-3. Average annual deaths by State caused by tornadoes: 1953-1993.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from National Oceanic Atmospheric Administration, 1993.*

the highest annual average, 11 deaths, followed by Mississippi with 8 deaths. Four States had an annual average of five deaths during that period, and four others had an annual average of four deaths.

Between 1975 and 1995, 106 major Federal disaster declarations included impacts caused by tornadoes. The States with the greatest number of tornado-related disasters were: Mississippi (14); Alabama and Illinois (9 each); Oklahoma (8); Wisconsin (7); Ohio (6); and Missouri, Minnesota, Louisiana, Georgia, and Arkansas (5 each).

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

The NWS evaluates each major tornado to determine the accuracy of its predictions and identifications based on weather data obtained from radar and other sources, local tornado spotters, emergency operations personnel, law enforcement agencies, and the general public. The NWS goal is to improve its ability to warn affected populations. Local governments and the news media routinely evaluate their capabilities and to identify areas where improvements are needed in the warning process.

The research community surveys damaged areas to understand how structures perform. The purposes of this research are to reduce damage and save lives during future tornadoes, and to transfer information to critical sources.

Based on post-event analyses, photogrammetric determinations of the motion of objects caught up in tornadoes documented on film and videotape, and measurement of speeds of objects using Doppler radar, it has been determined that the maximum wind speed in a tornado occurs 100 to 150 ft (30 to 50 m) above the ground (Golden and Snow, 1991). From their points of origin, 54 percent of tornadoes travel northeasterly, 22 percent travel easterly, 22 percent travel southeasterly, 8 percent travel northerly, 2 percent northwesterly, and 1 percent travel southerly, westerly, and southwesterly, respectively (Twisdale, 1978).

Dr. Theodore Fujita, professor of meteorology at the University of Chicago, conducted research on the complicated structure of tornado winds. He first documented the "suction spots" phenomenon from an aerial damage survey of the 1965 Palm Sunday event. In addition to suction vortices, other asymmetric flow configurations have been documented (Golden and Snow, 1991).

Experts believe suction vortices may help explain why one structure is destroyed while an adjacent structure is basically untouched.

Within the research community, there is no agreement regarding what causes the destruction of buildings. Some experts believe the difference in atmospheric pressure inside and outside causes buildings to explode. Others believe destruction is caused by wind-induced forces that tear structures apart from the outside.

MITIGATION APPROACHES

Mitigation opportunities for tornado winds are similar to mitigation measures for other wind hazards. However, the damage associated with violent tornadoes due to extreme wind speeds and pressures may be difficult to mitigate in a cost-effective manner. Attention to the type of structure used in tornado-prone areas may yield benefits, particularly by avoiding highly susceptible manufactured or mobile homes.

The greatest protection is afforded by quality construction and reinforcement of walls, floors, and ceilings. Proper anchoring of walls to foundations and roofs to walls is essential for a building to withstand certain wind speeds. In tornado damage studies, the wind engineering research community has found considerable variability in construction quality and material (Golden and Snow 1991). Code adoption by local jurisdictions, compliance by builders, and local government inspection of new homes could reduce the risk of destruction in tornado-prone areas.

Loss of life and injuries may be reduced if more individuals seek shelter in basements, small interior rooms, or hallways, and avoid rooms and buildings with large roof spans. An interior room or closet has less chance of collapse or failure than other areas. A reinforced, in-residence tornado shelter may be constructed for approximately $6,000 (1995 value), while the cost of retrofitting an interior room or closet in an existing house would be approximately $3,000 (Golden and Snow, 1991).

NOAA Natural Disaster Survey Reports highlight the need for local emergency managers, law enforcement officials, and local tornado spotters to provide information regarding tornado touchdowns. This allows NWS to quantify its radar findings and improve subsequent tornado watches and warnings.

RECOMMENDATIONS

Recommendations for reducing life safety risks associated with tornado events are identified in NOAA's Natural Disaster Reports, including:

- Improve radio and wire communications with the media and local emergency managers;
- Equip gathering places with weather radios with an audible alert of warning and require testing of response and preparedness plans;
- Continue awareness and preparedness efforts in schools; and
- Make special efforts to inform mobile homes residents about the impacts of the tornado hazard as well as locations of safe shelters in times of emergency.

BIBLIOGRAPHY AND REFERENCES

Angel, W. 1993. ***National Summary of Tornadoes, 1993.*** NOAA, National Environmental Satellite Data and Information Service, National Climatic Data Center.

Byrant, E. 1991. ***Natural Disasters***. New York, NY: Cambridge University Press.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human***. Upper Saddle River, NJ: Prentice Hall.

Galway, J.G. June 1981. "Ten Famous Tornado Outbreaks." ***Weatherwise Magazine***.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." ***Reviews of Geophysics.*** American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

National Weather Service. 1994. ***Natural Disaster Survey Report: Southeastern United States Palm Sunday Tornado Outbreak of March 27, 1994***. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1993. ***Natural Disaster Survey Report: The Widespread November 21-23, 1992, Tornado Outbreak—Houston to Raleigh and Gulf Coast to Ohio Valley***. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1993. ***Natural Disaster Survey Report: Tampa Bay Tornadoes—October 3, 1992***. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1991. ***Natural Disaster Survey Report: Wichita/Andover, KS, Tornado, April 26, 1991***. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1991. ***Natural Disaster Survey Report: The Plainfield/Crest Hill Tornado—Northern Illinois—August 28, 1990***. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1992. ***Tornadoes: Nature's Most Violent Storms***. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Ramsdell, J.V., and G.L. Andrews. 1986. ***Tornado Climatology of the Contiguous United States***. U.S. Department of Commerce, Pacific Northwest Laboratory, prepared for U.S. Nuclear Regulatory Commission.

Twisdale, L.A., and W.L. Dunn. 1983. "Wind Loading from Multivortex Tornadoes." ***Journal of Structural Engineering.*** American Society of Civil Engineers. Vol. 109, No. 8, pp. 2016-2022.

Twisdale, L.A., and W.L. Dunn. 1983. "Probabilistic Analysis of Tornado Wind Risks." ***Journal of Structural Engineering.*** American Society of Civil Engineers. Vol. 109, No. 2, pp. 468-488.

Twisdale, L.A. 1978. "Tornado Data Characterization and Windspeed Risk." ***Journal of the Structural Division***. American Society of Civil Engineers. Vol. 104, No. ST10, pp. 1611-1630.

CHAPTER

4

WINDSTORMS

Chapter Summary

Extreme winds other than tornados are experienced in all regions of the United States and its territories. Areas experiencing the highest wind speeds are coastal regions from Texas to Maine, under the influence of North Atlantic Ocean and Gulf of Mexico hurricane-related windstorms, and the Alaskan coast, under the influence of winter low-pressure systems in the Gulf of Alaska and North Pacific Ocean. Isolated wind phenomena in the Western States, such as the Chinook and Santa Ana winds, occur very locally along mountainous terrains.

It is difficult to separate the various wind components that cause damage from other wind-related natural events that often occur with or generate windstorms. For example, hurricanes with intense winds often spawn numerous tornados or generate severe thunderstorms producing strong, localized downdrafts.

Windstorms and wind-related events caused 63 fatalities in 1993. Florida suffered the highest number of deaths, 10. From 1981 to 1990, the insurance industry spent nearly $23 billion on wind-related catastrophic events. Over the past 20 years, 193 Federal disaster declarations involved wind-induced damage.

A project developed by the Wind Engineering Research Center at the Texas Tech University in Lubbock, TX and the Insurance Institute for Property Loss Reduction in Wheaton, IL created a new wind-resistance classification system for buildings (IIPLR, 1994). It allows owners to identify corrective actions needed to make buildings safer, and helps officials to pinpoint buildings for evacuation during windstorms.

Improved building codes, retrofitting, and land use are some mitigation approaches used to limit exposure to windstorms. Recently, the National Research Council urged that a National Wind Science and Engineering Program be implemented to revitalize wind-hazard research (NRC, 1993).

Photo: Red Cross

HAZARD IDENTIFICATION

Wind is defined as the motion of air relative to the earth's surface (Golden and Snow, 1991). The horizontal component of the three-dimensional flow and the near-surface wind phenomenon are the most significant aspects of the hazard. Extreme windstorm events are associated with extratropical and tropical cyclones, winter cyclones, and severe thunderstorms and accompanying mesoscale offspring such as tornados and downbursts (Golden and Snow, 1991). Winds vary from zero at ground level to 200 mph (89 m/s) in the upper atmospheric jet stream at 6 to 8 mi (10 to 13 km) above the earth's surface.

The damaging effects of windstorms associated with hurricanes may extend for distances in excess of 100 mi (160 km) from the center of storm activity. Isolated wind phenomena in the mountainous western regions have more localized effects.

In the mainland United States, the mean annual wind speed is reported to be 8 to 12 mph (4 to 5 m/s), with frequent speeds of 50 mph (22 m/s) and occasional wind speeds of greater than 70 mph (31 m/s). For coastal areas from Texas to Maine, tropical cyclone winds may exceed 100 mph (45 m/s).

Large-scale extreme wind phenomena are experienced over every region of the United States and its territories. Additional wind hazards occur on a very localized level due to downslope windstorms along mountainous terrains, such as the Chinook winds along the eastern slope of the Rocky Mountains in Montana, New Mexico, Colorado, and Wyoming, and the Santa Ana winds of southern California. These regional phenomena, known as foehn-type winds, result in winds exceeding 100 mph (45 m/s), but they are of short duration and affect a relatively small geographic area.

The Santa Ana winds only impact southern California. They generally occur during the late summer to early winter and are generated when the passage of dry, cold weather frontal systems is followed by a high pressure system developing over the Utah-Nevada area. The western flow of the cooler air mass loses moisture as it is forced to the west and funneled down through mountain passes along the western slopes of the mountains. With the rapid temperature increase as the winds descend, 5.5ºF for every 1,000 ft or 304 m of descent, the Santa Ana winds become very dry, hot, and fast.

The Chinook winds along the eastern slopes of the Rocky Mountains occur during the winter as a result of large atmospheric movement over mountain ridges. The downslope winds along the eastern side gather strong near-surface speeds, with record wind gusts up to 140 mph (63 m/s) measured in Boulder, Colorado. Other notable mountain windstorm events, such as Oregon's Columbia River Gorge winds and Utah's Wasatch Mountain winds, occur during cold fronts, when cold air masses funnel down through canyons.

Severe thunderstorms also produce wind downbursts and microbursts, as well as tornados. Severe windstorms result in as many as 1,000 tornados annually (Golden and Snow, 1991). NWS uses the NEXRAD Severe Weather Potential algorithm as an automated procedure to detect severe local storms and to forecast the potential for tornados, hail, and heavy rainfall (Kitzmiller, McGovern, and Saffle, 1992).

It is difficult to separate the various wind components that cause damage during a windstorm. For example, hurricanes have high winds rotating around the eye of the storm, spawn numerous tornados, and generate severe thunderstorms producing strong, localized downdrafts (downbursts and microbursts) (Golden and Snow, 1991).

RISK ASSESSMENT

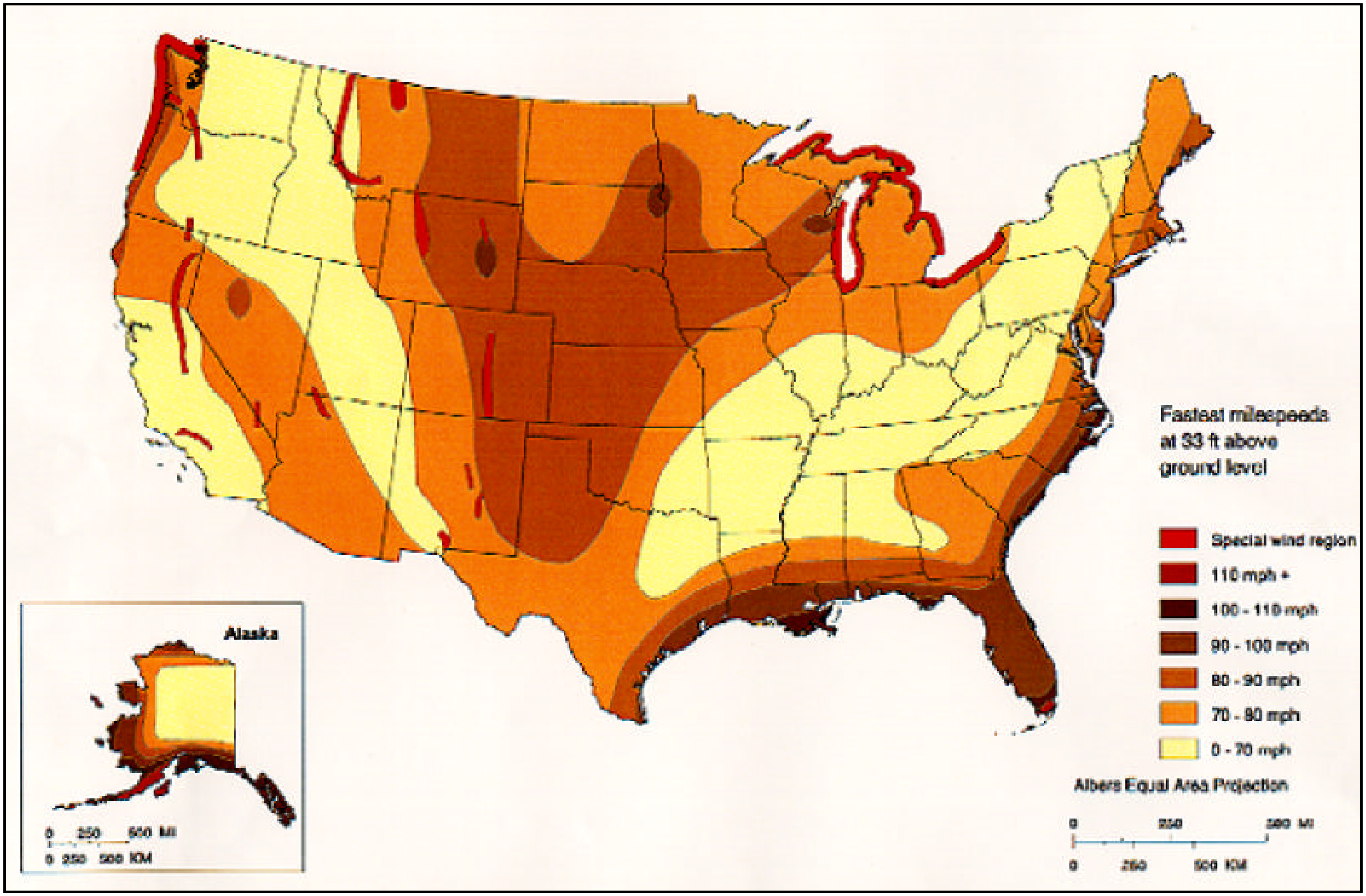
Probability and Frequency

Wind climatology and geographic distribution of windspeed variations are commonly associated with unique regional climatic and meteorological characteristics and seasonal patterns (Map 4-1). Coastal regions from Texas to North Carolina may experience intense winds from hurricanes and tropical storms. Most of Florida is susceptible to winds in excess of 100 mph (45 m/s) on a regular basis.

Wind climatology depicted on Map 4-1 shows the fastest mile wind speeds expected to be encountered with a return period interval of 50 years, an annual probability of 0.002. Certain regions of the United States have been identified and specially designated because wind speeds faster than 70 mph (31 m/s) occur more frequently than the 50-year return period, or there are special high wind features such as downslope winds (western United States) or lake-effect winds (Great Lakes region).

Exposure

Areas experiencing the highest wind speeds are coastal regions from Texas to Maine, under the influence of North Atlantic Ocean and Gulf of Mexico windstorms associated with tropical cyclones, and the Alaskan



Map 4-1. Wind climatology for the United States for special high wind regions and 50-year return period fastest mile speeds. Data not available for Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from American National Standards Institute, 1982.*

coast, under the influence of winter low-pressure-system windstorms in the Gulf of Alaska and North Pacific Ocean.

Property damage and loss of life from windstorms are increasing due to a variety of factors. Use of manufactured housing is on an upward trend, and this type of structure provides less resistance to wind than conventional construction. Uniform building codes for wind-resistant construction are not adopted by all States, and population trends show rapid growth in the highly exposed areas of the coastal zone from Texas to Maine.

Because of continued growth of the population in the coastal States susceptible to high winds from tropical cyclones, the deteriorating condition of older homes, and the increased use of aluminum-clad mobile homes, the impacts of wind hazards will likely continue to increase. The general design and construction of buildings in many high wind zones do not fully consider wind resistance and its importance to survival.

Consequences

Near-surface winds and associated pressure effects, positive, negative, and internal, exert pressure on structure walls, doors, windows, and roofs, causing the structural components to fail. Positive wind pressure is a direct and frontal assault on a structure, pushing walls, doors, and windows inward. Negative pressure affects the sides and roof where passing currents create lift and suction forces that act to pull building components and surfaces outward. The effects of winds are magnified in the upper levels of multi-storey structures.

Just as positive and negative forces impact and remove a windward protective building envelope (i.e., doors, windows, walls), internal pressures rise and result in roof or leeward building component failures and considerable structural damage or collapse. Debris carried along by extreme winds can directly contribute to loss of life and indirectly to the failure of protective building envelope components. Upon impact, wind-driven debris can rupture a building, allowing more significant positive and internal pressures.

The insurance industry spent nearly $23 billion on wind-related catastrophic events from 1981 to 1990 (NRC, 1993). Of the three primary sources, hurricanes and tropical storms, severe thunderstorms, and winterstorms, severe local windstorms accounted for 51.3 percent of the expenditures. Windstorms in 1993 resulted in 40 fatalities, 129 injuries, and $231 million in damage, while thunderstorm/wind events resulted in 23 fatalities, 458 injuries, and $349 million in damage (NOAA, 1994).

The NWS reported a significant increase in wind-related fatalities between 1992 and 1993, from 28 to 63. Of the deaths, 74 percent occurred in open areas and in vehicles.

From June 1975 to May 1995, 193 Federal disaster declarations involved wind-induced natural hazards: 106 for s, 40 for hurricanes and tropical storms, 25 for typhoons, and 22 for high winds.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Key research on wind has been conducted by NWS branches and the Wind Engineering Research Center (WERC) at Texas Tech University, in conjunction with the Wind Damage Mitigation Committee of the Insurance Institute for Property Loss Reduction (IIPLR) and Dr. Theodore Fujita of the University of Chicago. Dr. Fujita's significant contributions to wind research include the development of the Fujita Scale to classify tornados, and the recent evaluation and assessment of downburst wind damages occurring with extreme thunderstorm and windstorm events, such as experienced in Kauai, HI during Hurricane Iniki in 1992.

The NWS modernization program and the deployment and implementation of the wind-measuring system NEXRAD has improved the operational observation program and the climatology database. NEXRAD enhances the ability to predict downbursts and wind shears near airports. The data prompt development of frequency-of-occurrence data for mesocyclones, the typical wind circulation environment exhibited prior to the development of a tornado or severe thunderstorm/wind event (NRC, 1993).

A WERC/IIPLR project developed an alternative to the wind-resistance classification system used by the Insurance Services Offices which correlates a building's wind resistance with fire resistance. The WERC/IIPLR classification system identifies the wind resistance capabilities of a building based on building type (material used and system employed during construction) and other related factors pertaining to environment, frame, roof envelope, wall envelope, and other considerations (IIPLR, 1994). The system allows for evaluation of the weak points of existing buildings, enabling owners to take appropriate corrective actions to make buildings safer. The system can be used to identify individual buildings for evacuation because of poor resistivity.

Published reports on U.S. windstorm hazards discuss damages and include maps of the severity and extent of various types of extreme events (Golden and Snow, 1991; NRC, 1993). Updated information on the number of occurrences of windstorms is acquired continually by the NWS on a national and State-by-State basis.

MITIGATION APPROACHES

Improved and consistent building codes have been recommended as a key measure to mitigate life and property losses associated with windstorms (NRC, 1993). Adoption, enforcement, and compliance with a unified code for all regions of the United States would help ensure construction standards needed to build structures resistant to the lateral loads and uplift forces of severe winds. Improvements could be made to structural cladding, shuttering systems, and materials that are resistant to the penetration of wind-blown debris and projectiles.

In addition to improved construction standards, land-use regulations in the regions susceptible to windstorm hazards could limit exposure. Zoning as a form of land-use management and control can regulate populations and residential, commercial, and industrial developments in locations of known high risk exposure. It also can be used to reduce building density, adjust timing of regional development plans, and define the type of developments allowable in these hazard areas (NRC, 1993).

RECOMMENDATIONS

The National Research Council's publication on windstorm hazards, *Wind and the Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation* (1993), presents several categories of recommendations: wind hazards and related issues; nature of wind; wind engineering; mitigation, preparedness, response and recovery; education and technology transfer; and cooperative efforts. The report identifies the establishment of a National Wind Science and Engineering Program as a critical element necessary to "revitalize wind-hazard research."

BIBLIOGRAPHY AND REFERENCES

American National Standards Institute. 1982. ***Building Code Requirements for Minimum Design Loads on Buildings and Other Structures.*** ANSI A58.1. New York, NY: American Society of Civil Engineers.

American Society of Civil Engineers. 1993. ***Minimum Design Loads for Building Other Structures.*** ASCE, July, 1993. New York, NY.

Brinkmann, Waltraud A.R. 1975. ***Local Windstorm in the United States: A Research Assessment.*** Institute of Behavioral Science, The University of Colorado, Boulder, CO.

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Chagnon, S.A., and J.M. Chagnon. 1992. "Storm Catastrophes in the United States." ***Natural Hazards***, Vol. 6, No. 2, pp. 93-107.

Finkl, C. W., Jr. (ed.). 1994. ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation***. The Coastal Education and Research Foundation, Inc.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." ***Reviews of Geophysics.*** American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Insurance Institute for Property Loss Reduction. 1994. ***Understanding the Wind Peril.***

Kitsmiller, D.H., W.E. McGovern, and R.E. Saffle. February 1992. ***The NEXRAD Severe Weather Potential Algorithm.*** NOAA Technical Memorandum, NWS TDL 81. Silver Spring, MD: Techniques Development Laboratory.

National Research Council. 1993. ***Wind and the Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation.***

National Weather Service. 1994. ***Thunderstorms and Lightning: The Underrated Killers.*** U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Ramsdell, J.V., D.L. Elliott, C.G. Holladay, and J.M. Hubbe. 1986. ***Methodology for Estimating Extreme Winds for Probabilistic Risk Assessments.*** Washington, DC: U.S. Nuclear Regulatory Commission.

Twisdale, L.A., and P.J. Vickery. 1993. "Analysis of Thunderstorm Occurrences and Windspeed Statistics." In: ***Proceedings of the 7th U.S. National Conference on Wind Engineering.*** Los Angeles, CA: University of California.

Twisdale, L.A. October 1988. "Probability of Facility Damage from Extreme Wind Effects." ***Journal of Structural Engineering.*** American Society of Civil Engineers. Vol. 114, No. 10, pp. 2190-2209.

CHAPTER

5

HAILSTORMS

Chapter Summary

Hailstorms develop from severe thunderstorms. Although they occur in every State on the mainland United States, hailstorms occur primarily in the Midwestern States. Only a localized area along the border of northern Colorado and southern Wyoming experiences hailstorms on 8 or more days each year. Most inland regions experience hailstorms at least 2 or more days each year.

Hailstorms cause nearly $1 billion in property and crop damage annually, as peak activity coincides with the Midwest's peak agricultural seasons. Long-stemmed vegetation is particularly vulnerable to damage by hail impact and accompanying winds. Severe hailstorms also cause considerable damage to buildings and automobiles, but rarely result in loss of life.

Efforts to reduce hailstorm damage generally are associated with mitigation activities for thunderstorms and windstorms, including building code improvement and enforcement and public awareness and education campaigns. Improvements in weather warning systems will enhance the ability to predict severe thunder and hailstorms.

Photo: Red Cross

HAZARD IDENTIFICATION

A hailstorm is an outgrowth of a severe thunderstorm in which balls or irregularly shaped lumps of ice greater than 0.75 in (1.91 cm) in diameter fall with rain (Gokhale, 1975). Early in the developmental stages of a hailstorm, ice crystals form within a low-pressure front due to warm air rising rapidly into the upper atmosphere and the subsequent cooling of the air mass. Frozen droplets gradually accumulate on the ice crystals until, having developed sufficient weight, they fall as precipitation.

The size of hailstones is a direct function of the severity and size of the storm. High velocity updraft winds are required to keep hail in suspension in thunderclouds. The strength of the updraft is a function of the intensity of heating at the Earth's surface. Higher temperature gradients relative to elevation above the surface result in increased suspension time and hailstone size (Bryant, 1991).

RISK ASSESSMENT

The areal extent and severity of hailstorm hazards are different from thunderstorms or tornados. Hailstorms occur more frequently during the late spring and early summer, when the jet stream migrates northward across the Great Plains. This period has extreme temperature changes from the ground surface upward into the jet stream, which produce the strong updraft winds needed for hail formation.

Probability and Frequency

Data on the probability and frequency of occurrence of hailstorms is limited, with little recent research. However, in *Natural Hazards* (1991), Byrant presented a map depicting the annual frequencies of hailstorm occurrences in the United States (from Eagleman, 1983). Recreated in Map 5-1, it shows that only a localized area along the border of northern Colorado and southern Wyoming experiences hailstorms 8 or more days each year. Outside of the coastal regions, most of the United States experiences hailstorms at least 2 or more days each year.

The areal extent and severity of the hailstorm hazard is not coincident with maximum thunderstorm or tornado activity. The middle areas of the Great Plains are most frequently affected by hailstorms. Multiple impacts of concurrent severe thunderstorm effects from extreme winds, tornados, and hail are very likely in this region, even though the Great Plains is not where each of these hazards, taken individually, occurs with the greatest frequency.

Exposure

Peak periods for hailstorms, late spring and early summer, coincide with the Midwest's peak agricultural seasons for crops such as wheat, corn, barley, oats, rye, tobacco, and fruit trees. Long-stemmed vegetation is particularly vulnerable to damage by hail impacts and winds. Severe hailstorms also cause considerable damage to buildings and automobiles, but rarely result in loss of life.

The land area affected by individual hail events is not much smaller than that of a parent thunderstorm, an average of 15 mi (24 km) in diameter around the center of a storm (Pearce and others, 1993).

Consequences

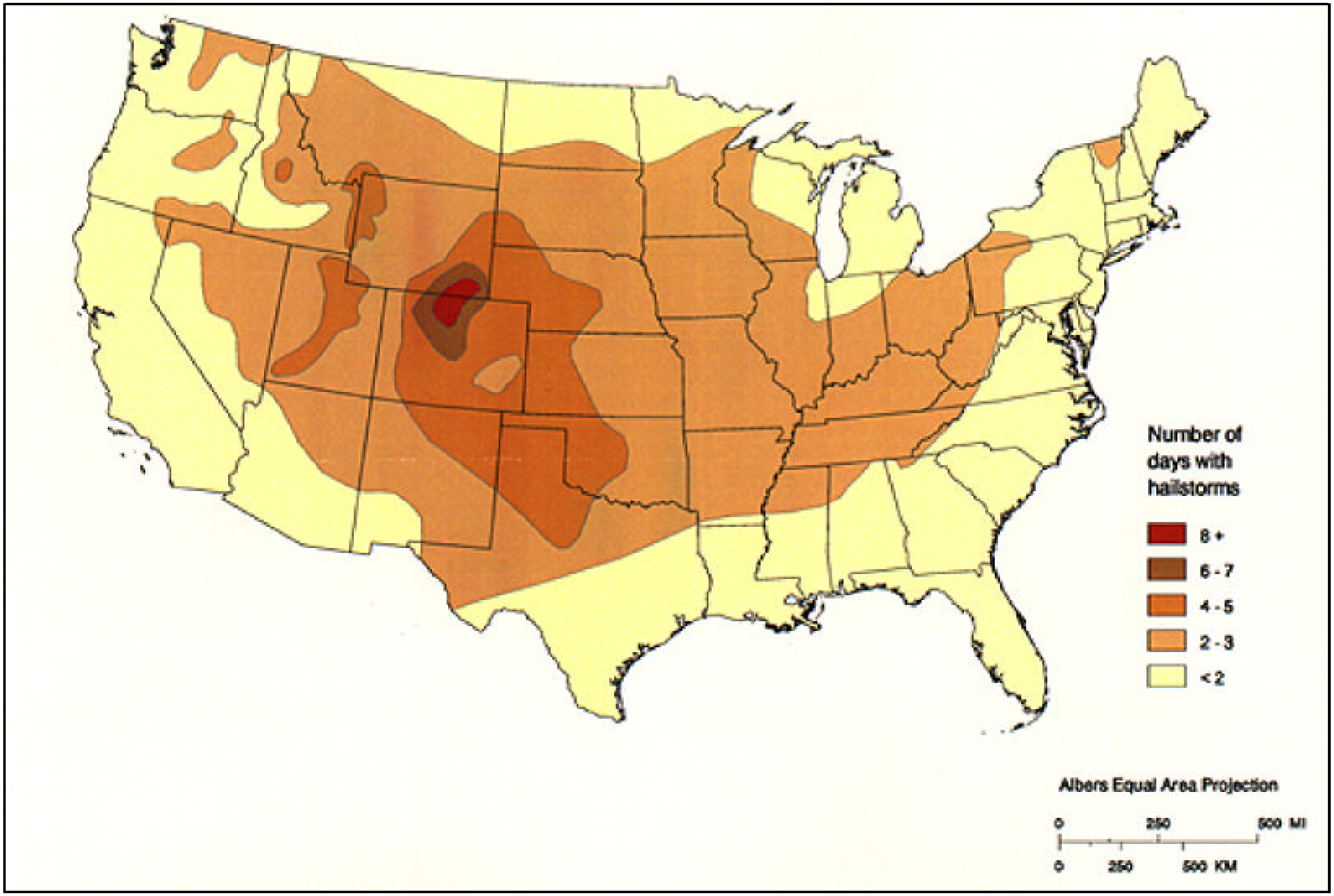
The development of hailstorms from thunderstorm events causes nearly $1 billion in property and crop damage each year (NWS, 1994). Recent significant hailstorms include events in Denver, CO (1994) and in the eastern Texas-Oklahoma region (1995).

The Property Loss Research Bureau indicates that the April-May 1995 hailstorm in the Texas-Oklahoma region may have been the worst on record in terms of non-agricultural property losses. However, more specific information is not readily available.

The Midwest hailstorm and tornado event in April 1994 lasted 4 days. According to Property Claims Services in Rahway, NJ, it produced 300,000 damage claims against insurers, more than Hurricane Andrew or the Northridge earthquake.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Recent unpublished private research has used the hail dataset available from the National Climatic Data Center (NCDC) in Asheville, NC, to model hailstorm frequency and hailstone size. The model is geocoded into 6-mi (10-km) grid cells across the lower 48 States. When it is available to others, the hail model data may be integrated into existing geographic information systems to help develop a hail risk index methodology for identification of high-risk zones.



Map 5-1. Annual frequency of hailstorms in the United States.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Bryant, 1993, citing Eagleman, 1983.*

MITIGATION APPROACHES

Mitigation efforts to reduce hailstorm damage generally are similar to those associated with thunderstorm and windstorm hazards: building codes and public awareness and education campaigns. Weather warning system improvements and the modernization and implementation of NWS monitoring systems such as NEXRAD will improve prediction of the severe weather potential associated with thunderstorms and hailstorm development.

Seeding clouds with supercooled water containing silver iodide nuclei has been a hail suppression technique used around the world. Although it has reduced crop damage, the technique was discontinued in the United States in the early 1970s due to political controversy (Bryant, 1991).

RECOMMENDATIONS

Recent research on hailstorm hazards in the United States has not been published. Information collected by NCDC documents the annual incidence rate and damage. Recommendations on research, hazard mitigation, or hailstorm control were not found in available published reports.

In a June 1995 magazine article in *Business Geographics*, G. Mertz of DataMap, Inc., recommended the integration of the NCDC hail dataset into a geographic information system. A hailstorm exposure map and a hail index system could identify high- and low-risk areas. The index was discussed as a useful tool for FEMA and the insurance industry to evaluate exposure and risk for residential, automobile, crop, and business insurance ratings.

BIBLIOGRAPHY AND REFERENCES

Byrant, E. 1991. ***Natural Hazards.*** New York, NY: Cambridge University Press.

Eagleman, J.R. 1983. ***Severe and Unusual Weather.*** New York, NY: Van Nostran Reinhold.

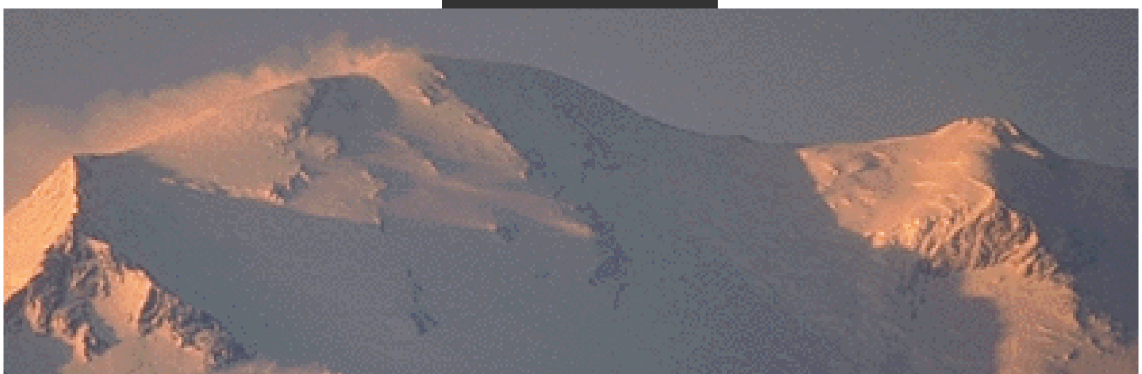
Gokhale, N.R. 1975. ***Hailstorms and Hailstone Growth.*** Albany, NY: State University of New York Press.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." ***Reviews of Geophysics.*** American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Pearce, L., H. Hightower, B. Konkin, S. Megalos, and J. Pernu. 1993. ***British Columbia: Hazard, Risk and Vulnerability Analysis***, Vol. 1. The Disaster Preparedness Resources Center, The University of British Columbia.

CHAPTER

6



SNOW AVALANCHES

Chapter Summary

Snow avalanches are not considered a major natural hazard because they impact relatively small areas of the United States. Compared with other hazards, snow avalanches have localized impacts and individually do not affect large numbers of people. However, the total number of deaths attributable to snow avalanches each year is exceeded only by those associated with floods, lightning, and tornadoes, and extreme heat.

Most of the 10,000 reported avalanches that occur each year are in remote, unpopulated mountainous areas, along recognized avalanche paths in previously identified hazard zones. The threat is most severe in the mountainous Western United States, including Alaska.

The sliding snow or ice mass in an avalanche moves at high velocities. It can shear trees, completely cover entire communities and highway routes, and level buildings. The primary threat is loss of life of back country skiers, climbers, and snowmobilers.

Since 1970, an average of 144 persons have been trapped in avalanches annually: on average 14 were injured and 14 died. The estimated annual average damage to structures is $500,000.

Recent avalanche mitigation approaches have included avalanche hazard zoning, evacuation, artificial release, and avalanche-control structures. Artificial release is the most common measure used in the United States. Where other methods are ineffective or cannot be used, control structures may be installed.

HAZARD IDENTIFICATION

A snow avalanche is a slope failure composed of a mass of rapidly moving, fluidized snow that slides down a mountainside. The flow can be composed of ice, water, soil, rock, and trees (Armstrong and Williams, 1992; NRC, 1990; Coch, 1995). The amount of damage depends on the type of avalanche, the composition and consistency of the material contained in the avalanche, the velocity and force of the flow, and the avalanche path.

The slope failure associated with an avalanche is caused by several factors, but is primarily due to large accumulations of snow on steep slopes. Avalanches occur on slopes averaging 25 to 50 degrees, and the majority start on slopes between 30 and 40 degrees. They are triggered by natural seismic or climatic factors such as earthquakes, thermal changes, and blizzards. Human factors, including snowmobiles, skiers, hikers, vehicle traffic, and elastic sound waves created by explosions can trigger events, as can direct dynamic loading from ice slabs falling off cornices (NRC, 1990).

Natural and human-induced snow avalanches most often result from structural weaknesses within the snowpack. They are caused by changes in the type and thickness of the snowcover layer resulting from thermal fluctuations or multiple snowfall events. The potential for a snow avalanche increases with significant temperature influences, which cause metamorphic crystal change in the snow layer, and with accumulations of dry and wet snow over time.

At the point where the shear forces of the overburdened upper layer overcome the resistant forces of the underlayer, the mass slips and begins sliding downslope. The intensity and impact of the resulting avalanche depend on the volume of snow accumulated in the upper layer, the density of the material, the slope of the starting area, the avalanche path, and the runout zone at the bottom of the slope.

Dry, low density avalanche releases can reach maximum velocities of 45 mph (20 m/s) to 157 mph (70 m/s), depending on the vertical fall distance (Mears, 1992). Slower estimated maximum velocities of 22 mph (10 m/s) to 78 mph (35 m/s) for similar vertical fall distances are reached by wet, high density avalanches which can be more destructive and exert greater impact forces on structures. The weight of moving, water-saturated snow can be 25 to 31 lb/ft^3 (400 to 500 kg/m^3) throughout the entire depth of an avalanche flow (Mears, 1992). The moving mass entrains rock, soil, and other solid debris.

The most common types of snow avalanches are loose-snow and slab avalanches. A loose-snow avalanche is composed of dry, fresh snow deposits that accumulate as a cohesionless and unstable mass atop a stable and cohesive snow or slick ice sublayer. A loose-snow avalanche releases when the shear force of its mass overcomes the underlying resistant forces of the cohesive layer.

A slab avalanche generally is composed of a thick, cohesive snowpack deposited or accumulated on top of a light, cohesionless snow layer or slick ice sublayer. At the starting surface or top of the slab, a deep fracture develops in the slope of well-bonded, cohesive snow. Fractures of more than 2 mi (3 km) in length have been observed, and they can reach across several starting zones. A slab avalanche release is usually triggered by turbulence or impulse waves. Release also occurs when the internal cohesive strength of the slab layer is greater than the bonding at the basal and lateral slab boundaries. As a release occurs, the slab accelerates, gaining mass and speed as it travels down the avalanche path.

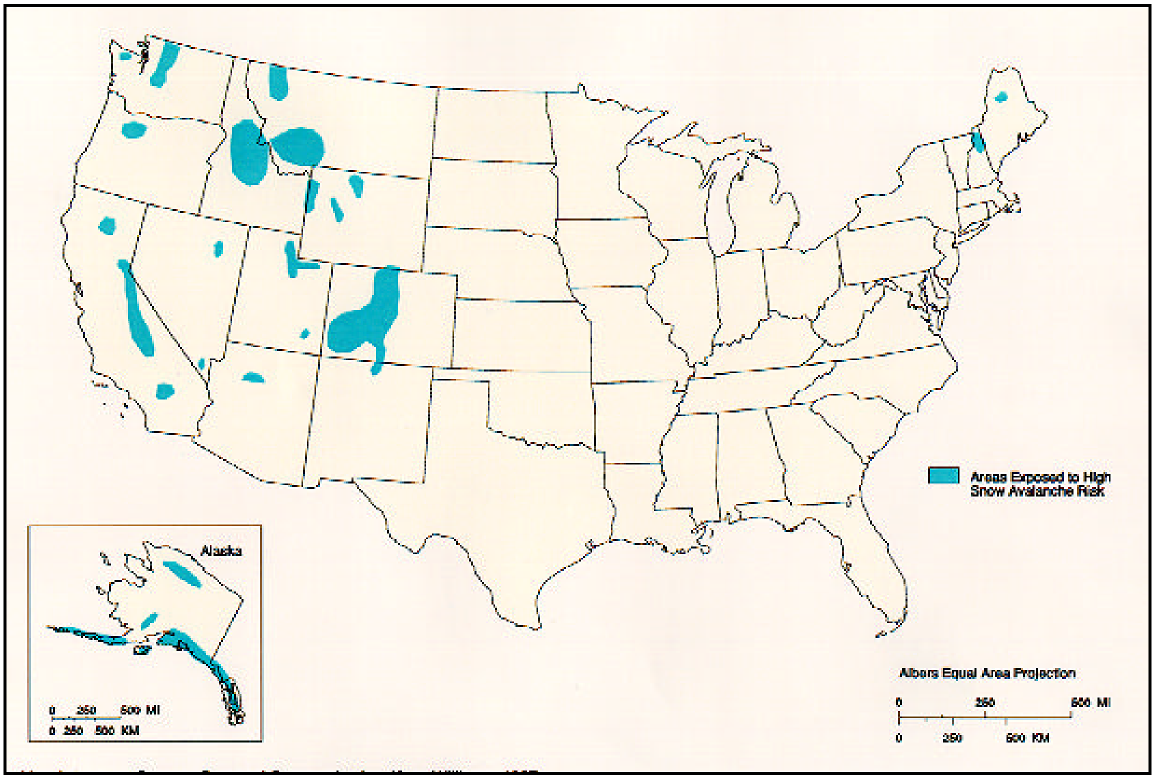
An avalanche path is determined by the physical limitations of the boundaries of the local terrain and manmade features. An avalanche may follow a path along a channelized or confined terrain, similar to debris flows or streams, before spreading onto alluvial fans or gentle slopes. In other instances, avalanches follow unconfined or planar slopes of a mountain side down to the abrupt slope change of the valley bottom (Mears, 1992). The avalanche path itself varies in width as it transitions along the path, depending on the confinement of the terrain and the velocity of flow.

Mears (1992) describes the avalanche path as having three specific transition zones:

- The Starting Zone is typically located near the top of the ridge, bowl or canyon, with steep slopes of 25 to 50 degrees;

- The Track Zone is the reach with mild slopes of 15 to 30 degrees and the area where the avalanche will achieve maximum velocity and considerable mass; and

- The Runout Zone is the gentler slopes of 5 to 15 degrees located at the base of the path, where the avalanche decelerates and massive snow and debris deposition occurs.



Map 6-1. Qualitative indicator of the severity of snow avalanches in the United States. Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories. Source: *Personal Communications, Knox Williams, 1995.*

RISK ASSESSMENT

Snow avalanches in the United States have varying levels of severity, depending on slope steepness and snow accumulation. As shown on Map 6-1, the threat is most severe in the mountainous western States, including Alaska. New England mountains have a low level of avalanche risk, and the rest of the United States has no risk.

Snow avalanches occur throughout the winter and may flow down the same paths several times during a season. In avalanche-prone areas, most State and local officials maintain records of previous events and have documented repetitive paths. As a result, avalanche hazard zones can be identified in many areas.

Probability and Frequency

The geophysical processes that contribute to snow avalanches during a particular year are statistically independent of past events. However, like other similar natural processes, a return period and probability of occurrence can be developed from historical records.

Avalanche occurrence is not directly attributed to a specific major meteorological event, such as the 1-percent-annual-chance or 100-year snowfall. It is more commonly a result of a combination of weather and snowpack conditions (Mears, 1992). Unfortunately, the short period of recorded and observed avalanches and associated conditions that contribute to the risk make it difficult to develop return periods for each avalanche-prone area in the United States.

The classification and delineation of avalanche hazard zones for Vail, CO, Ketchum, ID, and Juneau, AK, are similar to the Red and Blue Zones developed and used in the Swiss Alps. The Swiss zones are based on quantitative techniques for determining avalanche impact pressures and return periods. The Red Zone identifies areas of highest risk (NRC, 1990). Avalanches in Red Zones are either powerful (impact pressures greater than 630 lb/ft² (30kPa)) with a return period of 300 years or less, or all avalanches irrespective of intensity with return pereiods of up to 30 years. The Blue Zone identifies areas subject to less frequent avalanches with 30- to 300-year return periods, and impact pressures less than 630 lb/ft² (30 kPa).

Although the same zone designation system is used in the United States, the definition of each zone requires modification due to the short period of historical record. This limitation makes it more difficult to determine return periods for avalanches in most locations (Mears, 1992).

In the Colorado Geological Survey report on avalanches, *Snow Avalanche Hazard Analysis for Land-Use Planning and Engineering*, Mears discusses the techniques available to determine a return period for avalanches based on historic records, recent observations, aerial photography analyses, and vegetation characteristics (Mears, 1992). A snow avalanche will inflict damage and changes to the forests and vegetation along its path, unless they are protected by deep snowpack. Thus vegetation is a valuable tool in determining when previous events occurred. Vegetation indicators for avalanche frequency are listed in Table 6-1.

Avalanche activity along a path may be continuous throughout the season, in which case the annual probability of occurrence is constant regardless of the estimated return period of individual incidents. An encounter probability based on the relationship of the return period and annual probability was developed by LaChapelle (1966) to calculate the risk of an avalanche with a given return period occurring within a certain period of years. Even though the intensity and severity of an avalanche cannot be directly associated with a given frequency, return period, and encounter probability, the concepts are useful in land-use planning and engineering design.

Exposure

Back country skiers, backpackers, and snowmobilers in rural areas are at greatest risk of loss of life due to suffocation when buried in an avalanche. Avalanches can damage or destroy vehicles, highways, utilities, and buildings.

Table 6-1.—*Vegetation as an avalanche-frequency indicator*

Return Period	Vegetation Indicators
1-10 years	Track supports grasses, shrubs, flexible trees up to 6.5 ft. (2m) high; broken timber on ground and at path boundaries
10-30 years	Predominantly pioneer species; young trees similar to adjacent forest; broken timber on ground at path boundaries
30-100 years	Old uniform-aged trees of pioneer species; young trees of local climax species; old and partially decomposed debris
100-300 years	Mature, uniform-aged trees of local climax species; debris completely decomposed; increment core data required.

Source: *Mears, 1992.*

Most avalanches that affect people occur in and around mountain resorts used by winter recreational enthusiasts, while others affect downslope transportation routes and communities. Although the damage from avalanches is not as widespread as other natural hazards, on an annual basis fatalities exceed the average number of deaths due to all other hazards, except floods, lightning, tornadoes, and extreme heat.

The risk of avalanche loss is greatest on the flatter slope of the runout zone which is more conducive to development, transportation routes, and infrastructure. Exposure to the hazard has risen due to growth in winter recreational activities and resort facilities, mountain residences, highways, telecommunication lines, utilities, and mines in avalanche hazard zones.

Consequences

During the past two decades, snow avalanches have not prompted any federally-declared disasters, primarily because they tend to occur in areas with little development. Other reasons are improved and modernized monitoring techniques, awareness of the hazard, and remedial measures implemented to mitigate disaster potential. However, avalanches are still considered a prevalent hazard throughout the Rocky Mountain, Pacific Northwest, and Alaskan regions, with numerous incidents of property damage, injury, and death each year. From 1990 to 1995, 640 avalanches in the United States impacted individuals and property.

Only approximately 10,000 of the estimated 100,000 snow avalanches that occur each year are reported. Since 1970, an average of 144 persons have been trapped in avalanches annually, causing an annual average of 14 injuries and 14 deaths. Skiers, snowmobilers, and climbers in wooded and sloped areas in avalanche zones are most vulnerable (Armstrong and Williams, 1992). For many avalanches in which people have suffered injuries or loss of life, the triggering mechanism for the avalanche has been the victims themselves.

In the winter of 1994–95, California had more snow avalanches than any other State, with 4,787 reported at seven locations. However, over the 10 years from the winter of 1985–86 through the winter of 1994–95, Colorado's 65 fatalities were the highest. The activity with the highest fatality rate for the same period was back-country skiing, with 45 fatalities, followed by climbing, with 28 (Colorado Avalanche Information Center, 1995, unpublished).

Possibly the worst U.S. avalanche disaster occurred on March 1, 1910, in Wellington, WA. The avalanche derailed two trains, killing 96 persons (Armstrong and Williams, 1992).

TABLE 6-2.—*Avalanche Impact pressures related to damage.*

Impact Pressure *kPa*	*lbs/ft²*	**Potential Damage**
2-4	40-80	Break windows
3-6	60-100	Push in doors, damage walls, roofs
10	200	Severely damage wood frame structures
20-30	400-600	Destroy wood-frame structures, break trees
50-100	1000-2000	Destroy mature forests
>300	>6000	Move large boulders

Source: *Mears, 1992.*

Property damage associated with avalanches is a function of several factors. Large external lateral loads can cause significant damage to structures and facilities. Table 6-2 indicates the estimated potential damage that can be expected for a given range of impact pressures.

A breakdown of costs associated with all types of property damage due to snow avalanches is not available. The estimated average annual damage to buildings alone is $500,000. However, a tally of the impact on public property, includes forests and parkland, transportation routes, and utilities, coupled with the cost of litigation following injuries or deaths, raises the estimated annual cost of avalanches to more than $5 million.

NRC (1990) offers examples of avalanche damage described below:

- Avalanches cost the Washington State Department of Transportation an estimated $330,000 each year for avalanche control, snow removal, and plowing, not including salaries and expenses of State employees.
- Between 1977 and 1986, avalanche damages in Alaska were estimated to be $11.4 million.
- On March 31, 1981, an avalanche at California's Alpine Meadows ski resort area resulted in seven deaths and caused approximately $1.5 million in property damage. Litigation and out-of-court settlements sent the cost spiraling to $14 million.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Snowstorms and ice storms are monitored daily by weather observation centers and a network of State and regional avalanche forecast centers for Colorado, Utah, Montana, Washington, Oregon, and Wyoming. Data collection methodologies on the number and location of snowfalls improve with each passing storm. Prevailing wind direction and temperature fluctuations are analyzed to assess the probability of avalanches in high-risk areas.

These methods are not completely effective in identifying potential avalanche hazard zones. In areas with known historical avalanche paths, the impact of the hazard may be mitigated by local experience and understanding of the hazard and triggering mechanisms. This knowledge makes the forecast and prediction process more reliable and enhances the effectiveness of warnings.

Forecasting avalanches can be accomplished by different methods with varying degrees of success. As warranted by climatic conditions, various methods are used. Weather forecasting of snowfall amounts, winds, and temperature are important tools to analyze snowpack conditions and avalanche potential for large geographic areas.

Local area avalanche forecasting involves snow pit analysis. This technique requires assessing sublayer conditions and the composition of each layer to detect the existence of unstable boundaries between cohesive and cohesionless snow and ice layers.

Large-scale computer-based forecasting methods require a historical and statistical database. Regional avalanche centers collect data on snow avalanches from a network of measuring sites. Nationwide programs for computer-based forecasting do not exist.

MITIGATION APPROACHES

Hazard mitigation efforts have been successful in reducing the exposure of people and property to snow avalanche hazards. Warnings are issued through radio and television, and posted, if possible, on bulletin boards in avalanche hazard areas.

The potential for property damage has prompted local avalanche zoning ordinances in California, Colorado, Idaho, Utah, and Washington. For example, hazard zones have been established in Vail, CO, and Ketchum, ID, based on avalanche studies and assessments (Armstrong and Williams, 1992; Mears, 1992). They are delineated and mapped based on historic evidence, recorded seasonal events, and terrain features that indicate the potential for event occurrence. In Vail, avalanche zones have been adopted in the City's comprehensive land-use plan and are used to evaluate proposed residential and commercial development.

To regulate land use effectively and to reduce the risk of damage from avalanches, hazard zones may be adopted in local ordinances. As a result of legislation passed in 1974, many avalanche-prone counties in Colorado have hazard plans or land-use rules that specifically address avalanche hazards. Even though Juneau, AK had determined its avalanche hazard zones based on studies and a geophysical investigation in the 1970s, and despite numerous avalanches, as of 1991 it had not adopted a zoning ordinance to regulate at-risk development (Armstrong and Williams, 1992).

The key mitigation recommendations in the Colorado Geological Survey's Bulletin 49 (1992) to either eliminate or reduce the hazard include avalanche hazard zoning, evacuation, artificial release, and avalanche-control structures. Artificial release is the most common measure used in the United States, but it is not 100-percent effective.

Control structures are used in areas where snow avalanches are unavoidable and other measures are ineffective or cannot be employed. Structures currently in use include supporting structures, snow-drift fences, deflecting berms, catching berms, catching structures, and direct-protection structures. Mechanical compaction and disruption of the cohesive slabs compresses or densifies the snow to strengthen the slope. It is commonly employed in ski resort areas to stabilize snow in starting zones (NRC, 1990).

RECOMMENDATIONS

The recommendations presented by NRC have addressed issues related to national leadership, hazard delineation and regulation, control measures, forecasting, research, and communications (NRC, 1990). NRC recognized snow avalanches as the "most frequent catastrophic mass movement in the Nation" and one of many components leading to extensive ground-failure hazards.

NRC concluded that, even though snow avalanches are the greatest natural hazard affecting winter activities in mountainous regions, the hazard receives little attention. Greater funding support is needed in order to better understand, predict, and mitigate snow avalanche hazards, and to educate local officials and emergency managers.

BIBLIOGRAPHY AND REFERENCES

Armstrong, B.R., and K. Williams. 1992. ***The Avalanche Book, Revised and Updated.*** Golden, CO: Fulcrum Publishing.

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Colorado Avalanche Information Center (unpublished report). 1995. Denver, CO: Colorado Department of Natural Resources.

La Chapelle, E.R. 1966. ***Encounter Probabilities for Avalanche Damage.*** U.S. Department of Agriculture, Forest Service, Alta Avalanche Study Center. Miscellaneous Report No. 10.

Mears, A.I. 1989. "Regional Comparisons of Avalanche-Profile and Runout Data." ***Arctic and Alpine Research.*** Vol. 21, No. 3, pp. 232-238.

Mears, A.I. 1992. "Snow Avalanche Hazard Analysis for Land-Use Planning and Engineering." ***Colorado Geological Survey Bulletin No 49.*** Denver, CO: Department of Natural Resources.

National Research Council. 1990. ***Snow Avalanche Hazards and Mitigation in the United States.*** Washington D.C.: National Academy Press.

Perla, R., T.T. Cheng, and D.M. McClung. 1980. "A Two-Parameter Model of Snow-Avalanche Motion." ***Journal of Glaciology.*** Vol. 26, No. 94, pp.197-208.

Perla, R., K. Lied, and K. Kristensen. 1984. "Particle Simulation of Snow Avalanche Motion." ***Cold Regions Science and Technology.*** Vol. 9, pp. 191-202.

Salm, B., A. Burkard, and H. Gubler. 1990. ***Berechnung von Fliesslawinen eine Anleitung fur Praktiker mit Beispeilen:*** Mitteilungen des Eidgenossischen Istituts fur Schnee-und Lawinenforschung. No. 47, pp. 37.

Williams, K. Personal Communication, 1995. Fort Collins, CO: Colorado Avalanche Information Center.

CHAPTER

7

SEVERE WINTERSTORMS

Chapter Summary

Winterstorms consisting of extreme cold and heavy concentrations of snowfall or ice affect every State in the continental United States and Alaska. Areas where such weather is rare, such as the extreme South, are disrupted more severely by winterstorms than are regions that experience severe weather more frequently.

Winterstorms are known to spawn other natural hazards, such as coastal flooding and erosion, severe thunderstorms and tornados, and extreme winds. These effects disrupt commerce and transportation and often result in loss of life due to accidents or hypothermia.

Between 1988 and 1991, a total of 372 deaths, an average of 93 each year, was attributed to severe winterstorms. The Superstorm of March 1993, considered among the worst non-tropical weather events in the United States, killed at least 79 people, injured more than 600, and caused $2 billion in property damage across portions of 20 States and the District of Columbia.

Experience has shown that no area can fully prepare for severe winterstorms. The March 1993 Superstorm was one of the most widely forecast severe winter events, yet it devastated many parts of the Eastern United States for more than a week.

Photo: Red Cross

Photo: Red Cross

HAZARD IDENTIFICATION

Winterstorms and blizzards originate as mid-latitude depressions or cyclonic weather systems, sometimes following the meandering path of the jet stream (Bryant, 1991). A blizzard combines heavy snowfall, high winds, extreme cold, and ice storms. The origins of the weather patterns that cause severe winterstorms, such as snowstorms, blizzards, and ice storms, are primarily from four sources in the continental United States.

In the Northwestern States, cyclonic weather systems from the North Pacific Ocean or the Aleutian Island region sweep in as massive low-pressure systems with heavy snow and blizzards. In the Midwestern and Upper Plains States, Canadian and Arctic cold fronts push ice and snow deep into the interior region and, in some instances, all the way down to Florida. In the Northeast, lake effect snowstorms develop from the passage of cold air over the relatively warm surfaces of the Great Lakes, causing heavy snowfall and blizzard conditions. The Eastern and Northeastern States are affected by extra-tropical cyclonic weather systems in the Atlantic Ocean and Gulf of Mexico that produce snow, ice storms, and occasional blizzards.

Many winter depressions give rise to exceptionally heavy rain and widespread flooding and conditions worsen if the precipitation falls in the form of snow. Snow volume exceeds that of rain by a factor of 7 to 10. Affected regions may be subjected to heavy snowfall. The winterstorm season varies widely, depending on latitude, altitude, and proximity to moderating influences.

Severe winterstorms have affected every State in the continental United States and Alaska. Hawaii, Puerto Rico, the U.S. Virgin Islands, and the Pacific territories are not affected by this hazard.

RISK ASSESSMENT

Probability and Frequency

Analysis of recorded snow level (depth) data can yield probability and frequency of occurrence associated with severe winterstorms. Snow level measurements are recorded each day at sites within the conterminous United States and Alaska. Snow level is an indicator of severity of winterstorms based on accumulation and associated snow loading. The weight of accumulated snow or ice results in snow load forces that can cause building collapse and damage to infrastructure.

Map 7-1 shows the probability of a snow of given depth (in centimeters) occurring within geographic areas of the conterminous United States with a 5-percent chance of being equaled or exceeded in a given year. The map is based on daily recorded data by the U.S. Department of Commerce's National Climatic Data Center in Asheville, NC and the U.S. Department of Energy's National Renewable Energy Laboratory in Golden, CO. The data are available in a 1993 CD-ROM entitled *Solar and Meteorological Surface Observation Network* 1961-1990 (NCDC, 1993).

Regional studies of the mean annual snowfall for the Northeastern United States and the Great Lakes States show that the mean distribution of seasonal snowfall depends on latitude. Seasonal mean snowfall amounts range from 5.85 in (15 cm) in Virginia to more than 98 in (250 cm) in the New England States, New York, and West Virginia (Kocin and Uccellini, 1990). To establish the relationship between probability and frequency of occurrence for snowfall, historical records are analyzed for snowfall totals, ice accumulation, and the number and location of severe winterstorms.

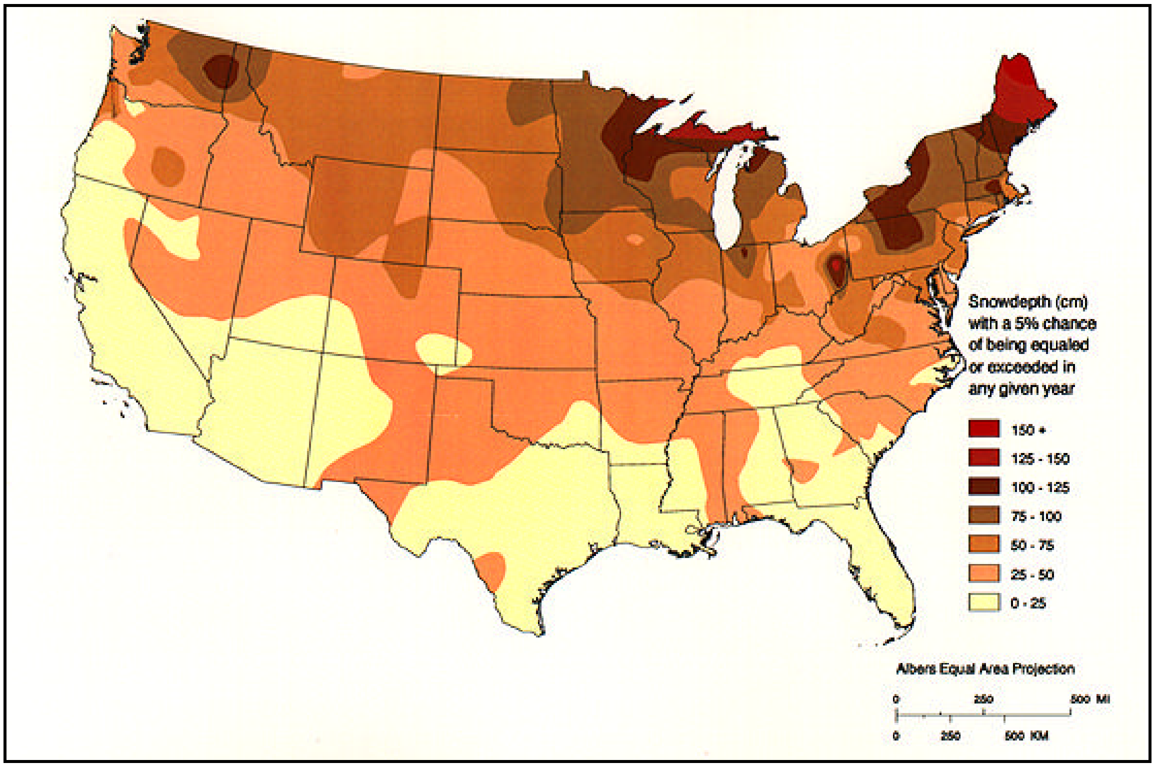
Exposure

Nearly the entire United States, except the extreme southern States, Hawaii, and the U.S. territories, are considered at risk for severe winterstorms. The degree of exposure depends on the normal severity of local winter weather.

All of Alaska and some areas of the continental United States tend to be more susceptible than others to severe winterstorms, including the Upper Midwestern and Northeastern States. Generally, these regions are more prepared for severe winter weather. Those areas where such weather is rare are more likely to experience damage and disruptions when winterstorms hit.

Heavily populated areas are particularly impacted when severe winterstorms disrupt communication and power due to downed distribution lines. Snow and ice removal from roads and highways is difficult when accumulations build faster than equipment can clear. Debris associated with heavy icing may impact utility systems and transportation routes.

Damage to buildings occurs especially in areas where normally anticipated snowfall depths do not warrant recognition in building codes. Roof collapse damages residential, commercial, and industrial structures.



Map 7-1. Snowdepth (in centimeters) with a 5% chance of being equaled or exceeded in any given year, from Solar and Meteorlogical Surface Observation Network 1961 - 1990
Data not shown for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories
(Source: Data from National Climatic Data Center, 1993)

The Superstorm of March 1993 illustrated that a severe winterstorm can be devastating. Table 7-1 presents the number of deaths and injuries and the estimated amount of damage resulting from the storm. In terms of reporting, NOAA found that problems arose in forecasting (before the event) and damage assessment (after the event). For example, NWS could have improved the coastal flood watches and warnings for the Florida Gulf Coast. An insufficient number of coastal observations and water-level measurements and a lack of storm-surge guidance products hampered effective forecasting.

Consequences

The occurrence of large snow storms, ice storms, and severe blizzards has a substantial impact on communities, utilities, and transportation systems, and often results in loss of life due to accidents or hypothermia. In addition to the impacts on transportation, power transmission, communications, agriculture, and people, severe winterstorms can cause extensive coastal flooding, erosion, and property loss.

Between 1988 and 1991, NWS recorded 372 deaths that could be attributed to snowfall, ice storms, or extreme cold weather, an average of 93 deaths per year. In 1991, winter snows and blizzards were responsible for the deaths of 37 people and injuries to 350 nationwide.

The Superstorm of March 1993 was among the worst non-tropical weather events in the United States, according to the Natural Disaster Survey Report published by NOAA (1994). The Superstorm caused more than $2 billion in property damage across portions of 20 States and the District of Columbia. It slowed commerce, snarled traffic, disrupted communications and power, and drove tens of millions of people indoors for extended periods of time during the worst of the storm.

The Superstorm is notable for its impact on a vast geographic area spanning virtually the entire eastern half of the United States. The NOAA report documents the impacts in six geographic regions, described below:

- The Florida Gulf Coast was struck by an unprecedented extra-tropical storm surge of 9 to 12 ft (3 to 4 m), damaging or destroying thousands of residences and businesses.

TABLE 7-1.—*Superstorm of March 1993: deaths, injuries, and damages by State*

State	Deaths Direct/ Indirect	Injuries	Estimated Damages *(in millions)*
Alabama	14/0	0	$100.0
Delaware	0/2	0	$0.5
District of Columbia	0/1	2	$0.5
Florida	28/22	150	$1,600.0
Georgia	15/0	420	$355.0
Maryland	1/0	0	$22.0
New York	8/0	4	$25.0
North Carolina	2/7	13	$13.5
Ohio	0/0	8	$5.0
Pennsylvania	4/48	0	$10.0
South Carolina	2/2	4	$22.2
Tennessee	2/13	0	$0.5
Virginia	0/11	0	$16.0
West Virginia	3/6	0	$0.5
Totals	**79/112**	**601**	**$2,170.7**

Information unavailable for Connecticut, New Jersey, Rhode Island, Massachusetts, Vermont, Maine, and New Hampshire

Source: *From NOAA, National Weather Service, 1994*

- Damage to the Southeastern States, particularly in southeastern Georgia and central eastern North Carolina, centered on beachfront property and marinas, although heavy inland agricultural damage caused by extremely high winds was reported. The storm caused considerable flooding along the Outer Banks of North Carolina.

- Areas of the southern Appalachians as far south as Alabama reported blizzard conditions, with heavy snow combining with rapidly falling temperatures and very high winds. Snow accumulation and frigid temperatures in northern Georgia collapsed roofs, downed power lines, and resulted in at least 27 fatalities, most of which were due to exposure.

- Blizzard conditions in the central Appalachians were less severe than those reported to the south, primarily due to reduced wind speeds. The worst snowfalls in five decades were reported in portions of eastern Kentucky and West Virginia. A state of emergency was declared in 25 counties in eastern Ohio due to snowfall and heavy winds.

- The Middle Atlantic and Northeastern States were hit hard by blizzard conditions. The greatest incidence of power outages was reported in the Washington, D.C., area. Outages resulted from the coupled effects of urban density and severe ice accumulation.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Snow, ice storm, and ice concentration data are collected at the Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, MI. Data are analyzed and stored at the Snow and Ice Data Center at the Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder.

Snow and ice research is conducted at the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, NH. Research addresses engineering and design for cold regions, cold weather hydrology, climatology of winterstorms, and studies on snow, ice, and permafrost.

The Snow Survey and Water Supply Forecasting Program operated by the Natural Resources Conservation Service in Portland, OR, determines the relationship of snowpack and potential runoff from mountain watersheds through field surveys. The network of data sites provides daily data on streamflow potential that are useful for predicting snowmelt runoff and preparing water supply forecasts.

MITIGATION APPROACHES

Experience has shown that no area can prepare fully for severe winterstorms. The Superstorm of March 1993 was among the most widely forecast winter events. Nonetheless, the unprecedented southward penetration of blizzard conditions paralyzed parts of the South for more than a week.

Specific snow and ice storm mitigation approaches and program information currently in use throughout the United States were not identified for review and incorporation into this report. However, measures may include enhanced building codes, planned deployment of resources, underground utility lines for critical facilities, and increased tree trimming along utilities.

RECOMMENDATIONS

Recommendations pertinent to severe winterstorm hazards are included in the 1993 *Natural Disaster Survey Report: Superstorm of March 1993* (NOAA, 1993).

BIBLIOGRAPHY AND REFERENCES

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Kocin, P.J., and L. W. Uccellini. 1990. ***Snowstorms Along the Northeastern Coast of the United States: 1955 to 1985.*** American Meteorological Society, Meteorological Monographs. Vol. 22, No. 44.

National Climatic Data Center. 1993. ***Solar and Meteorological Surface Observation Network 1961–1990, Version 1.0. (CD-ROM).*** U.S. Department of Commerce, National Climatic Data Center, and U.S. Department of Energy, National Renewable Energy Laboratory.

NOAA, National Weather Service. 1994. ***Natural Disaster Survey Report: Superstorm of March 1993, March 12-14, 1993.***

CHAPTER

8

EXTREME SUMMER WEATHER

Chapter Summary

Extreme summer weather is characterized by a combination of very high temperatures and exceptionally humid conditions. When persisting over a period of time, it is called a heat wave. Many areas of the United States are susceptible to heat waves.

The major threat of extreme summer weather is heatstroke, a medical emergency that can be fatal. Most at risk are outdoor laborers, the elderly, children, and people in poor physical health. The combined effects of high temperatures and high humidity are more intense in urban centers than in rural areas. The States that have experienced a higher degree of exposure to this hazard are Louisiana, Arkansas, Illinois, South Dakota, Arizona, Florida, and Pennsylvania.

Approximately 200 deaths a year are attributable to extreme heat. In 1980, when summer temperatures reached all-time levels in most of the Central and Southern States, more than 1,700 deaths were diagnosed as heat-related. A July 1995 heat wave caused 670 deaths—375 in the Chicago area alone.

Extreme summer weather is also hazardous to livestock and agricultural crops. It can cause water shortages, exacerbate fire hazards, and typically prompts excessive demands for energy. Roads, bridges, and railroad tracks are susceptible to damage from extreme heat. In the summer of 1988, a drought/heat wave in the Central and Eastern States resulted in $40 billion in damage as well as many fatalities.

Air conditioning effectively mitigates the effects of excessive heat on humans. However, a study by Kilbourne (1989) found that, at temperatures above 99ºF, the increased air movement produced by fans may actually exacerbate heat stress.

HAZARD IDENTIFICATION

Generally, heat stress is divided into four categories (Table 8-1). Steadman (1979) developed a heat index that includes the combined effects of high temperature and humidity. The NWS gathers and compiles information used to estimate the index, and index values are distributed to the public and the weather broadcasting industry. The heat index is a measure of the severity of extreme summer weather.

An estimation of the heat index is a relationship between dry bulb temperatures (at different humidities) and the skin's resistance to heat and moisture transfer. Because skin resistance is directly related to skin temperature, a relation between ambient temperature and relative humidity versus skin (or apparent) temperature can be determined. If the relative humidity is higher (or lower) than the base value, then the apparent temperature is higher (or lower) than the ambient temperature.

Steadman (1979) presented data relating air temperature and relative humidity to the heat index or the apparent temperature using various factors. To indirectly arrive at a "heat index equation" using more conventional variables, a multiple regression analysis was performed on the data from Steadman's table.

The major human risks associated with extreme heat are described below.

- **Heatstroke.** Heatstroke, considered a medical emergency, is often fatal. It occurs when perspiration and the vasomotor, hemodynamic, and adaptive behavioral responses to heat stress are insufficient to prevent a substantial rise in core body temperature. Although standardized diagnostic criteria do not exist, a medical condition is usually designated as heatstroke when rectal temperature rises above 105ºF as a result of environmental temperatures (Kilbourne, 1989). Patients may be delirious, stuporous, or comatose. Rapid cooling is essential to prevent permanent neurological damage or death. The death-to-care ratio in reported cases varies from 0 to about 40 percent, and averages about 15 percent (Vicario and others, 1986).

- **Heat Exhaustion.** Much less severe than heatstroke, heat exhaustion victims may complain of dizziness, weakness, or fatigue. Body temperature may be normal or slightly to moderately elevated. The primary cause of heat exhaustion is fluid and electrolyte (salt) imbalance due to increased perspiration in response to intense heat. Therefore, treatment is directed to the normalization of fluid and electrolyte status, and the prognosis is generally good (Knochell, 1974).

- **Heat Syncope.** Usually associated with exercise by people who are not acclimatized, heat syncope refers to a sudden loss of consciousness. Consciousness returns promptly when the person lies down. The cause is thought to be circulatory instability in response to heat, and the condition causes little or no harm to the individual.

- **Heat Cramps.** Heat cramps occur when people unaccustomed to heat exercise outdoors. The cramps are thought to be due to mild fluid and electrolyte imbalances and generally cease to be a problem after acclimatization (Knochell, 1974).

TABLE 8-1.—*Heat index/heat disorders*

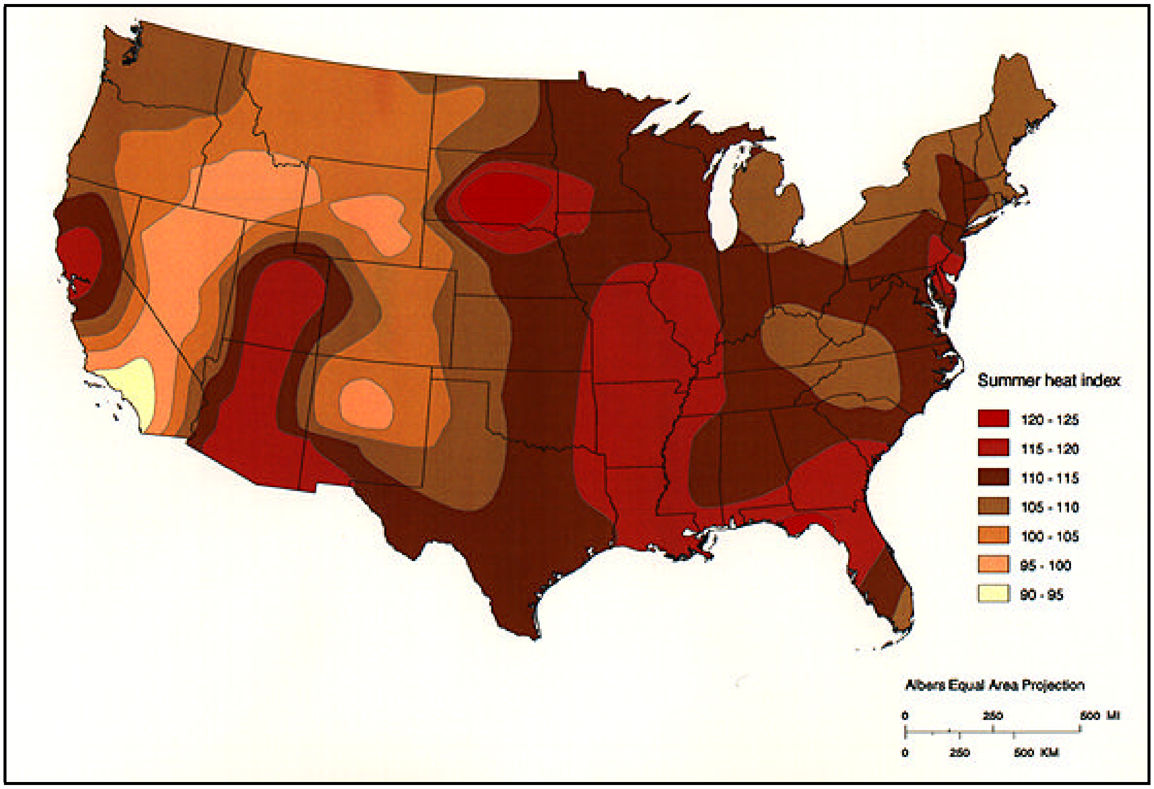
Danger Category	**Heat Disorders**	**Apparent Temperature** *(^0F)*
IV Extreme Danger	Heatstroke or sunstroke imminent.	>130
III Danger	Sunstroke, heat cramps, or heat exhaustion likely; heat stroke possible with prolonged exposure and physical activity.	105-130
II Extreme Caution	Sunstroke, heat cramps, and heat exhaustion possible with prolonged exposure and physical activity.	90-105
I Caution	Fatigue possible with prolonged exposure and physical activity.	80-90

Source: *From National Weather Service, 1997.*

RISK ASSESSMENT

Probability and Frequency

The apparent temperature or heat index is a quantitative measure of extreme summer weather that can be used to characterize the probability and frequency of heat hazards. Map 8-1 shows one approach to describe the geographic distribution and frequency of extreme summer weather. It was developed from 30 years (1961-90) of relative humidity and temperature data at 48 climatic stations in the conterminous United States (NOAA and DOE, 1993).



Map 8-1. Severity and areal extent of extreme summer heat in the United States, based on NWS heat index. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from U.S. Department of Commerce and Others, 1993.*

Because of the limited number of climatic stations, the map shows a broad generalization of trends in heat index, and may not show all areas that are subject to extreme summer weather.

Data used to compile Map 8-1 included hourly readings for between 2 p.m. and 5 p.m. for June, July, and August, assuming that the annual maximum temperature and relative humidity occurs during summer afternoons. The annual maximum values for the four time readings and the three months were used in a frequency analysis to determine the percent chance of a given heat index being exceeded in any year. The annual maximum values were ranked, and the annual percent chance of exceedance was computed by the Weibull plotting position formula to determine the heat index with a 5 percent chance of being exceeded in any given year. Minor adjustments to the data were required to address apparent measuring or recording errors, and temperatures below 70ºF were not used.

Exposure

Each year, many areas of the United States and its territories experience periods of prolonged high temperatures combined with high humidity. In susceptible areas, people usually are aware of the hazard, anticipate it, and are accustomed to avoiding its potentially dangerous effects. However, extreme summer heat does strike areas not accustomed to the phenomenon, where people tend to be less prepared.

The areas subject to heat index values in excess of 115ºF for the 5-percent-annual-chance event are the Southeastern, Southwestern, and Midwestern States (Map 8-1). Areas near the coast experience a combination of high temperatures and relative humidity that results in high apparent temperatures. Southwestern States experience low to moderate relative humidity, but extremely high temperatures.

Extreme summer weather poses the greatest danger to outdoor laborers, the elderly, children, people in poor physical health, and people residing in homes without air conditioning. During prolonged periods of extreme summer weather, local governments, voluntary organizations, and medical and health-care facilities may be burdened.

Previous research indicates that people over age 75 are most susceptible to extreme summer heat. The elderly are more likely to have chronic diseases or to be taking medications that can increase risks. Sweating is the body's natural mechanism for reducing high body temperature, and the body temperature at which sweating begins increases with age. People taking neuroleptic and anticholinergic drugs should be counseled regarding possible increased sensitivity to heat (Kilbourne, 1989).

More deaths from extreme summer weather occur in urban centers than in rural areas. One reason that the effects of hot weather may be more extensive in urban areas is that poor air quality may exacerbate severe conditions. The masses of stone, brick, concrete, and asphalt that are typical of urban architecture absorb radiant heat energy from the sun during the day and radiate that heat during nights that would otherwise be cooler. Tall city buildings may effectively decrease wind velocity, thereby decreasing the contribution of moving air to evaporative and convective cooling. The heat differential was documented during the 1980 heat wave in Kansas City, where there was a difference of 2.5ºC in the daily maximum temperature and 4.1ºC in the daily minimum temperature between downtown and the suburban airport.

Consequences

In years during which a major heat wave does not occur in the United States, an average of approximately 200 heat-related deaths are reported (Kilbourne, 1989). When prolonged periods of abnormally high temperature or heat waves affect large areas, the number of deaths attributed to heat rises greatly. In 1980, when summer temperatures reached all-time highs in much of the Central and Southern States, over 1,700 deaths were identified as heat-related.

The Central Plains and Corn Belt States experienced a heat wave during July 15-19, 1995 during which apparent temperatures climbed above 120ºF. A significant portion of the Eastern States was in the danger category during that same period, with apparent temperatures ranging from 105ºF to 120ºF.

The relative poverty of some urban areas may contribute to the severity of the extreme summer weather hazard. Low-income people are less able to afford cooling devices and the energy needed to operate them (Kilbourne, 1989).

The U.S. Department of Commerce reported that the 1995 heat wave caused 670 deaths—375 in the Chicago metropolitan area alone. Many deaths were among low-income elderly in residential units not equipped with air conditioning. Local utilities were forced to impose controlled power outages because of excessive energy demands, and water suppliers reported very low levels of water in storage. This intense heat also caused the loss of tens of millions of cattle and poultry throughout the Midwest.

When heat waves are accompanied by drought, agricultural losses can be high. A drought/heat wave during the summer of 1993 affected the Southeastern United States, causing approximately $1 billion in damage and an undetermined number of deaths. Another drought/heat wave during the summer of 1988 affected the Central and Eastern United States, causing approximately $40 billion in damage and many deaths. A drought/heat wave during the summer of 1980 caused an estimated $20 billion in damage and many deaths.

Extreme summer weather can cause damage to roads, bridges, and railroads. High temperatures can be partially responsible for deflection of rails and related railroad accidents.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Several scientists have attempted to develop mathematical models to quantify the increase in number of deaths expected for a given temperature increase. These models take into account such factors as the usual seasonal trends in mortality, acclimatization, the age of structures, and previous hot weather exposure of the at-risk population. However, they have not yet been useful in the prediction of adverse, heat-related health effects (Kilbourne, 1989).

MITIGATION APPROACHES

As with most natural hazards, public education about the effects of extreme heat and how to mitigate those effects is useful. NWS, through local television and radio announcements, alerts people about the onset of extreme summer weather and poor air quality. The alerts, advising high risk people to reduce physical activity and stay in air-conditioned buildings, have helped reduce fatalities and injuries.

BIBLIOGRAPHY AND REFERENCES

Kilbourne, E.D. 1989. "Heat Waves." In ***The Public Health Consequences of Disasters 1989.*** CDC Monograph. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, Atlanta, GA.

Knochel, J.P. 1974. "Environmental Heat Illness: An Eclectic Review." ***Archives of Internal Medicine.*** Vol. 133, pp. 841-864.

National Weather Serivice. 1997. Online. Accessible at http://www.nws.noaa.gov/sr/ohx/heat.htm.

Steadman, R.G. 1979. "The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science." ***Journal of Applied Meteorology.*** Vol. 18, pp. 861-873.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. July 1995. ***Weekly Climate Bulletin.***

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. July 1995-September 1996. ***Climate Outlook.***

National Oceanic and Atmospheric Administration, National Climatic Data Center, and U.S. Department of Energy, National Renewable Energy Laboratory. September 1993. ***Solar and Meteorologic Surface Observation Network, 1961-1990, Version 1 on 3 CD-ROMs.***

Vicario, S.J., R. Okabajue, and T. Haltom. 1986. "Rapid Cooling in Classic Heatstroke: Effect on Mortality Rates." ***American Journal of Emergency Medicine.*** Vol. 4, pp. 394-398.

Subpart B

GEOLOGIC

HAZARDS

Introduction

Non-seismic ground failures involving landslides, land subsidence, and expansive soils are significant hazards that affect life and property in the United States. These hazards receive limited public attention and funding for hazard assessment and research. However, the combined average annual damage may be comparable to that caused by floods, earthquakes, and volcanoes.

The occurrence of geologic hazards is often interrelated with other natural phenomena: heavy rainstorms prompted by atmospheric hazards can lead to flooding which can cause debris flows; land subsidence can exacerbate flooding; droughts can provoke shrinking of expansive soils; and ground failures often occur during earthquakes and volcanic activity.

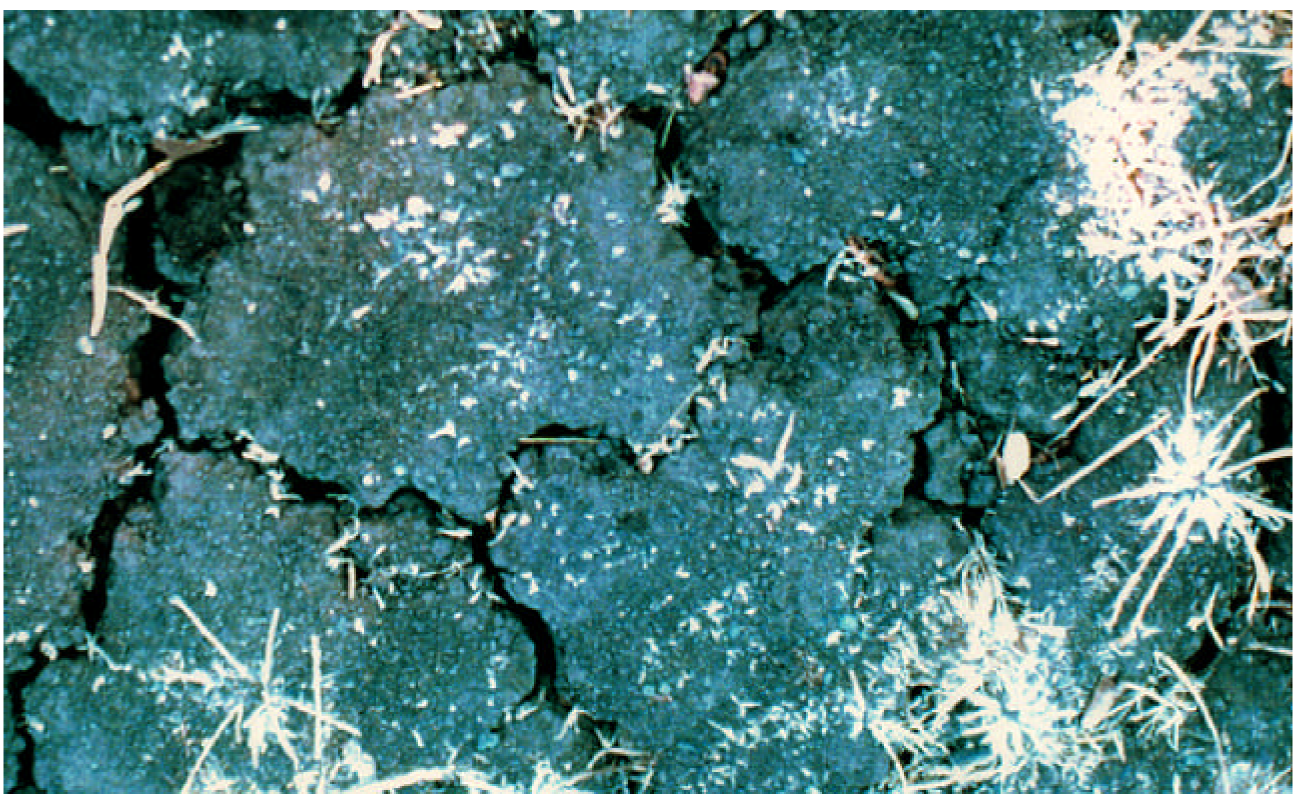
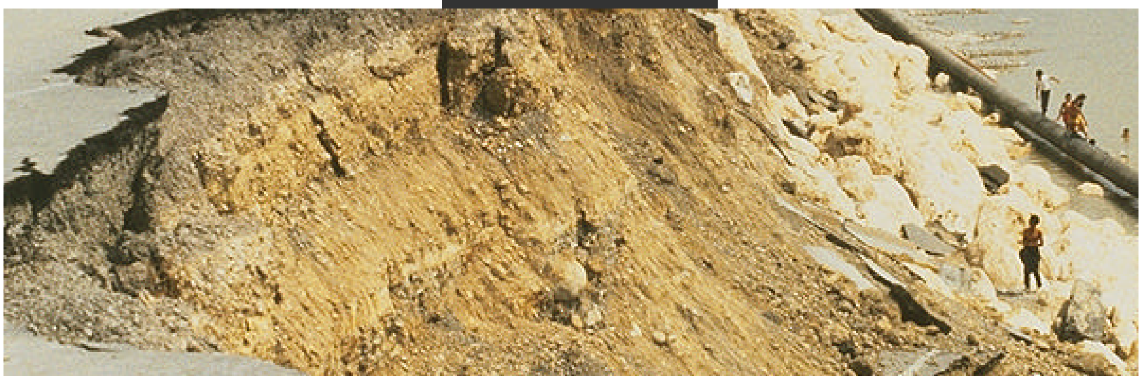


Photo: JCP Geologists, Inc.

CHAPTER

9



LANDSLIDES

Chapter Summary

Several human and natural factors may contribute to or influence landslides. Understanding how these factors interrelate is important in analyzing landslide hazards. The principal human factors are mining and construction of highways, buildings, and railroads. The principal natural factors are topography, geology, and precipitation.

Landslides occur in every State and in Guam, Puerto Rico, the U.S. Virgin Islands, and American Samoa. They are most common in the coastal ranges of California, the Colorado Plateau, the Rocky Mountains, and the Appalachian Mountains. During the past 20 years, landslides have resulted in 38 disaster declarations, 15 of them in California. According to a 1985 study, roughly 40 percent of the U.S. population is exposed to direct and indirect effects of landslides.

Landslides have damaged or destroyed roads, railroads, pipelines, electrical and telephone lines, mines, oil wells, buildings, canals, sewers, bridges, dams, seaports, airports, forests, parks, and farms. Landslides often are triggered by other natural events such as floods, earthquakes, and volcanic eruptions. The damage caused by landslides often is attributed to the triggering events. The best estimates of annual losses resulting from landslides in the United States are 25 to 50 lives and $1 to $2 billion in property damage.

Successful mitigation programs have been undertaken at the local level, but the Federal effort is relatively underfunded. Recent efforts involved identification of landslide-prone areas, anticipating landslide events, and implementation of warning systems. Hazard reduction efforts involve reducing the frequency of landslides, reducing the likelihood that they will cause damage, and minimizing damage.

Photo: Red Cross

Photo: Lynn Forman

HAZARD IDENTIFICATION

"Landslide" is used to describe the downward and outward movement of slope-forming materials reacting under the force of gravity. The term covers a broad category of events, including mudflows, mudslides, debris flows, rock falls, rock slides, debris avalanches, debris slides, and earth flows. Landslides may consist of natural rock, soil, artificial fill, or combinations of these materials. Earthquakes trigger many landslides, as does heavy and prolonged rains which lead to saturated conditions.

Landslides are classified by type of movement and type of material (Varnes, 1978). The types of movement are slides, flows, lateral spreads, and falls and topples (Varnes, 1978; Pearce and others, 1993; Fleming and Varnes, 1991). The types of material are bedrock and soils, where soils are described as predominately coarse or predominately fine. A combination of two or more of the principle types of flows is referred to as a "complex movement."

- **Slides.** Slides of soil or rock involve downward displacement along one or more failure surfaces. The material from the slide may be broken into a number of pieces or remain a single, intact mass. Sliding can be rotational, where movement involves turning about a specific point. Sliding can be translational, where movement is downslope on a path roughly parallel to the failure surface. The most common example of a rotational slide is a slump, which has a strong, backward rotational component and a curved, upwardly-concave failure surface.

- **Flows.** Flows are characterized by shear strains distributed throughout the mass of material. Flows are distinguished from slides by high water content and the distribution of velocities resembles that of viscous fluids. Debris flows are common occurrences in much of North America. These flows are a form of rapid mass movement in which loose soils, rocks, and organic matter, combined with air and water, form a slurry that flows downslope. The term "debris avalanche" describes a variety of very rapid to extremely rapid debris flows associated with volcanic hazards, and is discussed in Chapter 18. The term "avalanche," if unmodified, normally refers to slope movements of snow and ice, and is discussed in Chapter 6. Mudflows are flows of fine-grained materials, such as sand, silt, or clay, with a high water content. A subcategory of debris flows, mudflows contain less than 50 percent gravel.

- **Lateral Spreads.** Large elements of distributed, lateral displacement of materials characterize lateral spreads. They occur in rock, but the process is not well-documented and the movement rates apparently are very slow. Lateral spreads can occur in fine-grained, sensitive soils such as quick clays, particularly if remolded or disturbed by construction and grading. Loose, granular soils commonly produce lateral spreads through liquefaction. Liquefaction can occur spontaneously, presumably because of changes in pore-water pressures, or in response to vibrations such as those produced by strong earthquakes.

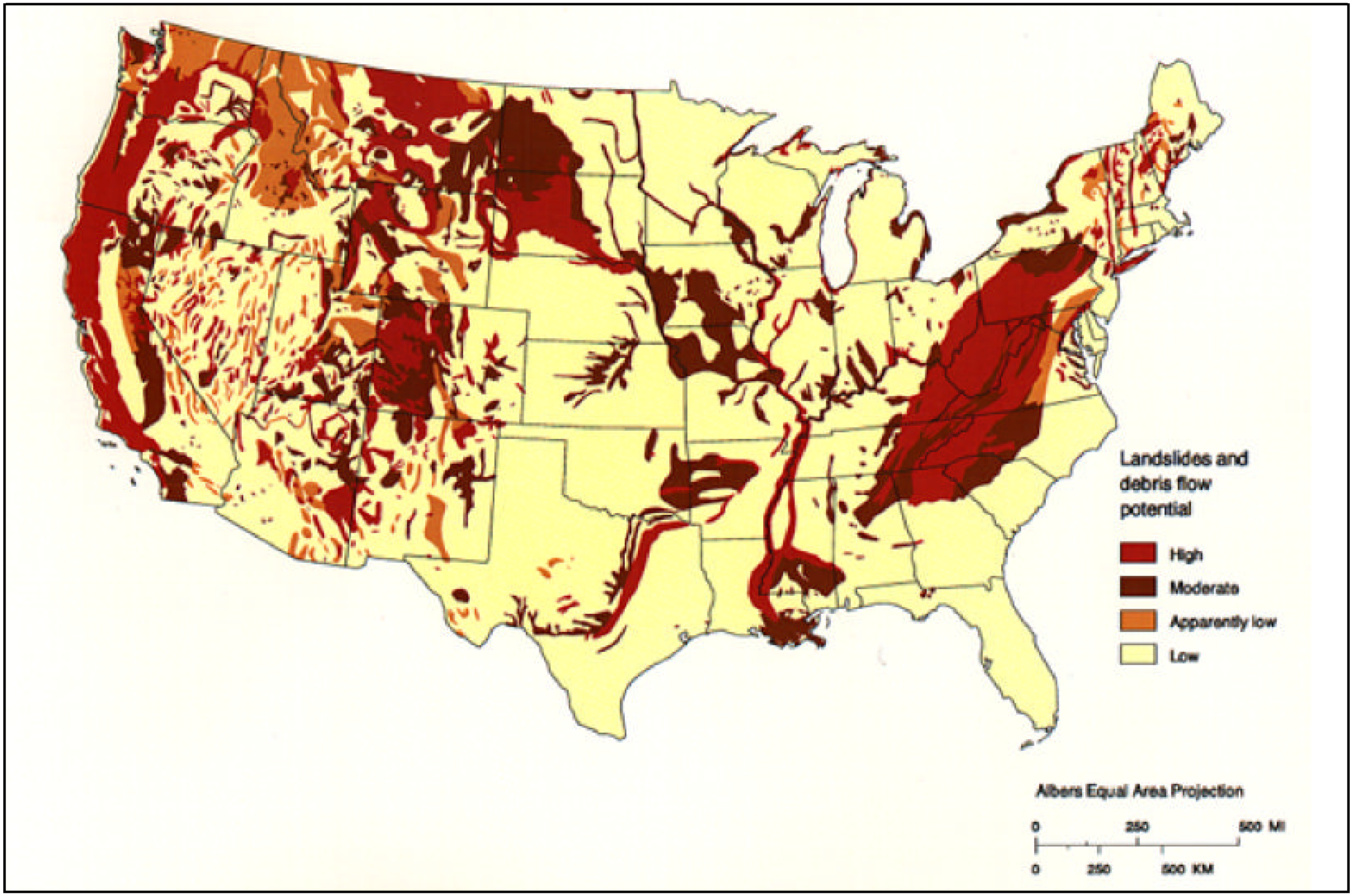
- **Falls and Topples.** Falls occur when masses of rock or other material detach from a steep slope or cliff and descend by free fall, rolling, or bouncing. Movements are rapid to extremely rapid. Rock falls commonly are triggered by earthquakes. Topples consist of the forward rotation of rocks or other materials about a pivot point on a hillslope. Toppling may culminate in abrupt falling, sliding, or bouncing, but the movement is tilting without collapse. Data on rates of movement and control measures for topples is sparse.

A few nationwide studies of landslides and debris flows have been conducted. The studies attempt to assess areas of the United States where landslides have occurred and areas that are susceptible to landslides.

Baker and Chiuruzzi (1958) performed the first regional evaluation of landslides in the United States. They based their evaluation on the results of questionnaires completed by State and Federal agencies, companies, and consultants, and a review of 267 landslide articles and texts published prior to 1950. A list was developed of the most destructive types of landslides, along with estimates of the sediment volume and a small-scale map showing the areas of major, medium, minor, and non-existent landslide intensity.

Radbruch-Hall and others (1976) conducted a survey of the distribution of landslide deposits and materials susceptible to landsliding in the United States. Krohn and Slosson (1976) independently prepared a map of landslide potential as part of a comprehensive survey of natural hazards.

Wiggins and others (1978) combined topographic, geologic and rainfall information from maps prepared by Baker and Chiuruzzi (1958) and Radbruch-Hall and others (1976). The combination map yielded landslide potential based on adverse formations associated with past landslide activity (Map 9-1).



Map 9-1. Landslide potential based on adverse formations associated with past landslide activity.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *J.H. Higgins, 1978, modifying USGS mapped information.*

Radbruch-Hall and others (1982) prepared Map 9-2 by evaluating formations and groups of formations shown on a geologic map of the United States (King and Beikman, 1974) and classifying them as having high, moderate, or low landslide incidence (number of landslides), and high, moderate, or low susceptibility to landsliding. Map units or parts of map units with more than 15 percent of their area involved in landsliding were classified as high incidence. Those with 1.5 to 15 percent of their area involved in landsliding were classified as moderate incidence. Those with less than 1.5 percent of their area involved were classified as low incidence. High, moderate, and low susceptibility were defined by the same percentages. Alluvial fans and earthquake influences were not evaluated.

Several natural and human factors may contribute to or influence landslides. How these factors interrelate is important in analyzing the hazard. The three principal natural factors are topography, geology, and precipitation. The principal human activities are cut-and-fill construction for highways, construction of buildings and railroads, and mining operations.

Topography and geology are related. Topography influences stream erosion and other energy sources that, in turn, influence slope angle and gradient. The steeper a slope, the more gravity plays a role in a landslide. The strength of rocks, measured in terms of their resistance to weathering, is a basic geologic factor in the landslide process. Certain bedrock formations or rock (soil) types appear to be more susceptible than others to landslide activity.

Precipitation has a pronounced effect on the morphology of the landscape. Slope development is influenced by precipitation that runs off the slope by way of established drainage courses and may have the capacity to erode and undermine slope surfaces. Precipitation that is absorbed increases pore water pressure and lubricates inherently weak zones of rock or soil.

RISK ASSESSMENT

Landslides often are involved in or triggered by other natural hazards. For example, the safety of a dam can be severely compromised by upstream landsliding or collapse of slopes bordering the reservoir or dam abutments. Landsliding and flooding are closely related because both involve precipitation, runoff, and ground saturation. Debris flows usually occur in small, steep stream channels and often are mistaken for floods. Landslides often result from seismic activity as experienced during the 1964 Alaska earthquake, and volcanic activity such as occurred after the 1980 eruption of Mount St. Helens. The simultaneous or sequential occurrence of interactive hazards may produce cumulative effects that differ significantly from those expected from any one of the components.

Alger and Brabb (1985) listed 6,500 references or sources that either incidentally mentioned or discussed in depth the subject of landslides. Brabb and Harrod's (1989) state-by-state analysis of landslides was the first of its kind, and included a 4-year reconnaissance of all States, the U.S. Virgin Islands, and Puerto Rico, as well as extensive conversations and cooperative programs with geologists and engineers in State geological surveys and State departments of transportation.

Probability and Frequency

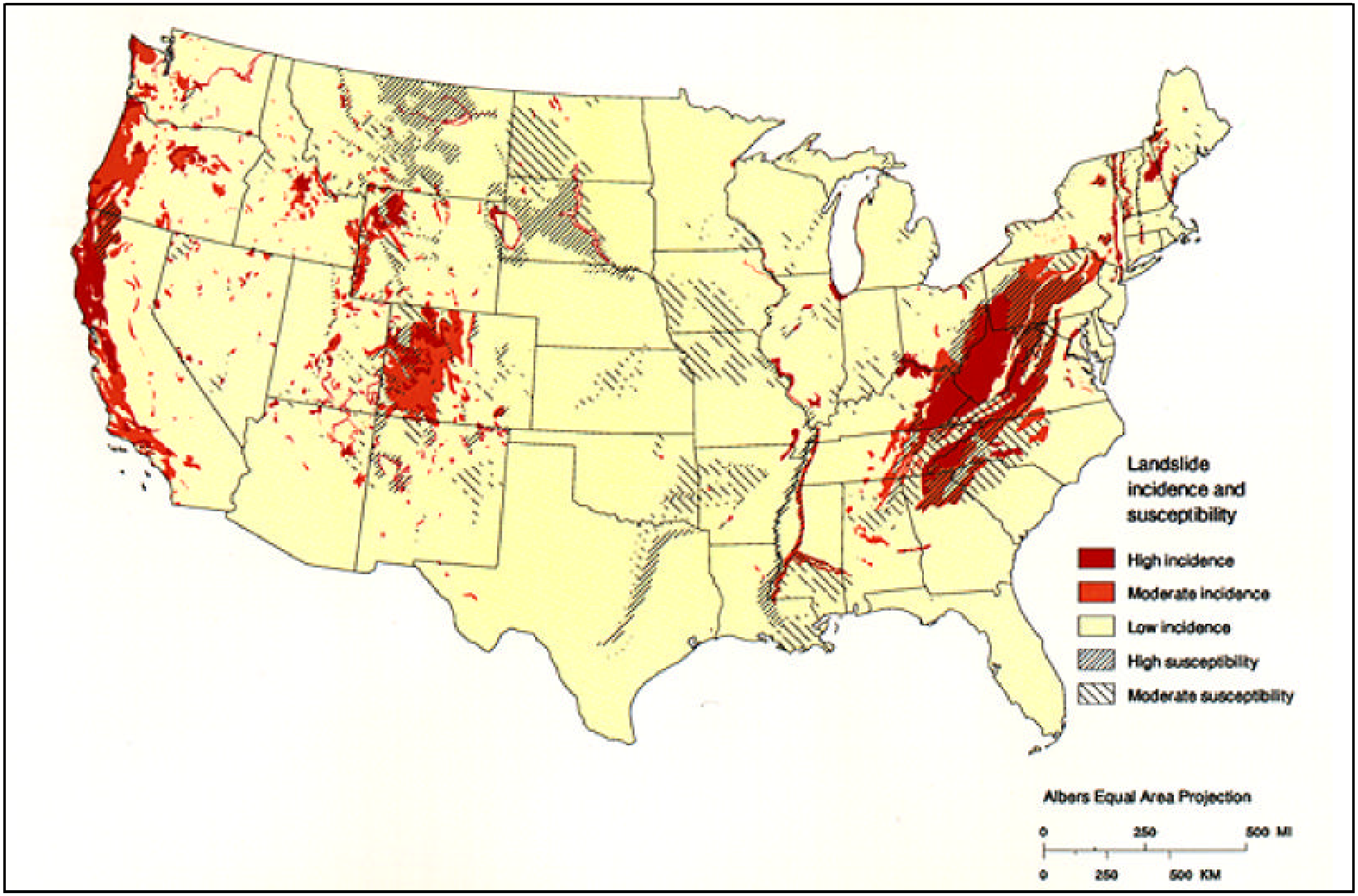
Maps 9-1 and 9-2 are combinations of inventory maps showing areas of known landslides, and susceptibility maps showing areas that are likely to experience slope failures. The incidence of, and susceptibility to, landsliding are rated qualitatively as high, moderate, or low. Ratings are assigned on the basis of the number of known landslides and the potential for future landslides. Frequency of occurrence or probability of exceedance are not associated with the information presented.

Jager and Wieczorek (1994) describe a methodology for estimating the spatial probability of a landslide in a given area. This regional model of landslide susceptibility (probability) was developed for the Finger Lakes Region in New York. The occurrence or non-occurrence of landslides based on inventory maps and field inspections in 270-ft (90-m) grid cells (GIS database) was identified throughout the study area. Logistic regression analysis was used to develop a model to predict the susceptibility (probability) of landslides in a given grid cell as a function of soil type, land slope, and historic lake levels. Three levels of susceptibility were defined: low (probability < 0.02); moderate ($0.02 \leq$ probability ≤ 0.05); and high (probability > 0.05).

The method developed by Jager and Wieczorek (1994) could be used in any area of the United States where adequate landslide inventory maps are available. Note, however, that the probability associated with the susceptibility map is simply the probability of a landslide occurring in a given grid cell and has no implication for repetitive occurrence over time.

Exposure

Landslides occur in every State and in Guam, Puerto Rico, the U.S. Virgin Islands, and American Samoa. They have damaged or destroyed roads, railroads, pipelines, electrical and telephone transmission lines, mining facilities, petroleum wells and production facil-



Map 9-2. Landslide incidence and susceptibility in the conterminous United States.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Radbruch-Hall and others, 1982.*

ities, residential and commercial buildings, canals, sewers, bridges, dams, reservoirs, port facilities, airports, forests, fisheries, parks, recreation areas, and farms.

Damage caused directly by landslides is largely undocumented or often is mis-reported. The devastating effects of landslides often are attributed to a triggering principal event, such as a flood, earthquake, volcanic eruption, hurricane, or coastal storm. The magnitude of landslide-related financial losses may exceed all other types of damage commonly attributed to the principal event (Brabb and Harrod, 1989). The best estimates of the direct and indirect costs of landslide damage in the United States is $1 to $2 billion annually. Deaths related to landslides are estimated to be 25 to 50 annually (Schuster and Fleming, 1986; Wold and Jochim, 1989).

Brabb and Harrod (1989) provided an estimate of the number of people per square kilometer who are exposed to the effects of landslides in each State. These estimates were developed by constructing a slope index map of the United States and determining the area of mountainous, hilly, and steep valley terrain, where landslides are likely to occur. The 1985 population by State was superimposed on the mountainous, hilly, and steep valley areas to determine the number of people per square kilometer. This analysis indicated approximately 108 million people, or more than 40 percent of the 1985 population, were exposed to direct and indirect effects of landslides in the United States and its territories.

Consequences

Public and private economic losses from landslides include not only the direct costs of replacing and repairing damaged facilities, but also the indirect costs associated with lost productivity, disruption of utility and transportation systems, and reduced property values. Some indirect costs of landslides are difficult to evaluate, thus estimates are conservative or ignored. If indirect costs were rigorously determined, they likely would exceed direct costs (Schuster and Fleming, 1986).

Much of the economic loss is borne by Federal, State, and local agencies responsible for disaster assistance, flood insurance, and highway maintenance and repair. Private costs involve mainly damage to land and structures. A severe landslide can result in financial ruin for affected property owners because landslide insurance (except for debris flow coverage) or other means of spreading the costs of damage are unavailable.

The most financially devastating slope failures in the United States were associated with the Alaska earthquake of 1964, the 1980 landslides in southern California, the eruption of Mount St. Helens in Washington, the 1982 landslides in the San Francisco Bay area, and the 1983-84 landslides in Utah. Combined, these events caused estimated damages in excess of $2 billion.

Ground failure caused approximately 60 percent of the $311 million total damage from the 1964 Alaska earthquake (Youd, 1978). About one-third of the cost of the $1.5 billion 1980 eruption of Mount St. Helens can be attributed to landslides (Schuster, 1983). That same year, total losses in six southern California counties resulting from landslides triggered by high-intensity rainfall approximated $500 million (Slosson and Krohn, 1982).

The intense storms of early January 1982 in the San Francisco Bay region triggered thousands of debris flows, resulting in 25 deaths and $66 million in property damage. Following the San Francisco catastrophe, 930 lawsuits and claims totaling nearly $300 million were filed against city and county agencies in the region, an amount several times greater than the total property losses (Smith, 1982).

Total direct costs of landslides in Utah in the spring of 1983 were estimated at $250 million (Anderson and others, 1984), while estimates of the 1984 events were as high as $50 million (Schuster and Fleming, 1986).

During the past 20 years, landslides have resulted in 38 disaster declarations—15 of them in California, and the rest scattered among 15 other States. While many States have adopted programs to investigate and resolve problems related to landslides, the total effort is relatively minor.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

The level of effort directed to landslide research and hazard assessment is small compared to some other hazards. At the Federal level, Brabb and Harrod (1989) concluded that the USGS devoted no more than 20 person-years each year to landslide research. According to Sangrey and others (1985), USGS spent the bulk (about one-fourth) of the $10 million allocated for landslide research by all Federal agencies.

Information about landslide work conducted by other Federal agencies is sparse. However, FEMA, the Federal Highway Administration, U.S. Bureau of Reclamation, U.S. Forest Service, and the National Science Foundation have all contributed.

In response to the severe rainstorm in January 1982 that triggered more than 18,000 debris flows and other landslides in the San Francisco Bay area, USGS and NWS developed and currently operate a system for warning the public when conditions reach levels sufficient to trigger debris flows. During the rainy season (October through April), USGS monitors more than 50 radio-telemetered rain gauges in the network coordinated by NWS.

The rainfall data and measurements of soil moisture at a study site in the hills south of San Francisco are used to estimate moisture level of soils throughout the Bay area. Once the soils have reached a sufficient moisture level, USGS monitors NWS forecasts and uses real-time rainfall data from the gauge network to determine the potential for imminent debris flows.

USGS developed thresholds that describe the minimum rainfall rates that may trigger abundant debris flows on natural slopes in the San Francisco Bay region. NWS broadcasts warnings over weather radio and as an emergency broadcast system announcement over many radio and television stations.

MITIGATION APPROACHES

Successful and cost-effective landslide mitigation programs can be implemented. Such programs exist in other countries, including Japan. Although there have been some impressive and successful local demonstrations of landslide control programs, information has not been widely disseminated. This is characteristic of the scattered and diffused state of landslide knowledge in the United States. As noted by NRC (1985), there is no recognized national leadership or systematic basis for communication.

Landslides stand out as a severe hazard, yet mitigation efforts are relatively underfunded. Practical application of land-use zoning measures, based on appropriate research and enforced by local regulations, can lead to dramatic loss reductions. This has been demonstrated in the Los Angeles area, where 92-97 percent reductions in losses were achieved for new construction (Slosson and Krohn, 1982).

There are two distinct components to reducing the cost associated with landsliding: emergency management and response, and long-term hazard reduction (NRC, 1985). Emergency management includes: anticipation, prediction, and issuance of warnings of the impending occurrence of life- and property-threatening landslides; response that is required when landslides occur; identification of landslide-prone areas; and planning, training, and other preparatory measures necessary to ensure effective warning and response.

Long-term hazard reduction focuses on reducing the frequency of landslides, reducing the likelihood that landslides will cause damage, and minimizing damage when landslides do occur. Landslide losses can be reduced in two ways: reduce the occurrence by requiring that excavation, grading, landscaping, and construction be carried out in ways that do not contribute to slope instability; and minimize the damage when landslides do occur by restricting development in landslide-prone terrain and by protecting buildings and other structures from landslide damage (NRC, 1985). Wold and Jochim (1989) provide additional details for reducing long-term losses.

Although NRC (1985) identifies insurance as a long-term hazard-reduction measure, Wold and Jochim (1989) note that insurance does not reduce losses, but provides financial protection to individual owners, Although insurance for landslides is not available, damage from debris flows (mudflows) is covered under the NFIP. Campbell and others (1985) describe flows and slides that are and are not covered under the NFIP.

Kockelman (1986) discusses additional techniques for reducing landslide losses:

- Through land-use planning, discourage new developments in identified hazard areas by informing and educating the public and posting warnings of potential hazards;
- Remove or convert existing development through acquiring, exchanging, or removing susceptible properties and discontinuing non-conforming uses; and
- Provide financial incentives or disincentives by adopting lending policies that reflect risk of loss or conditioning Federal and State financial assistance.

RECOMMENDATIONS

Several programs have been proposed to reduce the cost of landslide-related damage in the United States. The NRC Committee on Ground Failure Hazards (1985) recommended: more effective land-use regulation; building codes; research on landslide initiation and processes, landslide hazard delineation, mapping, and control; technology transfer; landslide insurance (exclusive of debris flows, for which insurance already exists); national leadership; and legislation to direct a governmental or private program to reduce landslide losses.

The USGS proposed elements of a landslide loss-reduction program. At FEMA's request, USGS prepared a feasibility study for a nationwide landslide mapping effort (Campbell, 1985).

BIBLIOGRAPHY AND REFERENCES

Alger, C.S., and E.E. Brabb. 1985. ***Bibliography of United States Landslide Maps and Reports.*** U.S. Geological Survey Open-File Report 85-585.

Anderson, L.R., J.R. Keaton, T. Saarinen, and W.G. Wells, II. 1984. ***The Utah Landslides, Debris Flows, and Floods of May-June 1983.*** National Research Council. Washington, DC: National Academy Press.

Baker, R.F., and R. Chiuruzzi. 1958. "Regional Concept of Landslide Occurrence." ***Highway Research Board Bulletin.*** No. 216, pp. 1-17.

Brabb, E.E., and B.L. Harrod. (Eds) 1989. ***Landslides: Extent and Economic Significance.*** Proceedings of the 28th International Geological Congress: Symposium on Landslides. Washington, DC, Rotterdam: Balkema.

Campbell, R.H. (Ed.). 1985. ***Feasibility of a Nationwide Program for the Identification and Delineation of Hazards from Mud Flows and Other Landslides.*** U.S. Geological Survey Open-File Report 85-276A.

Fleming, R.W., and J.D. Varnes. 1991. "Slope Movements," Chapter 9 in ***The Heritage of Engineering Geology: The First Hundred Years,*** Kiersch, G.A. (Ed.) Centennial Special Volume 3. Boulder, CO: Geological Society of America.

Fleming, R.W., and F.A. Taylor. 1980. ***Estimating the Costs of Landslide Damage in the United States.*** U.S. Geological Survey Circular 832.

Harp, E.L., and R.W. Jibson. 1995. ***Inventory of Landslides Triggered by the 1994 Northridge, California, Earthquake.*** U.S. Geological Survey Open-File Report 95-213.

Jager, S., and G.F. Wieczorek. 1994. ***Landslide Susceptibility in the Tully Valley Area, Finger Lakes Region, New York.*** U.S. Geological Survey Open-File Report 94-615.

King, P.B., and H.M. Beikman. 1974. ***Geologic Map of the United States (exclusive of Alaska and Hawaii).*** Scale 1:2,500,000. U.S. Geological Survey.

Kockelman, W.J. 1986. "Some Techniques for Reducing Landslide Hazards." ***Association of Engineering Geologists Bulletin.*** Vol. 33, No. 1, pp. 29-52.

Krohn, J.P., and J.E. Slosson. 1976. "Landslide Potential in the United States." ***California Geology.*** Vol. 29, No. 10, pp. 224-231.

National Research Council. 1985. ***Reducing Losses from Landsliding in the United States.*** Washington, DC: National Academy Press.

Pearce, L., H. Hightower, B. Konkin, S. Megalos, and J. Pernu. 1993. ***British Columbia: Hazard, Risk and Vulnerability Analysis.*** Vol. 1. The Disaster Preparedness Resources Center, The University of British Columbia.

Radbruch-Hall, D.H., R.B. Colton, W.E. Davies, I. Lucchita, B.A. Skipp, and D.J. Varnes. 1982. ***Landslide Overview Map of the Conterminous United States.*** Scale 1:7,500,000. U.S. Geological Survey Professional Paper 1183.

Radbruch-Hall, D.H., R.B. Colton, W.E. Davies, B.A. Skipp, I. Lucchita, and D.J. Varnes. 1976. Preliminary ***Landslide Overview Map of the Conterminous United States.*** Scale 1:7,500,000. U.S. Geological Survey Miscellaneous Field Studies Map MF-771.

Sangrey, D.A., and others. 1985. ***U.S. Geological Survey Landslide Research Program's Report of the Committee for Review of the U.S. Geological Survey Ground Failure and Construction Hazards Program.*** U.S. Geological Survey Administrative Report.

Schuster, R.L., and R.W. Fleming. 1986. "Economic Losses and Fatalities Due to Landslides." ***Association of Engineering Geologists Bulletin.*** Vol. 23, No.1, pp. 11-28.

Slosson, J.E., and J.P. Krohn. 1982. "Southern California Landslides of 1978 and 1980." ***Storms, Floods and Debris Flows in Southern California and Arizona, 1978 and 1980: Proceedings of a Symposium.*** Washington, DC: National Academy Press.

Smith, T.C. 1982. "Lawsuits and Claims Against Cities and Counties Mount After January 1982 Storm." ***California Geology.*** Vol. 35, No. 7, pp.163-164.

Toppozada, T., G. Borchardt, W. Haydon, M. Peterson, R. Olson, H. Lagorio, and T. Anvik. January 1995. ***Planning Scenario in Humboldt and Del Norte Counties, California, for a Great Earthquake on the Cascadia Subduction Zone.*** California Department of Conservation, Division of Mines and Geology, Special Publication 115.

Varnes, D.J.. 1978. "Slope Movement Types and Processes," in ***Landslides: Analysis and Control,*** Schuster, R.L., and R.J. Krizek (ed.). National Academy of Sciences, National Research Council, Transportation Research Board. Special Report No. 176, pp. 11-33.

Wiggins, J.H., J.E. Slosson, and J.P. Krohn. 1978. ***Natural Hazards: Earthquake, Landslide, Expansive Soil Loss Models.*** Institute of Behavioral Science. The University of Colorado, Boulder, CO.

Wold, R.L. Jr., and C.L. Jochim. 1989. ***Landslide Loss Reduction: A Guide for State and Local Government Planning.*** Denver, CO: Colorado Geological Survey, Department of Natural Resources.

Youd, T.L. 1978. "Major Cause of Earthquake Damage is Ground Failure." ***Civil Engineering.*** American Society of Civil Engineers. Vol. 48, No. 4, pp. 47-51.

CHAPTER

10

LAND SUBSIDENCE

Chapter Summary

Land subsidence, the loss of surface elevation due to the removal of subsurface support, ranges from broad, regional lowering of the land surface to localized collapse. The primary causes of most subsidence are human activities: underground mining of coal, groundwater or petroleum withdrawal, and drainage of organic soils. This hazard affects parts of at least 45 States. However, because of the broad range of causes and impacts, there has been limited national focus on this hazard.

Regional lowering of land elevation occurs gradually over time. It may aggravate flooding potential, particularly in coastal areas. Collapses, such as the sudden formation of sinkholes or the collapse of an abandoned mine, may destroy buildings, roads, and utilities.

Generally, subsidence poses a greater risk to property than to life. The average annual damage from all types of subsidence is conservatively estimated to be at least $125 million. Damage consists primarily of direct structural damage and property loss and depreciation of land values, but also includes business and personal losses that accrue during periods of repair.

Current efforts to address subsidence include improved hazard identification, public information programs, mapping, regulation of subsurface resources and land development, land-use management and building codes, and insurance. Mitigation measures generally are designed for specific situations.

Photo: Bettmann

HAZARD IDENTIFICATION

Land subsidence affects parts of at least 45 States. More than 17,000 mi^2 (44,000 km^2) of land has been lowered. Resource development and land-use practices, particularly underground mining of coal, groundwater and petroleum withdrawal, and drainage of organic soils, are the primary causes (NRC, 1991). Land subsidence due to surface faulting and liquefaction, triggered by earthquakes, is discussed in Chapter 16.

Subsidence is caused by a diverse set of human activities and natural processes that include mining of coal, metallic ores, limestone, salt, and sulfur; withdrawal of groundwater, petroleum, and geothermal fluids; dewatering of organic soils; wetting of dry, low-density deposits known as hydrocompaction; natural sediment compaction; melting of permafrost; liquefaction; and crustal deformation. This diversity and the broad range of impacts probably influence lack of a national focus on subsidence. Instead, many industries, professions, and Federal, State, and local agencies are involved independently.

Collapse Into Voids. Collapse of surficial materials into underground voids is the most dramatic form of subsidence. Most of the subsidence-related voids in the United States were created by coal mining. Coal-mine subsidence is caused by collapse of the mined-out or tunneled voids, and depends on the number, type, and extent of the voids. Abandoned tunnels and underground mining of metallic ores, limestone, and salt contribute to a much smaller extent, although problems may be severe at specific locations. For example, hundreds of subsidence occurrences in the Midwest have been associated with failures of abandoned lead-zinc mines.

In the longwall method of mining coal, in which most of the coal seam is removed along a single face, the roof above the mined-out seam is allowed to collapse as the mining progresses. Subsidence above longwall mines is rapid, generally ending within a few months after removal of subsurface supports.

Subsidence associated with partial extraction mining is usually unplanned. In this method, only a portion of the coal called the "rooms" is removed; the unmined portions, the "pillars," are left to provide support. Subsidence resulting from collapse into rooms may take years to manifest. Examples of collapses occurring 100 years after mines were abandoned have been documented (NRC, 1991).

Although most collapses are human-induced, some cavities in bedrock were formed prior to human activities. This is particularly true of carbonates such as limestone, because rates of solution are so low. Cavities in halite can be an exception because of its high solubility. For example, in the last 30 years several dozen sinkholes have formed in Kansas as a result of dissolution of salt beds by leaks through casings of brine-disposal wells. A recent example is a 200-ft (60-m) wide, 110-ft (33-m) deep sinkhole that formed during the summer of 1988 near Macksville, KS (Geotimes, 1988). Catastrophic subsidence is most commonly induced by water-table lowering, rapid water-table fluctuation, diversion of surface water, construction, use of explosives, or impoundment of water.

Sediment Compaction. Sediment compaction typically causes broad regional subsidence. Exceptions include ground rupture and hydrocompaction. Rates of subsidence usually are low, ranging from a few millimeters to centimeters per year, but total subsidence may reach several meters over decades. Sediment compaction results from underground fluid withdrawal, natural compaction, and hydrocompaction.

Underground fluid withdrawal is one of the major causes of sediment compaction in the United States. The weight of the overburden above fluid reservoirs is supported by both the fluid pressures and stresses transmitted through the solid skeleton of the reservoir soil or rock. When fluids are withdrawn, fluid pressures decline and support of the overburden is transferred to the solid skeleton. If the reservoir soil or rock is compressible, sediment compaction and subsidence occur.

Another type of sediment compaction occurs naturally as older sediment is buried by younger sediment. Natural subsidence is occurring most rapidly in the Mississippi River Delta area of southern Louisiana, where approximately 1,500 mi^2 (3,900 km^2) of land are subsiding. Estimated average rates of subsidence range from 0.3 to 0.4 in (0.8 to 1.0 cm) per century (Penland and others, 1988). Maximum rates measured by geodetic surveys are approximately 0.5 in (1.3 cm) per year.

Hydrocompaction occurs when dry, low-density sediments collapse because moisture content increases. These sediments, known as collapsible soils, generally are of two types: mudflow deposits in alluvial fans, and wind-deposited, moisture-deficient silt called loess. Most collapsible soils have low densities because they remained moisture deficient throughout their post-depositional history. When water percolates through the root zone into these soils, the structure collapses, the soil compacts, and very localized subsidence may result.

Drainage of Organic Soils. Drainage of organic soils, particularly peat and muck, induces a series of processes that reduces the volume of soil. These processes include biological oxidation, compaction, and desiccation. Biological oxidation usually dominates in warm climates. The principal areas of organic soil subsidence in the United States are the greater New Orleans, LA area; the Sacramento-San Joaquin River Delta, CA; and parts of the Florida Everglades. Maximum observed subsidence is 21.0 ft (6.4 m) in the Sacramento-San Joaquin River Delta (Ireland and others, 1984).

RISK ASSESSMENT

The National Research Council compiled maps showing the cumulative damage by State resulting from various types of land subsidence (NRC, 1991). These maps, which appear in the subsection on Consequences, can be used as a measure of the risk associated with land subsidence. The time periods for compilation of the cumulative costs vary from state-to-state, and the costs were not converted to constant dollars. In general, the costs indicated are considered to be conservative estimates.

Probability and Frequency

Land subsidence occurs slowly and continuously over time or on abrupt occasions, as in the case of sudden formation of sinkholes. Procedures for determining the probability or frequency of land subsidence have not been recommended. The cumulative damage land subsidence maps discussed later in this chapter do not imply probability or frequency of occurrence.

Exposure

Exposure of people and property is a function of the type and duration of subsidence, and extent of the area affected.

Collapse Into Voids. Collapse of surficial materials into underground voids is most commonly associated with coal mining. Coal is found in 37 States and mined underground in 22 States (HRB-Singer, 1980). Approximately 12,400 mi^2 (32,000 km^2) of land is undermined, and it is anticipated that the area will ultimately increase to 62,500 mi^2 (162,000 km^2). Approximately 3,100 mi^2 (8,000 km^2) of the undermined area, most of which is in the Eastern United States, already has experienced subsidence.

The U.S. Bureau of Mines estimates that 620 mi^2 (1,600 km^2) of land in urban areas is threatened (Johnson and Miller, 1979). Seventy-one percent of this area is in Pennsylvania, Illinois, and West Virginia.

Davies and others (1976) indicate more than 500,000 mi^2 (1.4 million km^2) of land in 39 States is underlain by cavernous limestone and marble. More than 11,600 mi^2 (30,000 km^2) of this area lies beneath Standard Metropolitan Statistical Areas inhabited by 33 million people (HRB-Singer, 1977). However, only a small portion is actually underlain by voids and considered to be at-risk of subsidence.

The States with the greatest number of active sinkholes are Alabama, Florida, Georgia, Indiana, Missouri, Pennsylvania, and Tennessee. Newton (1986) estimates that more than 6,000 collapses have occurred in the Eastern United States since around 1950.

Sediment Compaction. Sediment compaction subsidence is caused by pumping groundwater and petroleum. More than 30 areas in seven States have experienced land subsidence of this type. The two largest areas are in the San Joaquin Valley, CA, and Houston, TX, where approximately 5,200 mi^2 and 4,800 mi^2 (13,500 km^2 and 12,500 km^2), respectively, have subsided because of groundwater withdrawal. Maximum elevation loss from this type of subsidence has been 30 ft (9 m) in the San Joaquin Valley from the mid-1920s to 1977 (Ireland and others, 1984). Petroleum withdrawal in Long Beach, CA, caused parts of the City's harbor facility to subside almost 29.6 ft (9 m) from 1937 to 1966.

Groundwater withdrawal in Houston, TX, caused some coastal areas to subside more than 6 ft (2 m). Approximately 30 mi^2 (80 km^2) of land were inundated. Several hundred square kilometers, including the 500-unit Brownwood Subdivision in Baytown which was abandoned in 1983, were added to areas susceptible to flooding by storm surges. Some areas of local subsidence in the Houston area resulted from the extraction of gas and oil.

Damaging hydrocompaction has been reported in 17 States. The three largest affected areas are the alluvial slopes of the western San Joaquin Valley and loess-covered areas in the Missouri River basin and the Pacific Northwest. Other known areas of hydrocompaction include the Heart Mountain-Chapman Beach and Riverton areas in Wyoming; Hysham Bench, MT; Denver, CO; and the Washington-Hurricane-Cedar City areas in southwest and central Utah. The major impact has been on design and operation of hydraulic structures such as canals, aqueducts, and dams. Locally significant impacts have been sustained by buildings and highways. Irrigation for agriculture has caused differential hydrocompaction that required re-leveling of fields.

Drainage of Organic Soils. Approximately 3,600 mi^2 (9,400 km^2) of land underlain by organic soil has subsided because of drainage of organic soils. An even larger area is susceptible to subsidence. Approximately 39,000 mi^2 (101,000 km^2) of the conterminous United States are covered by peat and muck soils (Stephens and others, 1984) and more than 10,000 mi^2 (26,000 km^2) of organic wetlands are in Standard Metropolitan Statistical Areas (HRB-Singer, 1977).

Consequences

The average annual damage from all types of subsidence is estimated conservatively to be at least $125 million. The estimated annual damage by type of subsidence is given in Table 10-1 (NRC, 1991). The practical impacts of land subsidence depend on the specific form of surface deformation. Regional lowering may either aggravate the flood potential or permanently inundate an area, particularly in coastal or riverine settings. Local collapse may impair or destroy buildings, roads, and utilities.

The major damage results from underground mining of coal, withdrawal of underground water and petroleum, and drainage of organic soils. The costs consist primarily of direct structural and property losses and depreciation of land values, but also include business and personal losses incurred during periods of repair. Subsidence is more hazardous to property than to life, because of the typically low rates of surface lowering, and has caused few casualties. However, subsidence increases the potential for loss of life in flood-prone areas by increasing the depth of floodwaters and extent of areas susceptible to flooding.

TABLE 10-1.—*Estimated annual damage from land subsidence*

Type of Subsidence	Damage
Organic soils	$40,000,000
Underground fluid withdrawl	$35,000,000
Mines	$30,000,000
Natural compaction	$10,000,000
Sinkholes	$10,000,000
Hydrocompaction	(Not available)
Total	**$125,000,000**

Source: *National Research Council, 1991*

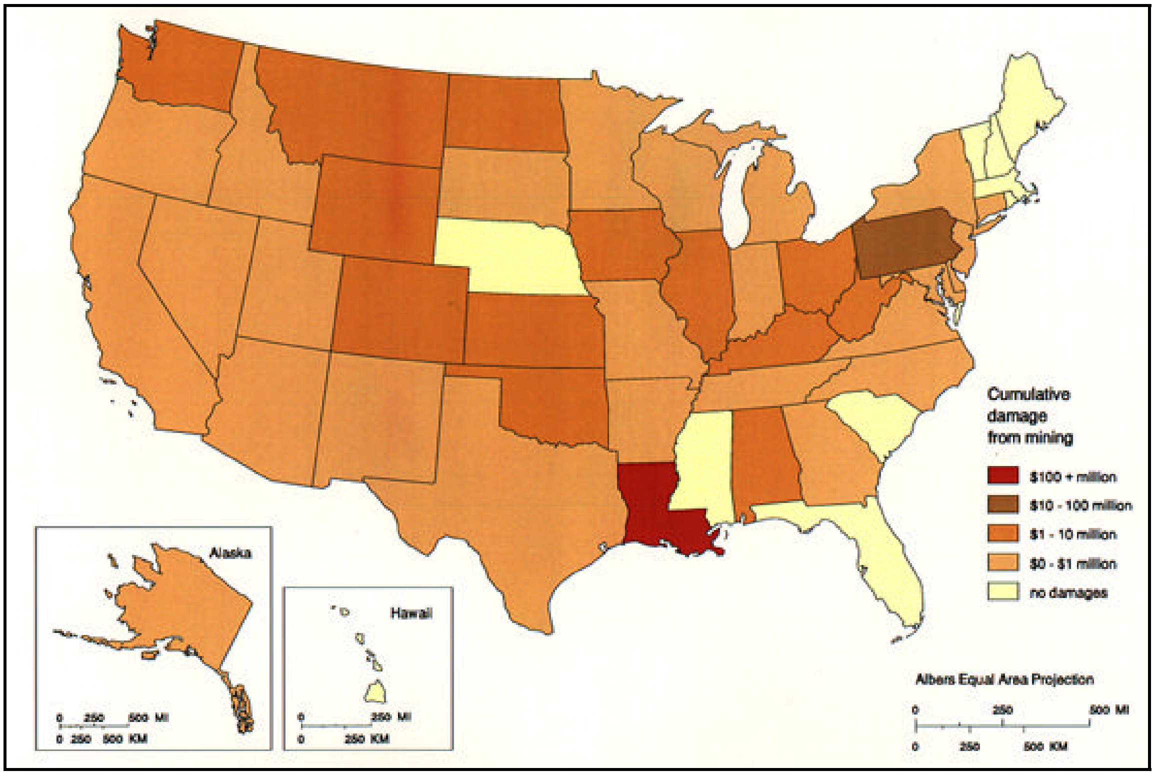
Although total annual damage associated with subsidence is small relative to the U.S. economy, subsidence imposes substantial costs on individual cities and neighborhoods. Cities where cumulative damage from subsidence exceed $100 million include Long Beach, CA; Houston, TX; and New Orleans, LA.

Collapse Into Voids. Most mine-related subsidence damage in the United States is associated with abandoned coal mines over which urban growth has occurred. Damage in urban areas has been estimated to cost more than $30 million annually (HRB-Singer, 1977). In Scranton, PA, and Seattle, WA, collapse of abandoned coal mines has damaged surface structures. In rural areas subsidence affects field drainage, reduces crop yields, and lowers property values. A study in Illinois indicated property values in rural areas affected by subsidence were discounted an average of 16 percent (Illinois Department of Energy and Natural Resources, 1985).

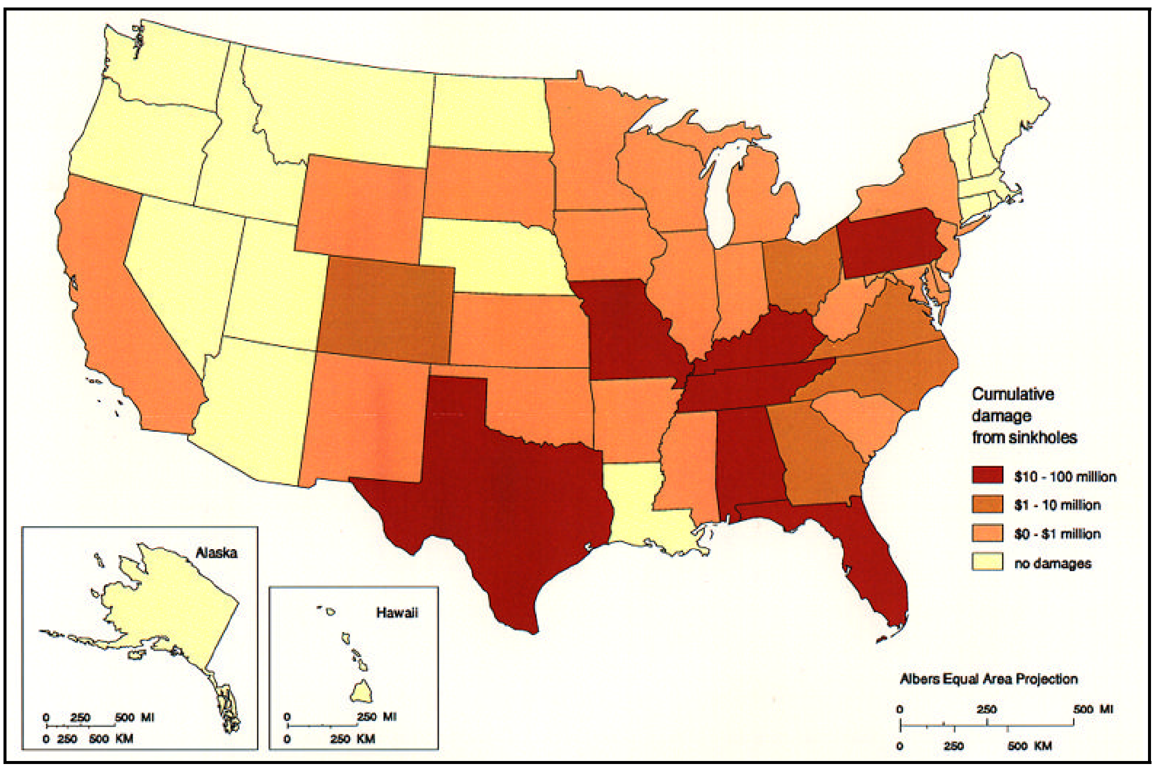
The cumulative costs of damage from subsidence caused by underground mining are shown in Map 10-1. States with cumulative damage in excess of $1 million are concentrated in the Ohio Valley and the Northern Plains States, however the most significant damage is in Pennsylvania and Louisiana.

Costs of preventive measures and damage from sinkhole activity, incurred primarily in the Eastern United States since 1970, are more than $170 million (Newton, 1986). The costs are dominated by expenditures of $130 million at five dams to minimize or eliminate sinkhole activity. Sinkhole potential is usually evaluated during siting of major engineered structures in limestone terrain, a factor that helps to minimize future damage.

The cumulative costs associated with sinkholes are shown in Map 10-2. Texas, Florida, Tennessee, Kentucky, Arkansas, Louisiana and Pennsylvania experienced the most damage. The Winter Park, FL, sinkhole collapse of May 8-9, 1981, is probably one of the better known incidents of land subsidence in an area of limestone geology. A 324-ft (100-m) wide, 100-ft (30-m) deep sinkhole formed in approximately 36 hours. The collapse was caused in part by the prevailing drought. Economic loss was estimated to exceed $2 million, including a house, several cars, portions of several businesses, streets, and the municipal swimming pool (Hays, 1981).



Map 10-1. Cumulative subsidence damage caused by mining. Time periods which estimates are based vary by State, and costs are not converted to constant dollars.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *National Research Council, 1991.*



Map 10-2. Cumulative subsidence damage caused by sinkholes. Time periods which estimates are based vary by State, and costs are not converted to constant dollars.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *National Research Council, 1991.*

Sediment Compaction. Damage from compaction caused by withdrawal of underground fluids is dominated by large losses in a few areas. For example, although subsidence caused by petroleum withdrawal in Long Beach, CA, is under control, mitigation activities cost approximately $150 million from 1937 to 1966 (Mayuga, 1970).

Jones (1977) estimated that damage in the Houston area averaged $31.7 million annually from 1969 to 1974. Costs were nearly equally divided between decreased property values and actual damage, and most were associated with increased flood risk and permanent inundation. Prokopovich and Marriott (1983) estimated that post-construction rehabilitation of subsidence damage to California's Central Valley Project canals cost $34 million.

The only available estimate of subsidence damage to well fields was prepared by Roll (1967) for Santa Clara Valley, CA, where more than $4 million was spent to repair or replace well casings.

The cumulative damage by State associated with subsidence due to underground fluid withdrawal is shown in Map 10-3. Cumulative damage exceeds $100 million in Texas and California. Losses from natural compaction, particularly in the Mississippi River Delta, are difficult to estimate because of the uncertain value of coastal wetlands. Increased flooding potential is the principal impact because affected areas commonly are low lying and naturally subject to flooding. Annual revenue losses are possibly on the order of millions of dollars (NRC, 1991).

Nationwide, hydrocompaction damage and prevention expenditures are very poorly documented. The most costly individual impact documented was on the California Aqueduct along the western margin of the San Joaquin Valley, where an aggregate length of 96 mi (155 km) of canal was built on collapsible soils (James, 1974). Investigations and presetting to compact foundations resulted in mitigation costs of $20 million (Curtin, 1973). Design modifications to the nearby Central Valley Project led to an $8 million mitigation cost (Prokopovich and Marriott, 1983). The most costly reported urban incident is a $3-million decrease in property value in Cedar City, UT, where structural damage totaled approximately $1 million (Kaliser, 1982).

Even areas with humid climates have incurred significant costs. For example, collapsible soils added more than $2.5 million in mitigation costs to interstate highway construction in Louisiana (Arman and Thornton, 1972).

The cumulative damage, by State, associated with subsidence due to hydrocompaction is shown in Map 10-4. The States with the highest damage costs are California and Louisiana.

Drainage of Organic Soils. Costs associated with structural damage due to differential subsidence caused by drainage of organic soils appear to be high. HRB-Singer (1977) estimated that approximately $30 million was spent annually in New Orleans to repair damage and maintain property. A study in New Orleans indicated that costs are disproportionately distributed: 45 percent of homeowners sampled encountered problems and 5 percent reported serious problems (Earle, 1975).

Increased flooding is the most serious problem associated with organic soil subsidence. The low relative elevation of organic soil areas makes them vulnerable to flooding even in their natural state. Their high compressibility makes them a poor foundation material for structures. Consequently, special construction practices that rely on piles driven to firm materials are commonly employed. These practices have led to subsiding land surfaces relative to the structures.

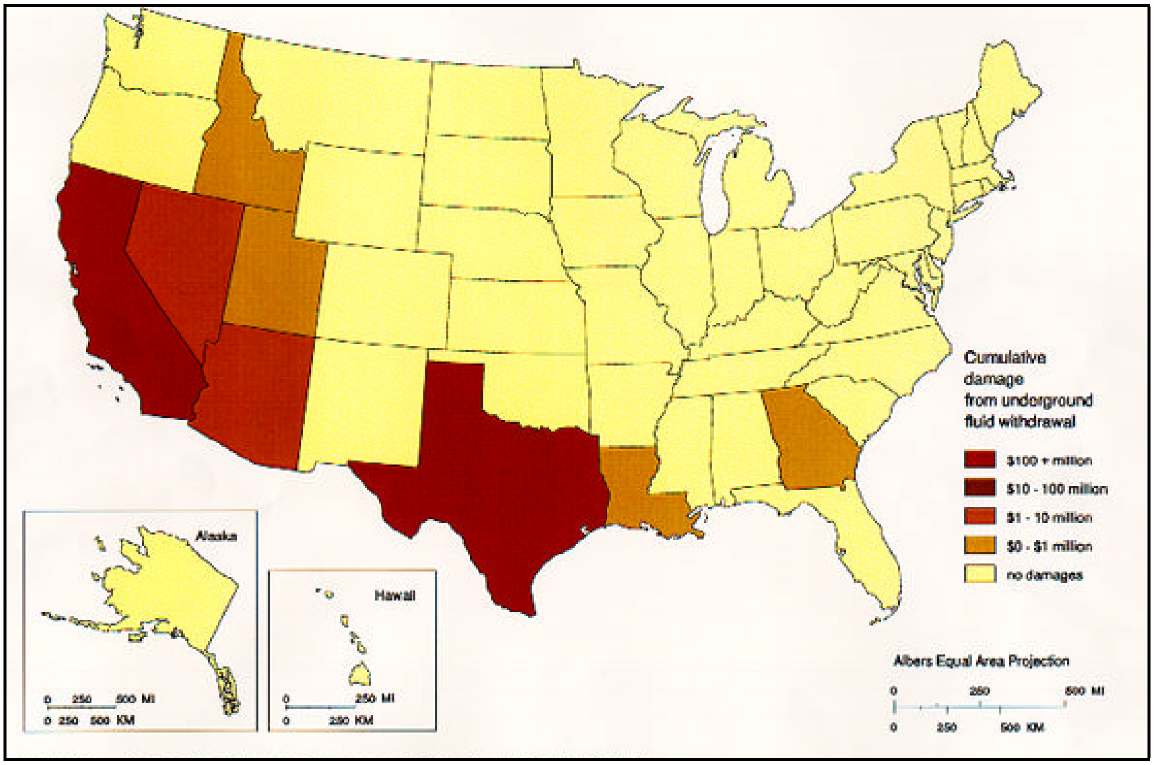
The cumulative damage, by State, associated with subsidence due to drainage of organic soils is shown in Map 10-5. Cumulative damage exceeds $100 million in California, Louisiana, and Florida.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

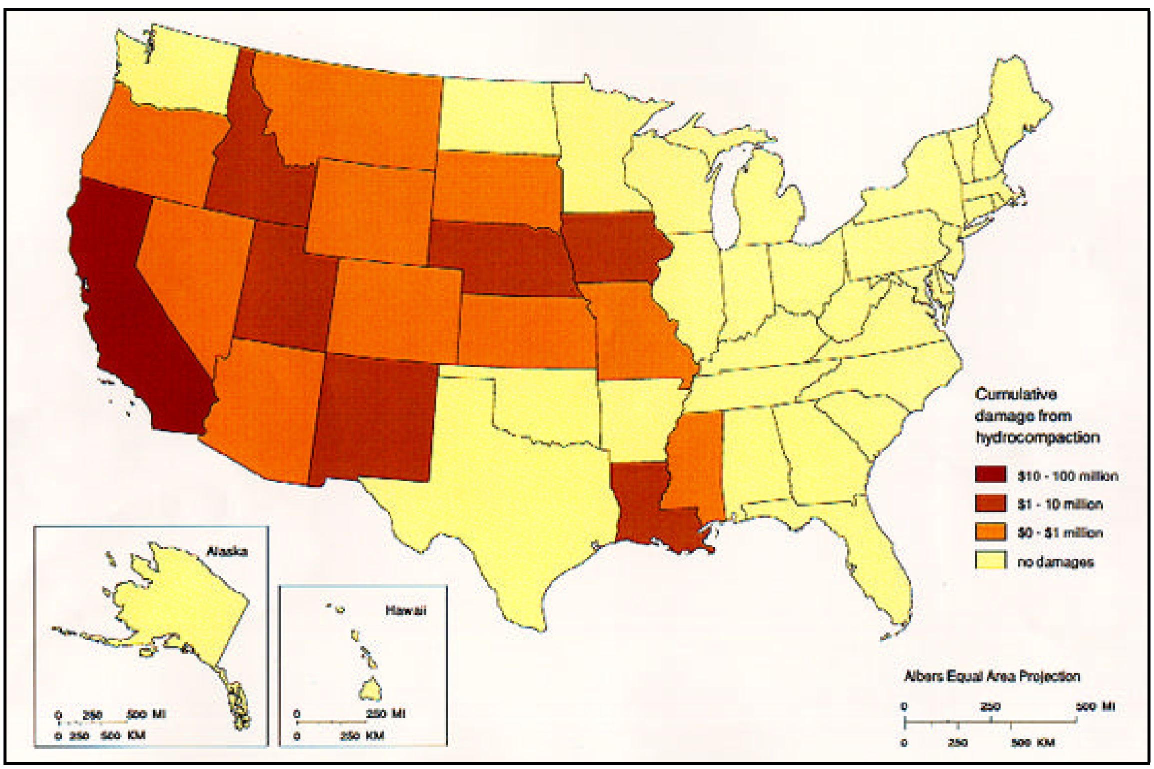
The National Research Council (1991) suggests that primary data collection and mapping of land subsidence should be carried out by State geological surveys, USGS, and the Natural Resources Conservation Service (formerly Soil Conservation Service). Special research to define mapping criteria and to identify and solve complex causes of subsidence should be the responsibility of Federal agencies such as USGS, the U.S. Bureau of Mines, and the USDA Agricultural Research Service.

Research on land subsidence is primarily conducted or funded by Federal agencies. The U.S. Bureau of Mines has been primarily responsible for research on mining; USGS for underground fluid withdrawal, natural compaction, sinkholes, and geologic aspects of mining; U.S. Bureau of Reclamation for hydrocompaction; and the USDA Agricultural Research Service for organic soils (NRC, 1991).

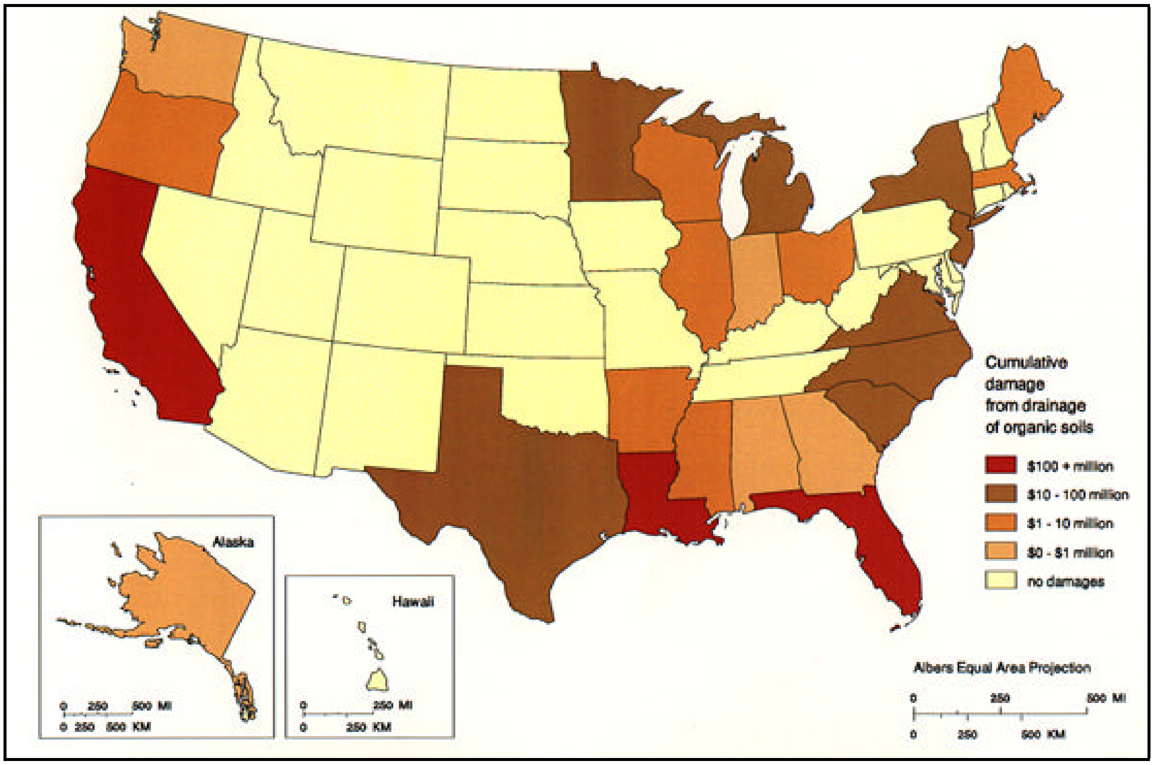
USGS research on land subsidence resulting from groundwater withdrawal illustrates research by a Federal agency. Holzer (1984) describes the areas in



Map 10-3. Cumulative subsidence damage caused by underground fluid withdrawl. Time periods on which estimates are based vary by State, and costs are not converted to constant dollars. Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *National Research Council, 1991.*



Map 10-4. Cumulative subsidence damage caused by hydrocompaction in the United States. Time periods on which estimates are based vary by State, and costs are not converted to constant dollars. Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *National Research Council, 1991.*



Map 10-5. Cumulative subsidence damage caused by drainage of organic soils. Time periods which estimates are based vary by State, and costs are not converted to constant dollars. Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories. Source: *National Research Council, 1991.*

the Western United States where ground failure due to groundwater withdrawal is a problem. Ireland and others (1984) summarize studies of land subsidence in the San Joaquin Valley, CA. Hanson and Benedict (1993) describe how a groundwater model can be used to simulate potential land subsidence in the Upper Santa Cruz Basin in Arizona. Leake (1990, 1991) describes the vertical compaction component of a groundwater model useful in subsidence studies.

MITIGATION APPROACHES

The many causes and forms of land subsidence have led to a variety of mitigation efforts. Because of the diverse impacts, mitigation measures generally are designed for specific situations and address problems in areas that are already developed or proposed for development. The NRC (1991) discussed several approaches for dealing with subsidence, described below.

- **Public Information Programs.** Many problems related to land subsidence are hazardous only if they are unexpected. An informed public can minimize exposure to financial loss and personal injury. For this reason, public information programs are underway in most areas experiencing significant problems. They range from very informal campaigns led by local college professors to highly organized efforts conducted by special-interest groups to publication of non-technical literature by many Federal, State, and local agencies.

- **Mapping Programs.** Mapping programs are an important element in efforts to identify and manage subsidence. Such programs frequently are an early step in mitigation efforts. Depending on the type of subsidence, the scope and objectives of mapping programs vary, as does the degree of interaction among Federal, State, and local agencies.

- **Regulation of Resource and Land Development—Prevention and Control.** Regulation of the activities that cause subsidence is the most direct approach to mitigation of damage. Approaches for preventing or controlling subsidence to minimize damage vary widely. In the case of resource extraction, they range from banning extraction to controlling how materials are removed. In the case of land development practices that cause subsidence, approaches range from banning development to regulating construction practices. Subsidence caused by active coal mining is regulated by the Surface Mining Control and

Reclamation Act of 1977, which requires coal mine operators to submit Subsidence Control Plans as part of permit applications. Around Houston, the Harris-Galveston Coastal Subsidence District regulates groundwater withdrawal through a permit process.

- **Land-Use Management and Building Codes.** Land-use management and regulation in the presence of real or potential subsidence is an alternative to regulating subsurface resource development. Techniques include land-use planning and codes, specialized building codes, official maps, and constraints on public utilities.

- **Market-Based Mitigation Efforts.** The objective of market-based efforts is to internalize the cost of subsidence by transferring those costs to the parties responsible for it or to the ultimate consumers. Internalizing subsidence costs may come about through taxes or fees on the parties causing the subsidence or by directly requiring those parties to carry out prevention measures.

- **Insurance.** Insurance programs to provide relief from subsidence damage have been used in several areas to distribute losses more equitably and to encourage risk reduction actions. Programs have been implemented to insure against losses from coal-mine subsidence and catastrophic subsidence associated with sinkhole collapse. The NFIP offers insurance in areas impacted by flooding aggravated by subsidence. Coal-mine subsidence insurance is available in Pennsylvania, Illinois, West Virginia, and Kentucky, and is under consideration in other States. In 1981, sinkhole insurance coverage in Florida was extended to all structures, although insurance companies were given an option not to provide coverage for commercial and government buildings.

RECOMMENDATIONS

The National Research Council (1991) recommended efforts in three general areas to address subsidence problems:

- Collection of a broad range of earth science data in order to assess the incidence and potential impact from each type of subsidence, both locally and regionally;

- Technical research to improve the capability to predict the time, rate, magnitude, and place of subsidence, and to develop engineering designs that are resistant to subsidence damage; and

- Evaluation of methods of subsidence mitigation for cost effectiveness and suitability for each type of subsidence.

The NRC (1991) expressed concern that efforts to reduce the Federal deficit, which have jeopardized the small but effective subsidence research programs in Federal agencies, will halt scientific and technical progress. Data and research results from Federal programs historically have complemented State and local efforts by establishing much of the technical basis for recognition of subsidence potential, as well as its prevention or mitigation. The NRC supported the maintenance of Federal budgets in order to provide data and techniques required by State and local governments and industry to mitigate subsidence in a timely and cost-effective manner.

BIBLIOGRAPHY AND REFERENCES

Arman, A., and S.I. Thornton, 1972. ***Collapsible Soils in Louisiana.*** Louisiana State University Engineering Research Bulletin No. 111.

Curtin, G. 1973. "Collapsing Soil and Subsidence." In: D.E. Moran and others (Eds.), ***Geology, Seismicity, and Environmental Impact.*** Association of Engineering Geologists.

Davies, W.E., J.H. Simpson, G.C. Ohlmacher, and G.J. Newton. 1976. ***Map Showing Engineering Aspects of Karst in the United States.*** Scale 1:7,500,000. U.S. Geological Survey Open-File Report 76-625.

Earle, D.W. 1975. ***Land Subsidence Problems and Maintenance Costs to Homeowners in East New Orleans, Louisiana.*** Ph.D. Dissertation. Louisiana State University.

Geotimes. 1988. “Kansas Sinkholes.” Vol. 33, No. 11, p. 15.

Hanson, R.T., and J.F. Benedict. 1994. ***Simulation of Groundwater Flow and Potential Land Subsidence, Upper Santa Cruz Basin, Arizona.*** U.S. Geological Survey Water, Resources Investigations Report 93-4196.

Hays, W.W. 1981. ***Facing Geologic and Hydrologic Hazards: Earth Science Considerations.*** U.S. Geological Survey Professional Paper 1240-B.

Holzer, T.L. 1989. "State and Local Response to Damaging Land Subsidence in United States Urban Areas." ***Engineering Geology.*** Vol. 27, pp. 449-466.

Holzer, T.L. 1984. "Ground Failure Induced by Groundwater Withdrawal from Unconsolidated Sediments." In: T.L. Holzer (Ed.), ***Man-Induced Land Subsidence.*** Geological Society of Amercia, Reviews in Engineering Geology. Vol. 6.

HRB-Singer, Inc. 1977. ***Nature and Distribution of Subsidence Problems Affecting HUD and Urban Areas.*** U.S. Department of Housing and Urban Development. National Technical Information Services. Report No. PB80172778.

HRB-Singer, Inc. 1980. ***Technical and Economic Evaluation of Underground Disposal of Coal Mining Wastes.*** Report prepared for Bureau of Mines. Contract No. J0285008.

Illinois Department of Energy and Natural Resources. 1985. ***The Economic Effects of Underground Mining Upon Land Used for Illinois Agriculture.*** Illinois Department of Energy and Natural Resources Document No. 85/01.

Ireland, R.L., J.F. Poland, and F.S. Riley. 1984. ***Land Subsidence in San Joaquin Valley, California, as of 1980.*** U.S. Geological Survey Professional Paper 437-I.

James, L.B. 1974. ***The Role of Engineering Geology in Building the California State Water Project.*** Centenaire de la Societe Geologique de Belgique Colloque. Geologie de L'Ingenieur, Liege.

Johnson, W., and G.C. Miller, 1979. ***Abandoned Coal-mined Lands: Nature, Extent, and Cost of Reclamation.*** U.S. Bureau of Mines Special Publication No. 6-79.

Jones, L.L. 1977. ***External Costs of Surface Subsidence: Upper Galveston Bay, Texas.*** International Association of Hydrological Sciences Publication No. 121.

Kaliser, B.N. 1982. "Hydrocompaction Affecting Cedar City, Utah." ***Proceedings of the 19th Engineering Geology and Soils Engineering Symposium.*** Pp. 145-160.

Leake, S.A. 1990. "Interbed Storage Changes and Compaction in Models of Regional Groundwater Flow." ***Water Resources Research.*** Vol. 26, No. 9, pp. 1939-1950.

Leake, S.A. 1991. "Simulation of Vertical Compaction in Models of Regional Groundwater Flow." ***Land Subsidence, Proceedings of the Fourth International Symposium on Land Subsidence.*** International Association of Hydrological Sciences Publication No. 200.

Mayuga, M.N. 1970. "Geology and Development of California's Giant-Wilimington Oil Field." ***Geology of Giant Petroleum Fields***. American Association of Petroleum Geologists Memoir No. 14.

National Research Council. 1991. ***Mitigating Losses from Land Subsidence in the United States.*** Washington, D.C.: National Academy Press.

Newton, J.G. 1986. ***Natural and Induced Sinkhole Development in the Eastern United States.*** International Association of Hydrological Sciences Publication No. 151.

Penland, S., K.E. Ramsey, R.A. McBride, J.T. Mestayer, and K.AA. Westphal. 1988. ***Relative Sea Level Rise and Delta-Plain Development in Terrebonne Parish Region.*** Louisiana Geological Survey. Coastal Geology Publication Technical Report No. 4.

Prokopovich, N.P., and M.J. Marriott. 1983. "Cost of Subsidence to the Central Valley Project, California." ***Association of Engineers Geologists Bulletin 20.*** Vol. 3, pp. 325-332.

Roll, J.R. 1976. "Effect of Subsidence on Well Fields." ***American Water Works Association Journal.*** Vol. 59, No. 1, pp. 80-88.

Stephens, J.C., L.H. Allen Jr., and E. Chen. 1984. "Organic Soil Subsidence." In: T.L. Holzer (Ed.), ***Man-Induced Land Subsidence.*** Geological Society of America, Reviews in Engineering Geology. Vol. 6.

Turney, J.E. 1985. ***Subsidence Above Inactive Coal Mines: Information for the Homeowner.*** Colorado Geological Survey Special Publication No. 26.

CHAPTER

11

EXPANSIVE SOILS

Chapter Summary

Soils and soft rock that tend to swell or shrink due to changes in moisture content are commonly known as expansive soils. Changes in soil volume present a hazard primarily to structures built on top of expansive soils. The most extensive damage occurs to highways and streets.

In the United States, two major groups of rocks serve as parent materials of expansive soils, and occur more commonly in the West than in the East. The first group consists of ash, glass, and rocks of volcanic origin. The aluminum silicate minerals in these volcanic materials often decompose to form expansive clay minerals of the smectite group, the best known of which is montmorillonite. The second group consists of sedimentary rock containing clay minerals, examples of which are the shales of the semiarid West-Central States. Because clay materials are most susceptible to swelling and shrinking, expansive soils are often referred to as swelling clays.

The effects of expansive soils are most prevalent in regions of moderate to high precipitation, where prolonged periods of drought are followed by long periods of rainfall. The hazard occurs in many parts of the Southern, Central, and Western United States. Recent estimates put the annual damage from expansive soils as high as $7 billion. However, because the hazard develops gradually and seldom presents a threat to life, expansive soils have received limited attention, despite their costly effects.

The best means of preventing or reducing the damage from expansive soils is to avoid building on them. When that is not possible, commonly applied engineering practices include removal of the soil, application of heavy loads to offset the swelling pressure, preventing access to water, presetting, and chemical stabilization.

Photo: JCP Geologists, Inc.

Photo: JCP Geologists, Inc.

HAZARD IDENTIFICATION

"Clay" is defined as a natural, earthy, fine-grained material that develops plasticity when mixed with a limited amount of water. A swelling clay, according to the American Geological Institute Glossary of Geology (Bates and Jackson, 1980), is a "clay that is capable of absorbing large quantities of water, thus increasing greatly in volume. . . ."

Dry clays that are capable of absorbing water, if unconfined, will increase in volume in an amount proportional to the amount of water absorbed. The amount of water absorbed and the degree of expansiveness are dependent on several variable and interrelated factors. The increase in soil volume causes damage to foundations and structures. These same clays may also be a source of engineering problems due to shrinkage resulting from loss of moisture.

Dry swelling clays absorb much larger quantities of water before becoming plastic than do dry, non-swelling clays. They also remain plastic over a wider range of moisture content, referred to as the plasticity index (PI). The PI is expressed as the numerical difference between the plastic limit (the percent moisture content at which clay passes from the solid to the plastic state) and the liquid limit (the percent moisture content at which clay passes from the plastic to the liquid state). The PI bears a direct relation to the amount and type of clay minerals present and to the orientation and size of clay particles. Other factors remaining constant, the PI increases with amount of clay minerals, decreases with degree of parallel orientation of the clay minerals, and decreases with clay particle size.

The plasticity index is generally a good indicator of swelling potential. Seed and others (1962), who found the PI to be the single most useful indicator of swelling potential, noted ". . . this parameter alone can provide an assessment of swelling that is probably accurate to within 35 percent." Sowers and Kennedy (1967) found the PI to be "the most reliable working tool" in identifying potentially troublesome clays in the humid coastal plains of the southeastern United States.

Expansive soils can be recognized either by visual inspection in the field or by conducting laboratory analyses. Shales, clay shales, weathered volcanic rocks, and residual soils containing smectite often have a characteristic "popcorn" texture, especially in semiarid areas.

The most successful methods of recognizing expansive soils involve laboratory analysis of the clay-mineral content in solid and soft rock, including X-ray diffraction, differential thermal analysis, and microscopic examination. The most common methods used to identify expansive soils on the basis of physical characteristics related to volume change are free swell tests, plasticity tests, and direct measurements of volume change.

Swelling potential refers to the amount of volume increase due to swelling that is possible in a clay in its natural environment. Swelling potential is influenced by many factors, some of which are inherent to the clay and others that are related to its environment. Inherent factors determine the maximum increase in volume that can take place under optimum conditions, and include clay mineral composition, amount of non-clay material present, density, void ratio, size and orientation of clay particles, cementation, macrostructure, size and thickness of clay body, and depth below ground surface.

Volume changes in clay caused by variations in moisture content occur within approximately 30 ft (10 m) of the ground surface (Jones and Holtz, 1973). Most changes that cause engineering problems occur at depths less than 10 ft (3 m) (Hamilton, 1963; Gromko, 1974).

Clays beneath the water table have no swelling potential because they are completely saturated with no capacity for moisture absorption. Clays above the water table are generally unsaturated and will have capacities for moisture and swelling that will differ according to their degree of saturation. Generally, saturation levels are high and swelling potentials are low for clays just above the water table, because they have access to abundant moisture due to capillary action (Olive and others, 1989).

Clays in the weathering zone, which may extend to more than 30 ft (10 m) below the surface, usually have minimum moisture contents that are determined by climate. Variations in moisture content and volume changes are greatest in clays found in regions of moderate to high precipitation, where prolonged periods of drought are followed by long periods of rainfall. It is in these regions, which include many of the Southern, Central, and Western States, that swelling of clays resulting from climatic fluctuations cause the most severe engineering problems.

RISK ASSESSMENT

Probability and Frequency

The risk associated with expansive soils is related to swelling potential in a qualitative manner: high, moderate to slight, and little to no swelling potential. Swelling clay potential is defined in a spatial sense with no implications over time. Probability and frequency analyses have not been prepared because of the nature of occurrence of this hazard. This is consistent with other geologic hazards that occur rarely or slowly over time.

Exposure

Olive and others (1989) developed a map of the conterminous United States to show the distribution and potential of swelling clays (Map 11-1). Geologic units as shown on the geologic map of the United States (King and Beikman, 1974) were classified according to the amount and swelling potential of clay they contain.

The availability of data on expansive soils varies greatly. In or near metropolitan centers and at dam sites, abundant information on the amount of clay generally is available. However, for large areas of the United States, little information is reported other than field observations of the physical characteristics of clay of a particular stratigraphic unit. Therefore, fixed criteria for determining the swelling potential have not been devised. The method adopted by Olive and others (1989) is largely subjective and the classification presented was based on the authors' appraisal of pertinent data that, for a single clay body or geologic unit, may vary considerably in quantity and quality from one area to another.

The swelling-clay classification of Olive and others (1989) was based mostly on numerous published descriptions of the physical and mineralogic properties of clays. Other data, often unpublished, were obtained from communication with practicing engineering geologists and geotechnical engineers. The map developed by Olive and others (1989) is consistent with maps developed by Patrick and Snethen (1976) and a map published by the American Society of Civil Engineers (ASCE) in *Civil Engineering* in October 1978.

Compared to Olive's map, another expansive soil map by Wiggins and others (1978) has similar patterns but some noticeable differences as well. The differences are due to the different approaches for identifying swelling clay potential. Wiggins used soil taxonomy obtained from the Soil Geography Unit of the U.S. Soil Conservation Service, while Olive related clay swelling potential to geologic units.

Consequences

Most engineering problems caused by volume changes in swelling clays result from human activities that modify the local environment. They commonly involve swelling clays beneath areas covered by buildings and slabs or layers of concrete and asphalt, such as those used in construction of highways, canal linings, walkways, and airport runways.

Damage to the built environment results from differential vertical movement that occurs as clay moisture content adjusts to the changed environment. In a highway pavement, differential movement of 0.4 in (1 cm) within a horizontal distance of 20 ft (6 m) is enough to pose an engineering problem if high standards for fast travel are to be maintained (Williams, 1965).

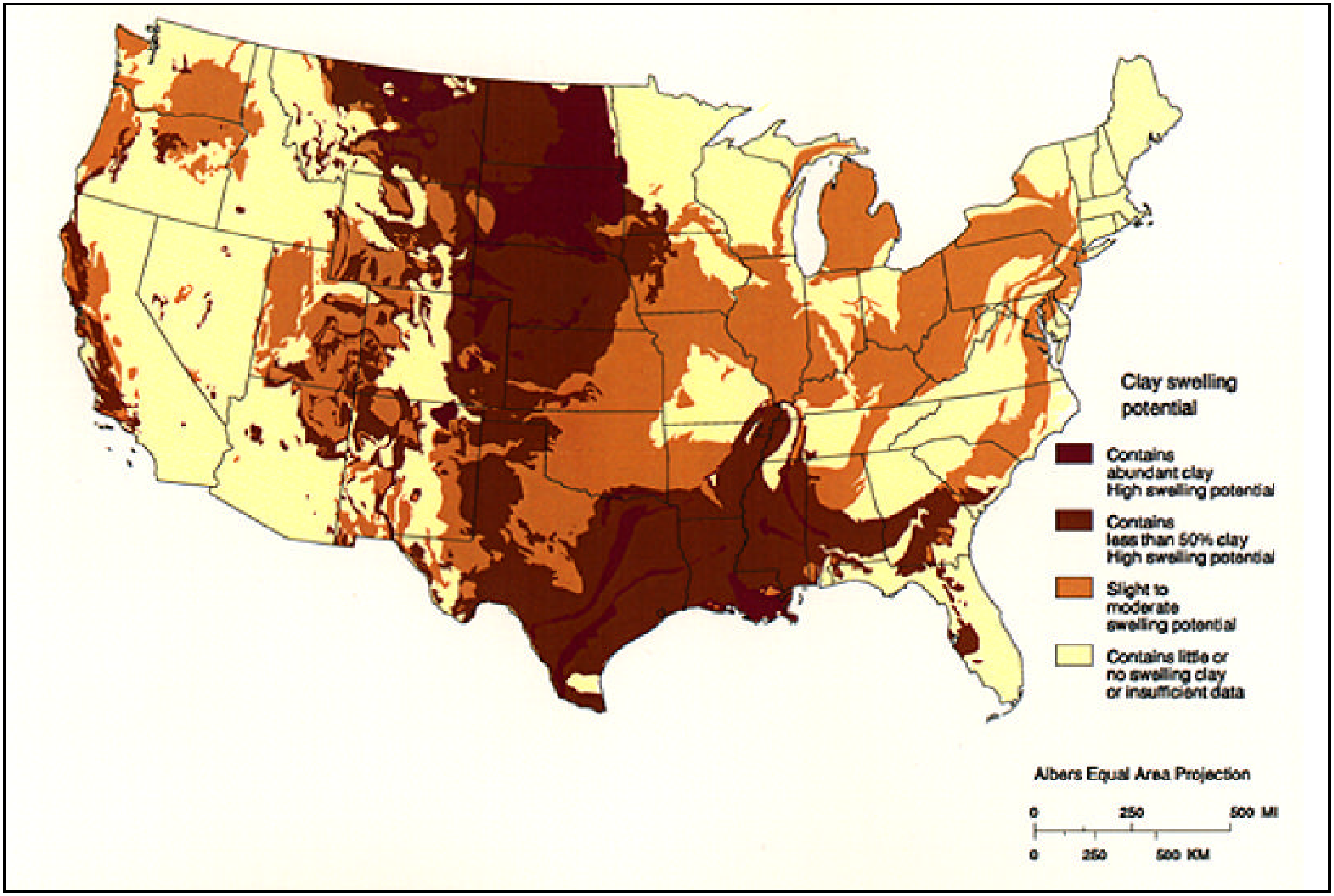
Buildings are capable of withstanding even less differential movement before structural damage occurs. Generally, a differential movement of 0.25 in (0.61 cm) between adjacent columns will cause cracking in load-bearing walls of a 20-ft wide (6-m wide) bay. With differential movement of 1.5 in (3.7 cm) over a span of 20 ft (6 m), beams are likely to be structurally damaged (Skempton and McDonald, 1956).

Houses and one-story commercial buildings are more apt to be damaged by the expansion of swelling clays than are multi-story buildings, which usually are heavy enough to counter swelling pressures. However, if constructed on wet clay, multi-story buildings may be damaged by shrinkage of the clay if moisture levels are substantially reduced, such as by evapotranspiration or by evaporation from beneath heated buildings.

The most obvious manifestations of damage to buildings are sticking doors, uneven floors, and cracked foundations, floors, walls, ceilings, and windows. If damage is severe, the cost of repair may exceed the value of the building.

Probably the greatest amount small building damage has impacted those constructed when clays were dry, such as during a drought, followed by soaking rains that prompt swelling of clays. Other reported cases of damage involve volume increases due to moisture from broken or leaking water and sewer lines, watering of lawns and shrubbery, and modifications of the surface that produce ponding (Olive and others, 1989).

Jones and Holtz (1973) estimated the total annual expansive soil-related damage throughout the United States to be just under $2.5 billion (Table 11-1). This study represents a conservative estimate of the total damage attributed to expansive soils. Many problems are not recognized as being expansive-soil related or may be considered nuisances and not repaired. Also, these figures probably do not reflect the increased costs attributed to over-design of structures in areas either highly or moderately at risk for expansive soil problems (Wiggins and others, 1978).



Map 11-1. Clay swelling potential.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Olive and others, 1989.*

According to Jones and Holtz, the greatest amount of damage from expansive soils is to highways and streets. In response to a questionnaire submitted to highway departments in 48 States, Puerto Rico, and the District of Columbia, 36 departments acknowledged the occurrence of swelling clays. Nineteen departments ". . . recognize swelling soils as part of their pavement design criteria" (Lamb and Hanna, 1973). According to Lytton (1974), ". . . general pavement roughness . . . due to swelling clays, is one of the most costly single elements in any pavement design."

For all types of building construction, Jones and Holtz (1973) estimated annual losses of $740 million. Furthermore, it was reported that of the more than 250,000 homes built each year on expansive soils, 10 percent sustain significant damage during their useful lives, some beyond repair, and 60 percent sustain minor damage.

TABLE 11-1.—*Estimated annual soil-related damage costs*

Location	Cost
Single-family homes	$300,000,000
Commercial building	$360,000,000
Multi-story buildings	$80,000,000
Walks, driveways, parking areas	$110,000,000
Highways and streets	$1,140,000,000
Buried utilities and services	$100,000,000
Airport installations	$40,000,000
Involved in urban landslides	$25,000,000
Other	$100,000,000
TOTAL	$2,255,000,000

Source: *From Jones and Holtz, 1973*

Wiggins and others (1978) estimated that the 1970 nationwide damage to single and multi-family dwellings totaled $1.13 billion. Their estimate was based on: an expansive soils map; data on damage to single-family foundations in Dallas County, TX, and in California located in high, moderate, and low expansive soil zones; and a breakdown by soil zone and State of the population living in single and multi-family dwellings.

These estimates are significantly higher than the $740 million annual losses for all types of buildings made by Jones and Holtz (1973). Using projections in population, Wiggins estimated that the total losses to all types of building will be on the order of $2.7 billion by the year 2000 (expressed in 1970 dollars). Adjusted for inflation, this value would be over $10 billion in 1995 dollars. More recent estimates of annual damages from expansive soils are as high as $7 billion (Krohn and Slosson, 1980).

MITIGATION APPROACHES

The best means to prevent or reduce damage from expansive soils is avoidance. When other choices are not possible, engineering practices are necessary (Hays, 1981). The most commonly applied engineering practices are removal of the soil, application of heavy loads, preventing access to water, presetting, and stabilization.

Removal of expansive soils and replacement with non-expansive soils is sometimes possible. Usually, expansive soils extend to such a great depth that complete removal and backfill are not economical. Although most engineering problems occur due to moisture changes in the first 10 feet of soil depth, the amount of excavation and backfill needed to prevent the occurrence of destructive volume change is site specific. Backfill with non-expansive material must be of sufficient depth to provide the necessary weight to resist the uplift of the surrounding expansive soil.

Swelling can be prevented by loading an expansive soil so that the confining pressure is greater than the swelling pressure developed by the soil. Loads can be applied to a foundation soil by means of an embankment or blanket of non-expansive soil or by construction of large buildings.

Water entering expansive soils is usually surface water that moves downward. In semiarid areas, water often moves upward from the groundwater table by means of capillary flow. Methods for isolating expansive soils from moisture include installation of ditches or pipes to carry away surface water, use of sand and gravel to break the continuity of capillary flow, and enveloping expansive soil masses with impermeable membranes.

Concrete slabs and bituminous pavements on clay soils in semiarid areas inhibit the normal evaporation of capillary water, increasing the moisture content near the surface. The potential for damage can be reduced by presetting the underlying soils to the moisture contents expected while the slab and pavement are in service.

Chemical stabilization has been used successfully to prevent or minimize volume change of expansive soils.

The ionic character of the soil and water combination can be modified by the addition of certain chemicals, such as hydrated lime, to prevent volume change. This approach is based on studies that show that the ionic character of water has a major effect on volume change.

RECOMMENDATIONS

In contrast to earthquakes and landslides, expansive soil hazards are slow to develop and do not usually pose risks to public safety. Because of low visibility, this hazard has received relatively little attention in proportion to the projected annual damage.

Considerable data on swelling soils exist from construction in and around certain metropolitan areas, at dam sites, and other areas of construction of critical facilities. These data could be used to develop more quantitative methods of estimating the potential of future damage from expansive soils.

In areas where expansive soils create significant problems, procedures for control of new construction could be instigated in grading and building regulations, including proper slab design and emplacement procedures. Structural damage due to expansive soils is not covered by most insurance.

BIBLIOGRAPHY AND REFERENCES

Bates, R.L., and J.A. Jackson (Eds). 1980. ***Glossary of Geology.*** 2nd Edition. Washington, DC: American Geological Institute.

Building Research Advisory Board, National Research Council. 1968. "Criteria for Selection and Design of Residential Slab-on-ground." ***Federal Highway Administration Report No. 33.*** National Academy of Sciences Publication No. 1571.

Gromko, G.J. 1974. "Review of Expansive Soils." ***Journal of the Geotechnical Engineering Division.*** American Society of Civil Engineers. Vol. 100, No. GT6, pp. 667-687.

Hamilton, J.J. 1963. "Volume Changes in Undisturbed Clay Profiles in Western Canada." ***Canadian Geotechnical Journal.*** Vol. 1, No. 1, pp. 27-42.

Hays, W.W. (Ed). 1981. ***Facing Geologic and Hydrologic Hazards: Earth-Science Considerations.*** U.S. Geological Survey Professional Paper 1240-B.

Jones, D.E., and W.G. Holtz. 1973. "Expansive Soils—the Hidden Disaster." ***Civil Engineering.*** Vol. 43, No. 8, pp. 49-51.

King, P.B., and H.M. Beikman. 1974. ***Geologic Map of the United States (Exclusive of Alaska and Hawaii).*** Scale 1:2,500,000. U.S. Geological Survey.

Krohn, J.P., and J.E. Slosson. 1980. "Assessment of Expansive Soils in the United States." ***Proceedings of the Fourth International Conference on Expansive Soils.*** Volume 1, pp. 596-608.

Lamb, D.R., and S.J. Hanna. 1973. ***Summary of Proceedings of Workshop on Expansive Clays and Shales in Highway Design and Construction.*** Prepared for the Federal Highway Administration, Report No FHWA-RD-073-72. Washington, DC: U.S. Government Printing Office.

Lytton, R.L. 1974. "Expansive Clay Roughness in the Highway Design System in Active Clays in Engineering and Construction Practice." ***Association of Engineering Geologists Bulletin.*** Vol. 11, No. 4, pp. 399-419.

Olive, W.W., A.F. Chleborad, C.W. Frahme, J. Shlocker, R.R. Schneider, and R.L. Schuster. 1989. ***Swelling Clays Map of the Conterminous United States.*** U.S. Geological Survey Map I-1940.

Patrick, D.M., and D.R. Snethen. 1976. ***Expansive Earth Materials— a Survey by Physiographic Areas of Their Occurrence and Distribution.*** Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station.

Seed, H.G., R.J. Lundgren, Jr. 1962. "Prediction of Swelling Potential for Compacted Clays." ***Journal of Soil Mechanics and Foundations Division.*** American Society of Civil Engineers. Vol. 88, No. SM3, pp.53-87.

Skempton, A.W., and D.H. McDonald. 1956. "The Allowable Settlement of Buildings." ***Institute of Civil Engineers Proceedings.*** Vol. 5, Pt. 3, pp. 727-784.

Sowers, G.F., and C.M. Kennedy. July 1967. "High Volume Change Clays of the Southeastern Coastal Plain." ***Pan American Conference on Soil Mechanics and Foundations Engineering, 3rd (Caracas). Proceedings: Socieded Venezolana de Mecanica del Sueloe Ingeneria de Fundaciones.*** Vol. 2, pp. 99-120.

Wiggins, J.S., J.E. Slosson, and J.P. Krohn. 1978. ***Natural Hazards: Earthquake, Landslide, Expansive Soil Loss Models.*** Institute of Behavioral Science. the University of Colorado, Boulder, CO.

Williams, A.A.B. 1965. "The Deformation of Roads Resulting from Moisture Changes in Expansive Soils in South Africa." ***Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas—A Symposium in Print*** (Aitchison, G.D., ed.). Sydney, Australia: Butterworths.

Subpart C

HYDROLOGIC

HAZARDS

Introduction

Water-related damage caused by flooding along rivers and coasts in the United States accounts for over 75 percent of Federal disaster declarations. With annual costs averaging billions of dollars, focus on the identification and assessment of risk and exposure to hydrologic hazards is critical to the national strategy for building safer communities. Unwise development in floodplains increases potential risks and damage due to future hydrologic events.

Hydrologic hazards include floods, storm surges, coastal erosion, and droughts. It is important to understand the interrelationship of hydrologic hazards with other hazard groups. For example, extreme rainfall from a thunder and lightning event can cause flooding, and winds from a tropical cyclone can exacerbate storm surge and coastal erosion. The discussions address the influences of other hazards on the frequency of occurrence and damage from hydrologic hazards.

CHAPTER

12

FLOODS

Chapter Summary

Hundreds of floods occur each year in the United States, including overbank flooding of rivers and streams and shoreline inundation along lakes and coasts. Flooding typically results from large-scale weather systems generating prolonged rainfall or on-shore winds. Other causes of flooding include locally intense thunderstorms, snowmelt, ice jams, and dam failures. Flash floods, which are characterized by rapid on-set and high velocity waters, carry large amounts of debris. Floods are capable of undermining buildings and bridges, eroding shorelines and riverbanks, tearing out trees, washing out access routes, and causing loss of life and injuries.

Floods occur in all 50 States and in the U.S. territories. FEMA estimates that over 9 million households and $390 billion in property are at risk from flooding. The States with the greatest exposure to this hazard (based on a composite risk score that accounts for floodplain area and number and value of households) are Florida, California, Texas, Louisiana, and New Jersey. While the number of deaths remained fairly constant at an annual average of 125 people per 200 million population, property damage for the period from 1951 to 1985 escalated to roughly $2.15 billion a year.

The costliest flood disaster in U.S. history was the 1993 event in the Upper Mississippi River Basin which affected nine Midwestern States. As many as 47 people lost their lives, and damage totaled an estimated $12 to 16 billion, including agricultural losses.

The National Flood Insurance Program (NFIP), administered by FEMA, has been the most dominant influence on floodplain management during the past 25 years. In addition to providing affordable flood insurance, FEMA performs flood-risk studies and prepares maps of flood hazard areas. Communities that join the NFIP agree to manage designated special flood hazard areas to minimize future damage through zoning and building standards.

In addition to land-use planning and codes applicable to new development, mitigation measures include structural and non-structural measures to address susceptibility of development that pre-dates the NFIP. An important element of U.S. efforts to improve preparedness and reduce flood damage involves flood warnings and forecasts by the National Weather Service and others.

Photo: Red Cross

HAZARD IDENTIFICATION

Flooding is defined as the accumulation of water within a water body and the overflow of excess water onto adjacent floodplain lands. The floodplain is the land adjoining the channel of a river, stream, ocean, lake, or other watercourse or water body that is susceptible to flooding.

According to the Federal Interagency Floodplain Management Task Force, flooding in the United States can be separated into several types (L.R. Johnson Associates, FIA-18, 1992):

- Riverine flooding, including overflow from a river channel, flash floods, alluvial fan floods, and ice-jam floods.
- Riverine flooding includes dam-break floods (Chapter 20);
- Local drainage or high groundwater levels;
- Fluctuating lake levels;
- Coastal flooding, including storm surges (Chapter 13) and tsunamis (Chapter 17);
- Debris flows (Chapter 9); and
- Subsidence (Chapter 10).

Riverine Flooding. Overbank flooding of rivers and streams is the most common type of flood event. Riverine floodplains range from narrow, confined channels in the steep valleys of hilly and mountainous areas, and wide, flat areas in the Plains States and low-lying coastal regions. The volume of water in the floodplain is a function of the size of the contributing watershed and topographic characteristics such as watershed shape and slope, and climatic and land-use characteristics.

In steep, narrow valleys, flooding usually occurs quickly, is of short duration, and floodwaters are likely to be rapid and deep. In relatively flat floodplains, areas may remain inundated for days or even weeks, but floodwaters are typically slow-moving and relatively shallow, and may accumulate over long periods of time.

Flooding in large rivers usually results from large-scale weather systems that generate prolonged rainfall over wide areas. These same weather systems may cause flooding in hundreds of smaller basins that drain to major rivers. Small rivers and streams are susceptible to flooding from more localized weather systems that cause intense rainfall over small areas. In some parts of the Northern and Western States, annual spring floods result from snowmelt, and the extent of flooding depends on the depth of winter snowpack and spring weather patterns.

There is often no sharp distinction between riverine floods, flash floods, alluvial fan floods, ice-jam floods, and dam-break floods that occur due to structural failures or overtopping of embankments during flood events. Nevertheless, these types of floods are widely recognized and helpful in considering not only the range of flood risk but also appropriate responses.

Flash Floods. "Flash flood" is a term widely used by flood experts and the general population. However, there is no single definition, and a clear means to separate flash floods from the rest of the spectrum of riverine floods does not exist.

Flash floods are characterized by a rapid rise in water level, high velocity, and large amounts of debris. They are capable of tearing out trees, undermining buildings and bridges, and scouring new channels. Major factors in flash flooding are the intensity and duration of rainfall and the steepness of watershed and stream gradients. The amount of watershed vegetation, the natural and artificial flood storage areas, and the configuration of the stream bed and floodplain are also important.

Flash floods may result from the failure of a dam or the sudden breakup of an ice jam. Both can cause the release of a large volume of water in a short period of time. Flash flooding in urban areas is an increasingly serious problem due to removal of vegetation, paving and replacement of ground cover by impermeable surfaces that increase runoff, and construction of drainage systems that increase the speed of runoff.

Alluvial Fan Floods. Alluvial fans are deposits of rock and soil that have eroded from mountainsides and accumulated on valley floors in a fan-shaped pattern. The deposits are narrow and steep at the head of the fan, broadening as they spread out onto the valley floor. As rain runs off steep valley walls, it gains velocity, carrying large boulders and other debris. When the debris fills channels on the fan, floodwaters spill out and cut new channels. The process is then repeated, resulting in shifting channels and combined erosion and flooding problems over a large area (FEMA 165, 1989). Alluvial fan flooding is most prevalent in the arid Western States.

Alluvial fan floods can cause greater damage than typical riverine flooding because of the high velocity of flow, the amount of debris carried, and the broad area affected. Floodwaters typically move at velocities of 15 to 30 ft/s (5 to 10 m/s) due to steep slopes and lack of vegetation (L.R. Johnson Associates, FIA-18, 1992).

Human activities often exacerbate flooding and erosion problems on alluvial fans. Roads act as drainage channels, carrying high-velocity flows to lower portions of the fan, while fill, leveling, grading, and structures can alter flows patterns (FEMA 116, 1987).

Ice Jam Floods. Flooding caused by ice jams is similar to flash flooding. Ice jam formation causes a rapid rise of water at the jam and extending upstream. Failure or release of the jam causes sudden flooding downstream.

The formation of ice jams depends on the weather and physical conditions in river channels. Ice jams are most likely to occur where the channel slope naturally decreases, where culverts freeze solid, at headwaters of reservoirs, at natural channel constrictions such as bends and bridges, and along shallows where channels may freeze solid (FEMA 116, 1987).

Ice jam floods can occur during fall freeze-up from the formation of frazil ice, during midwinter periods when stream channels freeze solid forming anchor ice, and during spring breakup when rising water levels from snowmelt or rainfall break existing ice cover into large floating masses that lodge at bridges and other constrictions. Damage from ice jam flooding usually exceeds that caused by open water flooding. Flood elevations are usually higher than predicted for free-flow conditions and water levels may change rapidly. Additional physical damage is caused by the force of ice impacting buildings and other structures (FEMA 116, 1987).

Dam Break Floods. Dam failures can occur as a result of structural failures, such as progressive erosion of an embankment or overtopping and breaching by a severe flood. Earthquakes may weaken dams. Disastrous floods caused by dam failures, although not in the category of natural hazards, have caused great loss of life and property damage, primarily due to their unexpected nature and high velocity floodwater. A more detailed discussion of the effects of dam failures is in Chapter 20.

Local Drainage or High Groundwater Levels. Locally heavy precipitation may produce flooding in areas other than delineated floodplains or along recognizable drainage channels. If local conditions cannot accommodate intense precipitation through a combination of infiltration and surface runoff, water may accumulate and cause flooding problems. During winter and spring, frozen ground and accumulations of snow may contribute to inadequate drainage and localized ponding. Flooding problems of this nature generally occur in areas with flat gradients, and generally increase with urbanization which speeds the accumulation of floodwaters because of impervious areas. Shallow sheet flooding may result unless channels have been improved to account for increased flows.

High groundwater levels may be of concern and can cause problems even where there is no surface flooding. Basements are susceptible to high groundwater levels. Seasonally high groundwater is common in many areas, while in others high groundwater occurs only after long periods of above-average precipitation.

Fluctuating Lake Levels. Water levels in U.S. lakes can fluctuate on a short-term, seasonal basis, or on a long-term basis over periods of months or years. Heavy seasonal rainfall can cause high lake levels for short periods of time, and snowmelt can result in higher spring levels. Long-term fluctuations are a less-recognized phenomenon that can cause high water and subsequent flooding problems lasting for years or even decades.

While all lakes may experience fluctuations, water levels tend to vary the most in lakes that are completely landlocked or have inadequate outlets for maintaining a balance between inflow and outflow. These lakes, commonly referred to as closed-basin lakes, are particularly susceptible to dramatic fluctuations in water levels over long periods of time, as much as 5 to 15 ft (1 to 3 m).

The Great Salt Lake in Utah, the Salton Sea in California, and Devils Lake in North Dakota are notable closed-basin lakes. The Great Lakes are examples of lakes with inadequate outlets under extreme high water conditions. The "playa" or drainage lakes in the Western and Southwestern States, and sinkhole lakes in Florida, are subject to long-term fluctuations that are similar to closed-basin lakes.

RISK ASSESSMENT

For many years, the Federal Government has provided guidance and has been involved in risk assessment of flood hazards. By the early 1960s, the Tennessee Valley Authority (TVA) and the U.S. Army Corps of Engineers (USACE) were involved heavily in floodplain management studies. Recognizing the need for standardization among Federal, State and local agencies, they agreed on the 100-year, or 1-percent-annual-chance, flood as the standard for floodplain management purposes (FEMA, 1983).

The NFIP was authorized by the U.S. Congress with the enactment of the National Flood Insurance Act of 1968. Under the NFIP, flood insurance is made available at rates that are intended to be affordable in return for community adoption of ordinances to regulate development in mapped flood hazard areas. The U.S. Department of Housing and Urban Development (HUD) was designated to administer the program.

HUD convened a group of experts to advise on the best standards for risk assessment and management. The group recommended the 100-year, or "base" flood standard, which was adopted for the NFIP. The 100-year, or 1-percent-annual-chance event, was deemed to represent a degree of risk and damage worth protecting against, but was not considered to impose stringent requirements or burdens of excessive cost on property owners (FEMA, 1983).

During hearings prior to passage of the Flood Disaster Protection Act of 1973, the Senate Committee on Banking, Housing, and Urban Affairs heard arguments on both sides of the issue regarding the appropriateness of the 100-year flood standard. Several witnesses advocated a proposal to apply a lesser standard, and some recommended the use of the greatest flood of record.

HUD pointed out that the 100-year flood represents a compromise between minor floods and the greatest flood likely to occur in a given area, that the highest recorded flood level reflects what has happened rather than what could happen, and that in many cases the 100-year flood level is less than the flood of record. After considering the statements of all interested parties, the Senate Committee concluded that the 100-year flood standard was reasonable and consistent with national objectives for reducing flood losses (FEMA, 1983).

The 1-percent-annual-chance flood and the associated floodplain have been widely adopted as the common design and regulatory standard in the United States. The 1-percent-annual-chance flood was established formally as a standard for use by Federal agencies with the issuance of Executive Order for Floodplain Management, E.O. 11988, in 1977 (L.R. Johnson Associates, FIA-18, 1992). At the request of the Office of Management and Budget, in 1982 FEMA reviewed the appropriateness of the standard and recommended that it be retained and used as the minimum for flood hazard reduction actions (FEMA, 1983).

Probability and Frequency

Released in 1966, House Document No. 465, *A Unified National Program for Managing Flood Losses*, provided the impetus for the development of a uniform technique for determining flood flow frequency, and for a national floodplain management program. The U.S. Water Resources Council (USWRC) was directed to develop accurate and consistent procedures for flood flow frequency analyses.

In 1967, USWRC published Bulletin 15, *A Uniform Technique for Determining Flood Flow Frequencies*,(USWRC, 1967; Benson, 1967). The techniques presented were adopted by USWRC for use in all Federal planning involving water and related land resources. USWRC recommended that State and local governments and private organizations use the same techniques. The techniques included the fitting of the Pearson Type III frequency distribution to the logarithms of recorded annual peak flows to determine floods of different probability and frequency.

Bulletin 15 was updated several times: Bulletin 17 (USWRC, 1976), Bulletin 17A (USWRC, 1977a), and Bulletin 17B (USWRC, 1981). Editorial corrections were made to Bulletin 17B in 1982, and it was republished by the Interagency Advisory Committee on Water Data (IACWD) when the USWRC was disbanded in 1982. Thomas (1985) provided a description of the development of Bulletin 17 and subsequent revisions.

Bulletin 17B (IACWD, 1982) is used by practically all government agencies undertaking flood flow frequency and floodplain mapping studies. The guidelines include the addition of analytical procedures for identifying and adjusting for low and high outliers, incorporating historic information, and weighting station and generalized skew.

For streams with recorded annual peak flows, the 10-, 2-, 1- and 0.2-percent-annual-chance (10-, 50-, 100-, and 500-year) floods are determined using Bulletin 17B procedures. The flood discharges are used in evaluating flood hazards for the NFIP, with the 1-percent-annual-chance flood used as the base flood for regulatory purposes. At least 10 years of recorded annual peak flows are needed for frequency analysis (IACWD, 1982). For streams where there are no recorded annual peak flows, the 10-, 2-, 1-, and 0.2-percent-annual-chance floods are estimated by regional regression equations based on watershed and climatic characteristics or watershed models (FEMA 37, 1995).

The water depths and areas inundated by the 1- and 0.2-percent annual chance floods are determined through the use of hydraulic models that reflect topographic characteristics. Most often, a one-dimensional, steady-state model (a step-backwater model) is used to convert

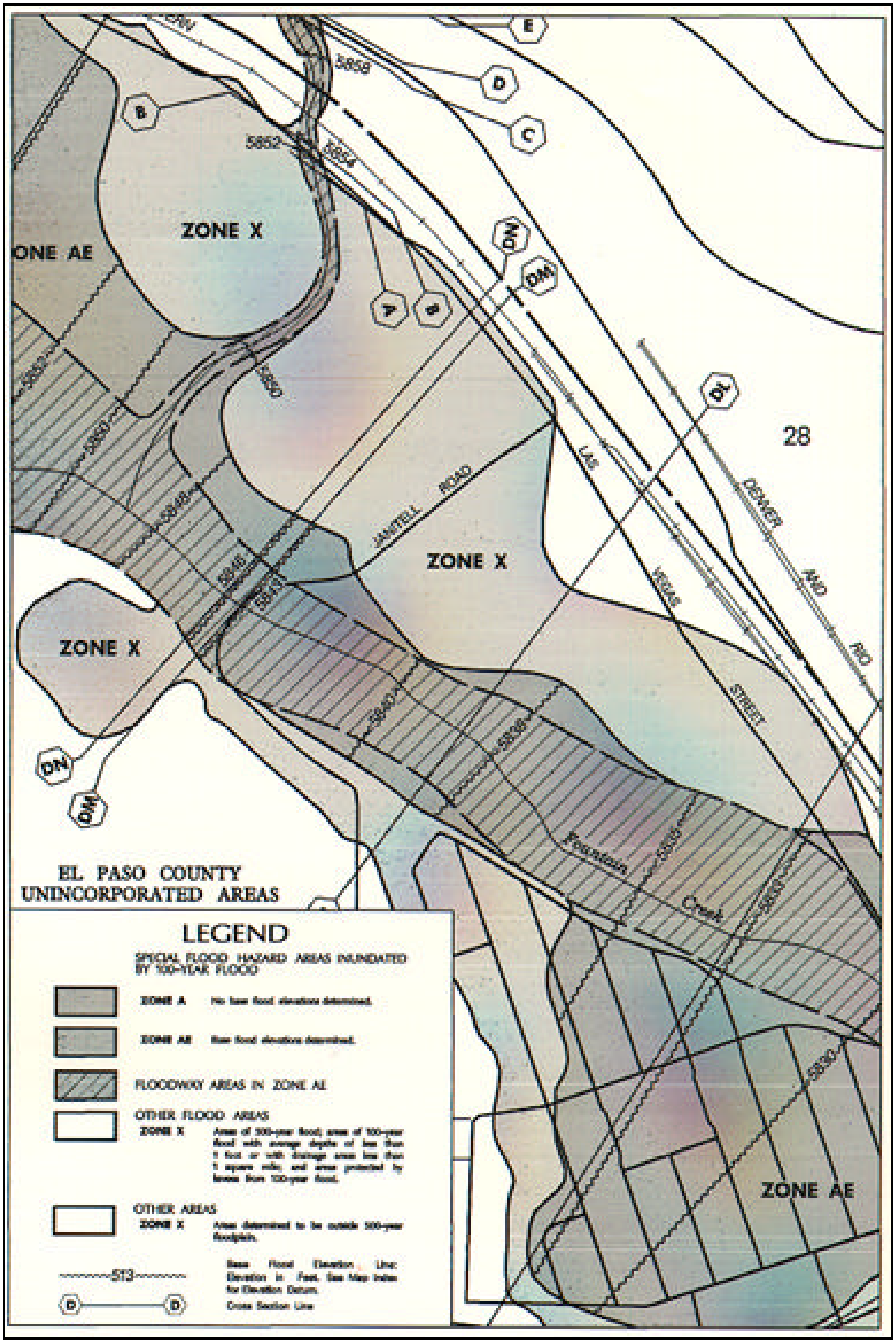


FIGURE 12-1.—Example of Digital Flood Insurance Rate Map, El Paso County, CO.

Source: *Federal Emergency Management Agency.*

flood discharges to water surface elevations. Occasionally, more complex one-dimensional, unsteady-state models, two-dimensional models, or sediment-transport models are used. FEMA provides guidelines to compute flood discharges and to convert them to water surface elevations using hydraulic models (FEMA 37, 1995).

Computed water surface elevations are combined with topographic mapping data to develop flood hazard maps, termed Flood Insurance Rate Maps (FIRMs). FIRMs are produced using traditional cartographic practices and digital techniques. An example of a FIRM panel, adapted from the digital map for El Paso County, CO and Incorporated Areas, is shown in Figure 12-1. The FIRM illustrates:

- Areas inundated by the 1-percent-annual-chance flood where water surface elevations or water depths are computed by hydraulic models (Zone AE);

- Areas inundated by the 1-percent-annual-chance flood for which flood elevations are not determined by hydraulic models (Zone A)

- Floodway areas (cross-hatched areas);

- Elevations of the 1-percent-annual-chance flood, also known as base flood elevations;

- Areas inundated by the 0.2-percent-annual-chance flood, areas of the 1-percent-annual-chance flood with average depths of less than 1 foot or with drainage areas less than 1 square mile, and areas protected by levees from the 1-percent-annual-chance flood;

- Areas outside the 0.2-percent-annual-chance flood (Zone X); and

- Locations of cross sections used to develop the hydraulic model.

The floodway is defined as the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the 1-percent-annual-chance flood without cumulatively increasing the water surface elevation by more than a designated height, usually 1.0 ft (0.3 m). Floodway development is regulated to strict standards, and the delineation should be retained by the community whenever possible.

The inundation areas for Zone A generally are determined by approximate study methods such as depth-frequency relations, normal-depth or slope-conveyance computations, reduced number of cross sections in a step-backwater model, or inundation patterns of historical floods that approximate the 1-percent-annual chance flood (Cobb, 1985). Base flood elevations are not provided in Zone A.

FIRMs provide information on areas subject to flooding. They are used to guide future development away from flood-prone areas and to regulate development that is proposed to occur within such areas. FIRMs are used by insurance agents to assign flood insurance rates.

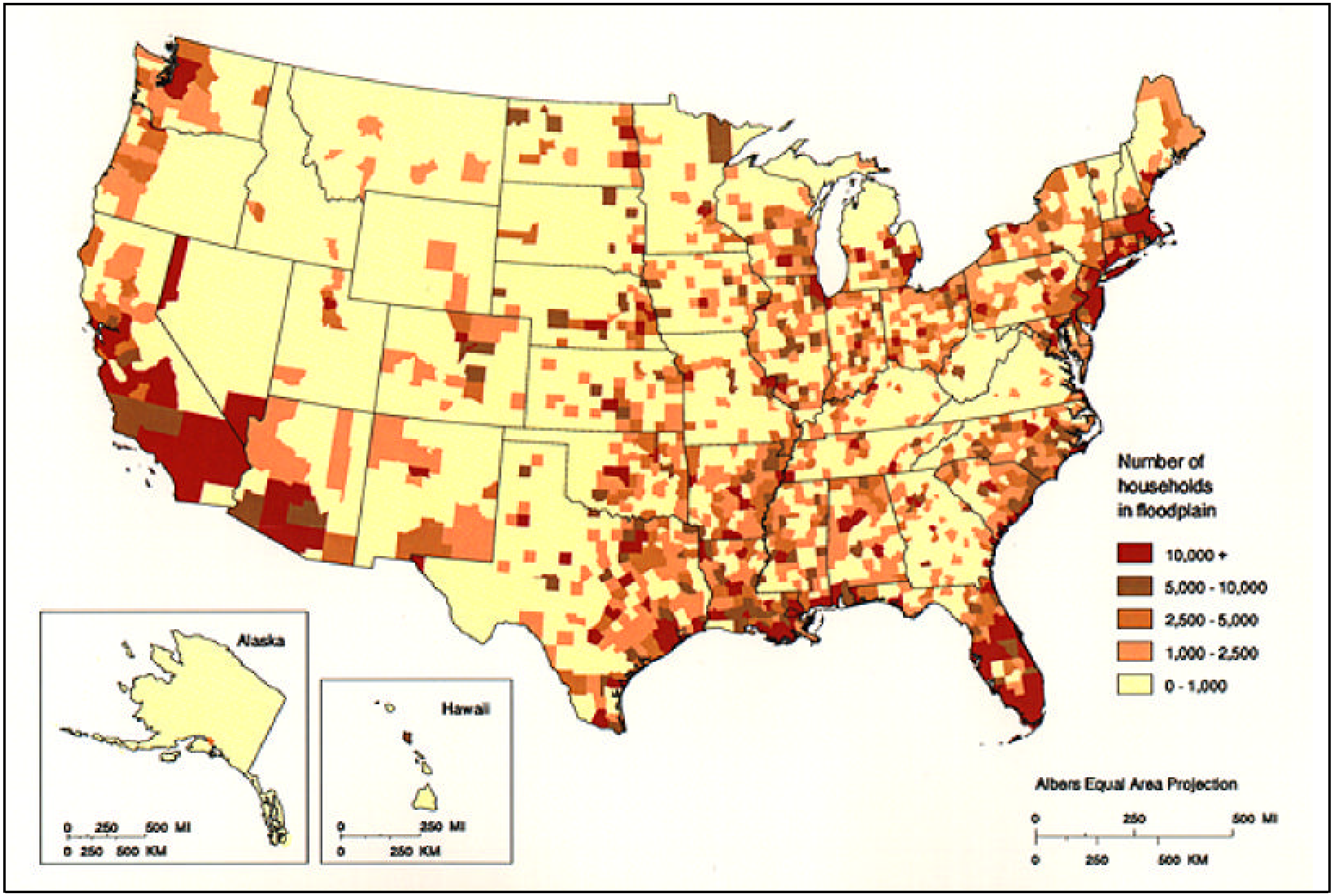
Exposure

Floods occur in all 50 States and the U.S. territories. Several studies estimate the land area subject to flooding in the United States (USWRC, 1977b; SCS, 1982; Donnelley, 1987). In a refinement of the 1987 Donnelley study, FEMA estimated that over 146,000 mi^2 (236,000 km^2), or more than 4 percent of the total area of the 50 States and the District of Columbia, are in the 1-percent-annual-chance floodplain.

FEMA indicated that the States with the most land area subject to flooding by the 1-percent-annual-chance flood are Texas, Louisiana, Florida, and Arkansas. In terms of percentage of a State's total land area, the States with the most flood-prone lands are Louisiana, Florida, Arkansas, and Mississippi. These figures are based on an examination of approximately 17,500 communities that have FIRMs (Donnelley, 1987). Therefore, the data are limited by the extent of floodplain mapping within each State. The floodplain acreages do not include remote areas for which NFIP maps are not printed, most floodplains with drainage areas less than 1 mi^2, and areas subject to flooding from local drainage.

Using the 1987 Donnelley study, FEMA concluded that over 9 million households and $390 billion in property are at risk from the 1-percent-annual-chance flood. Based on a composite risk score accounting for floodplain area and the number and value of households, Florida ranked as the State with the highest risk, followed by California, Texas, Louisiana, and New Jersey. Map 12-1 shows the estimated distribution by county of households in the 1-percent-annual-chance annual floodplain.

The Federal Insurance Administration reported at the end of 1994 that 18,561 of over 20,000 flood-prone communities were participating in the National Flood Insurance Program and administering floodplain management ordinances. In those communities, over 2.8 million flood insurance policies were in effect, providing financial protection in the event of flood damage.



Map 12-1. Geographic distribution by county of households in the United States in the 1-percent-annual-chance floodplain. Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Donnellay and FEMA, 1987.*

Consequences

Reasonably good information is available for the great floods that have caused serious loss of life or major property damage. However, equivalent information frequently is not available for the multitude of smaller flood events that occur each year but that do not prompt Federal response.

Interpretation of flood loss data is difficult, and estimates are not necessarily comparable due to differences in reporting flood losses and in adjusting dollar amounts to reflect changes in monetary values, as well as other problems in coordinating data sources (e.g., Federal versus non-Federal outlays). The most comprehensive source of annual flood loss data is prepared by NWS.

Flash floods pose more significant safety risks than other riverine floods because of the rapid onset, the high velocity of water, the potential for channel scour, and the debris load. In addition, more than one flood crest may result from a series of fast moving storms. Sudden destruction of structures and washout of access routes may result in loss of life. A high percentage of flood-related deaths are caused by motorists who underestimate the depth and velocity of floodwaters and attempt to cross swollen streams (FEMA 116, 1987).

Since 1902, NWS has compiled annual estimates of the number of lives lost and flood damage, excluding losses to agriculture. To provide data to the U.S. Congress by January of each year, the NWS damage estimates are produced immediately after the close of the Federal fiscal year on September 30 and are not revised to reflect damage figures for floods that occurred close to that date, or information that may be more accurate or complete. Despite known problems with the NWS data, they provide the most complete and consistent information over the longest period of record. While detailed analysis may be misleading, gross trend analyses are considered to be reasonably accurate.

Examination of flood-related deaths recorded by NWS does not indicate a trend once the numbers are adjusted for population changes. For the period from 1916 to 1989, the adjusted average annual deaths (per 200 million population) is 125. During the 25-year period from 1916 through 1940, there was an adjusted average of 154 deaths per year; during the period from 1941 through 1965, the average was 86; and during the period from 1966 through 1985, the average was 145. Given the impact on number of deaths that one or two catastrophic events can produce, there is no indication that flood-related deaths are increasing or decreasing on a per capita basis (L.R. Johnson Associates, FIA-18, 1992).

For the period 1916 to 1989, there has been a definite increase in flood damage. With adjustment for population and inflation, the average annual damage was $902 million for the 1916-to-1950 period, and $2.15 billion for the 1951-to-1985 period. In other words, annual flood damage was almost 2.5 times more during the latter period.

The most costly flood disasters in U.S. history were the 1993 floods in the Upper Mississippi River Basin. They were caused by a series of storms from April to September and affected parts of nine Midwestern States. The damage was estimated to be between $12 and $16 billion, with 38 to 47 flood-related deaths. Between $4 and $5 billion of the total damage is attributed to agricultural losses in upland areas (Interagency Floodplain Management Review Committee, 1994).

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Flood Frequency Research. Considerable research has been devoted to investigating the most appropriate frequency distribution and fitting method for flood-frequency analyses (Stedinger and others, 1993). Different frequency distributions and fitting methods have been suggested as superior to the Pearson Type III frequency distribution, which has been used widely for many years.

Thomas and others (1995) summarize the commonly-used frequency distributions and fitting methods and compare frequency estimates for flood data in the United States and Japan. They concluded that there are differences in the estimates yielded by various methods, but the differences are generally less than 20 percent.

From 1985 to 1987, the Interagency Committee on Water Data conducted a survey of all Federal agencies to identify problems or deficiencies in the Bulletin 17B guidelines. The results indicated that Bulletin 17B techniques are generally sound, that no substantial problems had been identified that could not be resolved by means included in the guidelines, and that no clearly superior alternative had emerged (Thomas, 1992). The survey did find that problems are sometimes encountered, and it was recommended that a new work group be formed to provide supplemental guidance to solve the problems.

Flood Warnings and Forecasts. Important elements in the U.S. program to reduce flood damage include flood warnings and forecasts. Timely warnings and forecasts save lives and aid disaster preparedness, which decreases property damage by an estimated $1 billion annually (Mason and Weiger, 1995).

NWS is the Federal agency responsible for weather forecasting and warning, and is charged by law with issuing river forecasts and warnings. USGS operates and maintains more than 85 percent of stream-gaging stations nationwide, including 98 percent of gages used for real-time forecasting. The USGS network comprises approximately 7,300 stations dispersed throughout the United States, 4,200 of which are equipped with earth-satellite radios to provide real-time communications. NWS uses data from 3,971 stations to forecast river depth and flow conditions at 4,017 forecast-service locations on major rivers and small streams in urban areas (Mason and Weiger, 1995).

New radar technologies, improved river forecast models, computer visualization, automated data transmission, and improved data collection techniques hold significant promise for improving the timeliness and accuracy of flood forecasts and warnings. However, ground-based verification of river discharges and rainfall will still be needed when new technologies are in place. Recent federal budget reductions have led to elimination of many USGS stream gages, causing concern that the timeliness and accuracy of flood forecasts and warnings may be impaired. Lack of records for hydrologically significant events may jeopardize frequency analyses in the future.

MITIGATION APPROACHES

A Federal Interagency Floodplain Management Task Force report (L.R. Johnson Associates, FIA-18, 1992) described four basic strategies for floodplain management: modify susceptibility to flood damage and disruption; modify flooding; modify the impacts of flooding; and manage natural and cultural resources. Specific activities to meet these strategies are identified below.

Modify susceptibility to flood damage and disruption

- Acquisition and demolition, and relocation of properties in flood-prone areas
- Floodplain regulations and building codes
- Development and redevelopment policies
- Floodproofing and elevation-in-place
- Disaster preparedness and response plans
- Flood forecasting and warning systems

Modify flooding

- Construction of dams and reservoirs
- Construction of dikes, levees, and floodwalls
- Channel alterations
- High flow diversions and spillways
- Land treatment measures

Modify the impacts of flooding

- Information and education
- Flood insurance
- Tax adjustments
- Flood emergency measures
- Disaster assistance
- Post-flood recovery

Manage natural and cultural resources

- Preservation and restoration strategies
- Regulations to protect floodplain natural and cultural resources
- Development and redevelopment policies and programs
- Information and education
- Tax adjustments
- Administrative measures

RECOMMENDATIONS

Recommendations for improving floodplain management are included in the report of the Interagency Floodplain Management Review Committee (1994) and the report by Galloway (1995). The recommendations can be grouped in major categories:

- Improve coordination of Federal, State, tribal, and local responsibilities for floodplain management, including the reactivation of the Water Resources Council or a comparable over-sight organization;
- Increase post-disaster flexibility for land acquisition programs, and increase environmental attention in

Federal operation and maintenance and disaster recovery activities;

- Enhance the efficiency and effectiveness of the NFIP by improving the marketing of flood insurance, reducing the amount of post-disaster support for those who choose not to buy insurance, and providing mitigation insurance to cover the cost of elevating, demolishing, or relocating substantially damaged buildings;

- Reduce exposure to flood damage of those in the floodplain by considering permanent evacuation of flood-prone areas, flood warning, floodproofing, creation of additional natural and artificial storage, and adequately sized and maintained levees;

- Require periodic review of completed flood control projects to ensure they continue to meet intended purposes;

- Assign USACE the principal responsibility for repair, rehabilitation, and construction of levees under Federal programs;

- Ensure proper siting, construction, and maintenance of non-Federal levees by States, local jurisdictions, private entities, and tribes;

- Capitalize on successes in pre-disaster, response, recovery, and mitigation efforts during and following the 1993 flood;

- Provide timely gathering and dissemination of the critical water resources information needed for floodplain management and disaster operations by establishing an information clearinghouse at USGS; and

- Exploit science and technology to support monitoring, analysis, modeling, and the development of decision-support systems and Geographic Information System applications for floodplain activities.

BIBLIOGRAPHY AND REFERENCES

Benson, M.A. 1967. "Uniform Flood-Frequency Estimating Methods for Federal Agencies." ***Water Resources Research.*** U.S. Geological Survey. Vol. 4, No 5, pp. 891-908.

Cobb, E.D. 1985. ***Evaluation of Streams in Selected Communities for the Application of Limited Detail Study Methods for Flood-Insurance Studies.*** U.S. Geological Survey Water Resources Investigations 85-4098.

Dracup, J.A., E.D.H. Cheng, J.M. Nigg, and T.A. Schroeder. 1991. ***Natural Disaster Studies Volume One: The New Year's Eve Flood on Oahu, Hawaii—December 31, 1987-January 1, 1988.*** National Research Council, Committee on Natural Disasters, Division of Natural Hazard Mitigation, Commission on Engineering and Technical Systems.

Donnelley Marketing Information Services. 1987. ***System Update Report.*** (Prepared for FEMA.)

Federal Emergency Management Agency. 1983. ***The 100-Year Base Flood Standard and the Floodplain Management Executive Order: A Review Prepared for the Office of Management and Budget.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1987. ***Reducing Losses in High Risk Areas: A Guidebook for Local Officials.*** FEMA 116. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1989. ***Alluvial Fans: Hazards and Management.*** FEMA 165. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1995. ***Flood Insurance Study Guidelines and Specifications for Study Contractors.*** FEMA 37. Washington, DC: U.S. Government Printing Office.

Galloway, G.E. 1995. "New Directions in Floodplain Management." ***Water Resources Bulletin.*** American Water Resources Association. Vol. 31, No. 3, pp. 351-357.

Interagency Advisory Committee on Water Data. 1982. ***Guidelines for Determining Flood Flow Frequency.*** Bulletin 17B of the Hydrology Subcommittee, Department of Interior, U.S. Geological Survey, Office of Water Data Coordination. Reston, VA.

Interagency Floodplain Management Review Committee. 1994. ***Sharing the Challenge: Floodplain Management into the 21st Century.*** Administration Floodplain Management Task Force. Washington DC.

L.R. Johnson Associates. 1992. ***Floodplain Management in the United States: An Assessment Report. Vol. 2; Full Report.*** Federal Interagency Floodplain Management Task Force, FIA-18.

Mason, R.R., and B.A. Weiger. 1995. ***Stream Gaging and Flood Forecasting.*** U.S. Geological Survey Fact Sheet 209-95.

Stedinger, J.R., R.M. Vogel, and E. Foufoula-Georgiou. 1993. "Frequency Analysis of Extreme Events." ***Handbook of Hydrology***. (D. Maidment, Ed.) New York, NY: McGraw-Hill Book Co.

Thomas, W.O., Jr. 1985. "A Uniform Technique for Flood Frequency Analysis." ***Journal of Water Resources Planning and Management.*** American Society of Civil Engineers. Vol. 111, No. 3, pp. 321-337.

Thomas, W.O., Jr. 1992. ***Status of At-Site Flood-Frequency Analysis Among Federal Agencies.*** Transportation Research Record No. 1350, Transportation Research Board, National Research Council. Washington, DC: National Academy Press.

Thomas, W.O., Jr., M. Kuriki, and T. Suetsugi. 1995. "An Evaluation of Frequency Distributions and Fitting Methods for Flood Hazard Analysis." ***Proceedings of the Third PWRI-USGS Workshop on Hydrology, Water Resources and Global Climate Change.*** Public Works Research Institute of Japan. Technical Memorandum No. 3373, pp. 119-166.

U.S. Department of Agriculture, Soil Conservation Service. 1982. ***Basic Statistics, 1977 National Resources Inventory.*** Bulletin No. 686. Iowa State University Statistical Laboratory.

U.S. Water Resources Council. December 1967. ***A Uniform Technique for Determining Flood Flow Frequency.*** Hydrology Committee, Bulletin No. 15, Washington, DC.

U.S. Water Resources Council. 1976a. ***Guidelines for Determining Flood Flow Frequency.*** Bulletin 17. Washington, DC: U.S. Government Printing Office.

U.S. Water Resources Council. 1976b. ***A Unified National Program for Flood Plain Management.*** Washington, DC: U.S. Government Printing Office.

U.S. Water Resources Council. 1977a. ***Guidelines for Determining Flood Flow Frequency.*** Bulletin 17A. Washington, DC: U.S. Government Printing Office.

U.S. Water Resources Council. 1977b. ***Estimated Flood Damages. Appendix B: Nationwide Analysis Report.*** Washington, DC: U.S. Government Printing Office.

U.S. Water Resources Council. 1981. ***Guidelines for Determining Flood Flow Frequency.*** Bulletin 17B. Washington, DC: U.S. Government Printing Office.

CHAPTER
13

STORM SURGES

Chapter Summary

Storm surges associated with extratropical cyclones (nor'easters) in the North Atlantic Ocean and the Gulf of Mexico, and severe winter low-pressure systems in the North Pacific Ocean and the Gulf of Alaska are responsible for coastal flooding and erosion. The storms that generate the large waves of coastal surges can develop year-round, but they are most frequent from late fall to early spring. Hurricanes, and other tropical cyclones, also generate storm surges (Chapter 1).

The effects of storm surges were included in more than two dozen Federal disaster declarations during the past 20 years. Those declarations also included the concurrent effects of severe winds, erosion, and rainfall flooding.

The most notable storm surge events on the Atlantic Coast are the Ash Wednesday storm of 1962 and the Halloween Nor'easter of 1991. The 1962 event affected over 620 mi (1,000 km) of shoreline and caused over $300 million in damage. The entire East Coast was impacted by the 1991 event. Along the Gulf of Mexico, the Superstorm of March 1993 produced storm surge elevations greater than 10 ft (3 m) in Florida, equivalent to those associated with Category 2 hurricanes. Along the California coast, the storm surge resulting from the severe winterstorms of 1982–83 caused more than $100 million in damage.

Mitigation actions for extratropical storm surge parallel those for flooding associated with tropical cyclones and coastal erosion. Strict building codes, land-use planning, and coastal setbacks have helped limit exposure. Post-disaster mitigation efforts include buyout programs and relocation. Reduction in loss of life and injuries are attributed to extensive public awareness campaigns.

HAZARD IDENTIFICATION

Storm surges occur when the water level of a tidally influenced body of water increases above the normal astronomical high tide. Storm surges commonly occur with coastal storms caused by massive low-pressure systems with cyclonic flows that are typical of tropical cyclones, nor'easters, and severe winterstorms. Other factors influencing storm intensity are listed in Table 13-1. Storm surges generated by coastal storms are controlled by four factors (Coch 1995), described below.

- The more intense storms have higher wind speeds that drive greater amounts of water across the shallow continental shelf, thereby increasing the volume and elevation of water pushed up against the coast. In areas with mild slopes and shallow depths, the resulting flooding can reach greater heights.

- The low barometric pressures experienced during coastal storms cause the water surface to rise, increasing the height of storm surges.

- Storms landfalling during peak astronomical tides have higher surge heights and more extensive flood inundation limits.

- Coastal shoreline configurations with concave features or narrowing bays create a resonance within the area as a result of the winds forcing in water, elevating the surface of the water higher than experienced along adjacent areas of open coast.

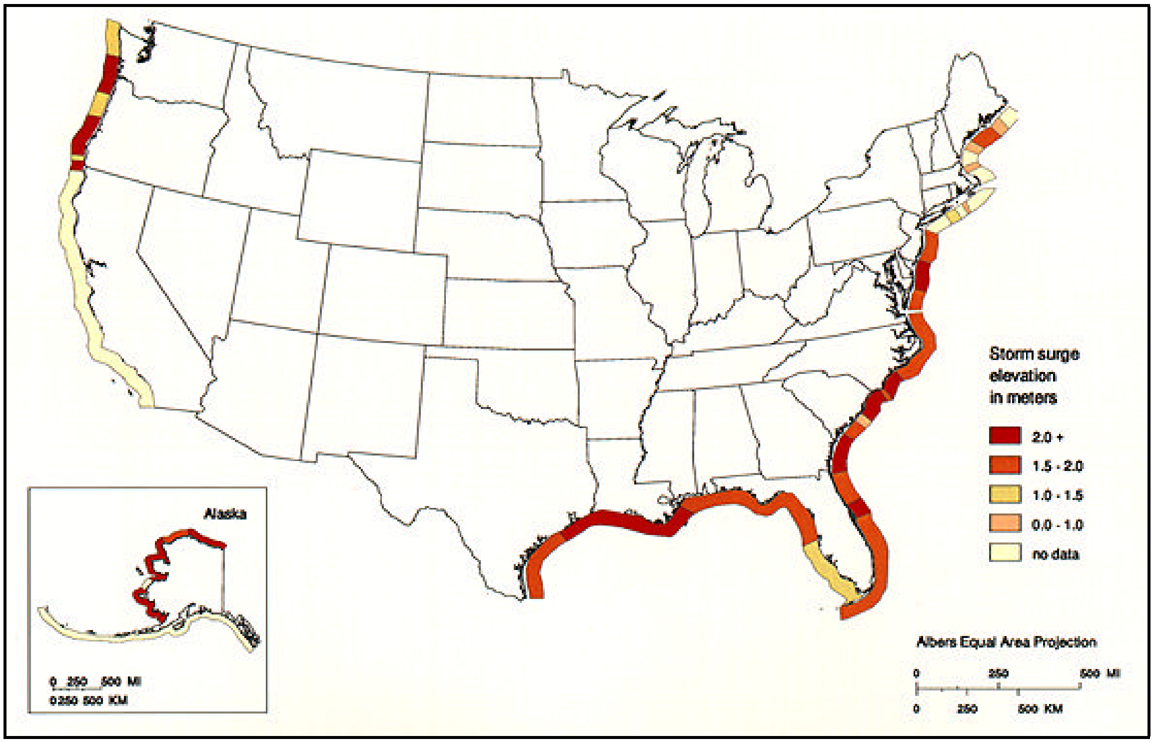
Although low-pressure systems and coastal storms can develop year-round, the most frequent and severe non-tropical low-pressure systems and nor'easters affecting the United States occur from late fall to early spring (Coch, 1995). The long duration, long fetch, and large area of circulation of nor'easters and severe winterstorms can affect many geographic areas and inflict damage to the shoreline along numerous coastal reaches over several days.

Storm surges inundate coastal floodplains by dune overwash, tidal elevation rise in inland bays and harbors, and backwater flooding through coastal river mouths. Severe winds associated with low-pressure

TABLE 13-1.—*Factors influencing the severity of coastal storms*

Factor	**Effect**
Wind Velocity	The higher the wind velocity the greater the damage.
Storm Surge Height	The higher the storm surge the greater the damage.
Coastal Shape	Concave shoreline sections sustain more damage because the water is driven into a confined area by the advancing storm, thus increasing storm surge height and storm surge flooding.
Storm Center Velocity	The slower the storm moves, the greater the damage. The worst possible situation is a storm that stalls along a coast, through several high tides.
Nature of Coast	Rocky coasts are least disturbed. Cliff sedimentary coasts can retreat by slumping or rockfalls, but damage is most severe on low-lying island barrier island shorelines because they are easily overwashed by storm waves and storm surges.
Previous Storm Damage	A coast weakened by even a minor previous storm will be subject to proportionally greater damage in a subsequent storm.
Human Activity	With increased development, property damage increases and more floating debris becomes available to knock down other structures.

Source: *Coch, 1995*



Map 13-1. Expected storm surge elevations with a 10-year recurrence interval.
Data not available for Great Lakes region, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories
Source: *Data from Anders and others, 1989.*

systems cause increases in tide levels and water-surface elevations due to setup, a stillwater component of the storm event. Storm systems also generate large waves that run up and flood coastal beaches. The combined effects create storm surges that affect the beach, dunes, and adjacent low-lying floodplains. Shallow offshore depths can cause storm-driven waves and tides to pile up against the shoreline and inside bays.

Storm surge flooding has reduced impacts in areas with steep coastal relief and terrain, deep offshore bathymetry, or large inland bays. Steep terrain at coastal bluffs reduces the volume and elevation of water pushed up against the shore, preventing flooding and reflecting potentially damaging wave energy. In addition, deep water along offshore troughs or canyons may cause wave heights to increase rapidly when approaching the shoreline, however the surge is lessened because the water levels will not pile up against the shoreline as dramatically as in other coastal areas.

Areas with large inland bays and numerous outlets to the ocean have pressure release valves for floodwaters returning to the open ocean after storms pass, allowing attenuation of the water surface rise and the absorption and storage of overwash and inland floodwaters during the storm event.

RISK ASSESSMENT

The storm surge levels associated with nor'easters, winter low-pressure systems, and other coastal storms with extreme tides and waves have been analyzed in numerous FEMA Flood Insurance Studies along the Atlantic and Pacific coasts. The information has been used to identify the coastal high hazard areas in addition to those influenced by tropical cyclone flooding.

Probability and Frequency

The most common reference to a return period for storm surges has been the elevation of the coastal flood having a 1-percent chance of being equaled or exceeded in any given year, also known as the 100-year flood. The 1-percent-annual-chance flood is derived from statistical hydrologic analyses to establish stage-frequency relationships of water surface elevations based on historical data.

Detailed hydraulic analyses include establishing the relationship of tide levels with wave heights and wave runup, or generation of synthetic populations of storm surge data based on hydrodynamic models. The storm surge inundation limits for the 1-percent-annual-chance coastal flood event are a function of the combined influence of the water surface elevation rise and accompanying wave heights and wave runup along the coastline.

In a study performed by the Coastal Engineering Research Center (CERC) and the University of Virginia, which was included in the 1989 USGS report and mapping (Anders and others, 1989), storm surges with a 10-year recurrence interval from all types of coastal low-pressure systems (extratropical, tropical, and winterstorms) were included in a coastal hazard assessment (Map 13-1).

The risk of storm surge elevations higher than 7 ft (2 m) exists along certain coastal segments of Oregon, Washington, and Alaska, and in every coastal State from Texas to New Jersey. Due to lack of data, the 1989 USGS report did not address the Great Lakes region, portions of the Alaskan coast, and the coasts of California, Hawaii, Puerto Rico, U.S. Virgin Islands, and the Pacific territories.

The University of Virginia/CERC assessment, included in the 1989 USGS report and mapping, concluded that the surge associated with storms of longer recurrence intervals would result in more storm surge flooding, higher water levels, larger waves, and an increased likelihood of dune overwash, wave damage, and possible breaching of barrier islands.

Bluff collapse, typically triggered by undercutting due to erosive waves, is a significant hazard along portions of the shorelines of California, Oregon, Washington, and around the Great Lakes.

Nor'easters can develop in the Atlantic Ocean from Florida to Maine and in the northern Gulf of Mexico. The Dolan/Davis nor'easter scale (Table 13-2) was developed to assist in rating and classifying nor'easter storm events in a manner similar to the Saffir/Simpson scale for hurricanes (Dolan and Davis, 1994). Using rankings from 1 to 5, the scale equates storm classes with intensity level and potential impact on beach erosion, dune erosion, overwash, and property damage. From 1987 to 1993, at least one class 4 or class 5 storm occurred each year, while seven class 5 events occurred from 1960 to 1993 (Coch, 1995).

Exposure

Increased coastal zone development and the estimated 45 million residents in these regions place a high number of people and structures at risk. Dense development of many oceanfront areas increases the number at risk because open space buffers along the waterfront typically are not preserved.

Increased storm surge levels result from the coincidence of severe winds and wind-driven waves with peak astronomical tides. However, the duration of a storm is the most influential factor affecting surges and exposure of people and property.

Storm surge can result in street and building flooding in coastal communities. The waves accompanying an event can impact structures with sufficient force to destroy wall systems and undermine foundations, causing collapse. Erosion of the protective frontal dune sys-

TABLE 13-2.— *Dolan/Davis nor'easter scale*

Storm Class	Beach Erosion	Dune Erosion	Overwash	Property Damage
Class 1 (Weak)	Minor changes	None	No	No
Class 2 (Moderate)	Modest: mostly to lower beach	Minor	No	Modest
Class 3 (Significant)	Erosion: extends across beach	Can be significant	No	Loss of many structures at local scale
Class 4 (Severe)	Severe beach erosion and recession	Severe dune erosion or destruction	On low beaches	Loss of structures at community scale
Class 5 (Extreme)	Extreme beach erosion	Dunes destroyed over extensive areas	Massive in sheets and channels	Extensive at regional scale; millions of dollars

Source: *Coch, 1995, modifying Davis and Dolan, 1993.*

tem by waves and overwash may expose buildings and structures to high velocity floodflows, interior flooding, foundation scour, and other damage.

Consequences

The effects of storm surge from coastal storms were included in more than two dozen Federal disaster declarations during the past 20 years. The declarations were not based specifically on storm surges, but included concurrent effects from severe winds, erosion, and rainfall flooding. In the Atlantic Ocean and Gulf of Mexico, 9 out of every 10 fatalities from a tropical cyclone result from drowning caused by storm surge flooding (Hebert and others, 1995).

Although severe coastal storms do not occur each year, several notable non-tropical storm surge events have occurred since 1960. The most significant in the Atlantic Ocean were the Ash Wednesday storm of 1962, which affected over 620 mi (1,000 km) of shoreline over four high tides and caused over $300 million in damage, and the Halloween Nor'easter of 1991, which caused severe flooding and coastal erosion along the entire East Coast.

In the Gulf of Mexico, the Superstorm of March 1993 generated storm surge elevations greater than 10 ft (3 m) north of Tampa, FL. These elevations are equivalent to those expected from Category 2 hurricanes.

Storm surges and waves generated by the California winter storms of 1982–83 caused coastal beach and bluff erosion from San Diego to San Francisco, resulting in damage to structures and property in excess of $100 million (Dean and others, 1984). Erosion of bluffs is a significant hazard along the shorelines of California, Oregon, Washington, and around the Great Lakes.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Studies of storm surge flooding effects caused by hurricanes and typhoons are conducted by the NWS's National Hurricane Center and Joint Typhoon Warning Center. The National Hurricane Center uses the SLOSH model to determine the coastal flood potential along the coasts of Gulf of Mexico and Atlantic Ocean.

The University of Virginia/CERC study included in the 1989 USGS report and mapping presented an assessment of storm surge risk (Anders and others, 1989). The study and mapping cover overall coastal hazards along the shorelines of the United States, including Alaska and Hawaii, but excluding the Great Lakes. Similar assessments of the Great Lakes coastal hazards will be undertaken in the near future.

The Dolan/Davis classification system for nor'easters rates storms based on a "storm power index," with the power defined as the maximum deep-water significant wave height squared, times the storm duration (Dolan and Davis, 1994). The classification system was developed from measured storm data for nor'easters from 1943 to 1984 and recently was updated to 1992. Data continue to be collected.

MITIGATION APPROACHES

The primary tools for mitigating the effects of storm surge flooding for all types of coastal storms focus on public safety and structures. Loss of life has been reduced significantly through extensive public awareness campaigns and implementation of evacuation plans during impending emergencies. The influx of coastal residents who are unaware of storm surge hazards requires that such programs be continued.

Regional hurricane evacuation planning efforts have been successful in alerting residents to the dangers of storm surge flooding and acknowledging the importance of evacuation of low-lying coastal floodplains. These plans also may support response to non-tropical storms.

Structural damage mitigation has been most successful where strict building codes for high wind and flood-prone areas have been adopted and enforced. Coastal setback and regulatory programs have helped limit exposure for some of the more recent developments near high risk coastal areas. During the past 25 years, intense development occurred so rapidly along the oceanfront and adjacent coastal floodplains that regulatory programs may not have been in place to control the type and nature of structures needed to resist storm surges.

Post-disaster mitigation efforts include more stringent building codes, buyout programs, relocation, elevation of structures, improved open-space preservation, and land-use planning.

Along selected reaches, beach nourishment and dune construction have been used as short-term measures to prevent storm surge flooding and to protect upland property. Such projects replenish depleted sand supplies and rebuild dunes to maintain a buffer zone between developed properties and the ocean.

RECOMMENDATIONS

The recommendations to reduce the impact of, and exposure to, storm surge hazards are related to those presented in chapters on tropical cyclones and coastal erosion. Refinement of hazard identification models and methods, increased public education and awareness, installation of flood warning systems, additional land-use regulations, and modified building codes will be beneficial.

BIBLIOGRAPHY AND REFERENCES

Anders, F., S. Kimball, and R. Dolan. 1989. ***Coastal Hazards: National Atlas of the United States.*** Map. U.S. Geological Survey.

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Daniels, R.C., V.N. Gornitz, A.J. Mehta, S.C. Lee, and R.M. Cushman. 1992. ***Adapting to Sea-Level Rise in the U.S. Southeast: The Influence of Built Infrastructure and Biophysical.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3915.

Davis, R.E., and R. Dolan. 1993. "Nor'easters." ***American Scientist.*** Vol. 81, pp. 428.

Dolan, R., and R.E. Davis. 1994. "Coastal Storm Hazards." ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Federal Emergency Management Agency, Federal Insurance Administration, Office of Risk Assessment. 1989. ***Erosion Rate Data Study Plan.*** Washington, DC.

Federal Emergency Management Agency, Federal Insurance Administration. 1991. ***Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program.*** Washington, DC.

Federal Emergency Management Agency, Federal Insurance Administration. 1994. ***Mitigation of Flood and Erosion Damage to Residential Buildings in Coastal Areas.*** Washington, DC.

Finkl, C.W., Jr. (Ed.). 1994. ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Gornitz, V.N., R.C. Daniels, T.W. White and K.R. Birdwell. 1994. "The Development of a Coastal Risk Assessment Database: Vulnerability to Sea-Level Rise in the U.S. Southeast." ***Journal of Coastal Research Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Gornitz, V.M., T.W. White, and R.C. Daniels (Eds.) 1994. ***A Coastal Hazards Data Base for the U.S. Gulf Coast.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 4101.

Gornitz, V.M., and T.W. White. 1992. ***A Coastal Hazards Data Base for the U.S. East Coast.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3913.

Griggs, G.B., J.E. Pepper, and M.E. Jordan. 1992. ***California's Coastal Hazards: A Critical Assessment of Existing Land-Use Policies and Practices.*** California Policy Seminar Research Report. Santa Cruz, CA: University of California.

Hebert, P.J., J.D. Jarrell, and M. Mayfield. 1995. "The Deadliest, Costliest, and Most Intense United States Hurricanes of This Century (And Other Frequently Requested Hurricane Facts)." ***Proceedings for 17th Annual National Hurricane Conference, April 11-14, 1995, Atlantic City, New Jersey.*** National Oceanic and Atmospheric Administration, National Weather Service.

National Academy of Sciences. 1994. ***Natural Disaster Studies Volume Six, Hurricane Hugo: Puerto Rico, the U.S. Virgin Islands, and South Carolina—September 17-22, 1989.*** Washington, DC: National Academy of Sciences/National Research Council, Committee on Natural Disasters, Board on Natural Disasters, Commission on Engineering and Technical Systems, Commission on Geosciences, Environment, and Resources.

National Oceanic and Atmospheric Administration, National Weather Service. 1993. ***Natural Disaster Survey Report: Hurricane Andrew—South Florida and Louisiana—August 23-26, 1992.***

National Oceanic and Atmospheric Administration, National Weather Service. 1993. ***Natural Disaster Survey Report: Hurricane Iniki—September 6-13, 1992.***

National Oceanic and Atmospheric Administration, National Weather Service. 1992. ***Natural Disaster Survey Report: The Halloween Nor'easter of 1991 East Coast of the United States...Maine to Florida and Puerto Rico—October 28 to November 1, 1991.***

National Oceanic and Atmospheric Administration, National Weather Service. 1994. ***Natural Disaster Survey Report: Superstorm of March 1993, March 12-14, 1993.***

Oregon Sea Grant. 1994. ***Improving Natural Hazards Management on the Oregon Coast: Recommendations of the Coastal Natural Hazards Policy Working Group.*** Report No. ORESU-T-94-002. Corvallis, OR: Oregon State University.

Palm, R.I., and M.E. Hodgson. 1993. ***Natural Hazards in Puerto Rico: Attitudes, Experience, and Behavior of Homeowners.*** Program on Environment and Behavior, Monograph No. 55. Natural Hazards Research and Applications Informations Center. Boulder, CO: University of Colorado.

CHAPTER

14

COASTAL EROSION

Chapter Summary

Coastal erosion affects every coastal State and territory in the United States. According to a 1971 USACE study, the only comprehensive assessment of the problem, approximately 20,500 mi (33,000 km) of the 84,240 mi (132,350 km) of U.S. shoreline experience "significant" erosion, while 2,700 mi (4,350 km) are subject to "critical" erosion.

Coastal erosion is measured as the rate of change in the position or horizontal displacement of a shoreline over a period of time. It is generally associated with storm surges, hurricanes, windstorms, and flooding hazards, and may be exacerbated by human activities such as boat wakes, shoreline hardening, and dredging.

Natural recovery after erosive episodes can take months or years. If a dune or beach does not recover quickly enough via natural processes, coastal and upland property may be exposed to further damage in subsequent events. Although death and injury are not associated with coastal erosion, it can cause the destruction of buildings and infrastructure.

Coastal erosion has been a factor in more than 25 Federal disaster declarations during the past 20 years. In addition, the 76 disaster declarations prompted by hurricanes, tropical storms, and typhoons may have indirectly included damage from coastal erosion.

Actions to supplement natural coastal processes, such as beach nourishment and dune stabilization, can modify erosion trends. Construction of shore protection structures can mitigate the hazard, but may exacerbate it under some circumstances. Other mitigation measures include relocation of utility lines, water mains, sewer lines, and roadways.

HAZARD IDENTIFICATION

Coastal erosion is a hydrologic hazard defined as the wearing away of land and loss of beach, shoreline, or dune material as a result of natural coastal processes or manmade influences (Skaggs and McDonald, 1991). It can be manifested as recession and degradation of major dune systems or development of steep scarps along the nearshore beach face (Figure 14-1). Natural coastal processes that cause coastal erosion include the actions of winds, waves, and currents (Table 14-1). Human influences include construction of seawalls, groins, jetties, navigation inlets and dredging, boat wakes, and other interruptions of physical processes.

Orientation of the shoreline and exposure to prevailing winds and open ocean swells and waves are important factors that influence erosion. The results may be reduced sediment influx, altered littoral processes, and a negative shoreline response (in the form of retreat) or bluff failure that can impact large geographic areas and development along the coastal floodplain.

Coastal erosion can occur as the result of rapid, short-term, daily, seasonal, or annual episodic events such as storm waves, storm surge, overwash, inland flooding, barrier island breach, rip currents, and undertow. Ice floes are natural factors that are unique to the Great Lakes shorelines.

Coastal erosion and shoreline change can be a function of multi-year impacts and long-term climatic changes. Long-term influences from natural factors include sea- or lake-level rise, sediment loss, subsidence, littoral transport losses, changes in sand-grain size distribution, natural inlets, inland flooding, and rip currents. Long-term human factors include shore protection structures, aquifer depletion, damming of rivers, sand mining, and destabilization of dunes.

Climatic trends can change a beach from naturally accreting to eroding due to increased episodic erosion events caused by waves from an above-average number of storms and high tides, or the long-term effects of fluctuations in sea or lake level.

Windstorm events can blow beach and dune sand overland into adjacent low-lying marshes, upland habitats, inland bays, and communities. Flooding from extreme rainfall can scour and erode dunes as inland floodwaters return through the dunes and beachface into the ocean.

Navigation inlets can have a great impact on coastal processes. The typical shoreline response is erosion and recession along beaches that are downdrift of inlet jetties. Erosion is caused by the interruption of the littoral transport and supply of sand to downdrift beaches. Dramatic inlet impacts can be seen at Ocean City, MD and St. Lucie, Martin County, FL.

In California, sand mining and damming of inland rivers with direct outlets at the coastline have reduced the sediment supply entering littoral transport cells along the shoreline. Without an adequate supply of sand, coastlines have no way of recovering the sand lost from nearshore beaches and upland dunes as a result of short-term episodic erosion events.

Shore protection structures such as seawalls and revetments often are built to attempt to stabilize the upland property. However, typically they eliminate natural wave runup and sand deposition processes and can increase reflected wave action and currents at the waterline. Increased wave action can cause localized scour in front of structures and prevent settlement of suspended sediment.

RISK ASSESSMENT

Two assessments of coastal erosion and risks of multiple coastal hazards in the eastern half of the United States have been conducted by the USGS and by the University of Virginia with the Coastal Engineering Research Center (CERC). The 1989 USGS report (Anders and others, 1989) used data from the UVA/CERC study to describe the specific influences of coastal erosion and accretion along the Gulf of Mexico and Atlantic Ocean shorelines. Historical data and measurements of average annual rates of shoreline change were used. A more recent coastal risk assessment was performed by the Oak Ridge National Laboratory (Gornitz and White, 1992; Daniels and others, 1992; Gornitz, White, and Daniels, 1994: and Gornitz, Daniels, White, and Birdwell, 1994).

The University of Virginia/CERC risk assessment included a coastal and modifying hazard factor for shoreline change. The shoreline change data used implicitly include the effects of sea-level rise in the analysis of change rates over specific periods of time.

Probability and Frequency

Coastal erosion is measured as the rate of change in the position or horizontal displacement of a shoreline over a specific period of record, measured in units of feet or meters per year. It is a quantitative assessment of average annual change for a given beach cross-section or profile (square feet or square meters per year) or volumetric change for continuous segments of the shoreline (cubic feet or meters per year).

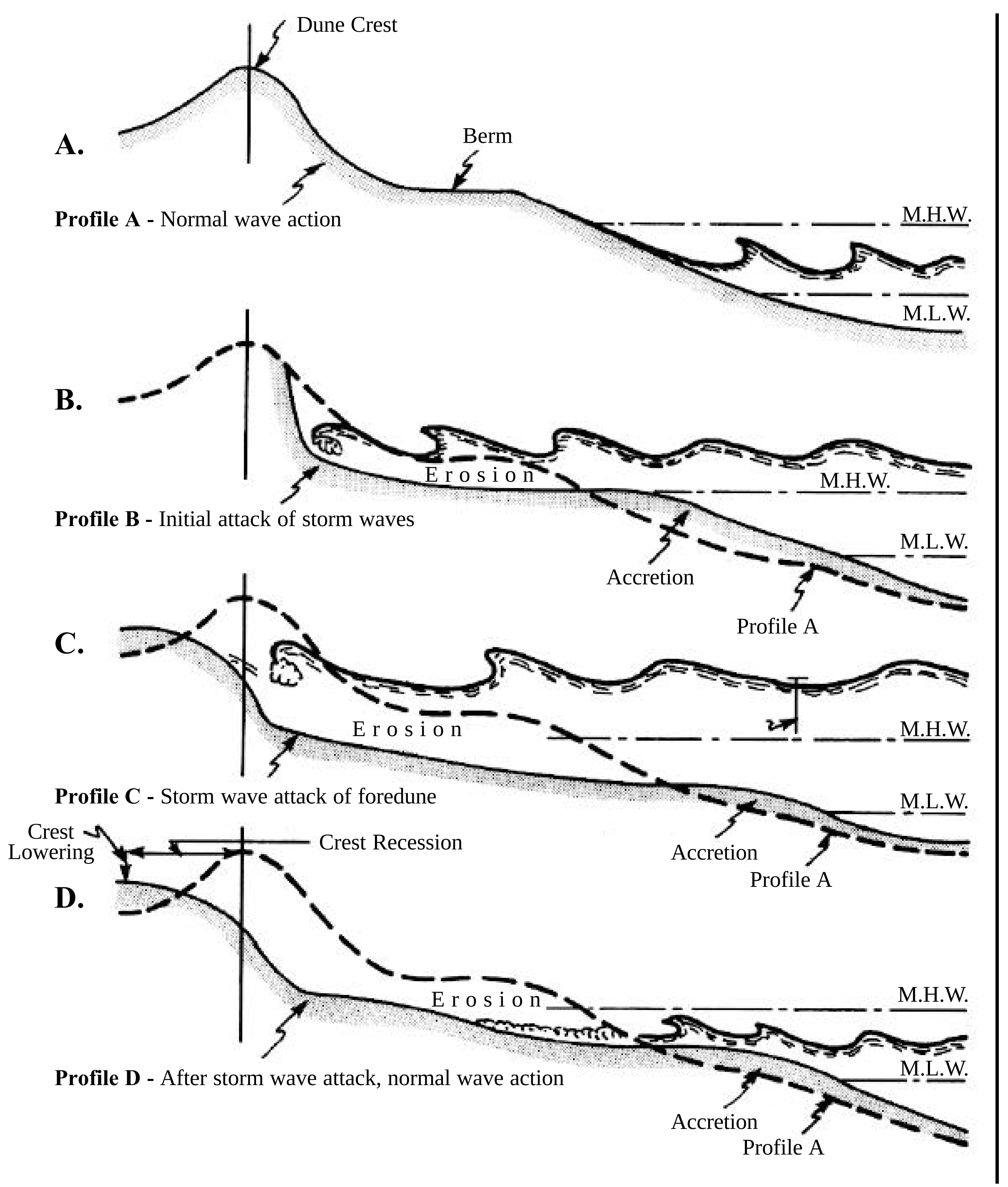


FIGURE 14-1.—Schematic diagram of storm wave attack on beach and dune.

Source: *Skeggs and McDonald, 1991; Waterways Experimental Station, 1984*

TABLE 14-1.—*Summary of natural factors affecting shoreline change*

Factor	Effect	Time Scale	Comments
Sediment supply (sources and sinks)	Accretion/erosion	Decades to millennia	Natural supply from inland (e.g., river floods, cliff erosion) or shoreface and inner shelf sources can contribute to shoreline stability or accretion
Sea level rise	Erosion	Centuries to millennia	Relative sea level rise, including effects of land subsidence, is important
Sea level change	Erosion (for increases in sea level)	Months to years	Causes poorly understood, interannual variations that may exceed 40 years of trend (e.g., El Niño)
Storm surge	Erosion	Hours to days	Very critical to erosion magnitude
Large wave height	Erosion	Hours to months	Individual storms or seasonal effects
Short wave period	Erosion	Hours to months	Individual storms or seasonal effects
Waves of small steepness	Accretion	Hours to months	Summer conditions
Alongshore currents	Accretion, no change, or erosion	Hours to millennia	Discontinuities (updrift ≠ downdrift) and nodal points
Rip currents	Erosion	Hours to months	Narrow seaward-flowing currents that may transport significant quantities of sediment offshore
Underflow	Erosion	Hours to days	Seaward-flowing near bottom currents may transport significant quantities of sediment during coastal storms
Inlet presence	Net erosion; high instability	Years to centuries	Inlet-adjacent shorelines tend to be unstable because of fluctuations or migration in inlet position; net effect of inlets is erosional owing to sand storage in tidal shoals
Overwash	Erosional	Hours to days	High tides and waves cause sand transport over barrier beaches
Wind	Erosional	Hours to centuries	Sand blown inland from beach
Subsidence			
Compaction	Erosion	Years to millennia	Natural or human-induced withdrawal of subsurface fluids
Tectonic	Erosion/accretion	Instantaneous	Earthquakes
Tectonic	Erosion/accretion	Centuries to millennia	Elevation or subsidence of plates

Source: *National Academy of Science, 1990*

Erosion rates vary as a function of shoreline type and are influenced primarily by episodic events. Monitoring of shoreline change based on a relatively short period of record does not always reflect actual conditions and can misrepresent long-term erosion rates.

The return period for an episodic erosion event is directly related to the return period of coastal storm or tropical cyclones and other factors influencing coastal processes. The 1-percent-annual-chance erosion event can be determined using a predictive model that establishes the 1-percent-annual-chance tide and water surface level, or surge elevation and the resulting wave heights. Storm wave heights, periods, and directions have specific impacts on the tides, currents, and other erosion processes. Analyses of coastal erosion impacts from the 1-percent-annual-chance flood event are included in high-hazard zone determinations shown on NFIP maps. The impacts may vary for each reach of coastline.

A more significant measure of coastal erosion is the average annual erosion rate. Erosion rates can be used in land-use and hazard management to define areas in which development should be limited or where special construction measures should be used. The average annual erosion rate is based on analysis of historical shorelines derived from maps, charts, surveys, and aerial photography obtained over a period of record.

Beaches that are accreting, stable, or experiencing mild rates of erosion over a long-term period are generally considered not to be subject to erosion hazards. However, short-term and daily erosion can expose a segment of coast to an episodic storm event and associated erosion damages at any given time. The shoreline change data used by Dolan and Kimball (1988) and shown on Map 14-1 and Map 14-2 revealed areas that are stable, accreting, or eroding.

Detailed methods of determining return periods and frequencies of occurrence of coastal erosion are difficult to develop because of limited information and the relatively short period of recorded data in most areas.

Exposure

According to the University of Virginia/CERC study, every coastal State has a least one segment of shoreline with a moderate rate of shoreline change of 3 to 10 ft (1 to 3 m) per year. At the local level, the degree of exposure may be a function of:

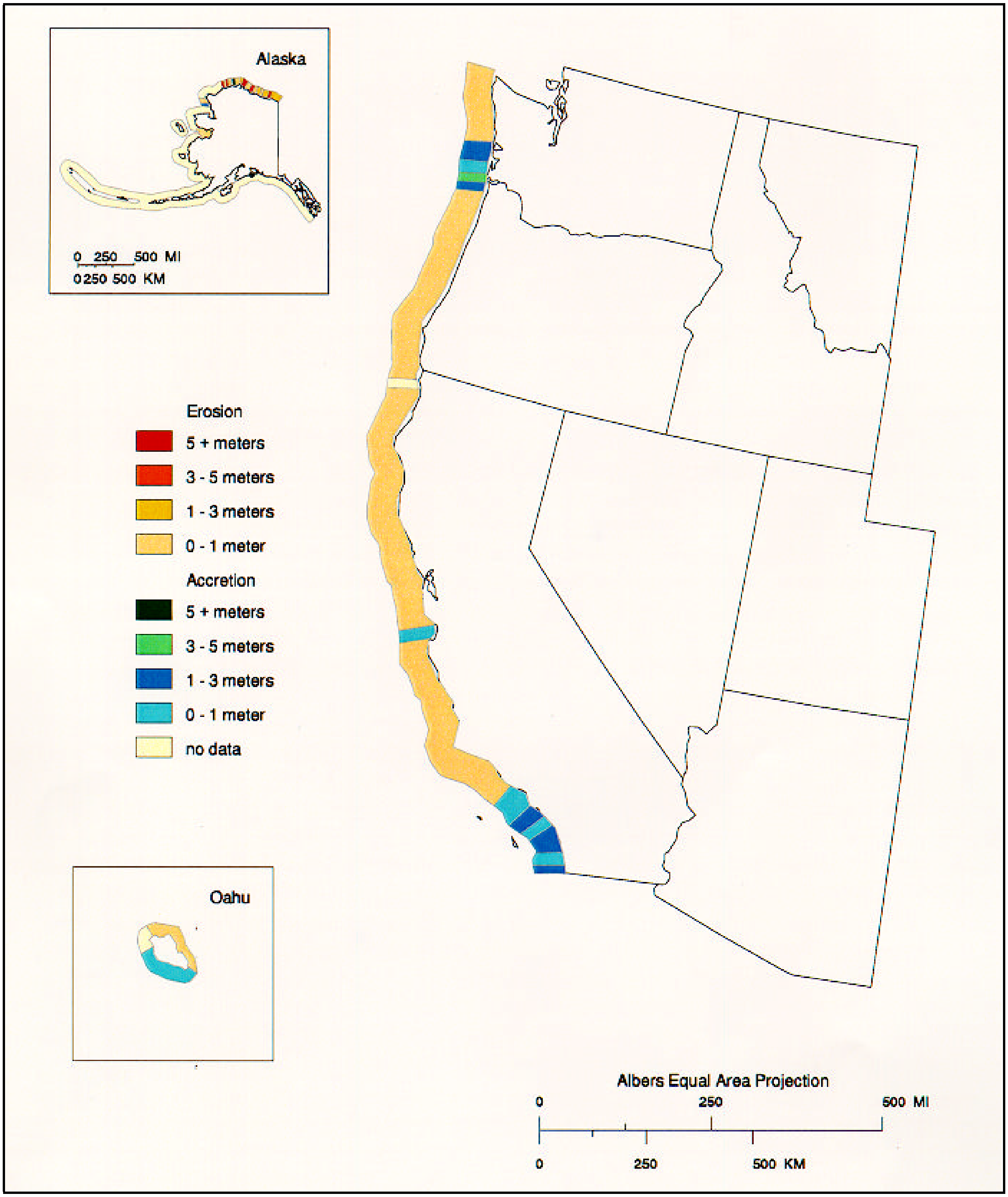
- Shoreline type;
- Geomorphology of the coast;
- Structure types along the shoreline;
- Density of development;
- Amount of encroachment into the high-hazard zone;
- Shoreline exposure to winds and waves;
- Proximity to erosion-inducing coastal structures;
- Nature of the coastal topography; and
- Elevation of coastal dunes and bluffs.

The 1971 USACE study concluded that approximately 20,500 mi (33,000 km) of shoreline are experiencing "significant" erosion. Approximately 2,700 mi (4,350 km) of the shorelines are subject to "critical" erosion. Table 14-2 summarizes the findings.

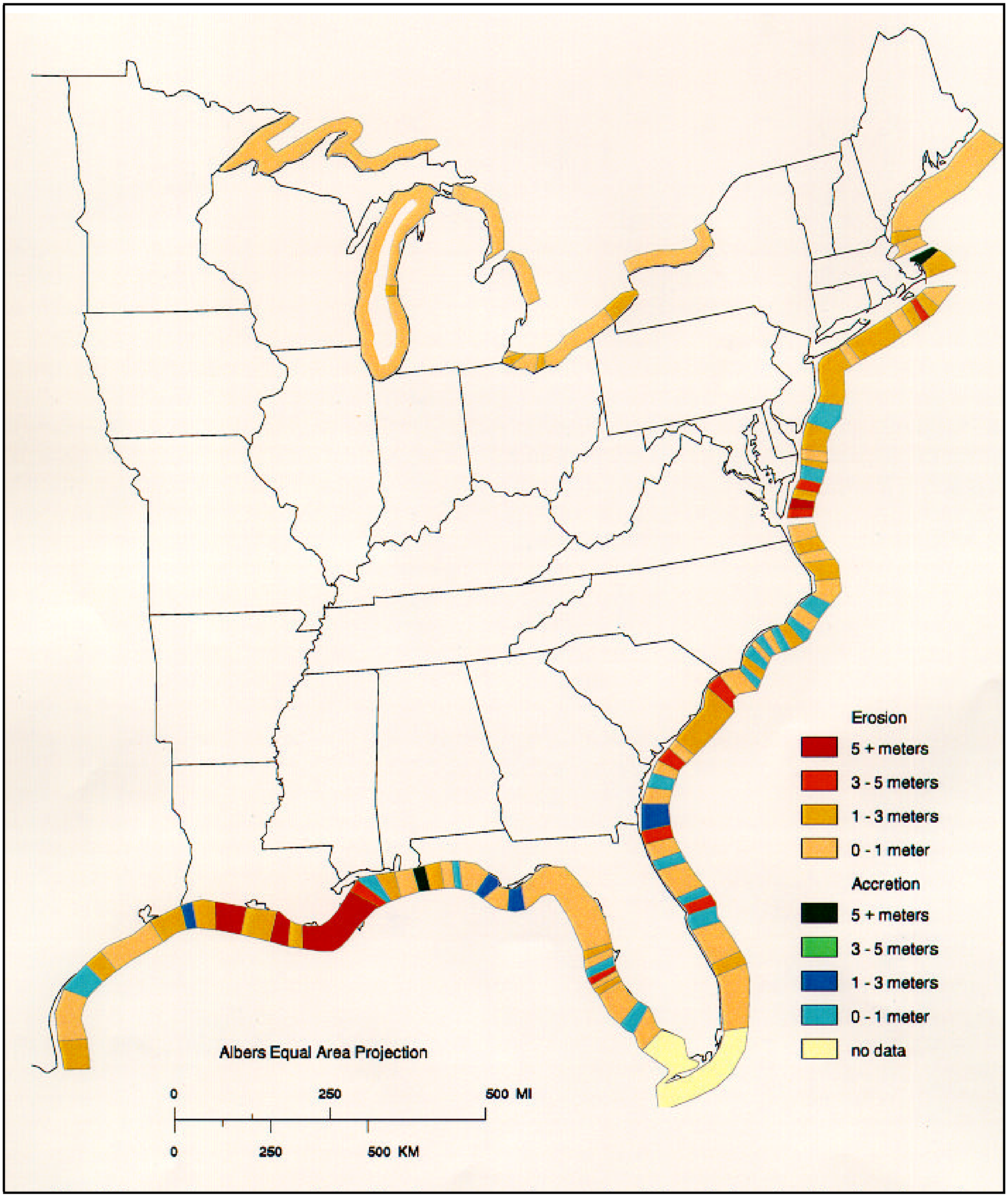
TABLE 14-2.—*Estimated extent of eroding shorelines: 1971*

Region	**Total Shoreline** *(miles)*	**"Significant Erosion"** *(miles)*	**Percent of Total Shoreline**
North Atlantic	8,620	7,460	88.5%
South Atlantic	14,620	2,820	19.2
Eastern Gulf/ Lower Mississippi	1,940	1,580	81.4
Texas Gulf	2,500	360	14.4
Great Lakes	3,680	1,260	34.2
California	1,810	1,550	85.6
North Pacific	2,840	260	9.1
Alaska	47,300	5,100	10.7
Hawaii	930	110	11.8
U.S. Total	84,240	20,500	24.3

Source: *Summarized by Platt and others, 1992 (modified from U.S. Army Corps of Engineers, 1971).*



Map 14-1. Average annual shoreline change rates for the Western United States (erosion and accretion zones depicted). Data not available for Hawaii (except Oahu), and the Pacific Territories.
Source: *Data from Dolan and Kimball, 1988.*



Map 14-2. Average annual shoreline change rates for coastlines of Great Lakes, Gulf, and the Eastern United States (erosion and accretion zones depicted).
Data not available for Puerto Rico and the Virgin Islands.
Source: *Data from Dolan and Kimball, 1988.*

Regional studies of shorelines experiencing erosion and negative rates of change have been conducted by various Federal, State, and local agencies and numerous universities. Recent studies show an increase in the percentage of shoreline experiencing problems. Increased awareness may be associated with increased development in many areas.

The Oak Ridge National Laboratory studies were performed for the Atlantic Coast (Gornitz and White, 1992), and the Gulf Coast (Gornitz, White and Daniels, 1994). Another Oak Ridge National Laboratory study (Daniels and others, 1992) addressed the issue of sea-level rise and specific regional impacts. In these studies, 13 variables were included in the coastal risk assessment database. Seven physical land and marine factors were subdivided to address distinct factors related to inundation and erosion potential. Six climatological factors addressed storm characteristics.

The shoreline erosion and accretion variables included in the Oak Ridge National Laboratory studies were derived from historical shoreline rates of change data obtained from the Coastal Erosion Information System (CEIS). CEIS was created from data collected by Dolan and Kimball (1988) and is accessible through the University of Virginia. Shorelines were evaluated based on mean shoreline displacement rates to determine five relative risk factors. Displacement rates of plus or minus 3 ft (1 m) per year were considered stable and represent only a moderate risk. Segments with the highest risk have erosion rates greater than 7 ft (2.0 m) per year. Segments with the lowest risk have accretion rates of more than 7 ft (2.0 m) per year.

Because of the Pacific Ocean's rocky shorelines, cliffs and bluffs, and pocket beaches, many beach communities may be affected by beach erosion and shoreline retreat. Although the 1989 USGS report and mapping (Anders and others, 1989) concluded that the shorelines along the Pacific Ocean generally are stable or accreting, significant site-specific erosion takes place. Many localized areas, referred to as "hot spots," have been identified in California, Oregon, and Washington, and are subject to moderate-to-high risk.

Studies on risk and coastal hazards for California (Griggs and others, 1992), Oregon (Oregon Sea Grant, 1994 and 1992), and Washington (Canning and Shipman, 1995; Phipps, 1990) document erosion and accretion trends and erosion hazard area assessments. Coastal development and urban growth along the Pacific Ocean have increased since 1970, following a 30-year period of infrequent storm activity, and have resulted in placing a larger coastal population at risk.

In Hawaii and American Samoa, coastal erosion is experienced primarily along shorelines subject to the direct impacts of 20- to 30-ft (6- to 10-m) high waves, storm surge from tropical cyclones, and tsunami waves. Low-lying coastal developments, roads, and utilities commonly are damaged by episodic erosion, with long-term damage to water supply and agriculture from salinization due to aggravated flooding.

Consequences

Coastal erosion has been a factor in more than 25 Federal disaster declarations during the past 20 years. In addition, 76 hurricanes, tropical storms, and typhoons may have indirectly included damage from coastal erosion as an influencing factor.

While generally not an imminent threat to public safety, coastal erosion destroys buildings, roads, and infrastructure. Damage often results from the combination of an episodic event with severe storm waves and dune or bluff erosion. In some areas, the loss of buildings can be directly linked to the long-term impact of shoreline or bluff recession.

Three large events are notable for widespread erosion damage: the Ash Wednesday Nor'easter of 1962; the Halloween storm of 1991 (NOAA, 1992); and the Superstorm of March 1993 (NOAA, 1994). The Ash Wednesday storm resulted in above-normal tide levels over four astronomical tide cycles. It removed 30 percent of the sand from beaches and dunes, and lowered the dune crest by almost 5 ft (1.5 m) in Virginia Beach, VA (Coch, 1995).

Widespread and damaging effects of short- and long-term erosion have had the greatest impact on heavily developed coastal communities in southern California, Texas, Florida, South Carolina, North Carolina, Michigan, Maryland, New Jersey, and New York. Loss of coastal barriers along Louisiana's coastline aggravates saltwater intrusion into wetlands and marshes. In the Great Lakes States, the greatest impact on dune and bluff erosion is attributed directly to changes in lake levels and severe waves.

Along the Gulf of Mexico and Atlantic Ocean coastlines, intense winter low pressure storm systems can cause extremely high tides that persist over several astronomical tide cycles. They often are accompanied by large wind-driven waves and strong currents that erode and overwash coastal dunes. Although the effects are experienced all along the shoreline, the North Atlantic coast from Cape Haterras, NC to Maine has been most affectedby winter storms.

In California, Oregon, Washington, Alaska, and Hawaii, coastal storms associated with extratropical cyclones and winter low pressure systems can cause extensive coastal erosion. Erosion during the winter of 1982–83 caused by high tides and waves caused beach erosion, cliff failure, collapse of shore protection structures, and extensive property damage along a 600-mi (965-km) segment from San Diego to San Francisco (Dean and others, 1984).

In the Hawaiian Islands, the limited sediment supply is the primary factor influencing shoreline change. Problems occur primarily along isolated pocket beaches and commercial developments in tourist resort areas, with most of the remaining shoreline protected by rocky headlands.

In Alaska, the coastal erosion that does occur is not a significant hazard because development is limited. In the U.S. territories of the western Pacific Ocean, most islands are protected by surrounding coral reefs. However, short-term impacts result from storm surges and waves from tropical cyclones.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Assessments of shoreline change are currently underway by many Federal, State, and local agencies using historical aerial photography and bathymetric and topographic maps. The position of shorelines is measured for positive and negative changes over known periods of record.

The Coastal Erosion Information System (CEIS) was created from data collected by Dolan and Kimball (1988). Accessible through the University of Virginia, it is a computerized database of shoreline rates of change for various geographic regions of the United States. CEIS data are used to compute average annual erosion rates for 165-ft (50-m) segments of shoreline. Many reaches are located adjacent to inlet jetties or major shore protection projects, which can influence the erosion trend data. However, these sites generally are isolated enough not to affect regional assessments.

The National Research Council documented coastal erosion hazards in a 1990 report (NRC, 1990). The report concluded that coastal erosion affects a large geographic area of the United States and has a high risk and exposure not adequately accounted for in coastal zone management programs and the National Flood Insurance Program.

The USACE CERC offices at Vicksburg, MS, and Duck, NC, are the primary centers for Federal research, data collection, and monitoring. The USGS study of coastal hazards is being updated to include assessments of shoreline change in the Great Lakes region. The USACE district office at Fort Shafter in Hawaii conducts research for the Hawaiian Islands and Pacific territories.

In response to the requirements of the National Flood Insurance Reform Act of 1994, FEMA is evaluating erosion hazards. The initial phase of the effort involves determining long-term erosion rates in representative coastal communities and preparing hazard maps. Subsequent phases will involve preparing an inventory of structures within mapped erosion hazard areas and an economic impact analysis of erosion and erosion hazard mapping on communities and the NFIP.

Individual State coastal zone management programs monitor, collect, and analyze shoreline change data to determine short- and long-term erosion rates. Universities are involved in research activities related to coastal erosion in the continental United States. Research on beach erosion processes, shoreline change rates, and development of numerical predictive erosion models is underway in at least one major university in each coastal State.

MITIGATION APPROACHES

Natural recovery from coastal erosion may take place over long periods of time. If dunes and beaches do not recover quickly by natural processes, property may be exposed to further damage in subsequent events. In some cases, costly artificial recovery mechanisms have been employed, including beach nourishment and dune restoration in attempts to restore the shore protection capacity of the natural beach and dune system.

Erosion trends may be modified by supplementing or mitigating interruptions in coastal processes. Beach nourishment is used to increase the amount of sand, to adjust the shoreline profile, to replenish depleted sand supplies and, through littoral transport processes, to supply sediment to downdrift shorelines.

Relocation of utility lines, water mains, sewer lines, and roadways in the immediate area of severe erosion may avoid or delay future damage. Evacuation of residents in high hazard areas prior to major storm events has proven successful in limiting injuries and deaths attributed to episodic erosion.

RECOMMENDATIONS

Numerous recommendations on research needs, land-use policies, regulatory programs, and mitigation of coastal erosion hazards can be found in several publications: 1990 NRC report; the 1994 Journal of Coastal Research, Special Issue No. 12; an Oregon State University publication (Oregon Sea Grant, 1994); and reports published by the Washington Department of Ecology (Phipps, 1978 and 1990; Canning and Shipman, 1995), the University of California (Griggs and others, 1992), and the University of Colorado (Platt and others, 1992).

BIBLIOGRAPHY AND REFERENCES

Anders, F., S. Kimball, and R. Dolan. 1989. ***Coastal Hazards: National Atlas of the United States.*** Map. U.S. Geological Survey.

Canning, D.J., and H. Shipman. 1995. ***Coastal Erosion Management Studies in Puget Sound, Washington: Executive Summary.*** Vol. 1. Report 94-74. Olympia, WA: Washington Department of Ecology, Shorelands Water Resources Program.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Daniels, R.C., V.N. Gornitz, A.J. Mehta, S.C. Lee, and R.M. Cushman. 1992. ***Adapting to Sea-Level Rise in the U.S. Southeast: The Influence of Built Infrastructure and Biophysical.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3915. Oak Ridge, TN.

Dean, R.G., G.A. Armstrong, and N. Sitar. 1984. ***California Coastal Erosion and Storm Damage the Winter of 1982-83.*** National Research Council, Committee on Natural Disasters, Commission on Engineering and Technical Systems. Washington, DC.

Dolan, R., and S. Kimball. 1988. ***Coastal Erosion and Accretion: National Atlas of the United States.*** U.S. Geological Survey.

Federal Emergency Management Agency, Federal Insurance Administration. 1991. ***Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program.*** Washington, DC.

Federal Emergency Management Agency, Federal Insurance Administration. 1994. ***Mitigation of Flood and Erosion Damage to Residential Buildings in Coastal Areas.*** Washington, DC.

Federal Emergency Management Agency, Office of Emergency Management. 1993. ***Principal Threats Facing Communities and Local Emergency Management Coordinators, A Report to the United States Senate Committee on Appropriations.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Federal Insurance Administration, Office of Risk Assessment. 1989. ***Erosion Rate Data Study Plan.*** Washington, DC.

Finkl, C.W., Jr. (Ed.). 1994. ***Journal of Coastal Research Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Gornitz, V.N., R.C. Daniels, T.W. White, and K.R. Birdwell. 1994. "The Development of a Coastal Risk Assessment Database: Vulnerability to Sea-Level Rise in the U.S. Southeast." ***Journal of Coastal Research, Special Issue No. 12.*** pp. 327-338.

Gornitz, V.M., T.W. White, and R.C. Daniels (ed.). 1994. ***A Coastal Hazards Database for the U.S. Gulf Coast.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 4101. Oak Ridge, TN.

Gornitz, V.M., and T.W. White. 1992. ***A Coastal Hazards Database for the U.S. East Coast.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3913. Oak Ridge, TN.

Griggs, G.B., J.E. Pepper, and M.E. Jordan. 1992. ***California's Coastal Hazards: A Critical Assessment of Existing Land-Use Policies and Practices.*** California Policy Seminar Research Report. Santa Cruz, CA: University of California.

National Academy of Sciences. 1990. ***Managing Coastal Erosion.*** Washington, DC: National Academy Press.

National Oceanic and Atmospheric Administration, National Weather Service. 1992. ***Natural Disaster Survey Report: The Halloween Nor'easter of 1991 East Coast of the United States...Maine to Florida and Puerto Rico - October 28 to November 1, 1991.*** Washington, DC.

National Oceanic and Atmospheric Administration, National Weather Service. 1994. ***Natural Disaster Survey Report: Superstorm of March 1993, March 12-14, 1993.*** Washington, DC.

Oregon Sea Grant. 1994. ***Improving Natural Hazards Management on the Oregon Coast: Recommendations of the Coastal Natural Hazards Policy Working Group.*** Report No. ORESU-T-94-002. Corvallis, OR: Oregon State University.

Palm, R.I., and M.E. Hodgson. 1993. ***Natural Hazards in Puerto Rico: Attitudes, Experience, and Behavior of Homeowners.*** Program on Environment and Behavior, Monograph No. 55. Boulder, CO: Institute of Behavioral Science, University of Colorado.

Phipps, J.B. April 1990. ***Coastal Accretion and Erosion in Southwest Washington: 1977-1987.*** Report 90-21. Olympia, WA: Washington Department of Ecology, Shorelands and Coastal Zone Management Program.

Phipps, J.B., and J.M. Smoth. 1978. ***Coastal Accretion and Erosion in Southwest Washington.*** Report 78-12. Aberdeen, WA: Grays Harbor College.

Platt, R.H., H.C. Miller, T. Beatley, J. Melville, and B.G. Mathenia. 1992. ***Coastal Erosion: Has Retreat Sounded?*** Program on Environment and Behavior, Monograph No. 53. Boulder, CO: Institute of Behavioral Science, University of Colorado.

Skaggs, L.L., and F.L. McDonald. 1991. ***National Economic Development Procedures Manual: Coastal Storm Damage and Erosion.*** U.S. Army Corps of Engineers, Water Resources Support Center, Institute for Water Resources. Ft. Belvoir, VA.

U.S. Army Corps of Engineers. 1971. ***Report on the National Shoreline Study.*** Washington, DC.

CHAPTER

15

DROUGHTS

Chapter Summary

Drought is a normal part of virtually all climates. It is caused by a deficiency of precipitation and can be aggravated by other factors such as high temperatures, high winds, and low relative humidity. The severity of a drought depends not only on its duration, intensity, and geographic extent, but also on the regional water supply demands made by human activities and vegetation. This multi-dimensional nature makes it difficult to define a drought and to perform comprehensive risk assessments.

Drought, which is defined as a water shortage caused by a deficiency of rainfall, differs from other natural hazards in three significant ways. First, a drought's onset and end are difficult to determine since the effects accumulate slowly and may linger even after the apparent termination of an episode. Second, the absence of a precise and universally accepted definition adds to the confusion about whether a drought exists, and if it does, the degree of severity. Third, unlike most other natural hazards, drought impacts are less obvious and are spread over a larger geographic area. These characteristics have hindered the development of accurate, reliable, and timely estimates of drought severity and effects and, ultimately, the formulation of drought contingency plans by many governments (Wilhite, 1993).

During severe droughts, agricultural crops do not mature, wildlife and livestock are undernourished, land values decline, and unemployment increases. Droughts can cause a shortage of water for human and industrial consumption, hydroelectric power, recreation, and navigation. Water quality may decline and the number and severity of wildfires may increase.

Nine notable droughts have occurred during the 20th century in the United States. Damage estimates are not available for most, however, estimates indicate that the 1976–77 drought in the Great Plains, Upper Midwest, and far Western States caused direct losses of $10–$15 billion. The 1987–89 drought in the Central and Eastern States cost $39 billion.

Historically, many States have relied upon the Federal Government to provide relief to drought victims. Since the mid-1970s, most States have taken a more active role and drought contingency plans are now in place in at least 27 States. A variety of mitigation actions have been adopted.

Photo: FEMA

HAZARD IDENTIFICATION

Drought is a normal part of virtually all climatic regimes, including areas with high and low average rainfall. Drought differs from normal aridity, which occurs in low-rainfall regions and is a permanent characteristic of the climate. Drought is the consequence of a natural reduction in the amount of precipitation expected over an extended period of time, usually a season or more in length.

Other climatic factors, such as high temperatures, prolonged high winds, and low relative humidity, can aggravate the severity of a drought. Severity depends not only on duration, intensity, and geographic extent of a specific drought event, but also on the demands made by human activities and vegetation on regional water supplies.

Types of Drought. Droughts can be grouped as meteorologic, hydrologic, agricultural, and socioeconomic (Wilhite and Glantz, 1985). Dziegielewski and others (1991) summarize a wide array of proposed definitions for each type of drought. Representative definitions commonly used to describe the types are summarized below.

- **Meteorologic drought** is defined solely on the degree of dryness, expressed as a departure of actual precipitation from an expected average or normal amount based on monthly, seasonal, or annual time scales.

- **Hydrologic drought** is related to the effects of precipitation shortfalls on streamflows and reservoir, lake, and groundwater levels.

- **Agricultural drought** is defined principally in terms of soil moisture deficiencies relative to water demands of plant life, usually crops.

- **Socioeconomic drought** associates the supply and demand of economic goods or services with elements of meteorologic, hydrologic, and agricultural drought. Socioeconomic drought occurs when the demand for water exceeds the supply as a result of a weather-related supply shortfall (Sanford, 1979). The World Meteorological Organization calls this a water management drought, in which water supply shortages are caused by failure of water management practices or facilities to bridge normal and abnormal dry periods and equalize the water supply throughout the year (Subrahmanyam, 1967). The incidence of this type of drought can increase because of a change in the amount of rainfall, a change in societal demands for water (or vulnerability to water shortages), or both.

Drought Characteristics and Severity. Many indices attempt to define the severity of different types of drought. Some commonly used indices are: departure from normal precipitation; Palmer Drought Severity Index (Palmer, 1965); Crop Moisture Index (Palmer, 1968); accumulated departure from normal streamflow (Paulson and others, 1991); low-flow frequency estimates (Thomas and Stedinger, 1991), and changes in water storage, groundwater levels and rates of decline, and lake levels. Redmond (1991) pointed out that a single index cannot describe everything about the original data, and that the indices are only approximations of real-world phenomena.

Droughts differ in terms of spatial or regional characteristics. Impacts typically evolve gradually, and regions of maximum intensity change with time. The severity of a drought is determined by areal extent as well as intensity and duration. The frequency of a drought is determined by analyzing the intensity for a given duration, which allows determination of the probability or percent chance of a more severe event occurring.

Streamflow can be used to illustrate hydrologic drought. Figure 15-1 shows the accumulative departure of monthly stream discharge from long-term mean monthly stream discharge at a hypothetical stream-gauging station (Paulson and others, 1991). The average streamflow for each calendar month for the period of record was assumed to be the long-term mean streamflow for that month. Periods of major hydrologic deficits and surpluses were identified from an analysis of accumulated departures. On the graph of accumulated departures, the difference between any two accumulated values indicates the deficit or surplus, relative to the long-term mean streamflow, between those two times. A sustained downward trend indicates a period of streamflow deficit (hydrologic drought) and occurs over a multi-year period in almost all instances.

Drought duration is the time difference between the peak and trough, indicated as the width of the shaded area. Frequency is determined by analyzing all accumulated deficiencies for a common duration. This analysis can include fitting a frequency distribution to the accumulated deficiencies or ranking the data and using a plotting position formula (Paulson and others, 1991).

The severity of significant hydrologic droughts in all 50 States, Puerto Rico, and the U.S. Virgin Islands is described by Paulson and others (1991). The areal extent and frequency of five significant droughts in each State was estimated by analyzing all droughts of similar duration during the period of streamflow records for selected gauging stations.

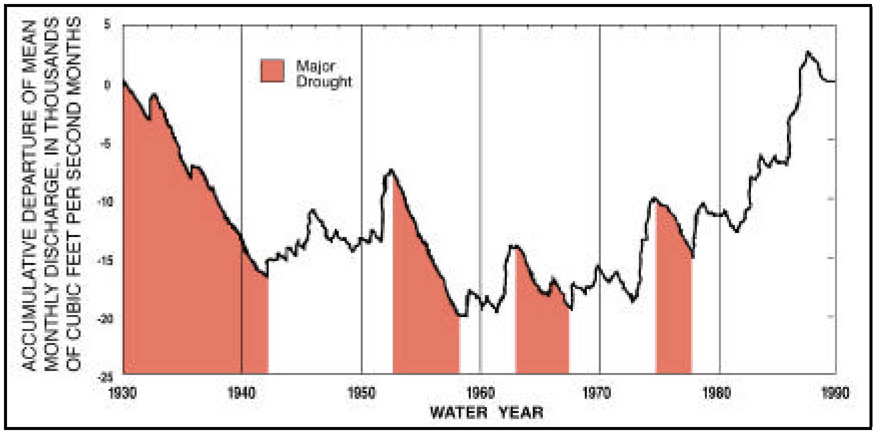


FIGURE 15-1.—Accumulative departure of monthly stream discharge from long-term mean monthly stream discharge at a hypothetical stream-gauging station.

Source: *After Paulson and others, 1991.*

RISK ASSESSMENT

There is no commonly accepted approach for assessing risks associated with droughts given the varying types and indices. Several indices can be used in risk assessment methodologies.

The Palmer Drought Severity Index (Palmer, 1965) is well-known, especially for measuring the severity of drought for agriculture and water resources management. Extreme droughts, as defined by Palmer, are far more frequent in some parts of the United States than others. Guttman and others (1992) demonstrated that the Palmer Drought Severity Index is not sufficiently consistent to characterize the risk of drought on a nationwide basis.

Probability and Frequency

The U.S. Army Corps of Engineers (USACE) is preparing the *National Drought Atlas* (Willeke and others, draft dated 1994) to provide information on the magnitude and frequency of minimum precipitation and streamflow for the conterminous United States. Monthly data are used to define the mean precipitation and streamflow for durations of 1, 2, 3, 6, and 12 months. The study will assess 49 different time series for streamflow and 52 different time series for precipitation. For example, the 6-month average for the period June to December for each year is one time series, the 6-month average for the period July to January for each year is another time series, and so forth. The annual n-month time series are then analyzed to determine the probability of precipitation and streamflow being less than a certain value for a given year.

A regional analysis of monthly precipitation for durations ranging from 1 to 60 months at 1,119 precipitation stations identified 111 clusters or regions of similar precipitation frequency in the conterminous United States. Using the maps and data provided in the draft *National Drought Atlas* (1994), the magnitude and frequency of precipitation at locations within the clusters can be estimated. Thus, the *Atlas* provides an approach for assessing the magnitude and frequency of meteorologic drought. While a regional analysis of streamflow is not provided, at-site frequency estimates of streamflow are computed and can be regionalized to characterize hydrologic drought are computed.

The streamflow stations used in the draft *National Drought Atlas* are in the USGS Hydro-Climatic Data Network (HCDN) described by Slack and Landwehr (1992). HCDN is composed of 1,659 streamflow stations in all 50 States and U.S. territories with 20 years or more of essentially unregulated records (i.e., monthly mean discharges were not significantly affected by land-use changes, diversions, reservoirs, etc.).

The standard water year period, October to September, is not a representative period for defining droughts because the lowest streamflows often occur in the August-to-October period. Generally the climatic year, April to March, is used in hydrologic analyses so that the low-flow period is near the middle of the period. An analysis of several 6-month periods was conducted to determine the period of lowest streamflow, indicating that, on average, the July-to-January period is the lowest 6-month period of streamflow throughout the conterminous United States.

For the purposes of characterizing hydrologic drought, the mean monthly streamflow for the July-to-January period can be used. Frequency estimates for streamflow, developed for the *National Drought Atlas*, were obtained for non-exceedance probabilities of 0.02, 0.05, 0.10, 0.20, 0.50, 0.80, 0.90, 0.95, and 0.98 for 1,456 of the stations in the HCDN. The frequency analysis of streamflow used a five-parameter Wakeby frequency distribution (Landwehr and others, 1979) fit to the various annual n-month time series. The five-parameter distribution was chosen because of the flexibility in fitting various types of hydrologic data. The parameters of the Wakeby distribution were determined using L-moments (Hosking, 1990).

Map 15-1, which shows regional trends, was constructed by determining the July-to-January mean streamflow with non-exceedance probabilities of 0.05 divided by the drainage area of the watershed to obtain cubic feet per second per square mile (cfsm.05). These values were plotted and areas of equal cfsm.05 were determined.

The July-to-January mean monthly flow with non-exceedance probability of 0.05 was selected as the variable characterize hydrologic drought. It has a 5-percent-chance of not being exceeded in any given year. Stated another way, the July-to-January mean monthly streamflow will be less than this value, on average, once in 20 years.

The 20-year low flow was chosen for illustrating the spatial characteristics of a hydrologic drought because, as stated by Riggs (1972), this is usually the most extreme value used in low-flow analyses. There is no commonly accepted return period or non-exceedance probability for defining the risk from hydrologic droughts that is analogous to the 100-year or 1-percent-annual-chance flood.

Exposure

An ample water supply is critical to the economic well being of the United States. During droughts, crops do not mature, wildlife and livestock are undernourished, land values decrease, and unemployment increases. Adverse consequences occur because of deficiencies in the following:

- Public and rural water supplies for human and livestock consumption;
- Natural soil water or irrigation water for agriculture;
- Water for hydroelectric power;
- Water for forests;
- Water quality;
- Water for recreation; and
- Water for navigation.

People throughout the United States, in high- and low-rainfall areas, may be subject to drought. The hydrologic index of drought presented in Map 15-1 illustrates the variability in streamflow, and hence the availability of surface water supplies. Other indices of hydrologic drought could have been used, such as groundwater levels, reservoir volumes, or water levels.

The geographic variations of the July-to-January mean streamflow shown on Map 15-1 also illustrate the influence of factors such as precipitation, elevation, and evapotranspiration. The highest cfsm.05 values are in the Pacific Northwest, where mean annual precipitation exceeds 100 in (254 cm) and evapotranspiration is low. Likewise, in the Northeastern United States runoff is high because of high rainfall and low evapotranspiration. High cfsm.05 values also occur in the Gulf Coast States, where precipitation is high.

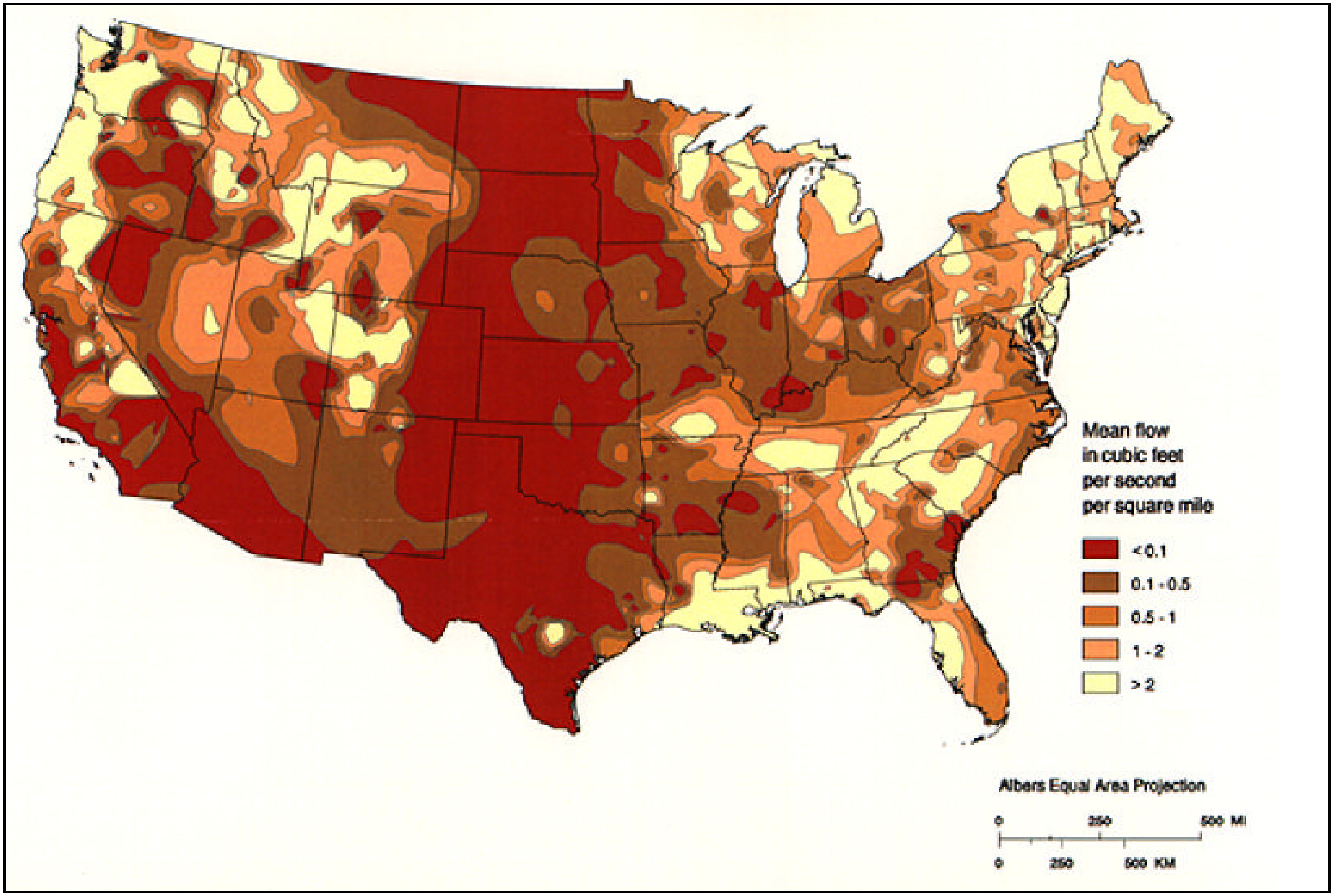
Consequences

Damage estimates are not available for most of the notable droughts that occurred in the United States during the 20th century:

1924-1934	California
1930-1940	Midwest (Dust Bowl)
1942-1956	Southwest
1952-1956	Midcontinent and Southeast
1961-1967	Northeastern States
1976-1977	Great Plains, Upper Midwest, and Western States
1980-1981	Central and Eastern States
1987-1989	Central and Eastern States
1987-1992	California and Upper Great Plains

Riebsame and others (1990) estimated that the 1976-77 drought caused total direct losses of $10-$15 billion. The California Department of Water Resources (California DWR, 1978) estimated losses of $2.7 billion in California alone. Riebsame and others (1990) and Dunbar and others (1995) estimated losses from the 1987-89 drought at $39 billion, including agricultural losses, river transportation disruption, economic impacts, water supply problems, and wildfires.

Generally speaking, States have relied on the Federal Government to provide relief to drought victims when water shortages reach near-disaster proportions



Map 15-1. Spatial variation in the July-to-January mean flow with a 5-percent chance of not being exceeded in any given year. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories. *(Source: Data from U.S. Geological Survey and U.S. Army Corps of Engineers.)*

(Wilhite, 1993). Forty separate drought relief programs administered by 16 Federal agencies provided nearly $8 billion in relief as a result of the series of drought years during the mid-1970s (Wilhite and others, 1986). Federal assistance efforts totaled more than $5 billion in response to the 1987-89 drought (Riebsame and others, 1990).

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Since 1989, the USACE Institute for Water Resources in Fort Belvoir, VA, has conducted the *National Study of Water Management During Drought*. The *National Drought Atlas* is a part of the study. There is interest and involvement from the States and other Federal agencies.

In addition to preparation of the *National Drought Atlas*, USACE is conducting several regional drought preparedness studies using a common method. They encompass emergency, tactical, and strategic planning, and are oriented to customer needs rather than agency mission (USACE IWR, 1991). Brumbaugh and others (1994) provide a listing of all reports published or being prepared under the *National Study of Water Management During Drought*. Reports address such topics as the purposes of USACE reservoirs and their susceptibility to drought, assessment of what is known about drought, lessons learned from the 1987-92 California drought, and computer models for water resources planning and management.

USGS is the primary Federal agency that collects and analyses streamflow data, while NWS is the primary agency that collects and publishes precipitation data. Many State and local agencies, and commercial and industrial users, rely on the USGS and NWS information for water resources planning and management decisions.

More than 600 Federal, State, and local agencies provide funding for the USGS stream-gaging program. In 1994, USGS operated approximately 7,300 stream-gaging stations in the 50 States, Puerto Rico, the U.S. Virgin Islands, and the Pacific territories (Wahl and others, 1995). In addition, measurements are made during low-flow periods at several hundred partial-record sites throughout the United States in order to better define the areal extent and severity of droughts. Thomas and Stedinger (1991) describe procedures for estimating low-flow characteristics at stream-gaging stations and partial-record sites that can be used in drought assessments.

In addition to streamflow data, USGS collects data on water quality, reservoir levels and contents, and groundwater levels for each State. These data are published annually in reports entitled *Water Resources Data [State Name], Water Year [XXXX]*.

NWS publishes precipitation data from approximately 9,100 non-recording and 2,100 recording stations in the United States. These data are published monthly, by State, in reports entitled *Climatological Data and Hourly Precipitation Data*.

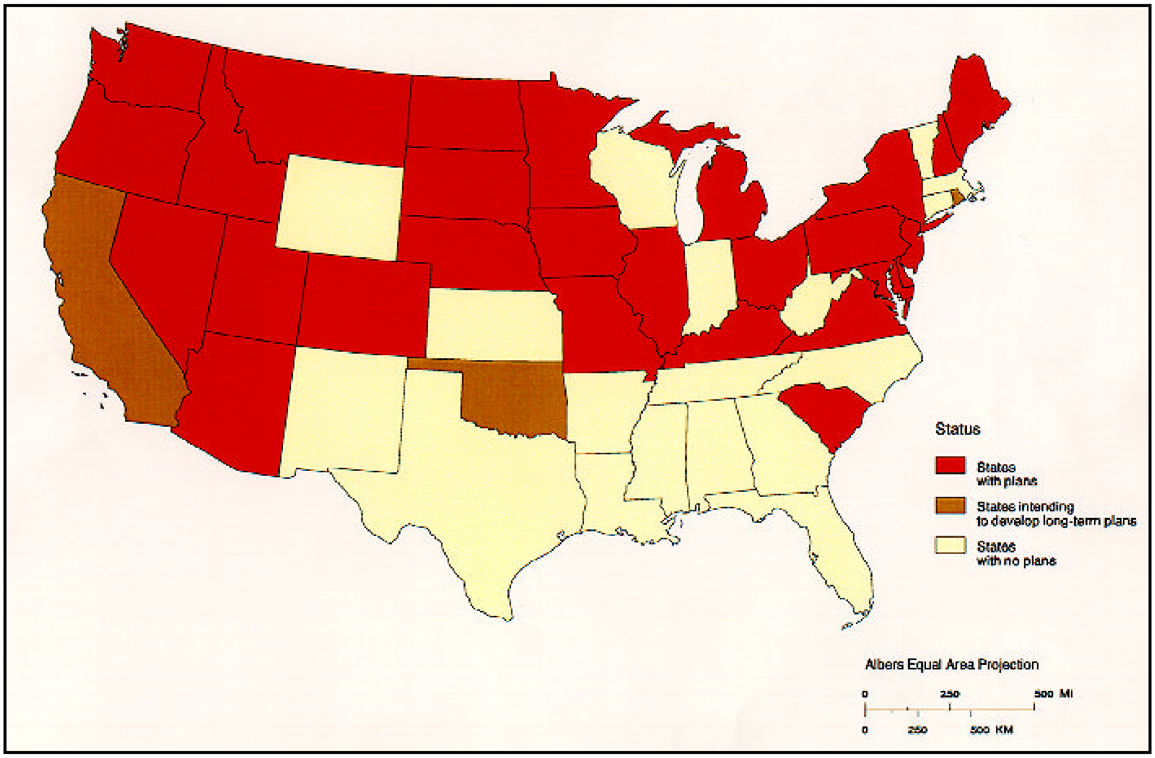
MITIGATION APPROACHES

Wilhite (1993) suggests the greatest potential for raising the level of drought preparedness, and thereby reducing losses from droughts, is through leadership by State agencies. Historically, States have played a relatively passive role in efforts to assess and respond to drought. During the widespread 1976-77 event, for example, no State had prepared a formal drought response strategy. By 1982, only three States had plans: South Dakota, New York, and Colorado.

Increasing awareness of inefficient past responses, calls for action, and the impacts of droughts of the late 1980s have generated considerable momentum at the State level for the establishment of contingency plans. By 1992, 27 States (Map 15-2) had developed and implemented formal drought contingency plans, and three more had expressed interest (Wilhite, 1993).

An examination of existing State drought plans reveals that they have certain key elements in common (Wilhite, 1991). Administratively, a task force is responsible for the operation of the system and is directly accountable to the Governor. The task force keeps the Governor advised of water availability and potential problem areas, and recommends policy options for consideration. Operationally, most drought plans have three common features (Wilhite, 1993):

- A water availability committee continuously monitors water conditions and prepares outlooks a month or season in advance;
- A formal mechanism usually exists to assess the potential impact of water shortages on the most important economic sectors; and
- A committee or task force considers current and potential impacts and recommends response options to the Governor.



Map 15-2. Status of drought planning in the United States, 1992.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories
Source: *Wilhite, 1993.*

States have adopted a wide variety of mitigation actions in response to the widespread, severe drought of 1987-1992 (Wilhite, 1992). Mitigation actions can be clustered into the following categories:

- Assessment programs;
- Legislation and public policy;
- Water supply augmentation and development of new supplies;
- Public awareness and education programs;
- Technical assistance on water conservation;
- Demand reduction and water conservation programs;
- Emergency response programs;
- Water use conflict resolution; and
- Drought contingency plans.

Mitigation programs implemented by States during recent droughts can be characterized as emergency or short-term actions taken to alleviate the crisis at hand. However, these actions were quite successful. Some activities have long-term impacts, such as legislative actions, contingency plan development, and the development of water conservation and public awareness programs. As States gain more experience assessing and responding to drought, future actions will undoubtedly become more timely, effective, and less reactive.

RECOMMENDATIONS

Founded in early 1995, the National Drought Mitigation Center builds on the work of the International Drought Information Center. Both are located at the University of Nebraska - Lincoln. The centers cooperate on drought policy and preparedness research, training seminars and conferences, and maintaining current databases related to droughts (National Drought Mitigation Center, 1995).

Wilhite (1993) offers recommendations for future State and Federal planning initiatives. The recommendations emphasize the need to focus more on long-term water management and planning issues; to integrate the activities of numerous agencies with drought-related missions into a coherent national approach; and to achieve better coordination of mitigation, response, and planning efforts between State and Federal officials.

Dziegielewski and others (1991) offer general research recommendations for development of an analytical framework for prioritizing all major uses of water. They recommend practical guidelines for measuring the economic value of water in alternative uses, and objective methods for quantifying non-market impacts of drought on those uses. Determining the social and environmental effects of restricting or temporarily eliminating certain uses of water during drought is advocated.

The proceedings of the National Science Foundation workshop on "Drought Research into the 3rd Millennium: Assessment of Scientific Knowledge, Monitoring, and Forecasting" contain many worthwhile recommendations on drought research and assessment in three areas: monitoring and assessment, descriptive studies and modeling, and forecasting (Haimes and Quarles, 1990).

BIBLIOGRAPHY AND REFERENCES

Brumbaugh, R., W. Werick, W. Teitz, and J. Lund. 1994. ***Executive Summary of Lessons Learned from the California Drought (1987-1992).*** U.S. Army Corps of Engineers. Institute for Water Resources Report No. 94-NDS-6.

California Department of Water Resources. 1978. ***The 1976–77 California Drought: A Review.*** Sacramento, CA.

Dunbar, P.K., S.C. Dane, and Park Kilho. 1995. ***Natural Hazards Data and Information in the United States.*** National Oceanic and Atmospheric Administration, National Geophysical Data Center, and the Geological Survey of Japan. Report No. 281, pp. 57-84.

Dziegielewski, B., G.D. Lynne, D.A. Wilhite, and D.P. Sheer. 1991. ***National Study of Water Management During Drought: A Research Assessment.*** U.S. Army Corps of Engineers. Institute for Water Resources Report No. 91-NDS-3.

Guttman, N.B., J.R. Wallis, and J.R.M. Hosking. December 1992. "Spatial Comparability of the Palmer Drought Severity Index." ***Water Resources Bulletin.*** Vol. 28, No. 6, pp. 1111-1119.

Haimes, Y.Y., and L.R. Quarles (Eds). 1990. ***Drought Research into the 3rd Millennium: Assessment of Scientific Knowledge, Monitoring and Forecasting.*** Proceedings of the National Science Foundation Workshop.

Hosking, J.R.M. 1990. "L-moments: Analysis and Estimation of Distributions Using Linear Combinations of Order Statistics." ***Journal of Royal Statistical Society.*** Bulletin 52, No. 1, pp. 105-124.

Landwehr, J.M., N.C. Matalas, and J.R. Wallis. 1979. "Estimation of Parameters and Qualities of Wakeby Distributions." ***Water Resources Research.*** Vol. 15, pp. 1055-1064.

National Drought Mitigation Center. 1995. [Online] Homepage: http://enso.unl.edu/ndmc

Palmer, W.C. 1965. ***Meteorological Drought.*** Research Paper No. 45. U.S. Department of Commerce, Weather Bureau.

Palmer, W.C. 1968. "Keeping Track of Crop Moisture Conditions Nationwide: The Crop Moisture Index." ***Weatherwise.*** Vol. 21, No 4, pp. 156-161.

Paulson, R.W., E.B. Chase, R.S. Roberts, and D.W. Moody. 1991. ***National Water Summary 1988-89, Hydrologic Events and Floods and Droughts.*** U.S. Geological Survey Water-Supply Paper 2375.

Redmond, K. 1991. "Climate Monitoring and Indices." In ***Drought Management and Planning.*** D.A. Wilhite, D.A. Wood, and P.A. Kay, eds. International Drought Information Center, Department of Agricultural Meteorology, University of Nebraska-Lincoln. IDIC Technical Report Series No. 91–1, pp. 29–33.

Riebsame, W.E., S.A. Changnon, and T.R. Karl. 1991. ***Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987-1989 Drought.*** Boulder, CO: Westview Press.

Riggs, H.C. 1972. "Low Flow Investigations." U.S. ***Geological Survey Techniques of Water-Resources Investigations***, Book 4, Chapter B1.

Sanford, S. 1979. "Towards a Definition of Drought." In M.T. Hinchey, ed., ***Botswana Drought Symposium.*** Botswana Society, Gaborone, Botswana.

Slack, J.R., and J.M. Landwehr. 1992. ***Hydro-Climatic Data Network (HCDN): A U.S. Geological Survey Streamflow Data Set for the United States for the Study of Climate Variations, 1874-1988.*** U.S. Geological Survey Open-File Report 92-129.

Subrahmanyam, V.P. 1967. ***Incidence and Spread of Continental Drought: World Organization, International Hydrological Decade.*** Reports on WMO/IHD Projects, No. 2, Geneva, Switzerland.

Thomas, W.O., and J.R. Stedinger. 1991. ***Estimating Low-Flow Characteristics at Gaging Stations and Through the Use of Base-Flow Measurements.*** U.S. Geological Survey Open-File Report 91-244, pp. 197-206.

U.S. Army Corps of Engineers, Institute for Water Resources. 1991. ***The National Study of Water Management During Drought: Report on the First Year of Study.*** IWR Report 91-NDS-1.

Wahl, K.L., W.O.Thomas, Jr., and R.M. Hirsch. 1995. ***The Stream-Gaging Program of the U.S. Geological Survey.*** U.S. Geological Survey Circular 1123.

Wilhite, D.A., and M.H. Glantz. 1985. "Understanding the Drought Phenomenon: The Role of Definitions." ***Water International.*** Vol. 10, pp.111-20.

Wilhite, D.A., N.J. Rosenberg, and M.H. Glantz. 1986. "Improving Federal Response to Drought." ***Journal of Climate and Applied Meteorology.*** Vol. 25, No. 3, pp. 322-342.

Wilhite, D.A. 1991. "Drought Planning and State Government: Current Status." ***Bulletin of the American Meteorological Society.*** Vol. 72, No. 10.

Wilhite, D.A. 1992. "Drought." ***Encyclopedia of Earth Systems Science*** Vol. 2, pp. 81-92. Academic Press.

Wilhite, D.A. (Ed.) 1993. ***Drought Assessment, Management, and Planning: Theory and Case Studies.*** Natural Resource Management and Policy. Norwell, MA: Kluwer Academic Publishers.

Willeke, G., J.R.M. Hosking, J.R. Wallis, and N.B. Guttman. 1994. ***The National Drought Atlas (Draft).*** U.S. Army Corps of Engineers, Institute for Water Resources Report 94-NDS-4.

Subpart D

SEISMIC

HAZARDS

Introduction

Earthquakes and tsunamis are considered seismic hazards. An earthquake is sudden ground motion or trembling caused by an abrupt release of accumulated strain acting on the tectonic plates that comprise the Earth's crust. When an earthquake occurs in the ocean, it may trigger tsunami waves. Earthquakes and tsunamis are more prevalent in the Western States and Pacific Territories.

Although earthquakes in the United States have caused less economic loss annually other hazards such as ground failures and floods, they have the potential to cause great sudden loss because devastation can occur in just minutes.

Tsunami waves can reach heights of 50 ft (15 m) or more. Damaging tsunami events are relatively infrequent, occurring about every 7 years in the high-risk areas of Alaska and Hawaii, flooding inland property up to 1 mi (1.6 km) from the coast.

Seismic hazards often trigger other devastating events: earthquakes cause landslides and fires; earthquake-damaged dams and levees may add to flood risks; and tsunamis can erode shorelines.

Photo: Red Cross

CHAPTER

16

EARTHQUAKES

Chapter Summary

Although earthquakes have caused much less economic loss annually in the United States than other hazards such as floods, they have the potential for causing great and sudden loss. Within 1 to 2 minutes, an earthquake can devastate part of an area through ground-shaking, surface fault ruptures, and ground failures.

The zone of greatest seismic activity is along the Pacific Coast in Alaska and California. However, the intermountain west, central, and eastern regions have experienced significant earthquakes. Social, physical, and economic impacts may be very long-term. The 1994 Northridge, CA event caused $20 billion in damage. The average annual loss from earthquakes is estimated at $1 billion.

According to a recent FEMA estimate, more than 109 million people and 4.3 million businesses in the United States are exposed to some degree of seismic risk. Houses, apartments, commercial buildings, nursing homes, railroads, highways, tunnels, bridges, canals, storm drains, water wells, waterlines, gaslines, and sewer lines all are exposed to damage from earthquakes. While direct deaths and injuries from an earthquake are unlikely, they can occur as an indirect result, when structures collapse.

FEMA and the National Institute of Building Sciences (NIBS) are developing a standardized methodology for estimating potential earthquake losses on a regional basis (Chapter 24). Other cooperative efforts include research into engineering techniques to reduce losses, developing effective means for saving lives and property and limiting social disruptions, and emergency planning. Building codes for rehabilitation of existing buildings and for new buildings have been adopted by several States and local jurisdictions.

Photo: Red Cross

Photo: Red Cross

HAZARD IDENTIFICATION

An earthquake is a sudden motion or trembling caused by an abrupt release of accumulated strain on the tectonic plates that comprise the Earth's crust. The theory of plate tectonics, introduced in 1967, holds that the Earth's crust is broken into several major plates. These rigid, 50- to 60-mi (80- to 96-km) thick plates move slowly and continuously over the interior of the earth, meeting in some areas and separating in others. Velocities of relative motion between adjacent plates range from less than a fraction of an inch to approximately 5 in (13 cm) per year. Although slow by human standards, the velocities are rapid by geologic standards. A movement of 2 in (5 cm) per year adds up to 30 mi (48 km) in only 1 million years.

As the tectonic plates move together they bump, slide, catch, and hold. Eventually, faults along or near plate boundaries slip abruptly when the stress exceeds the elastic limit of the rock, and an earthquake occurs. The ensuring seismic activity and ground motion provoke secondary hazards: surface faulting, ground failure, and tsunamis (Chapter 17).

The great majority of earthquakes strike near continental margins or in areas where large lithospheric plates collide or move past each other. However, earthquakes can occur within a major plate as evidenced by the major events that occurred in 1811-12 in the vicinity of New Madrid, MO. Other interior areas that have experienced earthquakes include parts of Montana, eastern Idaho, western Wyoming, Utah, and Nevada.

Ground Motion. Ground motion describes the vibration or shaking of the ground during an earthquake. In general, the severity of ground motion increases with the amount of energy released and decreases with distance from the causative fault or epicenter. When a fault ruptures, seismic waves are propagated in all directions, causing the ground to vibrate at frequencies ranging from 0.1 to 30 Hz. Seismic waves are referred to as P waves, S waves, and surface waves (Hays, 1981).

P (primary) waves, also called compressional or longitudinal waves, propagate through the Earth at a speed of approximately 15,000 mph (39,000 km/h) and are the first waves to cause vibration. They are longitudinal waves, similar in character to sound waves and cause back-and-forth oscillation along the direction of wave travel. The direction of particle motion is the same as the direction of wave propagation (Figure 16-1).

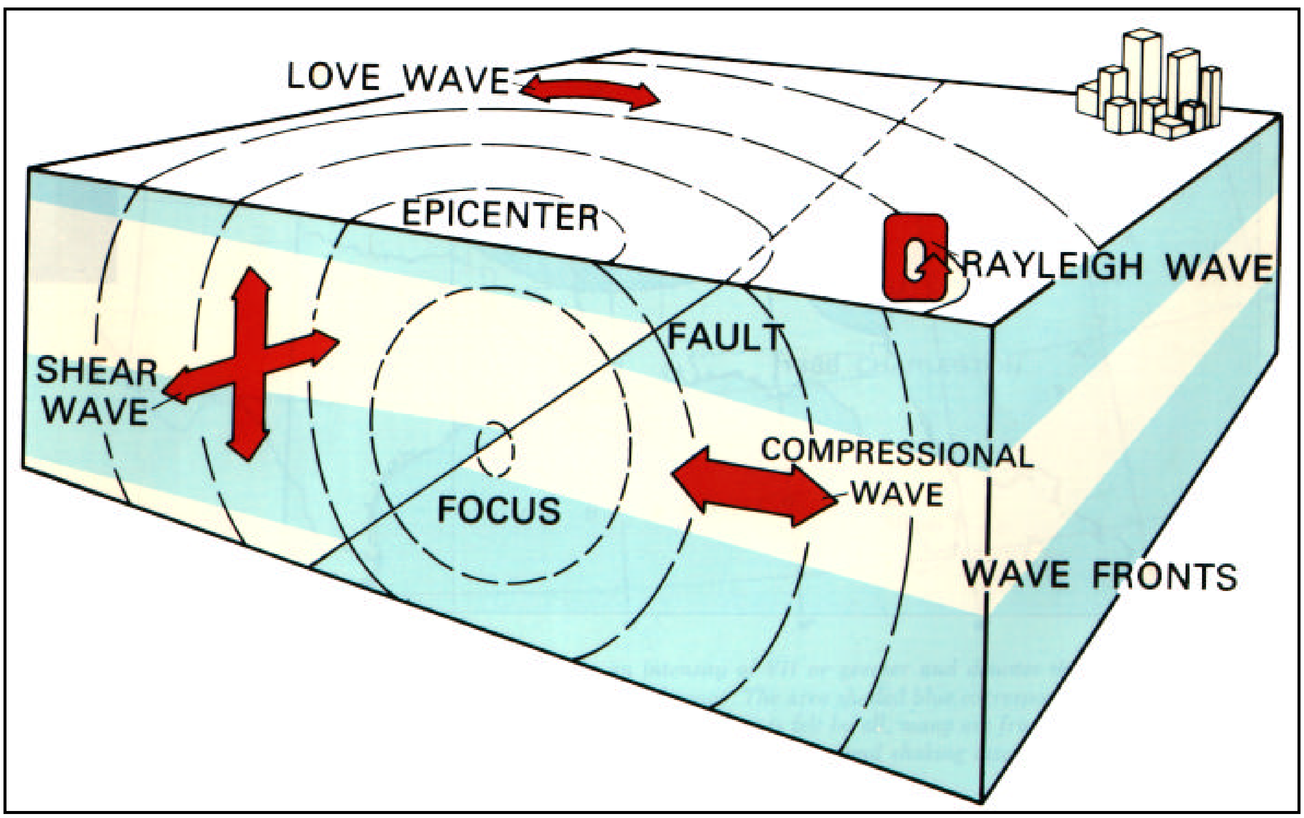


FIGURE 16-1.—Wave fronts: directions of vibrations.

Source: *Hays, 1981.*

S (secondary or shear) waves are slower and cause structures to vibrate from side to side. Particle motion is back and forth at right angles to the direction of wave travel (Figure 16-1). S waves are the most damaging waves because unreinforced buildings are more easily damaged by horizontal motion than by vertical motion.

Surface waves (Raleigh waves and Love waves) travel even slower than P and S waves, and propagate along the Earth's surface rather than through the interior. Particle motion is orbital, similar to motion in water waves. Particle motion in Rayleigh waves is elliptical in the vertical plane containing the direction of propagation, and amplitude decreases exponentially with depth. Particle motion in Love waves is horizontal, transverse to the direction of propagation, with no vertical motion. They both produce surface ground shaking, but very little deep motion.

P and S waves mainly cause high-frequency vibrations (greater than 1 Hz), which are more efficient than low-frequency waves in causing low buildings to vibrate. Rayleigh and Love waves mainly cause low-frequency vibrations, which are more efficient than high-frequency vibrations in causing tall buildings to vibrate. Because the amplitudes of low-frequency waves decay less rapidly than high-frequency vibrations as distance from the fault increases, tall buildings located at relatively great distances from a fault (60 mi (96 km)) are sometimes damaged.

Seismic Activity. Seismic activity is described in terms of magnitude and intensity. Magnitude (M) characterizes the total energy released, and Intensity (I) subjectively describes effects at a particular place. While an earthquake has only one magnitude, its intensity varies throughout the affected region.

In 1935, Charles Richter of the California Institute of Technology devised a logarithmic magnitude scale, referred to as the Richter Magnitude Scale, to define local magnitude (M_L) in terms of the motion that would be measured by a standard type of seismograph (Wood-Anderson torsion seismograph):

$$M_L = \log A - \log A_o$$

where A is the maximum amplitude traced by the seismograph (in millimeters), and $\log A_o$ is a standard value as a function of distance between the seismograph and the epicenter, where the distance is less than 370 mi (600 km).

Several other magnitude scales are in use. For example, body-wave magnitude and surface-wave magnitude are similar to the local magnitude (Richter), but are a function of measurable parameters of P, S, and surface waves. In technical and scientific applications, it is essential to specify the type of magnitude used rather than resort to or imply a generic "Richter magnitude" (Stover and Coffman, 1993).

On the Richter Scale, magnitude is expressed in whole numbers and decimals. In qualitative terms, an earthquake of 5.0 is a moderate event, 6.0 characterizes a strong event, 7.0 is a major earthquake, and a great quake exceeds 8.0. The scale is open-ended, but the highest magnitude known to have been calculated was approximately 9.5, while the lowest was approximately -3.0 (Stover and Coffman, 1993). On this logarithmic scale each whole number increase in magnitude represents a tenfold increase in measured amplitude. Furthermore, a magnitude 6.0 earthquake generates elastic-wave energy that is approximately 30 times greater than that generated by a magnitude 5.0 earthquake, 900 times (30 x 30) greater than that of a magnitude 4.0 earthquake, and so forth.

The effect of an earthquake on the Earth's surface is called the intensity. In the United States, the most commonly used intensity scale is the Modified Mercalli Intensity Scale (MMI) (Wood and Neuman, 1931). This scale, composed of 12 increasing levels of intensity ranging from imperceptible to catastrophic, is an evaluation of the severity of ground motion at a given location measured relative to the effects of earthquakes on people and property. It provides a convenient way for observers to summarize what happened at different locations (Table 16-1).

Principal earthquakes in the United States from 1568 through 1989 have been described (Stover and Coffman, 1993). To show magnitudes for earthquakes without computed values, a relation was established between magnitude and intensity. This was accomplished by correlating the maximum intensity with the average magnitude of earthquakes in four geographical areas where computed magnitudes and intensities were available: Western United States, Eastern United States, Hawaii, and Alaska. The results of the correlations for the four areas provide an approximate comparison of the two methods for measuring earthquake severity (Table 16-2).

Surface Faulting. Surface faulting is the differential movement of two sides of a fracture. While faults occur deep within the Earth, their effects at the surface can be severe. Surface faulting is an obvious hazard to structures built across active faults. In particular, surface faulting can damage railways and highways, and buried infrastructure such as pipelines and tunnels.

TABLE 16-1.—*Earthquake felt intensity: the modified Mercalli Intensity Scale*

MMI	Felt Intensity
I	Not felt except by a very few people under special condtions. Detected mostly by instruments.
II	Felt by a few people, especially those on upper floors of buildings. Suspended objects may swing.
III	Felt noticeably indoors. Standing automobiles may rock slightly.
IV	Felt by many people indoors, by a few outdoors. At night, some people are awakened. Dishes, windows, and doors rattle.
V	Felt by nearly everyone. Many people are awakened. Some dishes and windows are broken. Unstable objects are overturned.
VI	Felt by everyone. Many people become frightened and run outdoors. Some heavy furniture is moved. Some plaster falls.
VII	Most people are alarmed and run outside. Damage is negligible in buildings of good construction, considerable in buildings of poor construction.
VIII	Damage is slight in specially designed structures, considerable in ordinary buildings, great in poorly built structures. Heavy furniture is overturned.
IX	Damage is considerable in specially designed buildings. Buildings shift from their foundations and partly collapse. Underground pipes are broken.
X	Some well-built wooden structures are destroyed. Most masonry structures are destroyed. The ground is badly cracked. Considerable landslides occur on steep slopes.
XI	Few, if any, masonry structures remain standing. Rails are bent. Broad fissures appear in the ground.
XII	Virtually total destruction. Waves are seen on the ground surface. Objects are thrown in the air.

Source: *Pearce and others, 1993.*

The displacements, lengths, and widths of surface faulting vary widely. The differential movement of displacements in the United States has ranged from a fraction of an inch to more than 20 ft (6 m). The length of surface ruptures on land has ranged from less than 1 mi (1.6 km) to more than 200 mi (322 km).

Most fault displacements are confined to a narrow zone ranging in width from 6 to 1,000 ft (2 to 305 m). However, separate subsidiary fault ruptures may occur 2 to 3 mi (3.2 to 4.8 km) from the main fault. The area subject to disruption by surface faulting varies with the length and width of the rupture zone (Hays, 1981).

There are three general types of surface faulting, shown in Figure 16-2 and described below.

- **Strike-Slip Faults** are high-angle fractures in which displacement is horizontal, parallel to the strike of the fault plane. Little or no vertical movement occurs. Instead, these faults are expressed topographically by a straight, low ridge extending across the surface, which commonly marks a discontinuity in various landscapes.

- **Normal Faults** move mainly in the vertical. Rocks above the fault plane move downward relative to those beneath the fault plane. Most normal faults are steeply inclined, usually between 65 and 90 degrees.

TABLE 16-2.—*Relationship between Modified Mercalli Intensity Scale and seismic magnitude*

Western United States	
MMI	Magnitude
V	<5.0
VI	5.0
VII	5.5
VIII	6.0
IX	6.5
X-XII	7.0

Eastern United States	
MMI	Magnitude
VI	<5.
VII	5.
VIII	5.
IX	6.
X-XII	6.5

Hawaii	
MMI	Magnitude
V	<5.5
VI	5.5
VII	6.0
VIII	6.5
IX	7.0
X-XII	7.5

Alaska	
MMI	Magnitude
V	<6.0
VI	6.0
VII	6.5
VIII	7.0
IX	7.5
X-XII	8.0

Source: *Stover and Coffman, 1993*

- **Reverse (Thrust) Faults** are low-angle faults in which the hanging wall moves up and over the fault plane. Movement is predominately horizontal, and displacement can occur for more than 35 mi (56 km). These faults result from crustal shortening and are generally associated with intense folding caused by powerful horizontal compression of the crust.

EARTHQUAKE-RELATED GROUND FAILURE. Liquefaction is a physical process that takes place during some earthquakes and may lead to ground failure. Liquefaction is caused when clay-free soil deposits, primarily water-saturated sand and coarse silts, react to vibrations, temporarily lose strength, and behave as viscous fluids. Liquefaction takes place when seismic shear waves pass through a saturated granular soil layer, distort its granular structure, and cause some of the void spaces to collapse. If drainage is limited, the pore-water pressure increases. If it rises to about the pressure caused by the weight of soil, the granular soil behaves like a fluid rather than a solid for a short period of time and deformations can occur.

Generally, the younger and looser the sediment and the higher the water table, the more susceptible a soil is to liquefaction. Liquefaction enhances ground settlement and sometimes generates sand boils. Sand boils are caused by water laden with sediment venting from subsurface layers in which artesian pore-water pressures develop during liquefaction.

Liquefaction causes three types of ground failure, described below.

- **Lateral Spreads** involve the lateral movement of large blocks of soil as a result of liquefaction of an underlying layer. They generally develop on gentle slopes, most commonly on those between 0.3 and 3 degrees. Horizontal movements commonly are as much as 10 to 15 ft (3 to 5 m). However, where slopes are particularly favorable and the duration of ground shaking is long, lateral movement may be as much as 100 to 150 ft (30 to 50 m). Lateral spreads usually break up internally, forming numerous fissures and scarps.

- **Flow Failures,** consisting of liquefied soil or blocks of intact material riding on a layer of liquefied soil, are the most catastrophic type of ground failure caused by liquefaction. They commonly move scores of feet and up to dozens of miles under certain conditions. Flow failures usually form in loose saturated sand or silts on slopes greater than 3 degrees.

- **Loss of Bearing Strength** occurs when the soil supporting buildings or other structures liquefies. When

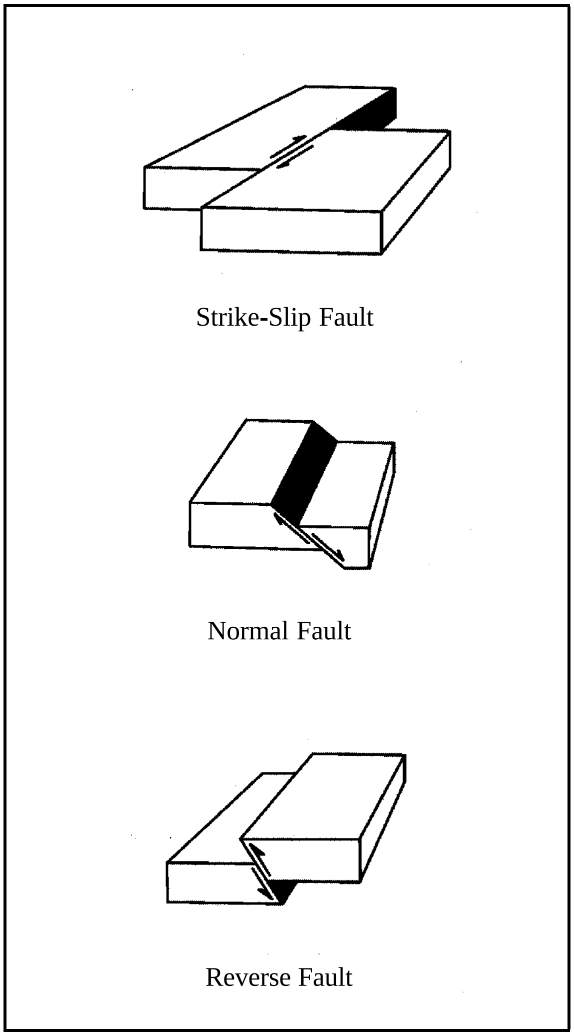


FIGURE 16-2.— Surface faulting.

Source: *Hays, 1981*

large deformations occur, structures settle and tip. The general subsurface geometry required for liquefaction-caused bearing failures is a layer of saturated, cohesionless soil that extends from near the ground surface to a depth equal to about the width of the building.

RISK ASSESSMENT

Published probabilistic ground motion maps can be used to assess the magnitude and frequency of seismic hazards. Twelve of these maps are published as part of the 1994 edition of the National Earthquake Hazards Reduction Program's *NEHRP Recommended Provisions* (FEMA-222A, 1994). NEHRP Maps 1 to 4, prepared by the Applied Technology Council, Redwood City, CA, and based on a probabilistic maximum ground acceleration map by Algermissen and Perkins (1976), were originally published as part of the *Tentative Provisions* in 1978. NEHRP Maps 5 to 12 were developed by USGS.

Probability and Frequency

Algermissen and Perkins (1976) described preparation of a probabilistic maximum ground acceleration map, described below.

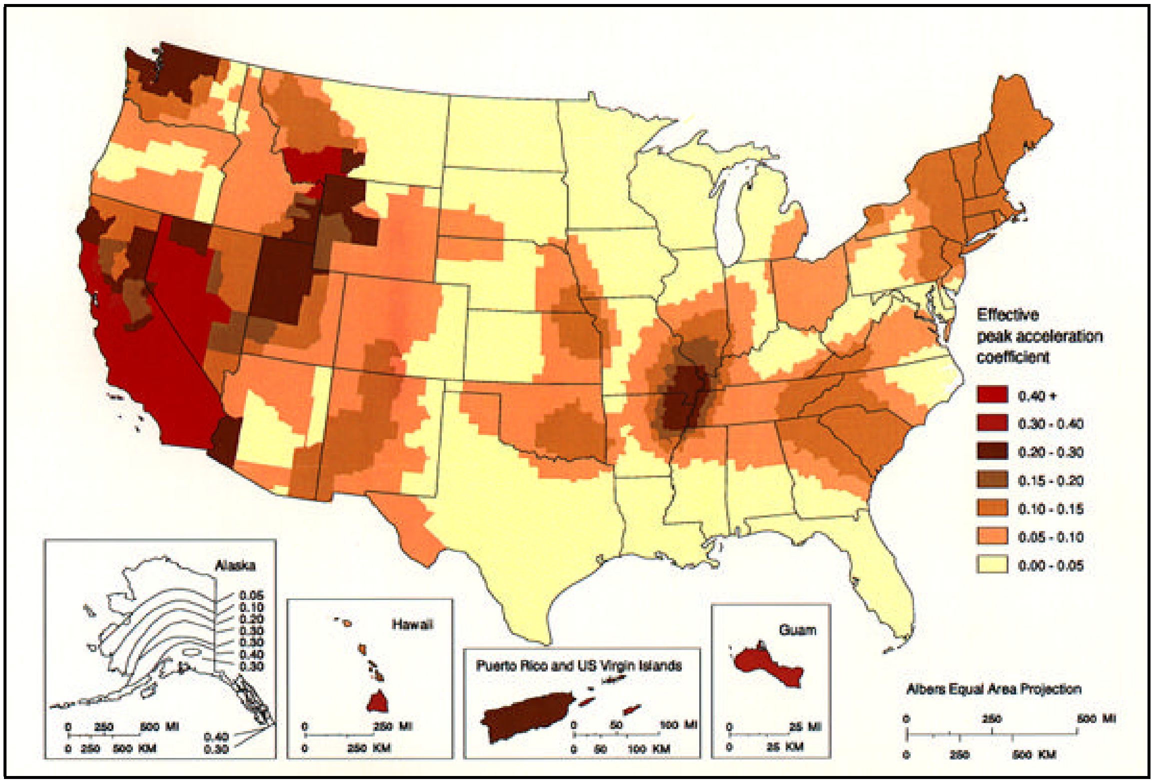
1. Source zones and faults in which, or along which, significant earthquakes (MMI of V or greater, magnitude of 4.0 or greater) can occur were identified and delineated on a map. Spatial occurrence of future earthquakes was assumed to be uniform throughout each source zone. Using historical seismicity, geological, and tectonic information, 71 seismic source zones were identified.

2. For each source zone, the rate at which earthquakes of different magnitudes can occur and the maximum credible magnitudes were estimated. The number of earthquakes per unit time per unit area were related linearly to the magnitude, with coefficients determined from known events in each source zone. Future earthquake occurrences were assumed to have the same general average time rate characteristics as past earthquakes.

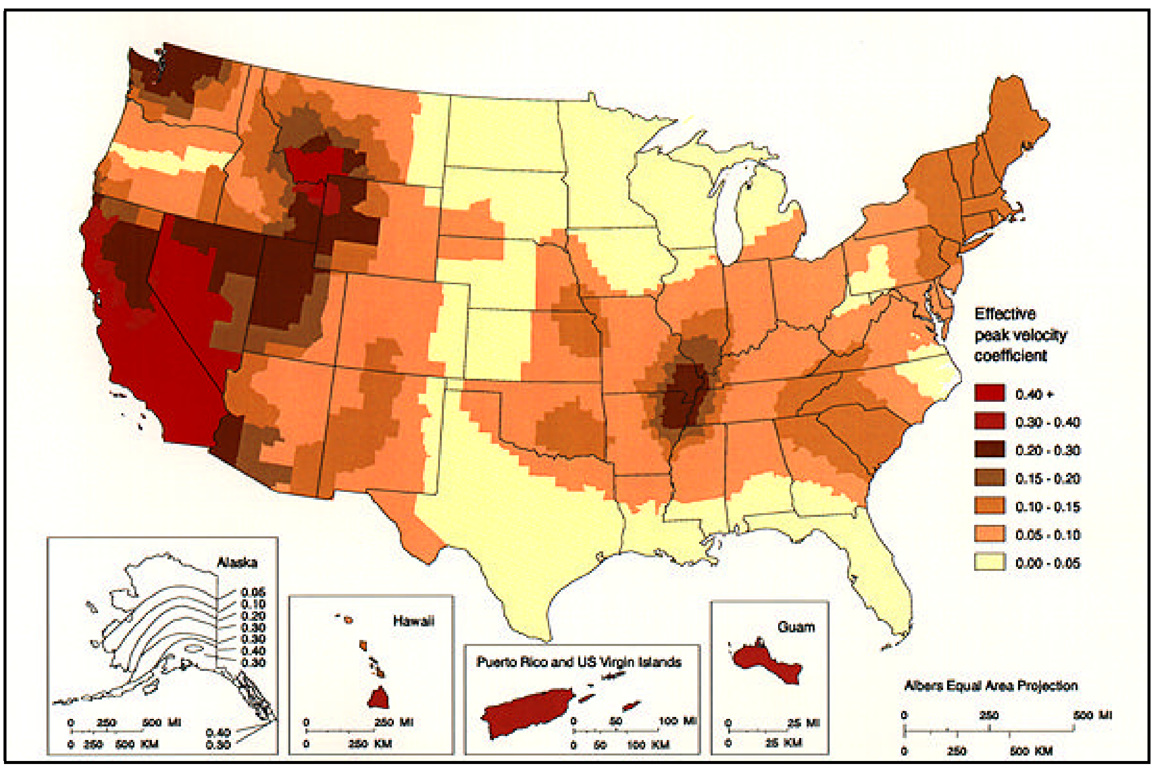
3. Acceleration attenuation curves were used to give the intensity of shaking as a function of magnitude and distance from an epicenter. Different attenuation curves were used for the Western and Eastern States.

4. The distribution of acceleration was computed for a number of sites in each source zone. The expected number of times a particular acceleration is likely to occur in a given period of years was determined, and the maximum acceleration in a given number of years corresponding to a given level of exceedance probability was estimated. The probabilistic model assumed that the occurrences of major earthquakes is a Poisson process and that they are independent and identically distributed events. The assumption of a Poisson process results in an exponential probability distribution of the time between occurrences of major earthquakes.

5. The maximum acceleration with a 10-percent chance of being exceeded in 50 years was computed and mapped. The return period for this acceleration is approximately 475 years, or, stated alternatively, there is a 0.21-percent chance of it being exceeded in any given year.



Map 16-1. Spatial variation in the effective peak acceleration coefficient (A_a), by county.
Data not available for American Samoa.
Source: *Map 1 in 1994 edition of the "NEHRP Recommended Provisions."*



Map 16-2. Spatial variation in the effective peak velocity coefficient (A_v), by county.
Data not available for American Samoa.
Source: *Map 2 in 1994 edition of the "NEHRP Recommended Provisions."*

In developing NEHRP Maps 1-4, two parameters were used to characterize the intensity of ground shaking: effective peak acceleration (EPA), and effective peak velocity (EPV). EPA, which is related to oscillation of buildings, is computed for periods in the range of 0.1 to 0.5 seconds and is generally less than the peak ground acceleration. EPV is computed for approximately 1-second-long periods and is generally greater than peak ground velocity at large distances from major earthquakes.

For the purpose of computing seismic design coefficients, EPA and EPV are replaced by dimensionless coefficients A_a and A_v. EPA is equal to A_a when expressed as a decimal fraction of the acceleration of gravity, such that if EPA = 0.2G, then $A_a = 0.2$. A_v is equal to EPV divided by 30 (FEMA-223A, 1994).

NEHRP Map 1 (Map 16-1), which shows values A_a of by county, was developed to avoid operational difficulties associated with having different zones within a single jurisdiction.

NEHRP Map 2 (Map 16-2), which shows values of A_v by county, was converted to a county-by-county map from the contour map published as NEHRP Map 4, which originates from NEHRP Map 3, a contour map of A_a.

Algermissen and Perkins (1976) originally developed peak ground accelerations with a 10-percent chance of being exceeded in a 50-year period. However, because the mapped values of A_a and A_v (as illustrated in Maps 16-1 and 16-2) were truncated, adjusted, and smoothed, the percent chance of exceedance cannot be estimated precisely, and the risk may not be the same at all locations.

The percent chance of exceedance of A_a and A_v in Maps 16-1 and 16-2, is believed to be in the range of 10 to 20 percent for a 50-year period. This would imply that the return period is on the order of 225 to 475 years, or that the percent chance of exceedance in any given year is on the order of 0.44 to 0.21 percent. The use of a 50-year period to characterize the percent chance of exceedance is rather arbitrary for convenience, and does not imply that all buildings are thought to have a useful life of 50 years (FEMA-223A, 1994).

Exposure

The zone of greatest seismic activity in the United States is along the Pacific Coast in Alaska and California. However, the Central and Eastern States have also experienced seismic activity: the Boston vicinity (1755); the central Mississippi Valley at New Madrid, MO (1811-1812); Charleston, SC (1880s); and at Hebgen Lake, MT (1959). In 1973, earthquakes were felt in 34 States. All or parts of 39 States lie in regions classified as having major or moderate seismic risk (Hays, 1981).

FEMA recently conducted a study of the number of people and businesses that are exposed to various hazards, including seismic risks of 0.1 percent or greater ($A_a \geq 0.1$). When evaluated by county and State, over 109 million people and 4.3 million businesses may be exposed. The study did not provide information on potential losses from earthquakes.

Consequences

Damages and deaths associated with significant U.S. earthquakes that measured 6.4 and higher on the Richter scale from 1964 to 1994 are summarized in Table 16.3. Different sources report varying values of magnitude, damages, and deaths for these events. In general, the values reported in Stover and Coffman (1993) were used to achieve some measure of consistency.

Recent significant earthquakes have occurred in the Western United States. Losses can be catastrophic, as evidenced by the $20 billion in damage caused by the 1994 Northridge earthquake where collapse of structures due to ground shaking was a major cause of damage. Hays (1990) estimates that the average annual losses from all U.S. earthquakes are approximately $1 billion. The average loss from earthquakes measuring 6.4 or greater is approximately $900 million.

Deaths and injuries from surface faulting are unlikely, but casualties can occur indirectly through damage to structures. Surface faulting, in the case of a strike-slip fault, generally affects a long narrow zone whose total area is small compared with the total area affected by ground shaking. Nevertheless, damage to structures located in a fault zone can be very high, especially where land use is intensive.

A variety of structures have been damaged by surface faulting, including houses, apartments, commercial buildings, nursing homes, railroads, highways, tunnels, bridges, canals, storm drains, water wells, waterlines, gaslines, and sewer lines. Damage to these structures has ranged from minor to very severe. An example of severe damage occurred in 1952 when three railroad tunnels in California were badly damaged. As a result, traffic on a major line linking northern and southern California was stopped for 25 days, despite an around-the-clock repair effort (Hays, 1981).

TABLE 16-3.—*Significant U.S. earthquakes: 1964 – 1994.*

Location	Date	Magnitude *	Damages *(in millions)*	Deaths
Prince William Sound, AK	March 27, 1964	8.4	$311.0	125
Puget Sound, WA	April 29, 1965	6.4	$12.5	7
San Fernando, CA	February 9, 1971	6.6	$505.0	65
Island of Hawaii	November 29, 1975	7.2	$4.1	2
Imperial Valley, CA	October 15, 1979	6.5	$30.0	0
Coalinga, CA	May 2, 1983	6.4	$10.0	0
Borah Peak, ID	October 28, 1983	6.5	$12.5	2
Island of Hawaii	November 16, 1983	6.6	$7.0	0
Loma Prieta, CA	October 17, 1989	7.1	$6,000.0	63
Northridge, CA	January 17, 1994	6.7	$20,000.0	61

*Sometimes an average of different magnitude types.

Sources: *From Stover and Coffman, 1993; Heliker, 1990; Hays, 1980; FEMA, 1993.*

Damage caused by lateral spreads is seldom catastrophic, but usually is disruptive. For example, during the 1964 earthquake in Alaska, more than 200 bridges were damaged or destroyed by lateral spreading of floodplain soils toward river channels. The spreading deposits compressed bridges over channels, buckled decks, thrust sedimentary beds over abutments, and shifted and tilted abutments and piers (Hays, 1981). A number of major water pipeline breaks occurred during the 1906 earthquake in San Francisco, CA, hampering efforts to fight fires. Thus, rather inconspicuous ground-failure displacements of less than 7 ft (2.2 m) contributed significantly to the overall devastation.

Flow failures can originate underwater or on land. Many of the largest and most damaging flow failures have taken place underwater in coastal areas. For example, large sections of port facilities at Seward, Whittier, and Valdez, AK, were carried away during the 1964 earthquake. These flow failures, in turn, generated large sea waves that overran parts of the coastal floodplain, causing additional damage and casualties.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Susceptibility of Lateral-Spread Ground Failure. A new methodology to determine the spatial susceptibility of earthquake-induced lateral-spread ground failure (liquefaction) is described by Pike and others (1994) for a study area along the Monterey Bay coast of central California. Using Probit regression analysis, a regional model was developed to estimate the susceptibility of liquefaction based on age and sand content of the sedimentary deposits, horizontal distance to nearest surface water, and ground slope. The occurrence (or non-occurrence) of liquefaction in 100-m (309-ft) grid cells was identified throughout the study area. The methodology could be used where adequate data on liquefaction are available. Susceptibility has no implications for frequency of occurrence.

Loss Estimation Methodology. The National Institute of Building Sciences (NIBS), under a cooperative agreement with FEMA, is developing a nationally applicable standardized methodology for estimating potential earthquake losses on a regional basis (Chapter 24). Known as HAZARD U.S. (HAZUS), the method will be used by local, State, and regional officials to plan and prepare for emergency response and recovery, and to stimulate mitigation actions. HAZUS may be used for rapid loss estimations following earthquake events. Pre-disaster assessments may support risk-based allocation of federal resources in the future.

National Earthquake Hazards Reduction Program (NEHRP). In 1977, the U.S. Congress passed the National Earthquake Hazards Reduction Act (P.L. 95-124). NEHRP, a program to reduce or mitigate the nation's losses from earthquakes, was initiated in June 1978. Fundamental research on earthquake hazards and engineering techniques to reduce losses has been carried out or funded by FEMA, USGS, NIST, and NSF.

Recently, a strategy for a new National Earthquake Program (NEP) to strengthen and extend NEHRP was formulated by the National Earthquake Strategy Working Group (NESW) for the National Science and Technology Council and the White House Office of Science and Technology Policy (NESW, 1995). NEP aims to focus scarce research and development dollars on the most effective means for saving lives and property, limiting social disruptions from earthquakes, coordinating Federal research and development, and supporting emergency planning in other Federal agencies. The objectives are to avoid duplication, ensure focus on priority goals, and cooperate with the private sector and State and local jurisdictions to apply effective mitigation strategies and measures.

Leadership and coordination for NEP is provided by FEMA. FEMA's responsibilities include transfer of research results to the user communities and keeping research focused on the NEP goals.

Parkfield Earthquake Prediction Experiment. The San Andreas fault at Parkfield, CA, is one of the most active faults in the United States. Earthquakes of magnitude 6.0 or more occurred in 1857, 1881, 1901, 1922, 1934, and 1966, for an average of 22 years between events. In 1985, USGS published a prediction that the next Parkfield earthquake was expected in a time window centered on 1988, with a 95-percent chance of occurrence by the end of 1992 (Bakun and Lindh, 1985). The National Earthquake Prediction Evaluation Council working group (NEPEC) reviewed the prediction favorably, and USGS located a focused experiment at Parkfield.

The USGS and the State of California have instrumented the Parkfield area with over 20 observational networks, including seismometers, creep meters, borehole strain meters, a two-color laser geodimeter, water wells, and magnetometers. Five networks are monitored in real-time. The experiment has two scientific goals: to record geophysical data before, during, and after the expected earthquake; and to issue a short-term prediction. With the involvement of the State, the experiment took on an important public policy aspect, serving as a test bed for communication between earthquake scientists and public officials (NEPEC, 1994).

Although the predicted earthquake did not occur by 1992, Parkfield still is considered to be more likely to experience a strong (magnitude 6.0) earthquake than any other place in the United States. Several estimates of the percent chance of occurrence of an event cluster around a value of approximately 10 percent per year. Such a probability is high enough that monitoring of the Parkfield area is continuing.

Spectral Response Maps. The earthquake maps used to administer building codes have their origin in the Algermissen and Perkins peak acceleration map (1976). Maps of spectral response ordinates at natural periods of 0.3 and 1.0 seconds for a reference site condition were developed in 1994 and are available for the entire United States (Leyendecker and others, 1995). They are for a 10-percent chance of exceedance for exposure times of 50 and 250 years (return periods of approximately 475 and 2,370 years). The spectral response maps are revisions of those first prepared and published in the 1991 *NEHRP Recommended Provisions.* The 1994 revision gives recognition to the increased likelihood of occurrence of large earthquakes on the Cascadia subduction zone off the coast of the Northwestern United States (Leyendecker and others, 1995).

MITIGATION APPROACHES

Considerable interagency cooperation and research have supported adoption of State and local building codes and regulations designed to reduce losses sustained by new and existing construction due to seismic hazards. The cooperating organizations included ATC, NIST, NSF, ASCE, NIBS, and FEMA.

The emergence of FEMA as the agency responsible for implementing the Earthquake Hazards Reduction Act and NEHRP required the establishment of a mechanism to obtain a broad public and private consensus on recommended improvements for building design and construction regulatory provisions. Following a series of meetings with ASCE, NSF, NIST, and NIBS, the Building Seismic Safety Council (BSSC) was created in 1979 under the auspices of NIBS and is located in Washington, DC.

BSSC was established as an independent, voluntary membership body to deal with the complex regulatory, technical, social, and economic issues involved in developing and promulgating national regulatory provisions. BSSC, which represents all of the needed expertise and all relevant public and private interests (50+ organizations), has improved the seismic safety provisions published by FEMA (FEMA-222A, 1994). BSSC coordinates the activities of 12 technical subcommittees that address technical, social, political, legal, administrative, and regulatory issues.

Two important programs coordinated by FEMA and supported by many other agencies are the rehabilitation of existing buildings and the seismic safety of new buildings. Many publications provide guidance on mitigation techniques have resulted.

Publications related to rehabilitation of existing buildings include:

- Rapid visual screening of buildings for potential seismic hazards (FEMA-154 and FEMA-155, 1988);
- Techniques for the seismic evaluation and rehabilitation of existing buildings (FEMA-178 and FEMA-172, 1992);
- Typical costs and benefit-cost model for the seismic rehabilitation of existing buildings (FEMA-156, 1994; FEMA-157, 1995; FEMA-227 and FEMA-228, 1992);
- Establishing programs and priorities for the seismic rehabilitation of buildings (FEMA-173 and FEMA-174, 1989);
- Financial incentives for seismic rehabilitation of buildings (FEMA-198 and FEMA-199, 1990); and
- Identification and resolution of issues related to seismic rehabilitation of buildings (FEMA-237, 1992).

Publications related to seismic safety of new buildings include:

- The *NEHRP Recommended Provisions* for seismic regulation for new buildings, including the NEHRP probabilistic ground motion maps (FEMA-222A and FEMA-223A, 1994);
- The *Non-Technical Explanation of the 1994 NEHRP Recommended Provisions* (Building Seismic Safety Council, 1995);
- *Seismic Consideration for Communities at Risk* (Building Seismic Safety Council, 1990);
- Selected readings on societal implications (FEMA-84, 1985);
- Seismic considerations for elementary and secondary schools (FEMA-149, 1990), health care facilities (FEMA-150, 1990), hotels and motels (FEMA-151, 1990), apartment buildings (FEMA-152, 1988), and office buildings (FEMA-153, 1988); and
- Interim guidelines for evaluation, repair, modification and design of steel moment frame structures (FEMA-267, 1995).

RECOMMENDATIONS

The National Earthquake Strategy Working Group (1995) provided recommendations for a new strategy for earthquake loss reduction. The 1994 *NEHRP Recommended Provisions* includes recommendations for the safe seismic design of new buildings (FEMA-222A and FEMA-223A, 1995). FEMA provided several recommendations for loss-reduction measures (FEMA-200, 1990).

The Applied Technology Council, a nonprofit organization established by the Structural Engineers Association of California to conduct projects, workshops, and seminars in support of structural engineering, especially earthquake-related topics, is developing nationally accepted guidelines for the seismic rehabilitation of buildings. The guidelines will incorporate information from the many publications produced, and will provide recommendations.

Experts on the 12 technical subcommittees of BSSC are evaluating the impacts of adopting the new USGS spectral response probabilistic ground motion maps described by Leyendecker and others (1995).

BIBLIOGRAPHY AND REFERENCES

Algermissen, S.T., D.M. Perkins, P.C. Thenhaus, S.L. Hanson, and B.L. Bender. 1982. ***Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States.*** U.S. Geological Survey Open-File Report 82-1033.

Algermissen, S.T., and D.M. Perkins. 1976. ***A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States.*** U.S. Geological Survey Open-File Report 76-416.

Bakun, W.H., and A.G. Lindh. 1985. "The Parkerfield, California, Earthquake Prediction." ***Science.*** Vol. 229, pp. 619-624.

Building Seismic Safety Council. 1994. ***NEHRP Recommended Provisions for Seismic Regulations for New Buildings. Part 1: Provisions.*** Washington, DC.

Building Seismic Safety Council. 1995. ***NEHRP Recommended Provisions for Seismic Regulations for New Buildings. Part 2: Commentary.*** Washington, DC.

Building Seismic Safety Council. 1995. ***Non-Technical Explanation of the 1994 NEHRP Recommended Provisions.*** Washington, DC.

Building Seismic Safety Council. 1995. ***Seismic Consideration for Communities at Risk.*** Washington, DC.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Federal Emergency Management Agency. 1985. ***Societal Implications: Selected Readings.*** FEMA-84. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1988. ***Seismic Considerations: Apartment Buildings.*** FEMA-152. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1988. ***Seismic Considerations: Office Buildings.*** FEMA-153. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1988. ***Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook.*** FEMA-154. Prepared by Applied Technology Council. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1988. ***Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation.*** FEMA-155. Prepared by Applied Technology Council. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1989. ***Establishing Programs and Priorities for the Seismic Rehabilitation of Buildings: Supporting Report.*** FEMA-173. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1989. ***Establishing Programs and Priorities for the Seismic Rehabilitation of Buildings: A Handbook.*** FEMA-174. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1990. ***Seismic Considerations: Elementary and Secondary Schools.*** FEMA-149. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1990. ***Seismic Considerations: Health and Care Facilities.*** FEMA-150. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1990. ***Seismic Considerations: Hotels and Motels.*** FEMA-151. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1990. ***Financial Incentives for Seismic Rehabilitation of Buildings - An Agenda for Action - Volume 1 - Findings, Conclusions and Recommendations.*** FEMA-198. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1990. ***Financial Incentives for Seismic Rehabilitation of Buildings - An Agenda for Action - Volume 2 - State and Local Case Studies and Recommendations.*** FEMA-199. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1990. ***Loss-Reduction Provisions of a Federal Earthquake Insurance Program - Final Report.*** FEMA-200. Los Angeles, CA: Dames and Moore.

Federal Emergency Management Agency. 1992. ***SNEHRP Handbook of Techniques for the Seismic Rehabilitation of Existing Buildings.*** FEMA-172. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1992. ***NEHRP Handbook for Seismic Evaluation of Existing Buildings.*** FEMA-178. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1992. ***A Benefit-Cost Midel for Seismic Rehabilitation of Buildings, Volume I: A User's Manual.*** FEMA-227. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1992. ***A Benefit-Cost Model for the Seismic Rehabilitation of Buildings Volume II: Supporting Documentation.*** FEMA-228. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1992. ***Seismic Rehabilitation of Buildings, Phase I: Issues, Identification and Resolution.*** FEMA-237. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1994. ***Typical Costs for Seismic Rehabilitation of Existing Buildings, Second Edition, Volume I - Summary.*** FEMA-156. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1994. ***NEHRP Recommended Provisions for the Development of Regulations for New Buildings Part 1, Provision.*** FEMA-222A. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1994. ***NEHRP Recommended Provisions for Commentary Part II.*** FEMA-223A. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. June 1994. ***Assessment of the State-of-the-Art Earthquake Loss Estimation Methodologies, Earthquake Hazards Reduction Series 70.*** FEMA-249. Washington, DC: National Institute of Building Sciences.

Federal Emergency Management Agency. 1995. ***Typical Costs for Seismic Rehabilitation of Existing Buildings, Second Edition, Volume II - Supporting Documentation.*** FEMA-157. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1995. ***Interim Guidelines: Evaluation, Repair, Modification, and Design of Welded Steel Moment Frame structures.*** FEMA-267. Washington, DC: U.S. Government Printing Office.

Hays, W.W. 1990. "Perspectives on the International Decade for Natural Disaster Reduction." ***Earthquake Spectra.*** Vol. 1. U.S. Geological Survey.

Heliker, C. 1990. ***Volcanic and Seismic Hazards on the Island of Hawaii.*** U.S. Geological Survey.

Hays, W.W. (ed). 1981. ***Facing Geologic and Hydrologic Hazards: Earth-Science Considerations.*** U.S. Geological Survey Professional Paper 1240-B.

Lyendecker, E.V., D.M. Perkins, S.T. Algermissen, P.C. Thenhaus, and S.L. Hansen. 1995. ***USGS Spectral Response Maps and their Relationship with Seismic Design Forces in Building Codes.*** U.S. Geological Survey Open-File Report 95-596.

National Earthquake Prediction Evaluation Council. 1994. ***Earthquake Research at Parkfield, California, 1993 and Beyond--Report of the NEPEC Working Group to Evaluate the Parkfield Earthquake Prediction Experiment.*** U.S. Geological Survey Circular 116. Washington, DC: U.S. Government Printing Office.

National Earthquake Strategy Working Group for National Science and Technology Council and White House Office of Science and Technology. 1995. ***Strategy for National Earthquake Loss Reduction.*** Washington, DC.

Palm, R.I., and M.E. Hodgson. 1993. ***Natural Hazards in Puerto Rico: Attitudes, Experience, and Behavior of Homeowners.*** Monograph No. 55. Boulder, CO: Institute of Behavioral Science, University of Colorado.

Pike, R.J., R.L. Bernknoff, J.C. Tinsley, III, and R.K. Mark. 1994. ***Hazard of Earthquake-Induced Lateral-Spread Ground Failure on the Central California Coast Modeled from Earth-Science Map Data in a Geographic Information System.*** U.S. Geological Survey Open-File Report 94-662.

Stover, C.W., and F.L. Coffman. 1993. ***Seismicity of the United States 1568-1989 (Revised).*** U.S. Geological Survey Professional Paper 1527.

Toppozada, T., G. Borchardt, W. Haydon, M. Peterson, R. Olson, H. Lagorio, and T. Anvik. 1995. ***Planning Scenario in Humboldt and Del Norte Counties, California, for a Great Earthquake on the Cascadia Subduction Zone.*** California Department of Conservation, Division of Mines and Geology, Special Publication No. 115.

U.S. Department of the Interior, Geological Survey. 1995. ***USGS Spectral Response Maps and Their Relationship With Seismic Design Forces in Building Codes.*** U.S. Geological Survey Open-File Report 95-956. Washington, DC.

Wold, R.L., and C.L. Jochim. 1989. ***Landslide Loss Reduction: A Guide for State and Local Government Planning.*** Colorado Department of Natural Resources, Colorado Geological Survey. Denver, CO.

Wood, H.O., and F. Neumann. 1931. "Modified Mercalli Intensity Scale of 1931." ***Seismological Society of America Bulletin.*** Vol. 21, No. 4, pp. 277-283.

CHAPTER

17

TSUNAMI EVENTS

Chapter Summary

The tsunami, a Japanese word meaning "harbor wave," occurs most commonly in the Pacific Ocean. Tsunami waves have resulted in significant coastal flooding and damage in the Western States, Alaska, Hawaii, and American Samoa. Events in the Atlantic Ocean and Caribbean Sea have occurred in the vicinity of Puerto Rico and the U.S. Virgin Islands, but are much less frequent.

Tsunamis are large seismic sea waves, usually generated by shallow-focus, underwater earthquakes. A tsunami wave can travel across the ocean at speeds up to 500 mph (800 km/h). Upon hitting a coastline, a wave can cause significant damage to shore protection structures and buildings, severe erosion, extensive inland flooding, and loss of life.

Tsunami events affecting the United States and its territories have been responsible for almost 470 fatalities and hundreds of million dollars in property, infrastructure, transportation, and lifeline damage. The United States has not experienced a major tsunami event since the Great Alaskan Earthquake at Prince William Sound on March 28, 1964. That event killed 10 people and caused more than $7 million in property damage in Crescent City, CA. It caused 106 fatalities and more than $84 million in damage in Alaska. The worst tsunami in U.S. history occurred in the Aleutian Islands on April 1, 1946, and was responsible for 159 deaths and $26 million in damage.

Hawaii is subject to remote-source tsunamis generated by earthquakes throughout the Pacific. The remaining tsunami-prone areas along the coasts of the continental United States, Alaska, Puerto Rico and the U.S. Virgin Islands are affected by locally generated events caused by subduction, underwater landslides, and volcanic activity. Since 1770, more than 46 remote-source generated tsunamis and 18 local tsunamis have been observed along the West Coast.

Hazard identification and risk assessment efforts include detailed mapping of tsunami wave runup and flood inundation limits, as well as related hazards that are expected concurrently with tsunamis. Public education campaigns are important to increase awareness. Mitigation measures include construction of shore-protection structures, land-use planning and building techniques, and relocation of utility lines, water mains, sewer lines, and roadways in immediate impact areas.

Photo: Red Cross

HAZARD IDENTIFICATION

Tsunamis are large seismic sea waves, impulsively generated by shallow-focus earthquakes. They typically are induced by a rapid, vertical thrust along the subsurface fault line between two tectonic plates of the earth's crust (Camfield, 1994). When a large mass of earth on the ocean bottom impulsively sinks or uplifts, the column of water directly above it is displaced, forming a tsunami wave on the surface. Tsunamis also are caused by volcanic activity and submarine landslides, but these triggering events occur less frequently than earthquakes. Earthquakes may induce landslides that contribute to wave size.

A tsunami wave can travel across the ocean at speeds up to 500 mph (800 km/h), depending on the location and source of the event. A tsunami is relatively unnoticeable until the shoaling effects of the nearshore continental shelf interact with the wave, boosting wave heights to 50 ft (15 m) or more. Astronomical tide levels, resonance in narrowing bays, and concave shoreline features may contribute to increases in wave height. Large tsunami waves have been known to damage and flood areas up to 1 mi (1.6 km) inland.

The height of a tsunami wave will be affected by its interaction with the shoreline. This influence will vary, depending on shoreline geometry (orientation and configuration), existence of submarine canyons, shoaling and refraction of incident waves, and large headland features. When waves reach coastal scarps, heights increase, while the nature of the wave period allows it to bend around obstacles. Coral reefs surrounding islands in the western North Pacific and the South Pacific generally cause waves to break, providing some protection to the islands.

Lander and Lockridge (1989) found the intensity of a tsunami wave to be directly related to:

- Magnitude of the shallow-focus earthquake;
- Area and shape of the rupture zone;
- Rate of displacement and sense of motion of the ocean floor in the source (epicenter) area;
- Amount of displacement of the rupture zone; and
- Depth of water above the rupture zone.

Radiation of a tsunami wave from the source area is directional, with wave periods ranging from 5 to 60 minutes. Long-period waves typically are associated with large-magnitude earthquakes, and smaller magnitude earthquakes generate short-period waves.

A remote-source tsunami may travel for more than 1 hour from its epicenter before it impacts a shoreline. While in deep water, its wave velocity is high. As the tsunami reaches shallow coastal waters, it slows down, its wavelength shortens, and its wave energy increases due to the shoaling effects of the nearshore subbottom. This effect can magnify a 3-ft (1-m) ocean tsunami wave to more than 50 ft (15 m) during coastal runup.

Depending on the reflection at the shoreline, Camfield (1994) reported the interaction of a tsunami with the shoreline could produce standing wave resonance at the shoreline, generation of edge waves by impulse of the incident waves, trapping of reflected waves by refraction, and the possibility of a Mach-stem along the shoreline. When a wave reaches the shoreline, it either breaks on the beach or rushes ashore as a bore-like, abrupt front of water (Lander and Lockridge 1989).

In Alaska, the principal tsunami source zones differ along exposed shorelines. Portions of the North Pacific Ocean coastline of Alaska are subject to tsunamis generated by landslides, tectonic plate movement (subduction), submarine landslides, and volcanic activity. The Aleutian Island coastlines are affected by remote-source earthquakes (Lander, 1994). In the Gulf of Alaska, tsunami waves may be generated by all sources. The coastline along the Bering Sea is not considered threatened by tsunami.

Because of its location in the central North Pacific basin, Hawaii is subject to remote-source tsunami generated by tectonic earthquakes from all Pacific regions. South Pacific seismic activity in the vicinity of American Samoa causes remote-source tsunami events. The remaining tsunami-prone areas along the coasts of the continental United States, Alaska, Puerto Rico and the U.S. Virgin Islands are affected by locally generated events caused by subduction, landslides, and volcanic activity.

The subduction zone off the West Coast is located relatively close to the shoreline, with the Juan De Fuca plate offshore of Oregon and Washington posing a likely source of locally-generated tsunamis. Researchers conducting sediment/soil investigations in the Pacific Northwest found sheets of sand deposited over coastal lowlands at ground elevations of up to 60 ft (18 m) above sea level, suggesting a tremendous tsunami event. Evidence that significant Cascadia subduction-zone tsunamis have occurred over the past 7,000 years has alerted officials to the exposure of coastal communities in the region. Tsunami researchers have predicted a recurrence of an event of this magnitude within the next 50 years (Preuss and Hebenstreit, 1991).

According to the American Samoa Department of Public Safety, TEMCO, draft *Survivable Crisis Management Plan* (1995), the tsunami hazard in American Samoa is primarily due to undersea earthquakes with magnitudes greater than 6.5 on the Richter scale. The abrupt rise of the islands from the ocean floor limits tsunami wave heights at the coastline.

RISK ASSESSMENT

Probability and Frequency

Since 1770, more than 46 remote-source generated tsunamis and 18 local tsunamis have been observed along the West Coast of the United States. Only the 1964 Prince William Sound Alaskan earthquake-induced event caused significant damage along the West Coast. Other major tsunami events occurred in the region in 1946 and 1957 in the Aleutian Islands, in 1952 on Kamchatka Island, and in 1975 in Hawaii.

Five tsunami hazard zones are identified in USGS Open-File Report 85-533 (USGS, 1985), prepared for the Interagency Committee on Seismic Safety in Construction (ICSSC). The report includes a map of general tsunami hazards for the United States and detailed mapping of hazard zones for the Hawaiian Islands. Map 17-1 reproduces predicted tsunami elevations with a 90-percent chance of not being exceeded in a 50-year period only for the Western United States, Alaska and Hawaii. The data and frequency curves were developed by the USACE Waterways Experiment Station (WES) in Vicksburg, MS, for FEMA Flood Insurance Studies from 1974 to 1980, and for a 1977 report on tsunami-wave elevation frequency of occurrence for Hawaii. The elevations along the Hawaiian shoreline include the combined effects of tsunami and astronomical tides, which are not included in determining hazard zones in other areas.

Coastal topography defines the landward penetration of tsunami wave runup and flood inundation. The elevation with a 1-percent chance of being equaled or exceeded in any given year, also known as the 100-year elevation, varies throughout the Pacific Ocean. Variations are due to differences in shoreline configuration, offshore bathymetry, upland topography, wave type, and proximity to sources of tsunami waves.

The principal tsunami-related risk in the Northwestern United States is considered to be from an offshore, subduction earthquake in the Cascadia fault zone. The last major Cascadia subduction-zone tsunami event, based on sedimentological records, occurred approximately 350 to 600 years ago (Preuss and Hebenstreit, 1991).

Along the coasts of California, Oregon, and Washington, predicted tsunami elevations are lower than the 1-percent-annual-chance coastal storm flood elevations caused by combined extreme wave heights and storm-surge tides. In Hawaii, tsunami wave runup elevations vary from 5 ft to over 20 ft (1.5 to +6 m).

Predicted tsunami elevations for American Samoa, with the exception of the Pago Pago area on Tutuila, are 4 ft (1.3 m), with inundation limits extending only 200 ft (61 m) inland. The 1-percent-annual-chance flood elevation at Pago Pago is approximately 11 ft (3.4 m) and is more associated with tropical cyclones than tsunamis.

In Puerto Rico, the potentially damaging effects of historical tsunami waves are acknowledged throughout the island. However, a return period and 1-percent-annual-chance tsunami elevation cannot be established because historical data are limited and tsunami waves occur infrequently.

Exposure

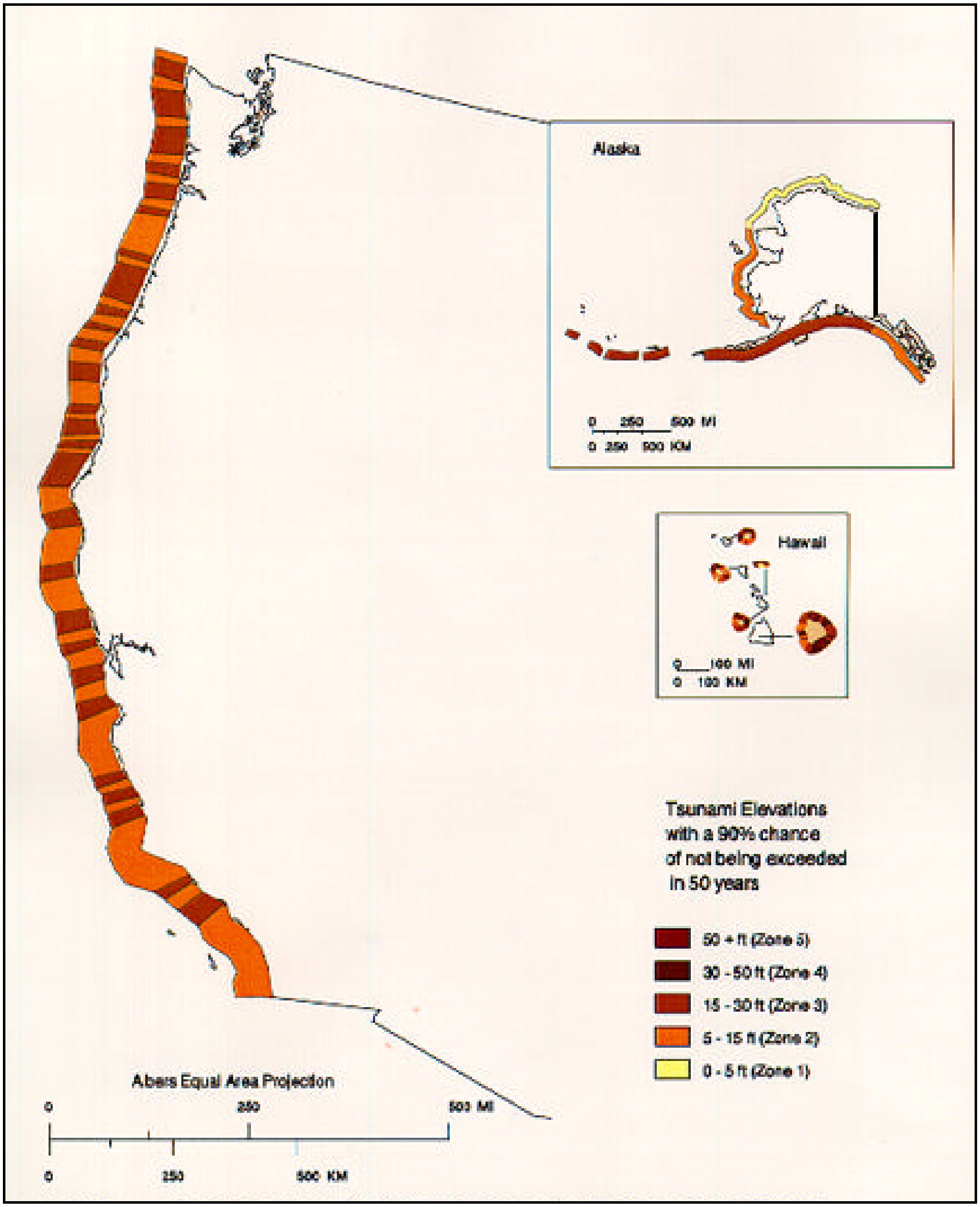
Buildings and infrastructure located in low-lying areas, in close proximity to the Pacific Ocean shoreline, and along the coasts of Puerto Rico and the U.S. Virgin Islands have the greatest exposure to the destructive forces of tsunamis.

Although a subduction-zone tsunami wave event has not occurred in recent history, exposure to potential disaster is high due to the heavily populated coastal area of the West Coast. A subduction-zone earthquake close to the shore could generate a tsunami wave that reaches the shoreline in less than 20 minutes. Thus, warning times would be insufficient to evacuate exposed areas.

During tsunami events affecting American Samoa, the village of Pago Pago on the island of Tutuila has suffered the greatest damage and flooding due to amplification of waves in its triangular bay. Damaging tsunamis occurred in the harbor at Pago Pago in 1917, 1919, 1922, 1952, 1960, and 1976. Comparatively, tropical cyclones cause greater damage throughout the island group than tsunamis.

Consequences

Tsunami events affecting the United States and its territories have been responsible for almost 470 fatalities and hundreds of million dollars in property, structure, facility, transportation, and lifeline damage (Lander and Lockridge, 1989). The high-risk areas of Alaska and Hawaii experience a damaging tsunami about every 7 years. During the past 20 years, tsunamis have not resulted in federally-declared disasters.



Map 17-1. Tsunami elevations with a 90-percent chance of not being exceeded in 50 years, also known as the 475-year return period elevation. Northern Puerto Rico and Virgin Islands (not shown) in Zone 3, southern Puerto Rico in Zone 2. Data not available for Pacific Territories. Source: *Data from U.S. Geological Survey, 1985*

The primary earthquake sources of tsunamis that impact the entire Pacific basin area are the Kamchatka Peninsula, Aleutian Islands, Gulf of Alaska, and coast of South America (Lander and Lockridge, 1989). Although about five tsunami events occur each year in the Pacific basin, only one is large enough to be observed or measured (Lander and others, 1993). A major, destructive tsunami occurs approximately once every 10 years somewhere around the Pacific Ocean.

The Great Alaskan earthquake at Prince William Sound in 1964 measured 9.2 on the Richter scale and generated waves throughout most of the Pacific basin. Several waves hit Crescent City, CA, causing over $7 million in property damage, flooding, and 10 fatalities (Toppozada and others, 1995). The first wave to reach Crescent City was 4.8 ft (1.5 m) high. The fourth wave was the largest, reaching 20.8 ft (6.3 m) and arriving hours after the first wave (Lander and others, 1993).

The 1964 event is the most significant in Alaskan history. The earthquake-generated main wave accounted for two to three dozen of the 106 fatalities attributed to the earthquake. The maximum tsunami wave elevation of approximately 200 ft (61 m) occurred in Valdez Inlet as a result of a local submarine landslide triggered by the earthquake (Lander, 1994). In all, the 1964 earthquake resulted in over $84 million worth of damage in Alaska.

The magnitude 7.3 earthquake in the Aleutian Islands in 1946, generated a tsunami with wave heights of 55 ft (17 m) in Hawaii. It is considered the worst tsunami in U.S. history, and was responsible for 159 fatalities and $26 million in damage (Lander and Lockridge, 1989).

The draft *Survivable Crisis Management Plan* for American Samoa reported that the May 22, 1960, tsunami in Pago Pago was the largest ever recorded in the island group. Tsunami wave runup at the end of Pago Pago Bay reached 10 ft (3 m), with a maximum runup elevation measured at 15.5 ft (4.7 m) in the village of Pago Pago. Damage was estimated at $50,000.

The most significant tsunami to impact Puerto Rico and the U.S. Virgin Islands occurred on November 18, 1867. Triggered by an earthquake in the Anegada Trough between St. Croix and St. Thomas, it reportedly damaged settlements in the Islands and eastern Puerto Rico (Palm and Hodgson, 1993). During another event in 1918, caused by an earthquake off the northwest coast of Puerto Rico, 40 people were killed in western part of the island.

RESEARCH, DATA COLLECTION AND MONITORING ACTIVITIES

Tsunami research has been conducted primarily by the International Tsunami Information Center at Honolulu, HI; the NWS Pacific Tsunami Warning Center (PTWC) at Ewa Beach, HI; the Alaska Tsunami Warning Center (ATWC) at Palmer, AK; the NOAA National Geophysical Data Center (NGDC) at Boulder, CO; and the NOAA Pacific Marine Environmental Laboratory (PMEL) at Seattle, WA.

Recent research efforts by FEMA, the California Division of Mines and Geology, Scientific Applications International Corporation (SAIC), the Urban Regional Research, and PMEL have focused on land-use planning and understanding the multiple-hazard impacts of a local tsunami event created by a Cascadia subduction zone earthquake.

MITIGATION APPROACHES

The potential for loss of life and property damage from a tsunami is significant enough to warrant extensive regional planning efforts to prepare pre-disaster response and mitigation plans. Hazard mitigation workshops were conducted by PMEL in 1994 and 1995, and studies were conducted for Grays Harbor, WA (Preuss and Hebenstreit, 1991), Humboldt and Del Norte Counties, CA (Toppozada and others, 1995), and Eureka and Crescent City, CA (Bernard and others, 1994). The resulting reports focus not only on the tsunami wave hazard, but also on assessment and integration of related hazards caused by a subduction-zone earthquake, mapping tsunami wave runup and multiple hazard impacts. Coastal community planning needs are addressed.

Key tsunami hazard mitigation concerns are focused on modernization and integration of existing capabilities and use of technological advancements for at-risk coastal communities. The efforts aim to provide effective hazard assessment, warning systems, and educated response to tsunami hazards, including detailed identification and mapping of tsunami wave runup and inundation limits. Warning systems must be real-time monitoring systems in order to provide information necessary to initiate emergency actions.

Public education campaigns are important to increase awareness and understanding of the hazard. They will also be vital to ensuring appropriate response in emergency situations.

Tsunami wave impacts can be mitigated in some areas through construction of shore-protection structures. The most effective means of mitigating damage to buildings are elevation above the flood levels and the use of engineered foundations to resist erosion and scour.

In some cases, the best way to prevent repetitive damage to structures is to acknowledge the risk and demolish or relocate existing buildings out of high-hazard areas. Shore protection structures can be effective in protecting upland property, given sufficient structural integrity, elevation, continuous length, and proper maintenance. Land-use and engineering practices aimed at limiting the exposure of new coastal development will help mitigate tsunami wave damage.

One land-use practice for tsunami wave hazard zones involves landscaping with vegetation capable of resisting and reflecting wave energy, thereby reducing wave height and potential damage. Planned coastal residential developments are also advised to ensure that streets and homes are located perpendicular to the waves to allow wave penetration along a path of least resistance and to reduce the likelihood of debris impact.

Other mitigation measures to reduce damage include relocation of utility lines, water mains, sewer lines, and roadways that in the immediate area of tsunami impacts. Evacuation of residents in tsunami hazard areas is undertaken to prevent loss of life.

RECOMMENDATIONS

A series of three tsunami hazard workshops were held at NOAA's Pacific Marine Environmental Laboratory (PMEL) between November 1993 and October 1994 to discuss "state-of-the-art" technology and to identify key needs and concerns of the users of NOAA's tsunami warning products. Attendees included 56 tsunami specialists from the fields of science, emergency planning, operations, and education, representing 41 different organizations of local, State, and Federal governments, and universities. The five key States affected by tsunami hazards (Alaska, California, Oregon, Washington, and Hawaii) were represented.

PMEL published the summary and conclusions of the workshops in a March 31, 1995 report to the United States Senate Appropriations Committee (PMEL, 1995). The report included recommendations that addressed three key concerns:

- Tsunami hazard assessment for identification and mapping of tsunami flood-prone areas;
- Tsunami warning systems for real-time monitoring and alerting vulnerable coastal communities and residents; and
- Proper response to the tsunami threat through public education and awareness.

BIBLIOGRAPHY AND REFERENCES

American Samoa, Department of Public Safety, TEMCO. 1995 (unpublished). ***Survivable Crisis Management (SCM) Plan for American Samoa (Draft).*** Pago Pago, American Samoa.

Bernard, E., C. Mader, G. Curtis, and K. Satake. 1994. ***Tsunami Inundation Model Study of Eureka and Crescent City, California.*** National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, NOAA Technical Memorandum No. ERL PMEL-103.

Bernard, E.N., and F.I. Gonzalez. 1994. ***Tsunami Inundation Modeling Workshop Report (November 16-18, 1993).*** National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory. NOAA Technical Memorandum No. ERL PMEL-100.

Blackford, M., and H. Kanamori. 1995. ***Tsunami Warning System Workshop Report (September 14-15, 1994).*** National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory. NOAA Technical Memorandum No. ERL PMEL-105.

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Camfield, F.E. 1994. "Tsunami Effects on Coastal Structures." ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Finkl, C. W., Jr. (Ed.). 1994. ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** The Coastal Education and Research Foundation, Inc.

Good, J.W. 1995. ***Tsunami Education Planning Workshop Findings and Recommendations.*** National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, NOAA Technical Memorandum No. ERL PMEL-106.

Lander, J.F., P.A. Lockridge, and M.J. Kozuch. 1993. ***Tsunamis Affecting the West Coast of the United States 1806-1992, Key to Geophysical Records Documentation No. 29.*** National Oceanic and Atmospheric Administration, National Geophysical Data Center.

Lander, J.F. 1994. "Alaskan Tsunamis Revisited." ***Tsunami '93: Proceedings of the IUGG/IOC International Tsunami Symposium.***

Lander, J.F., and P.A. Lockridge. 1989. ***United States Tsunamis 1690-1988 (Including United States Possessions).*** National Oceanic and Atmospheric Administration Publication 41-2. Boulder, CO: National Geophysical Data Center.

Lockridge, P.A., and R.H. Smith. 1984. ***Tsunamis in the Pacific Basin 1900-1983.*** Map. National Oceanic and Atmospheric Administration, National Geophysical Data Center.

Nishenko, S.P., and K.H. Jacob. 1990. "Seismic Potential of the Queen Charlotte-Alaska-Aleutian Seismic Zone." ***Journal of Geophysical Research.*** Vol. 95, pp. 2511-2532.

Pacific Marine Environmental Laboratory. 1995. ***Tsunami Hazard Mitigation: A Report to the Senate Appropriations Committee.*** National Oceanic and Atmospheric Administration.

Palm, R.I., and M.E. Hodgson. 1993. ***Natural Hazards in Puerto Rico: Attitudes, Experience, and Behavior of Homeowners.*** Monograph No. 55. Boulder, CO: Institute of Behavioral Science, University of Colorado.

Preuss, J., and G.T. Hebenstreit. 1991. ***Integrated Hazard Assessment for a Coastal Community: Grays Harbor.*** U.S. Geological Survey Open-File Report 91-441-M.

Soloviev, S.L., Ch.N. Go, and Kh.S. Kim. 1992. ***Catalog of Tsunamis in the Pacific 1969-1982.*** Academy of Sciences of the USSR, Soviet Geophysical Committee.

Toppozada, T., G. Borchardt, W. Haydon, M. Peterson, R. Olson, H. Lagorio, and T. Anvik. 1995. ***Planning Scenario in Humboldt and Del Norte Counties, California, for a Great Earthquake on the Cascadia Subduction Zone.*** California Department of Conservation, Division of Mines and Geology, Special Publication 115.

U.S. Geological Survey. 1985. ***Tsunamis: Hazard Definition and Effects on Facilities.*** U.S. Geological Survey Open-File Report 85-533.

Waethrich, B. 1994. "It's Official: Quake Danger in Northwest Rivals California's." ***Science.*** Vol. 265, pp. 1802-1803.

Subpart E

OTHER

NATURAL HAZARDS

Introduction

Volcanoes and wildfires are among the most frightening natural hazards and pose significant threats to people, property, and wildlife.

The United States has more than 65 potentially active volcanoes, with the greatest activity in the Western States, Alaska, and Hawaii. Nonexplosive and explosive volcanoes produce debris flows and avalanches, pyroclastic flows and surges, floods, lava flows and domes, volcanic ashfalls and gases, and lateral blasts. Lava flows tend to follow historic paths, simplifying identification of areas at greatest risk. Ashfall can spread well beyond the immediate eruption area. Volcanic activity often causes other hazardous events, such as landslides and wildfires.

Wildfires occur in virtually every State, however, more frequent incidents occur in the Western States, particularly California. Four types of wildfires constitute the hazard: wildland fires, interface or intermix fires, firestorms, and prescribed fires. Wildfires often are ignited by lightning. The severity of an event can be influenced by other natural hazards, such as drought and windstorms. As more people move into the forest interface and wildland settings, exposure to this hazard increases.

Photo: FEMA

CHAPTER

18

VOLCANIC HAZARDS

Chapter Summary

Hazards associated with the eruption of volcanoes endanger people, buildings, and infrastructure. Nonexplosive and explosive eruptions produce debris flows and avalanches, pyroclastic flows and surges, floods, lava flows and domes, ashfalls and gases, and lateral blasts. Areas at risk from volcanic eruptions primarily are those in or near the direct path of flows, although ashfalls affect people, the environment, and aircraft for extended distances.

In the 1980s, volcanoes worldwide killed over 28,500 people, more than during the first 80 years of this century (Wright and Pierson, 1992). This decade experienced more worldwide volcanic activity and crises than any other in recorded history (Lipman and Mullineaux, 1981). The cataclysmic Mount St. Helens eruption in 1980 resulted in approximately 60 deaths and over $1.5 billion in damage. Other volcanic activity during the 1980s included Mauna Loa and Kilauea in Hawaii, Long Valley Caldera in California, and Redoubt in Alaska.

More than 65 active or potentially active volcanoes exist in the United States, more than all other countries except Indonesia and Japan. Most are located in Alaska, and 55, including eight on the mainland, have been active since the United States was founded (Simkin and others, 1981).

Following the eruption of Redoubt in 1989, scientists monitored the volcano using ground and seismic signal amplitude measurements, slow-scan video photography, and lightning and debris-flow detection systems. Use of these technologies will enhance detection and warning. Disaster preparedness and evacuation planning may reduce injuries and loss of life. Identification of hazard zones for land-use planning may help address property damage.

Photo: Keith Ronnholm, FEMA

HAZARD IDENTIFICATION

Eruptions of U.S. volcanoes can generate serious hazards, any of which can be deadly (Wright and Pierson, 1992):

- Glowing rivers of molten rock or lava flows;
- Devastating shock waves and fiery blasts of debris from volcanic explosions, called pyroclastic surges;
- Red-hot avalanches of rock fragments racing down mountainsides, called pyroclastic flows; and
- Suffocating blankets of volcanic ash falling from the sky.

Volcanic eruptions are classified as nonexplosive or explosive. Nonexplosive eruptions generally are caused by an iron- and magnesium-rich magma (molten rock) that is relatively fluid and allows gas to escape readily. Lava flows on the Island of Hawaii are typically of nonexplosive eruptions.

In contrast, explosive eruptions are violent and are derived from a silica-rich magma that is not very fluid. These eruptions are common in the Cascade Range (Washington, Oregon, and California) and in the volcanic chain of Alaska. Explosive eruptions produce large amounts of fragmental debris in the form of airborne ash, pyroclastic flows and surges, debris flows, and other hazards on and beyond the flanks of the volcano, endangering people, infrastructure, and buildings (Hays, 1981).

Lava Flows. Lava flows are streams of molten rock that erupt relatively nonexplosively and move downslope. The distance traveled by a lava flow depends on such variables as viscosity, volume, slope steepness, and obstructions in the flow path. Lava flows typically extend from 6 to 30 mi (10 to 50 km).

Lava flows cause extensive damage or total destruction by burning, crushing, or burying everything in their paths. They need not directly threaten people, however, because they usually move slowly (a few feet to a few hundred feet per hour) and their paths can be roughly predicted. Lava flows that move onto snow and ice can cause destructive debris flows and floods, and those that move into forests can cause wildfires. The flanks of lava flows typically are unstable and collapse repeatedly, occasionally producing explosive blasts and small pyroclastic flows.

Pyroclastic Flows. Pyroclastic flows are high-density mixtures of hot, dry rock fragments and hot gases that move away from source vents at speeds of 30 to +90 mph (48 to +145 km/h), extending dozens of miles. They can result from explosive lateral eruptions of molten or solid rock fragments, from the collapse of vertical eruption columns of ash and larger rock fragments, or from the fall of hot rock debris from the surface of a dome or thick lava flow. Rock fragments in pyroclastic flows range widely in size and consist mostly of dense debris or pumice fragments (Hoblitt and others, 1987; Miller, 1989).

Pyroclastic flows are extremely hazardous because of rapid movement and very high temperatures. Objects and structures are destroyed or swept away by the impact of debris or associated hurricane-force winds. Wood and other combustible materials are burned, and people and animals may be burned or killed by contact with hot debris and gases.

Pyroclastic Surges. Pyroclastic surges are turbulent, low-density clouds of rock debris, air, and other gases that move over the ground surface at speeds similar to pyroclastic flows. Pyroclastic surges can be of two types: hot surges that consist of dry materials that have temperatures appreciably above 212ºF (100ºC); and cold surges that consist of cooler rock debris and steam or water. Both types can extend as far as 6 mi (10 km) from source vents and devastate life and property in their paths (Miller, 1989).

Lava Domes. Lava domes are masses of solid rock that are formed when viscous lava erupts slowly from a vent. If the lava is sufficiently viscous, it will pile up above the vent to form a dome rather than move away as a flow. The sides of most domes are very steep and typically are mantled with unstable rock debris formed by cooling during or shortly after dome formation.

Most domes are composed of silica-rich lavas that have a lower gas content than do the lavas that erupted earlier in the same eruptive sequence. Nevertheless, some dome lavas contain enough gas to cause explosions during formation. The direct effects of dome eruption include local burial or disruption of the preexisting ground surface by the dome itself, and widespread burial by rock debris if part of the dome collapses. Because of high temperatures, lava domes may start fires if they erupt into forests. Domes are extruded so slowly that they can be avoided by people and animals, but structures are endangered. The major hazard is pyroclastic flows that can occur without warning and move very rapidly, endangering life and property for distances up to 12 mi (20 km) from the source.

Volcanic Ash. Volcanic ash, called tephra, is composed of fragments of lava or rock blasted into the air by explosion or carried upward by a rising column of hot gases to form an ash plume. Fragments fall back to earth forming ash deposits, which blanket the ground with a layer that decreases in thickness and particle size away from the source.

Ash-producing eruptions range from short-lived weak ones that eject debris only a few feet into the air to cataclysmic explosions that throw debris dozens of miles into the atmosphere. Explosive eruptions that produce voluminous ash deposits commonly produce pyroclastic flows.

Close to an erupting vent, the main hazards to property posed by volcanic ash include high temperatures, burial, and impact of falling fragments. Large, falling blocks can kill or injure exposed people and animals. Significant property damage can result from the weight of volcanic ash, especially if it is wet: 8 in (20 cm) or more of ash depth may cause structures to collapse. Hot ash may set fire to forests and buildings.

Farther away from a vent, the chief danger to life is the effect of ash on respiratory systems. Even 2 in (5 cm) of volcanic ash will mechanically impair most vehicles and disrupt transportation, communication, and utility systems. Machinery is especially susceptible to the abrasive and corrosive effects of volcanic ash. These effects, together with decreased visibility or darkness during an eruption, may further disrupt normal services, and may cause psychological stress and panic among people whose lives may otherwise not be endangered.

Volcanic Gases. Volcanic gases consist predominately of steam, followed in abundance by carbon dioxide and compounds of sulfur and chlorine. Minor amounts of carbon monoxide, fluorine and boron compounds, ammonia, and several other compounds are found in some volcanic gases.

Distribution of volcanic gases is controlled primarily by wind. Gases may be concentrated near a vent, but become rapidly diluted downwind. However, even very dilute gases can have noticeable odors and can harm plants and some animals dozens of miles downwind from a vent.

Close to a vent, volcanic gases can endanger people's lives and health as well as property. Acids and ammonia and other compounds present in volcanic gases can damage eyes and respiratory systems of people and animals. Accumulations of gases heavier than air, like carbon dioxide, can lead to suffocation. Other harmful effects of volcanic gases and corrosion of metals and other property can be severe near and downwind from very active vents.

Lateral Blasts. Lateral blasts are inflated mixtures of hot rock debris, ash, and gases and may be hundreds of feet thick and move at high speeds along the ground surface with little or no influence by the underlying topography. Blasts are known to reach speeds up to 370 mph (595 km/h). Lateral blasts can produce pyroclastic flows or surges or both (Hoblitt and others, 1987).

Lateral blasts are among the most destructive of volcanic phenomena. Within minutes, they can devastate hundreds of square miles and kill virtually all living things in their wake by abrasion, impact, burial, and heat (Miller, 1989). A lateral blast at Mount St. Helens in 1980 devastated an area of 230 mi^2 (596 km^2), extending as much as 17 mi (27 km) from the volcano and killing more than 60 people.

Debris Avalanches. A debris avalanche is a sudden and very rapid movement of an incoherent and unsorted, wet or dry mixture of rock and soil that is mobilized by gravity. Debris avalanches commonly originate in massive rock slides which, during movement, disintegrate into fragments ranging from small particles to blocks hundreds of feet across. Debris avalanches occur occasionally on large, steep-sided volcanoes and are among the most hazardous of volcanic events (Voight and others, 1981; Crandell, 1984).

Deposits from volcanic debris avalanches can extend for dozens of miles and cover as much as 300 mi^2 (777 km^2). The debris avalanche and landslide associated with the May 18, 1980, eruption of Mount St. Helens deposited 0.7 mi^3 (2.8 km^3) of poorly sorted debris to an average depth of 150 ft (45 m) over approximately 25 mi^2 (60 km^2) of the North Fork Toutle River Valley. The level of Spirit Lake was raised approximately 200 ft (60 m) (Lipman and Mullineaux, 1981).

Debris avalanches can destroy everything in their path by direct impact or by burial beneath dozens of feet of debris. Because debris avalanches can occur with little or no warning and can travel at high speeds (Voight and others, 1981), areas that might be affected should be evacuated if an avalanche is anticipated.

Debris Flows. Debris flows are mixtures of water-saturated rock debris that flow downslope under the force of gravity. They are sometimes called mudflows or "lahars," an Indonesian word. Debris flows consist of material varying in size from clay particles to blocks several dozens of feet in dimension. When moving, they resemble masses of wet concrete and tend to flow along channels or stream valleys. Debris flows are formed when loose masses of unconsolidated debris become unstable due to wetting by rainfall, melting snow or ice, or by overflow of a crater lake.

Debris flows can travel great distances down valleys, and debris-flow fronts can move at speeds up to 60 mph (97 km/h). The debris flows that descended the southeast flank of Mount St. Helens in 1980 had initial flow velocities that exceeded 60 mph (97 km/h). Average flow velocities were approximately 40 mph (64 km/h) over the 14 mi (23 km) distance traveled before the flows entered a reservoir (Pierson, 1985).

The primary danger posed by debris flows to people is from burial or impact of boulders and other debris. People and animals can be severely burned by hot debris flows. Buildings and other property in the path of a flow can be buried, smashed, or carried away. Because of their relatively high density and viscosity, debris flows can move and even carry away vehicles and objects as large as bridges and locomotives (Miller, 1989).

Floods. Floods and hyperconcentrated flows can result from melting of snow and ice during eruptions, heavy rains that often accompany eruptions, and by transformation of debris flows to streamflows. Hyperconcentrated flow originally was defined by Beverage and Culbertson (1964) as streamflow with sediment concentrations between 40 and 80 percent by weight (20 and 60 percent by volume).

The sequence of flow events is from debris avalanche to debris flow to hyperconcentrated flow to flood, as the coarser materials come to rest and the water content increases. Pierson and Costa (1987) provide additional details on the classification of flows.

Floods carrying unusually large amounts of rock debris and sediment can leave thick deposits of sand and gravel at and beyond the mouths of canyons and on valley floors leading away from volcanoes. Eruption-caused floods can occur suddenly and can be large in volume if rivers are already high because of heavy rainfall or snowmelt. Floods also can be generated by eruption-caused seiches (waves) that overtop dams or move down outlet streams from lakes.

RISK ASSESSMENT

Probability and Frequency

An inverse relation exists between the size of the eruptions (volume of material erupted) and how often they occur. Small eruptions occur much more frequently than large ones. The volumes and frequencies of past eruptions provide the major criteria for defining hazard zones.

Newhall (1984) describes a procedure for quantifying the short-term (week-to-week or shorter), intermediate (month-to-month) and long-term (year-to-year) frequency of volcanic eruptions. Newhall's conditional probability analysis is very detailed and has not been applied to all U.S. volcanoes. One simplified approach to estimate the annual probability of exceedance is to divide the number of known explosive eruptions by the duration of the eruptive record (Mullineaux, 1976; Hoblitt and others, 1987). The annual probability of exceedance or frequency of active and potentially active volcanoes can be estimated from historical records which are summarized in Table 18-1 (Wright and Pierson, 1992).

TABLE 18-1.—Selected *active and potentially active U.S. volcanoes.*

Volcano	Eruption Type(s)	Eruptions in Past 200 Years	Last Active	Remarks
Kilauea, HI	Lava, most common; ash, rare	47	Ongoing from 1983	Explosive eruption at Kilauea summit in 1790 killed approximately 80 Hawaiian warriors. Eruptions presenting lava-flow hazard to coastal areas: four in the 19th century; five in the 20th century.
Mauna Loa, HI	Lava	30	1984	Eruptions presenting lava-flow hazard to coastal areas; eight in the 19th century; eight in the 20th century.
Hualalai, HI	Lava, ash	1	1800-1801	High hazard due to unusually fluid lava.
Mount Baker, WA	Ash, lava	1?	1870	Increased heat output and minor melting of summit glacier in 1975; some debris flows not related to eruption. History of extensive pyroclastic flows.
Mount Rainier, WA	Ash, lava	1?	1882 (?)	History of massive debris avalanches and debris flows. Occasional very shallow seismicity.

TABLE 18-1.—*Selected active and potentially active U.S. volcanoes. (continued)*

Volcano	Eruption Type(s)	Eruptions in Past 200 Years	Last Active	Remarks
Mount St. Helens, WA	Ash, dome, lava	2-3	1980 - present	Continuing intermittent volcanic activity.
Mount Jefferson, OR	Ash, lava	0	More than 50,000 years ago	Debris flows in 1934, 1955; young basaltic flows in nearby area.
Three Sisters, OR	Ash, lava	0	950?	Debris flows in this century.
Crater Lake, OR	Ash, lava, dome	0	4,000 years ago	Largest known eruption from Cascade Range volcano. Catastrophic, caldera-forming eruption 7,000 years ago; post-caldera lava and domes.
Mount Shasta, CA	Ash, dome	1	1786?	Debris flows in this century.
Lassen Peak, CA	Ash, dome	1	1914 - 1917	Lateral blast occurred in last eruption.
Clear Lake, CA	Lava, ash	0	Not known	Geothermal energy and long-period (volcanic) seismicity suggest "active" status.
Long Valley Caldera, CA	Ash, dome, ashflow	3?	About 1400	Youngest activity represented by nearly simultaneous eruptions of rhyolite at several of the Inyo craters; currently restless, shown by seismicity and ground deformation.
San Francisco Field, AZ	Lava	2	1065-1180	Sunset Crater; disrupted Anasazi settlements.
Bandera Field (McCarty's Flow), NM	Lava	1	About 1000	Most voluminous lava within past 1,000 years.
Craters of the Moon, ID	Lava	About 1	2,100 years ago	Youngest activity in the Snake River Plain.
Yellowstone Caldera, WY, MT, ID	Ashflow	0	70,000 years ago	Numerous hydrothermal explosions, geysers, geothermal activity; currently restless, shown by seismicity and ground deformation.
Wrangell, AK	Ash	1?	1902?	Emission of gases and vapors from vents (fumarolic activity).
Redoubt Volcano, AK	Ash, dome	4	Ongoing	Eruption began December 1989.
Mount Emmons—Pavlof Volcano, AK	Ash, lava	30	1987	Pavlof is most frequently active volcano in Alaska.
Kiska Volcano, AK	Ash, lava	7	1990	Steam and ash emission.
Pyre Peak (Seguam), AK	Ash, lava	5	1977	Eight lava fountains, as high as 90 meters.
Mount Cleveland, AK	Ash, lava	10	1987	1945 eruption resulted in only known fatality from Alaska volcanism.

Source: *Wright and Pierson, 1992.*

Exposure

With the exception of ashfalls, the areas at risk from volcanic eruptions primarily are those in or near the direct paths or channels of flowing material and debris. Thus, beyond the flanks of volcanoes, the most hazardous areas are the floors of valleys that head on volcanoes. Risks associated with volcanic hazards decrease as distance increases.

Western Conterminous United States. Mullineaux (1976) defined hazard zones for volcanoes in the Western States based on three categories: ashfall, lava flows, and other flow phenomena such as avalanches, debris flows, or floods. The major categories of hazards were described in terms of origin and characteristics, location, size of area affected by a single event, general effects, areas endangered by future eruptions, frequency in the conterminous United States as a whole, and degree of risk in affected areas.

Areas of the conterminous United States affected by volcanic hazards are shown on Map 18-1, adapted from Mullineaux (1976). Hazard zone boundaries are only approximate and the degree of hazard varies gradually from one zone to the next. The darkest areas shown are subject to lava flows and/or 2 inches or more of ashfall and include groups of volcanic vents termed volcanic fields, where future eruptions chiefly of lava flows and moderate volumes of ash are more likely than in nearby areas.

Areas subject to 2 in (5 cm) or more of ashfall from a large eruption that would occur once every 1,000 to 5,000 years (0.10 to 0.02 percent annual chance of exceedance) are the medium shaded regions. Finally, those areas subject to 2 in (5 cm) or more of ashfall from a very large eruption that would occur about once every 5,000 to 10,000 years (0.02 to 0.01 percent annual chance of exceedance) are shown lightly shaded.

Hoblitt and others (1987) provide a detailed analysis of hazards from 13 major volcanoes in the Cascade Range in the Western States, identifying areas subject to directed blasts, pyroclastic flows and surges, debris avalanches, lava flows, debris flows and floods, and accumulations of ashfall.

Hawaii. There are seven active or potentially active volcanoes in Hawaii. Six are on or just offshore of the Island of Hawaii. Kilauea and Mauna Loa have erupted 47 and 30 times, respectively, during the last 200 years, making them two of the most active volcanoes in the world. Kilauea has erupted continuously since 1983. The Haleakala volcano is located on Maui.

Lava flows are the most common direct volcanic hazard in Hawaii. Using data on the location and frequency of historic and prehistoric eruptions, Heliker (1990) developed a lava flow hazard zone map for the Island of Hawaii (Table 18-2).

Alaska. Most of the active or potentially active volcanoes in the United States are in a chain of volcanoes that extends 1,550 mi (2,500 km) from near Anchorage southwest along the Alaskan Peninsula to the western Aleutian Islands (Map 18-2). On average, at least one lcano in the chain erupts each year (Simkin and others, 1981). In 1912, Novarupta produced the largest eruption of the 20th century (Wright and Pierson, 1992).

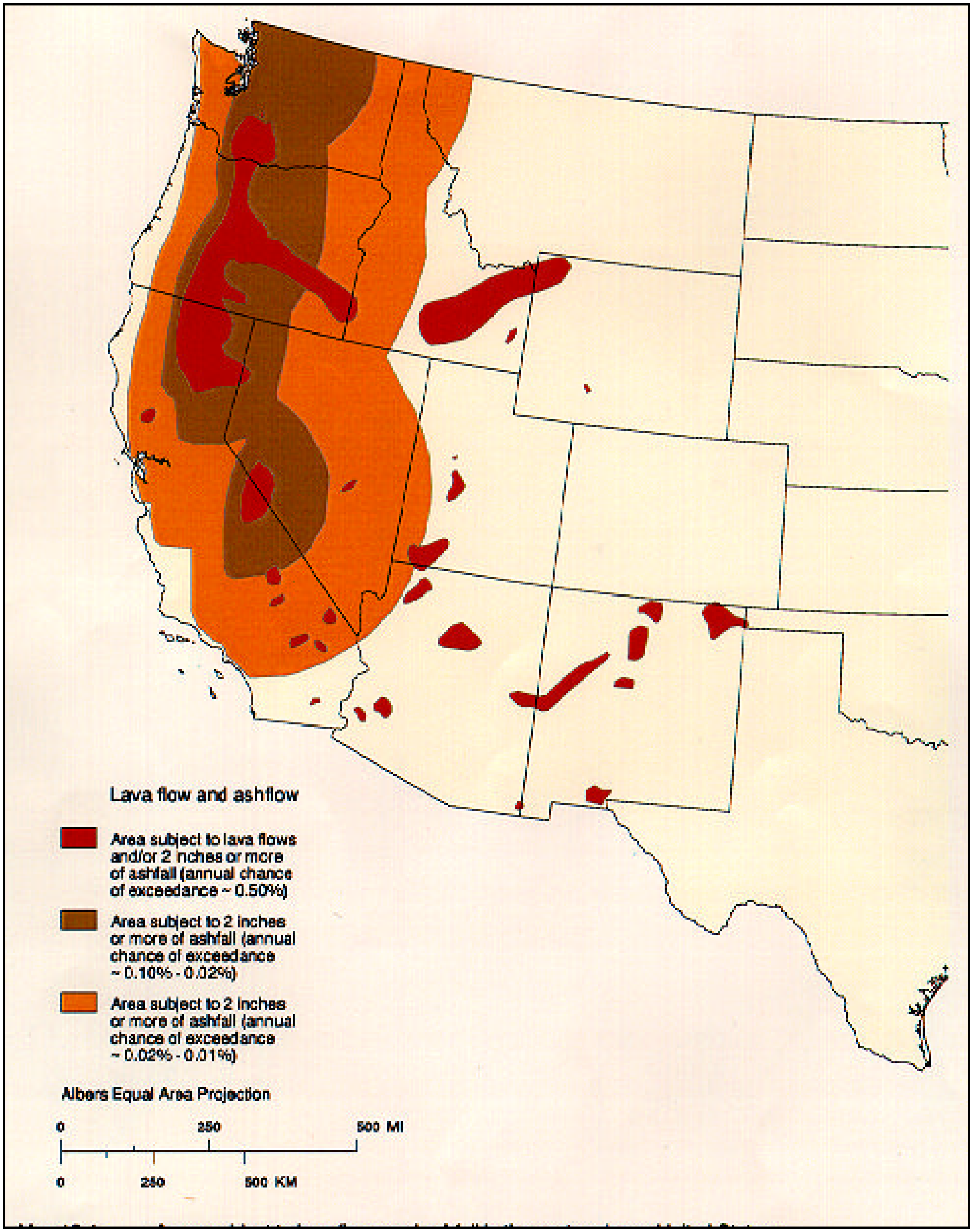
Scientists have identified more than 40 historically active volcanic centers along the chain. Eruptions could affect the Cook Inlet region, where 60 percent of Alaska's population resides and which is the State's major supply, business, and financial center (Brantley, 1990).

Consequences

Western Conterminous United States. Mount St. Helens, WA, erupted explosively in 1980, preceded by more than 10,000 local earthquakes and hundreds of steam blasts. Timber worth several million dollars was destroyed in a 596 km^2 (230 mi^2) area. Over 290 tons of ash were spread across 57,000 km^2 (22,000 mi^2) and extended as far east as North Dakota. Landslides along the volcano's flanks traveled about 14 mi (22.5 km) and mudflows destroyed bridges, temporarily halted shipping on the Columbia River, and disrupted highways and rail lines. Nearly 60 people were killed, and total costs exceeded $1.5 billion.

Despite no significant activity in the past 500 years, Mt. Rainier, WA, is considered to be the most hazardous volcano in the Cascades, primarily due to the threat of mudflows and floods. Twenty-six glaciers on the volcano contain large volumes of water that could be melted during active periods.

In western central California, the caldera known as Long Valley-Mono Lake was revealed to have some activity when an upward bulge of nearly 25 cm (10 in) was discovered during a 1980 survey of U.S. Route 395. The bulge is thought to be due to accumulations of rising magma. Geologic evidence of extensive ashfall from Long Valley has been found more than 1,000 km (600 mi) east and south of the site, covering all of Southern California, the entire States of Utah, Arizona, Colorado, and significant portions of New Mexico, Wyoming, Nebraska, and Kansas.



Map 18-1. Areas subject to lava flows and ashfall in the conterminous United States.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Mullineaux, 1976.*

Hawaii. Kilauea on the Island of Hawaii has been active since the early 1980s. By June 1991, the shield was over 60 m (37 ft) tall, had covered 78 km^2 (30 mi^2) of forest and grassland, and had destroyed 180 homes and closed highways. Land values in the area dropped rapidly, and some insurance companies refused to sell new policies. During the period 1984-86, fumes released from Pu'u 'O'o vent 12 mi (19 km) from the summit damaged crops. In 1790, Kilauea erupted with pyroclastic surges and ash fell 30 km (18.5 mi) from the summit. Suffocating gas killed many people.

Mauna Loa, the largest volcano on the Island of Hawaii, has erupted 15 times since 1900. Events lasted from 1 to 145 days. In 1984, the three-week long lava flow came within 6.5 km (4 mi) of buildings in the City of Hilo.

Alaska. Although sparsely populated, violent eruptions could threaten Alaska's towns and villages. At least one or two eruptions have occurred each year since 1900 (Brantley, 1994).

Ash is the most common and widespread volcanic hazard in Alaska, and is especially dangerous to aircraft (Brantley, 1990). At least four commercial jet aircraft suffered damage during the 1989-90 eruption of Redoubt Volcano. Ash generated by numerous explosive episodes caused significant damage to aircraft, severely disrupted air traffic above southern Alaska, and resulted in local power outages and school closings. The explosions produced hot, fast-moving clouds of ash, rock debris, and gas (pyroclastic flows) that swept across Redoubt's heavily glaciated north flank.

The most serious incident occurred on December 15, 1989, when a Boeing 747 jetliner carrying 231 passengers entered an ash cloud approximately 150 mi (240 km) northeast of Redoubt Volcano. The jet lost power in all four engines and dropped approximately 13,000 ft (4,000 m) before the pilot succeeded in restarting the engines. The plane landed safely in Anchorage, but sustained an estimated $80 million in damage (Steenblik, 1990). This near-tragic incident prompted government agencies to search for better ways to track ash plumes and to improve information for the airline industry.

The Redoubt eruption triggered massive debris flows in Drift River Valley, threatening an oil tanker terminal near the river's mouth. On two occasions, partial flooding of the terminal compound forced authorities to modify operating procedures which temporarily curtailed oil production from 10 platforms in Cook Inlet. The damage and loss of revenue from ash and debris

Table 18-2.—*Lava flow hazard zones for the Island of Hawaii*

Hazard Zone	Percent of Area Covered by Lava Since 1800	Percent of Area Covered by Lava in Last 750 Years	Explanation
Very high	>25 percent	>65 percent	Kilauea and Mauna Loa rift zones where vents have been very active in historic time.
High	15-25 percent	25-75 percent	Areas adjacent to and downslope of active rift zones.
Moderately high	1-5 percent	15-75 percent	Areas less because of greater distance from active vents or areas protected by topography.
Moderate	About 5 percent	<15 percent	Includes all of Hualalai, where frequency of eruptions is less than Kilauea and Mauna Loa.
Low	None	Very Little	Areas currently protected by topography or no eruptions in recorded history.

Source: *Modified from Heliker, 1990.*

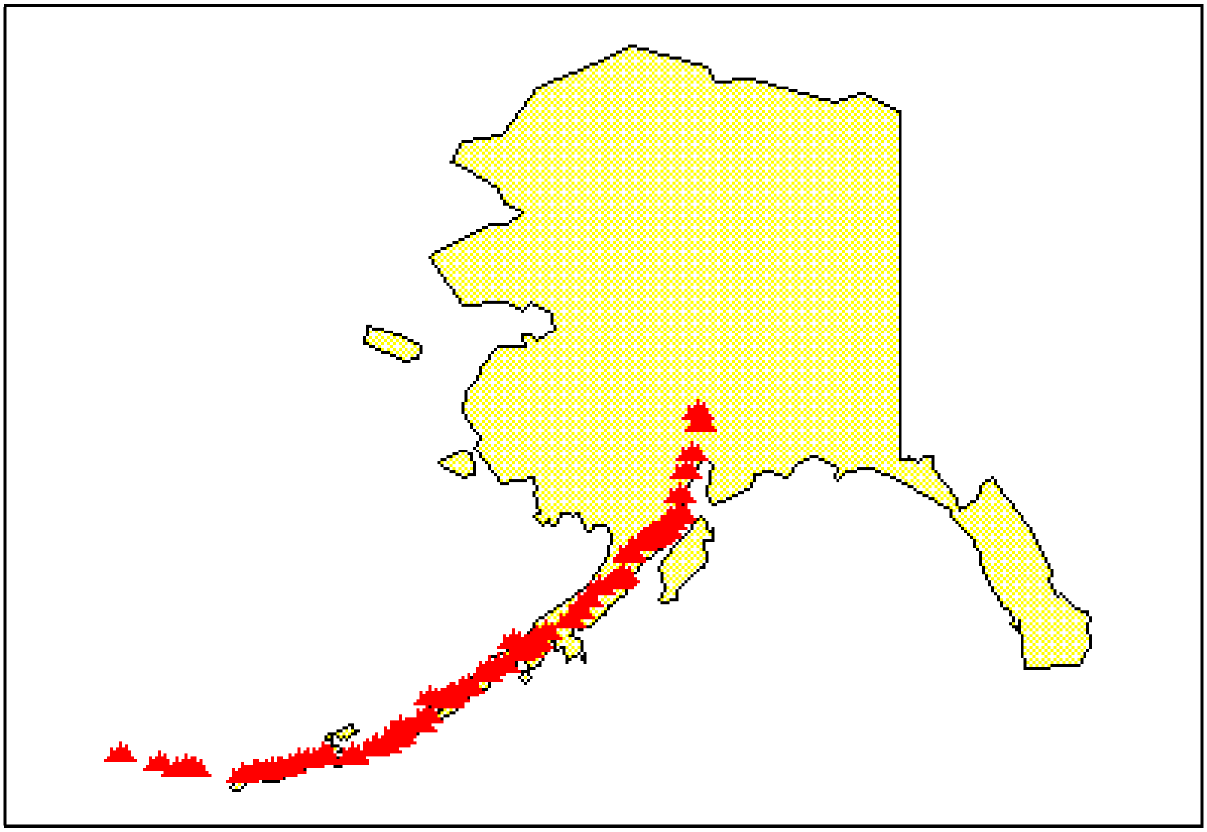


FIGURE 18-1.—Volcanoes of the Aleutian Arc.

Source: *Motyka, and others, 1993.*

flows was estimated at more than $100 million, the second most costly eruption in the history of the United States.

RESEARCH, MONITORING, AND DATA COLLECTION ACTIVITIES

The seismicity associated with earthquakes often provides the earliest warning of volcanic unrest, as earthquake swarms immediately precede most eruptions. Geodetic networks are set up to measure changes in volcano surface caused by the pressure of moving magma. Changes in the gas composition, or in the emission of sulfur dioxide and other gases, may be related to variation in magma supply rate, changes in magma type, or modifications in the pathways of gas escape induced by magma movement. Changes in electrical conductivity and magnetic field strength also trace magma movement. Changes in groundwater temperature or levels, rates of streamflow and sediment transport, and changes in lake levels, snow, and ice accumulation may be indicative of impending volcanic activity.

State-of-the-art technology was used to monitor the 1989 eruption of Redoubt Volcano. These techniques can improve detection and monitoring to enhance warning capabilities that lead to reduction of losses (Brantley, 1990):

- **REAL-TIME SEISMIC AMPLITUDE MEASUREMENT (RSAM).** Unlike other seismic data acquisition systems that continuously record the oscillation of the ground, RSAM computes and stores the average amplitude of ground oscillation over 10-minute intervals. As either the magnitude or number of earthquakes increases, and as volcanic tremors increase, the average amplitude of ground oscillation also increases. The advantage of the RSAM system is its ability to measure the level of seismicity during intense activity, especially during eruptions and volcanic tremor, and when earthquakes are so numerous that individual events cannot normally be distinguished and counted.

- **SEISMIC SPECTRAL AMPLITUDE MEASUREMENT (SSAM).** SSAM measures the relative amplitude of the seismic signal in specific frequency bands, permitting seismologists to determine which frequencies dominate a signal. Different seismic events generate signals with different characteristics. The system aids recognition of patterns of subtle seismic change prior to eruptive episodes.

- Slow-Scan Video Camera. Approximately 50 mi (80 km) east of Redoubt Volcano on the Kenai Peninsula, a slow-scan video camera was installed to provide images of the volcano during clear weather. It is nearly 3,500 times more sensitive to light than most home-video cameras, and thus can record at night. An image is transmitted every 35 seconds and displayed on a black-and-white monitor. The video system helps seismologists correlate seismic events with volcanic activity.

- Lightning-Detection System. This system was deployed experimentally, because the cause of eruption lightning is uncertain. It may result from friction between ash (tephra) particles and steam and other gases within an ash plume. Eruption lightning discharges include both cloud-to-ground and cloud-to-cloud strikes. During a large seismic event when the volcano is not visible, the presence of lightning dispels uncertainty in interpreting the seismicity. An ash plume is almost certainly present when sustained seismic signals and lightning occur together. For some episodes at Redoubt, lightning detection allowed scientists to conclude within minutes that an ash plume was forming above the volcano even though a plume could not be seen.

- Debris-Flow Detection System. This installation consists of three stations located adjacent to Drift River at increasing distances from the volcano. Each station consists of a seismometer sensitive to high-frequency (10-300 Hz) ground vibrations caused by flowing mixtures of water and rock debris and a radio to send the data to a receiving station. The signals are separated into frequency ranges and continuously analyzed by computer. Flow events can be detected on the basis of high-frequency character, even during volcanic activity and earthquakes. When the system is operating, all debris flows triggered by volcanic activity are detected.

MITIGATION APPROACHES

Losses from volcanic eruption can be reduced in several ways, described below.

- Past eruptive activity can be used to define the potential type, scale, location, extent, effect, and severity of future eruptions and to define hazard zones which can guide development through land-use planning.

- Establishment of detection and monitoring systems to measure physical changes that precede activity can enhance forecasting of impending eruptions and provide warning.

- Disaster preparedness and emergency evacuation can provide substantial loss reduction when the locations and types of hazards for a particular volcanic eruption are taken into consideration. Plans should be based on hazard-zone maps showing the relative severity, extent, and effect of specific volcanic eruptions. An important element is the development of emergency communication systems to warn and inform the public of potentially hazardous events.

- Protective measures can be effective in reducing losses from certain volcanic hazards. Relatively simple actions such as providing high-efficiency dust masks and goggles can protect people from respiratory damage and eye irritation. Changing oil and air filters can reduce damage to vehicles due to ashfalls. However, effective and economically feasible diversion or control lava flows, pyroclastic flows, and debris flows generally is not possible.

- Risk assessment, especially coupled with land-use planning, provides a strategy for reducing losses from volcanic hazards. Risk assessment involves determining the value of affected resources, the exposure of those resources, and the probability that a volcanic eruption of a certain magnitude will take place within a certain period of time. On the basis of the risk assessment, land-use decisions can be made that are consistent with goals for public safety.

RECOMMENDATIONS

Wright and Pierson (1992) describe several challenges for the future to improve the understanding of volcanic activity and the ability to communicate scientific results in a way that can be used by communities facing volcanic hazards:

- Early detection of volcanic unrest and potential eruption through establishment of telemetering networks to monitor baseline seismic activity (seismometers) and ground deformation (Global Positioning Systems);

- Volcanic hazard assessments at several active or potentially active U.S. volcanoes using GIS technology and computer models to study the paths of lava flows, debris flows, and debris avalanches;

- Research in volcanic processes using sophisticated geophysical techniques to improve the understanding of magma-water interactions, large-scale debris avalanches, large debris flows and related sediment-laden flood waves; and

- Improved communications and the development of emergency response plans that can be put in place quickly in areas that show signs of volcanic unrest, and the development and distribution of nontechnical publications that describe volcanic hazards and lessons learned from previous eruptions

BIBLIOGRAPHY AND REFERENCES

Brantley, S.R. (Ed.) 1990. ***The Eruption of Redoubt Volcano, Alaska, December 14, 1989-August 31, 1990.*** U.S. Geological Survey Circular 1061.

Brantley, S.R. 1994. ***Volcanoes of the United States.*** U.S. Geological Survey.

Beverage, J.P., and J.K. Culbertson. 1964. "Hyperconcentrations of Suspended Sediment." ***Journal of the Hydraulics Division.*** American Society of Civil Engineers. Vol. 90, No. HY6, pp. 117-126.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Crandell, D.R. 1984. “Catastrophic Debris Avalanche from Ancestral Mount Shasta Volcano, California." ***Geology.*** Vol. 12, pp. 143-146.

Hays, W.W. 1981. ***Facing Geologic and Hydrologic Hazards: Earth-Science Considerations.*** U.S. Geological Survey Professional Paper 1240-B.

Heliker, C. 1990. ***Volcanic and Seismic Hazards on the Island of Hawaii.*** U.S. Geological Survey.

Hoblitt, R.P., C.D. Miller, and W.E. Scott. 1987. ***Volcanic Hazards with Regard to Siting Nuclear-Power Plants in the Pacific Northwest.*** U.S. Geological Survey Open-File Report 87-297.

Lipman, P.W., and D.R. Mullineaux (eds). 1981. ***The 1980 Eruptions of Mount St. Helens, Washington.*** U.S. Geological Survey Professional Paper 1250.

Miller, C.D. 1989. ***Potential Hazards from Future Volcanic Eruptions in California.*** U.S. Geological Survey Bulletin 1847.

Motyka, R.J., S.A. Liss, C.J. Nye, and M.A. Moorman. 1993. ***Geothermal Resources of the Aleutian Arc***. Alaska Division of Geological and Geophysical Surveys Professional Report 114.

Mullineaux, D.R. 1976. ***Preliminary Overview Map of Volcanic Hazards in the 48 Conterminous United States.*** Scale 1:7,500,000. U.S. Geological Survey Miscellaneous Field Studies Map MF-786.

Newhall, C.G. 1984. ***Semiquantitative Assessment of Changing Volcanic Risk at Mount St. Helens, Washington.*** U.S. Geological Survey Open-File Report 84-272.

Pierson, T.C. 1985. "Initiation and Flow Behavior of the 1980 Pine Creek and Muddy River Lahars, Mount St. Helens, Washington." ***Geological Society of America Bulletin.*** Vol. 96, pp. 1056-1069.

Pierson, T.C., and J.E. Costa. 1987. "A Rheologic Classification of Subaerial Sediment-Water Flows." ***Geological Society of America, Reviews in Engineering Geology.*** Vol. 7, pp. 1-12.

Simkin, T. 1981. ***Volcanoes of the World: A Regional Directory, Gazatteer, and Chronology of Volcanism During the Last 10,000 Years.*** Stroudsburg, PA: Hutchinson Ross Publishing Co.

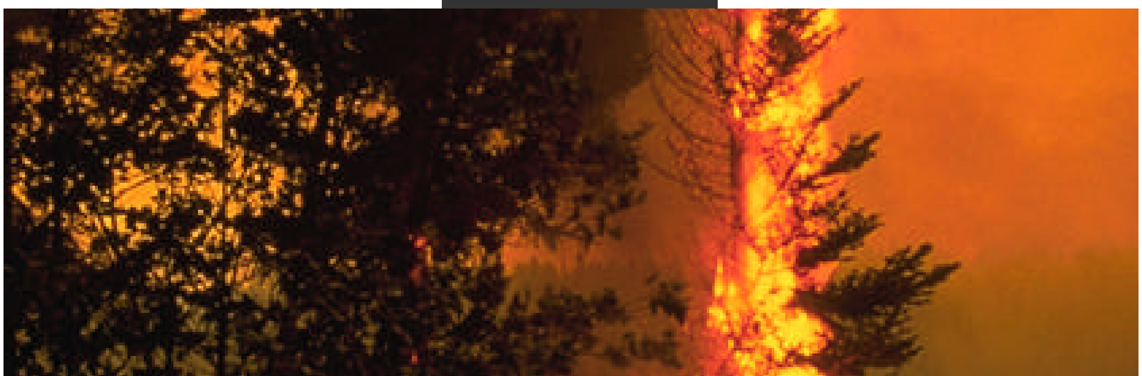
Steenblik, J.W. 1990. "Volcanic Ash: A Rain of Terra." ***Airline Pilot***, pp. 9-15.

Voight, B., H.X. Glicken, R.J. Janda, and P.M. Douglass. 1981. "Catastrophic Rockslide Avalanche of May 18." In ***The 1980 Eruptions of Mount St. Helens***, Lipman, P.W., and D.R. Mullineaux (eds.). U.S. Geological Survey Professional Paper 1250.

Wright, T, L., and T.C. Pierson. 1992. ***Living with Volcanoes: The U.S. Geological Survey's Volcano Hazards Program.*** U.S. Geological Survey Circular 1073.

CHAPTER

19



WILDFIRE HAZARDS

Chapter Summary

Periodic forest, grassland, and tundra fires are part of the natural environment, as natural and as vital as rain, snow, or wind (Mutch, 1995a). Wildfires are fueled by naturally occurring or non-native species of trees, brush, and grasses. Topography, fuel, and weather are the three principal factors that impact wildfire hazards and behavior.

Wildfires occur in virtually all of the United States. The Western States, with their more arid climate and prevalent conifer and brush fuel types, are subject to more frequent wildfires. Wildfires have proven to be the most destructive in California, but they have become an increasingly frequent and damaging phenomenon nationwide. People are becoming more vulnerable to wildfires by choosing to live in wildland settings, and the value of exposed property is increasing at a faster rate than population.

Most of the tools, data, and methodologies necessary to accurately assess wildfire risk and exposure on a national basis are not yet in place. However, the use of GIS technology, combined with the increased availability and utilization of satellite data, should facilitate progress.

Mitigation and rapid emergency response are the most effective activities for reducing the short-term impact of wildfires. However, the emphasis of Federal land management agencies is shifting from suppression toward mitigation and overall fire management, including the use of prescribed fires to reduce future risks.

Successful wildfire mitigation strategies can be complex, involving the participation of property owners who choose to live in at-risk areas, as well as many agencies, organizations, and individuals.

Photo: Red Cross

HAZARD IDENTIFICATION

The four categories of wildfires that are experienced throughout the United States are described below.

- **Wildland fires** are fueled almost exclusively by natural vegetation. They typically occur in national forests and parks, where Federal agencies are responsible for fire management and suppression.

- **Interface or intermix fires** are urban/wildland fires in which vegetation and the built-environment provide fuel.

- **Firestorms** are events of such extreme intensity that effective suppression is virtually impossible. Firestorms occur during extreme weather and generally burn until conditions change or the available fuel is exhausted.

- **Prescribed fires and prescribed natural fires** are fires that are intentionally set or selected natural fires that are allowed to burn for beneficial purposes.

U.S. Forest Service (USFS) figures for 1990 indicate that 25.7 percent of wildfires reported were caused by arson. Other ignition sources were debris burns (24 percent); lightning (13.3 percent); and other (16.7 percent). Lightning can present particularly difficult problems when dry thunderstorms move across an area that is suffering from seasonal drought. Multiple fires can be started simultaneously. In dry fuels, these fires can cause massive damage before containment.

Three principal factors have a direct impact on the behavior of wildfires: topography, fuel, and weather. Other hazards may trigger wildfires, and wildfires contribute to other hazards

TOPOGRAPHY. Topography can have a powerful influence on wildfire behavior. The movement of air over the terrain tends to direct a fire's course. Gulches and canyons can funnel air and act as a chimney, intensifying fire behavior and inducing faster rates of spread. Similarly, saddles on ridgetops tend to offer lower resistance to the passage of air and will draw fires. Solar heating of drier, south-facing slopes produces upslope thermal winds that can complicate behavior.

Slope is an important factor. If the percentage of uphill slope doubles, the rate of spread of wildfire will likely double. On steep slopes, fuels on the uphill side of the fire are closer physically to the source of heat. Radiation preheats and dries the fuel, thus intensifying fire behavior. Terrain can inhibit wildfires: fire travels downslope much more slowly than it does upslope, and ridgetops often mark the end of wildfire's rapid spread.

FUEL. Fuels are classified by weight or volume (fuel loading) and by type. Fuel loading, often expressed in tons per acre, can be used to describe the amount of vegetative material available. If fuel loading doubles, the energy released also can be expected to double. Each fuel type is given a burn index, which is an estimate of the amount of potential energy that may be released, the effort required to contain a fire in a given fuel, and the expected flame length. Different fuels have different burn qualities. Some fuels burn more easily or release more energy than others. Grass, for instance, releases relatively little energy, but can sustain very high rates of spread.

Continuity of fuels is an important factor. Continuity is expressed in terms of both the horizontal and vertical dimensions. Horizontal continuity is what can be seen from an aerial photograph and represents the distribution of fuels over the landscape. Vertical continuity links fuels at the ground surface with tree crowns via understory or "ladder" fuels.

Another essential factor is fuel moisture. Like humidity, fuel moisture is expressed as a percentage of total saturation and varies with antecedent weather. Low fuel moistures indicate the probability of severe fires. Given the same weather conditions, moisture in fuels of different diameters changes at different rates. A 1,000-hour fuel, which has a 3- to 8-in (8- to 20-cm) diameter, changes more slowly than a 1- or 10-hour fuel.

WEATHER. Of all the factors influencing wildfire behavior, weather is the most variable. Extreme weather leads to extreme events, and it is often a moderation of the weather that marks the end of a wildfire's growth and the beginning of successful containment. High temperatures and low humidity can produce very vigorous fire activity. The cooling and higher humidity brought by sunset can dramatically quiet fire behavior.

Fronts and thunderstorms can produce winds that are capable of radical and sudden changes in speed and direction, causing similar changes in fire activity. The rate of spread of a fire varies directly with wind velocity. Winds may play a dominant role in directing the course of a fire. The radical and devastating effect that wind can have on fire behavior is a primary safety concern for firefighters. In July 1994, a sudden change in wind speed and direction on Storm King Mountain led to a blowup that claimed the lives of 14 firefighters. The most damaging firestorms are usually marked by high winds.

Interaction of Other Hazards. Other hazard events can cause wildfires, and wildfires can intensify other hazards. According to a 1991 case study, winds gusting to 62 mph (100 km/h) downed powerlines, resulting in 92 separate wildland fires in Washington (The National Wildland/Urban Interface Fire Protection Initiative, 1992). Earthquakes have the potential to cause wildfires.

Large firestorms can create very powerful convective winds as air rushes in to feed the flames. These winds are capable of causing extensive damage but the ground effects are local. To the ground-level observer, fire and wind are perceived as one event. The upward rush of air in the convection column is powerful enough to carry burning embers far ahead of the fire before falling to the ground. By this spotting process, a fire may enlarge or create new fires.

By removing vegetative cover, wildfires can contribute to mudslides, landslides, and floods. According to the National Commission on Wildfire Disasters, the 1992 Foothills Fire near Boise, ID, was so hot that not only was the vegetation removed, but the soils were ". . . so heat damaged that they resist water penetration and cause flash runoff and erosion, as well as some that slide off steep slopes like dry sugar . . . " (MacLeary, 1993).

RISK ASSESSMENT

Using NWS data, the U.S. Forest Service administers the National Fire-Danger Rating System, used to assess the risk of wildfire at a given time. The system is used to make wide-scale estimates of real-time fire potential and behavior for very large acreages, but not structures. Fuel moisture, indicative of antecedent weather, combined with current and forecasted weather conditions are the main factors considered, but a variety of data are used.

A computerized network, the Weather Information Management System (WIMS), is the main tool used to organize data and to provide fire weather information. Input includes data from hundreds of remote automatic weather stations which provide data on temperature, humidity, wind, and fuel moisture for 1- and 10-hour fuels. The fuel moisture of larger fuels is determined by inference.

Input data collected by the TIROS-N series of polar orbiting weather satellites operated by NOAA are fed into WIMS (Loveland and others, 1991). The data are downloaded daily to the Earth Resources Observation System (EROS) and used to compile maps showing U.S. land cover characteristics.

One instrument aboard the TIROS-N satellites is the advanced very high resolution radiometer, an infrared sensor. Data from this instrument have been used to create a Normalized Difference Vegetation Index, which is essentially a measurement of vegetative "greenness" from which vegetative fuel moisture contents may be inferred. Figure 19-1 is an example of a departure from average greenness map which shows how green vegetation is compared to its average greenness for the current week. Similarmap products show relative green where each pixel is normalized to its own historical range, therefore all areas (dry or wet) can appear relatively green at some time during the growing season (USDA U.S. Forest Service, 1997).

Data from these sources can be accessed from any computer networked to WIMS. The most commonly used output is organized into reports of local Fire Danger Ratings. These reports include the adjective class rating (low to extreme), Manning Class (an indication of resistance to suppression), burn index (an estimate of flame length in light grasses), moisture content reading for 1,000-hour fuels, and energy release component (expressed in BTU per second per square foot). The public is informed of the adjective class rating through media reporting and roadside signs. Figure 19-2 is a sample of a Fire Danger Rating Map (USDA U.S. Forest Service, 1997).

Exposure

More and more people are being exposed to wildfires by choosing to live in or next to wildland settings. The value of exposed property is increasing more rapidly, especially in the Western States. With their more arid climate and conifer and brush fuel types, Western States are subject to more frequent wildfires than the rest of the United States. Western ecosystems have adapted to, and have even become dependent on, wildfires. Wildfires play an essential role by thinning forests and creating stands of different species and age groups.

Most of the tools, data, and methodologies necessary for accurate assessments of risk and exposure as they relate to wildfires have not been developed. However, the use of GIS technology by many Federal, State, and local agencies, combined with the increased availability and utilization of satellite and other remote-sensing data, provide a sound base for the development of advanced tools.

Spatial factors include topography, fuels, weather, and population distribution. Topographic data are available and are applicable to the degree of risk at a local level. Knowledge of where fuels and people co-exist is essen-

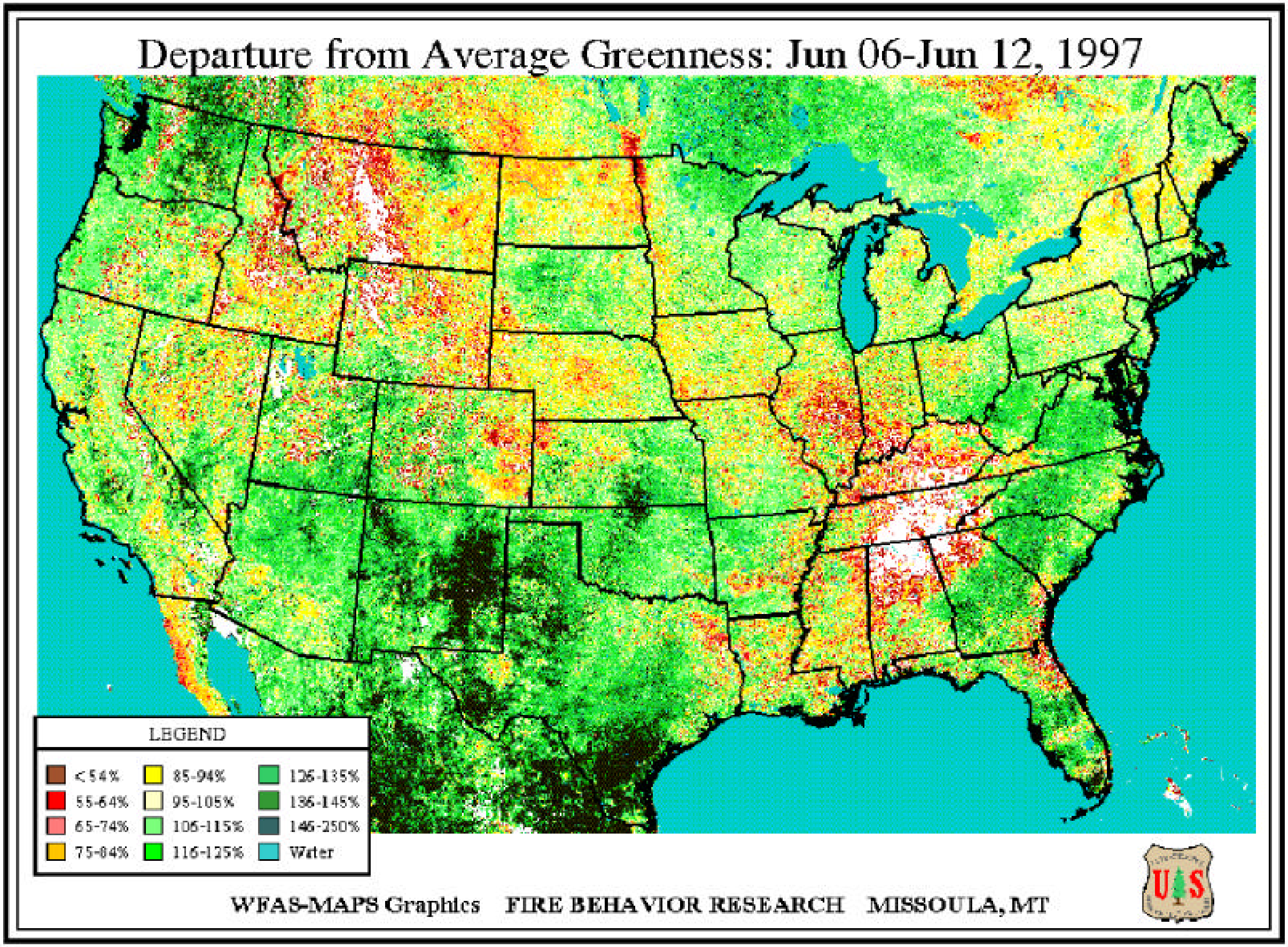


FIGURE 19-1.—Live fuel moisture - departure from average greenness.

Source: USDA Forest Service, www.fs.fed.us/land/wfas, 1997.

tial, but good fuel data generally are unavailable while the population density in some areas can be estimated only.

Weather, a short term temporal factor, is a critical indicator of fire potential and severity. the changes that time provides to the density of vegetation is a long term temporal factor.

Consequences

Historical statistics on the economic impact of wildfires, including resource and property losses, are available for specific, large incidents. However, reporting is incomplete and national statistics are not compiled. Therefore, accurate estimates of the economic impact of wildfires cannot be made.

Virtually all of the continental United States has experienced and will continue to experience wildfires. Wildfires are the most destructive in California, but they have become an increasingly frequent and damaging phenomenon elsewhere. It is impossible to assess fully the extent of wildfire damage due to incomplete reporting. The U.S. Forest Service (USFS), which compiles statistics for wildfires on Federal lands, is the primary Federal source of information.

According to National Interagency Fire Center statistics for fires on Federal lands from 1985 to 1994, an average of nearly 73,000 fires occur each year, resulting in over 3,000,000 acres (1,215,000 ha) burned and more than $411.5 million expended in suppression costs. The single worst event in terms of deaths in U.S. history occurred in Wisconsin in 1871, killing 1,182 people (FEMA, 1990).

The National Fire Protection Association (NFPA) is the best source of data for interface losses. The NFPA maintains two separate databases: the Fire Incident Data Organization (FIDO), which is a file of news clippings of actual incidents; and a statistical database of outdoor fires to which a fire department responded. The file is incomplete because not all fires are reported. In addition, the data do not permit determination of the number and value of structures lost to wildfires.

The available statistical data on interface fire losses tend to be specific to a particular event or region and, therefore, do not facilitate tracking of long-term national trends. According to Phillips (1994), 3,500 homes were destroyed by wildfires in California between 1920 and 1989, and well over 4,200 homes were destroyed between 1990 and 1993.

In 1988 in Alaska, wildfires destroyed 2.2 million acres (891,000 ha) of tundra and spruce forest, nearly twice the normal yearly average for the State. In California, over 9,800 fires burned more than 175,000 acres (70,875 ha), destroying 400 homes, barns, and other structures. The majority of the damage was the result of a 35,000-acre (14,175-ha) fire near Sacramento in September, which caused an estimated $22 million in damage (FEMA, 1990).

Some particularly devastating interface events that occurred during the 1990s are described below.

- During the 1,600-acre East Bay Fire in Oakland, CA, on October 20, 1991, 25 people were killed and 150 were injured; and 3,354 single-family homes and 456 apartments were damaged. The total estimated damage was $1.5 billion (California Office of Emergency Services, 1992).

- In October 1991, rural residents of counties near Spokane, WA, where the population increased by 76 percent between 1970 and 1990, reported 92 separate fires that burned 114 homes and 35,000 acres (14,465 ha). The winds that fanned the fires reached speeds of 62 mph (NFPA, 1992).

- Between October 25 and November 3, 1993, 21 major wildland fires broke out in California, fanned by two waves of hot, dry Santa Ana winds. The fires collectively burned over 189,000 acres (76,500 ha) and destroyed 1,171 structures. Three people died and hundreds were injured. Combined property damage was estimated at approximately $1 billion (Hazard Mitigation Survey Team Report, 1993).

- In 1994, one of the worst years since the early 1900s, 79,107 fires burned 4,073,579 acres (1,648,577 ha), and cost $924 million for suppression. Only 325 homes were lost, fewer than the 10-year average between 1985 and 1994 (900 homes per year). Tragically, 34 firefighters lost their lives. On July 6, 1994, 14 firefighters died in one terrible incident during the South Canyon Fire just west of Glenwood Springs, CO.

Federal agencies bear a significant portion of fire suppression costs and losses in interface areas. Of the nearly $1 billion in Federal funds spent on wildfire suppression in 1994, 30 to 50 percent was expended on protecting interface areas (Federal Wildland Fire Management Policy and Program Review, 1995).

During the past 20 years, seven wildfires resulted in major disaster declarations, with six occurring in California. An additional 95 wildfires have qualified for Federal fire suppression grants.

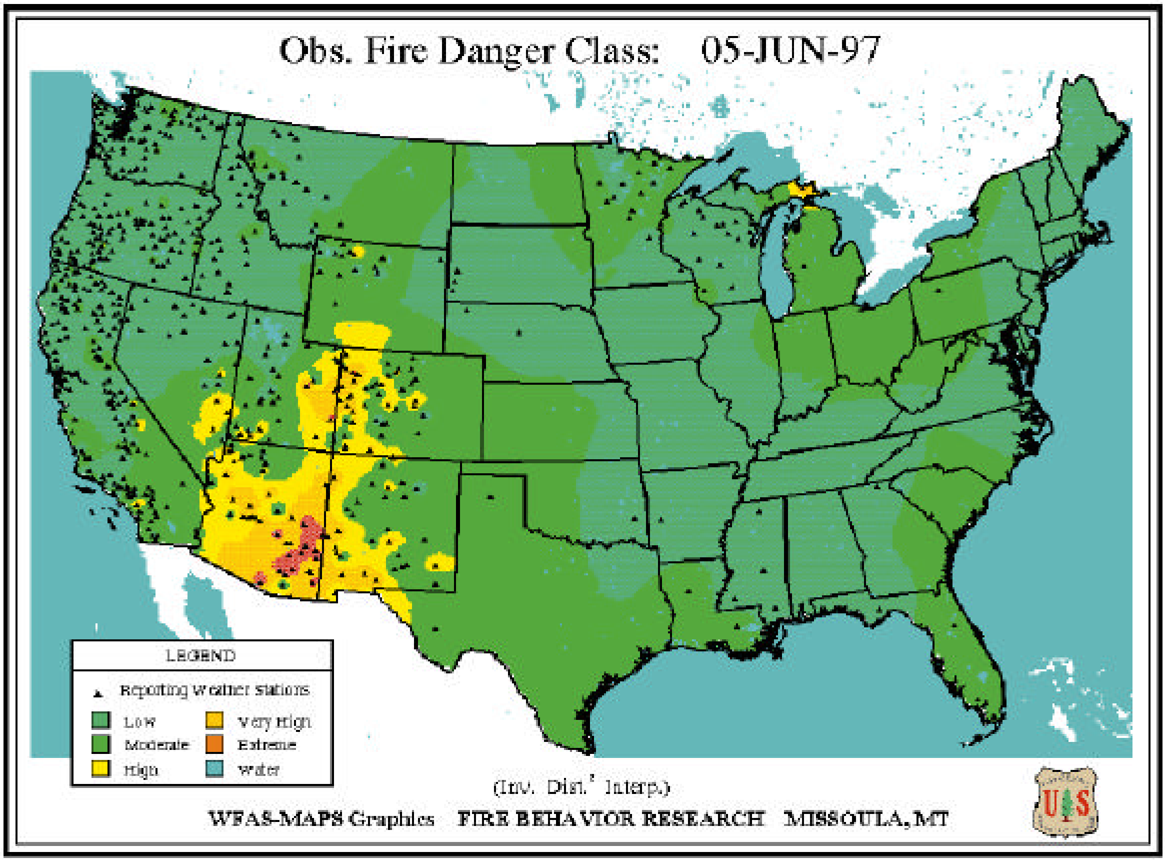


FIGURE 19-2.—Sample of a fire danger rating map, June 1997.

Source: *USDA Forest Service, www.fs.fed.us/land/wfas, 1997.*

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Nationally accepted models have not been developed to make wildfire risk or vulnerability assessments. However, models and methods do exist for predicting wildfire behavior. A computer modeling tool, BEHAVE uses topographic, fuel, fuel moisture, and weather data. BEHAVE is used by the U.S. Forest Service at its Florida and Missoula, MT Fire Research Laboratories. While a reliable indicator of fire intensity and rates of spread in simple fire events, the model has some severe limitations. Output is limited to surface fire behavior and more extreme wildfire events, such as crown fires, cannot be modeled. Farsite, a more advanced modeling tool configured for GIS, is currently under development.

BEHAVE's shortcomings are related primarily to the quality of available data and the complex relationship between the variables. Fuel moisture and weather data are probably good enough to support somewhat more advanced models. Topography, however, is dealt with in only a general way and may oversimplify much of the intricate interaction of air flow over terrain. An even more significant data quality issue lies in how fuel data are collected. The current approach involves observers matching photographs of fuel models to the appearance of local vegetation. This is often then extrapolated to apply to a wide area. Although useful for providing a comparative fuel rating, this simple approach does not support advanced fire behavior modeling.

A project under development by the Fire Behavior Research Work Unit of the U.S. Forest Services' Intermountain Research Station in Missoula, MT seeks to incorporate EROS data into an integrated fire danger/behavior system. Part of this project will involve the development of a national fuels map (Burgan and Hartford, 1993). This project has significant potential for a coarse-filter, national wildfire risk assessment approach.

MITIGATION APPROACHES

Since the 1920s, aggressive fire suppression has effectively excluded fire from a significant portion of the forestlands in the United States. As a result, stand densities and fuel loadings have reached unprecedented levels. Therefore, when wildfires do occur, they exhibit more unusual behavior, are more intense and damaging, and thus are more difficult and costly to suppress.

The paradox of aggressive fire suppression policies is that putting out most small fires creates conditions that are conducive for large fires. The emphasis of Federal land management agencies is shifting from suppression toward mitigation and overall fire management, including the use of prescribed fires.

Wildfire mitigation in the urban/wildland interface has primarily been the responsibility of property owners who choose to build and live in this vulnerable zone. Local officials are responsible for emergency management, fire protection, and land-use, building, and zoning regulations. State officials are involved in wildfire hazard issues primarily through the State forest services and emergency management offices. When property owners, local fire protection authorities, and local, State, and federal agencies work cooperatively, there is a high probability that wildfire mitigation projects will be developed.

Federal participation often begins with sharing of suppression and recovery costs. Federal land management agencies have the greatest fire suppression resources and often participate in suppression of interface fires. Agency roles and cost-sharing formula depend on specific agreements with State and local agencies.

The U.S. Fire Administration (USFA), a unit within FEMA, provides a training course on firefighting techniques for interface fires through the National Fire Academy. USFA also serves on the Federal Wildfire Coordination Group. FEMA provides funding for educational brochures and other publications addressing wildfire issues.

The Emergency Education Network (EENET), an outreach tool used by FEMA to enhance the training and education of fire and emergency management specialists nationwide, is produced at FEMA's Emergency Management Institute campus. EENET programs, which have won national videoconferencing awards, cover a wide array of problems, programs, and issues, including public awareness aspects of the wildland/urban interface.

In practice, successful wildfire strategies can be quite involved. The most important aspect of successful suppression is disruption of the continuity of fuels, achieved by creating firelines and fire breaks. Fuel is removed from the course of the fire. The time necessary to install firelines is gained by giving up space. For interface fires, where homes and other structures fill the space, fuel reduction is best accomplished before the fires begin.

In the interface, proximity to natural fuels, building materials, and construction features are crucial to the survival of homes in a wildfire. According to the NFPA, the principal causes of structure loss in interface fires are lack of defensible space and structures built with combustible materials and features (Baden, 1995).

Fuel-modification measures, such as fuel breaks and defensible spaces, can withstand a fire's run even in heavy fuels and during the worst fire conditions. The following is testimony to the effectiveness of fuel-modification measures:

> "At the height of the fire's fury, it encountered a stand of ponderosa pine that had been thinned two years earlier through a careful logging operation, then burned in the winter to reduce ground fuels. The racing crown fire, totally out of control at that encounter, dropped immediately to the ground as the greener, moister tree canopy refused to ignite, and then began to slow in response to reduced fuels on the ground. Firefighters were able to move in, build fire lines, and halt its advance. The thinned forest was virtually undamaged." (McLean, 1993)

For those involved in mitigation efforts, the resistance or apathy of property owners causes the greatest frustration. For many years, the public was told that all wildfires are "bad" and suppression is the cure. Public consciousness changes very slowly (Gardner and others, 1987). It will probably take considerable time, a vigorous re-education effort, and many disasters before the hazards posed by wildfires are well understood.

The adoption of regulations requiring fire-safe construction, such as NFPA's *Standard for Protection of Life and Property from Wildfire* (1991) and the International Fire Code Institute's *Urban-Wildland Interface Code* (draft, 1995), will likely gain more support. Land-use regulation issues may be more difficult to address. The appreciation of land values and other short-term economic advantages of development often create an active constituency strongly opposed to regulatory efforts which are perceived to increase the cost of construction.

With understanding and cooperation, much can be done to prevent or mitigate wildfire hazards. However, according to the report of the Operation Urban Wildfire Task Force, ". . . in spite of all the reports and good work, the message is still not reaching the public, and effective action is not yet being taken to reduce the fire threat" (Peterson, 1992).

Boulder County, CO. It often takes a damaging and frightening wildfire event to initiate an intensive mitigation program. On July 9, 1989, a human-caused wildfire blown by strong upslope winds swept out of Black Tiger Gulch into the foothill community of Sugarloaf. Within 6 hours, 44 homes and other structures were destroyed and many others were damaged. Property losses exceeded $10 million and suppression costs totaled another $1 million (NFPA, 1990). As a result, the State of Colorado and Boulder County updated their wildfire mitigation plans. Concerned citizens and firefighters approached the County Commissioners for help in mitigating the wildfire hazard in their communities.

The County Commissioners responded by creating the Boulder County Wildfire Mitigation Group, headed by staff of the County Land Use Department. The group grew to include representatives of the USFS, Sheriff's Department, Parks and Open Space, City of Boulder Fire Department, Colorado State Forest Service, U.S. Bureau of Land Management, University of Colorado, Colorado State University, volunteer firefighters, and homeowners. The cooperative effort was aimed at educating homeowners, providing support for community mitigation, and communicating needs to the County Commissioners.

To identify the people and structures vulnerable to wildfire, to quantify the hazards, and to present information in a useful and meaningful format, the Wildfire Mitigation Group used the Land Use Department's GIS to develop the Wildfire Hazard Information and Mitigation System (WHIMS). WHIMS combines expertise in hazard assessment, forest management, land use planning, wildfire behavior, and suppression with fire district and community involvement. Elements of BEHAVE are incorporated into the hazard rating modeling capability.

The City of Boulder adapted WHIMS for use under the name FIRMIT. Data related to each home are collected by volunteer firefighters during onsite visits. The Colorado State Forest Service provides fuel data and other support.

A pilot map produced by Boulder County from WHIMS data, indicating roof materials by lot, is shown in Figure 19-3. Rated from low to high flammability, roof materials are: metal or tile; composite or asphalt; treated shake; and untreated shake.

The Boulder County Wildfire Mitigation Group provided the impetus and support for regulations requiring that homebuilders in interface areas meet reasonable wildfire mitigation standards. A flexible rating system is used, permitting a great deal of choice. All new construction must meet the standards through the County's Site Plan Review process. These standards and the rating system are based on the WHIMS assumptions that the hazard rating elements are, in order of importance, topography or site location, building construction and design, landscaping/defensible space, access, and water.

In the year after the first pilot area survey, in the Pine Brook Hills Fire Protection District, 22 percent of the homeowners took mitigative actions such as changing roof type, limbing tree branches, moving firewood away from houses, and properly identifying street addresses. In subsequent years, additional homeowners have participated through such activities as a joint defensible space plan for 22 adjoining properties that is now serving as a model for others in Boulder County.

Since the first pilot area survey, 8 of the County's 16 fire districts have become involved in the WHIMS project, scheduled for completion by 1999. To date, almost 2,000 parcels have been impacted by WHIMS (in Boulder County) or FIRMIT (in the City of Boulder), with an estimated 6,000 more needed for completion. WHIMS has encouraged participation by local fire departments and has created a direct interface between firefighters and homeowners, resulting in increased knowledge and awareness for both.

Other Local Initiatives. Use of GIS as a wildfire assessment and mitigation tool is underway in Oakland and Laguna Beach, CA, and Missoula, MT (Mullenix, 1995).

The Northern Rockies Coordinating Group is another example of how cooperation leads to progress. This multi-jurisdictional group, formed in 1984, includes both wildland and structural fire protection agencies. A long-range interface program was initiated in 1988, including public education, legislative action, and modifications of engines serving interface areas. Group members approached local zoning and planning commissions to urge fire protection consideration in covenants and regulations.

In Billings, Helena, Dillon, and Kalispell, MT, Coeur d'Alene, ID, and other States, interagency dispatch centers have been formed. Response time has improved by eliminating jurisdictional disputes and confusion when fires occur in interface areas (NFPA,1991).

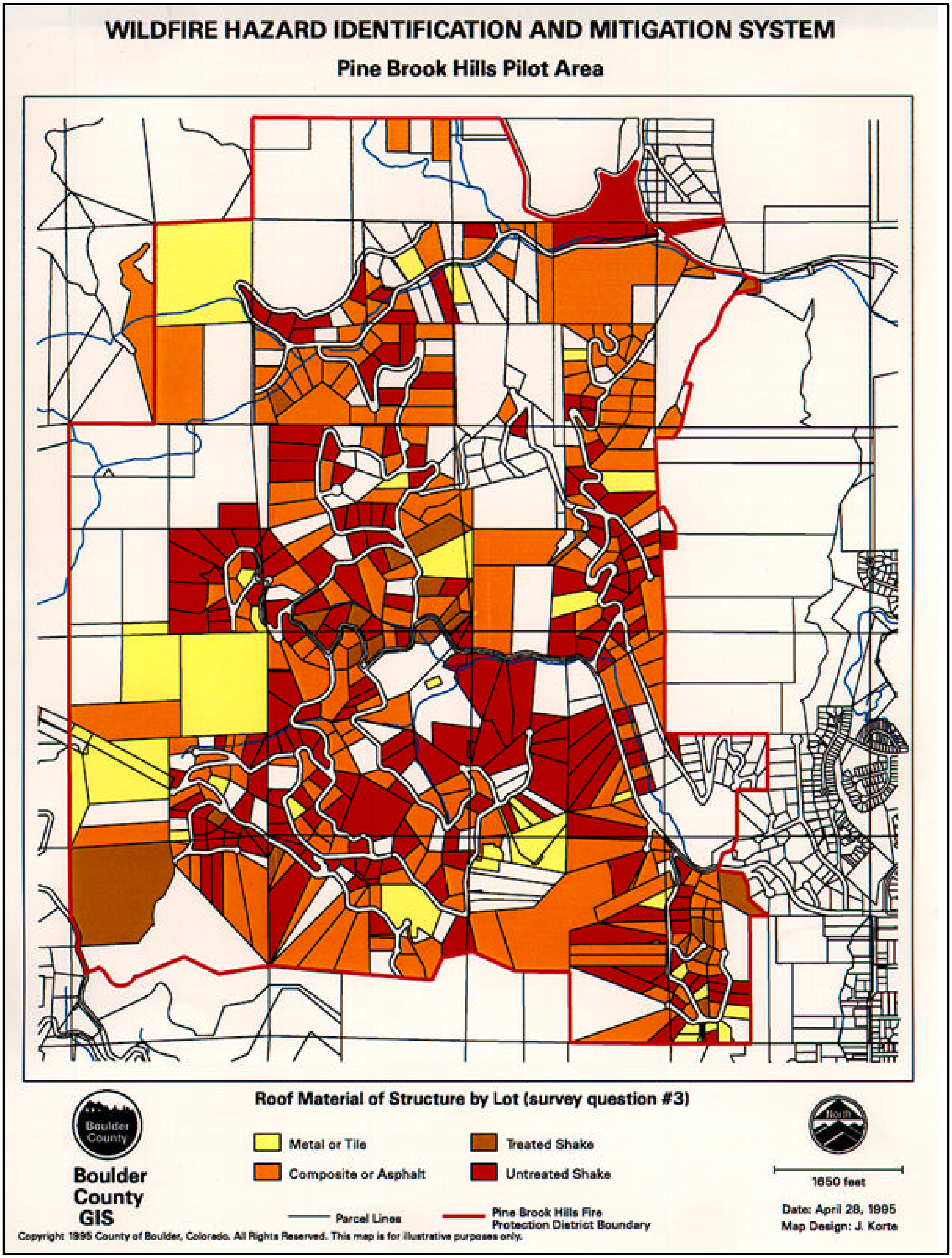


FIGURE 19-3.—Boulder County wildfire hazard pilot map.

Source: *Land Use Department, Boulder County, CO*

RECOMMENDATIONS

The development of a national wildfire hazard mitigation strategy will require the participation and cooperation of many agencies, organizations, and individuals. Recommendations from several sources have been considered and are described below.

- Design and implement a comprehensive educational campaign at both the national and local levels. The campaign should focus on fire ecology and ecosystem stewardship, wildfire risk, exposure, and sound mitigation measures. It should target homeowners, firefighters, local officials, landscapers, architects, foresters, builders, planners, insurance companies, and the media.

- Develop a practical way to use the EROS database in the development of a prototype GIS and remote-sensing wildfire risk and vulnerability assessment tool.

- Identify the temporal factors to be used in making wildfire risk and vulnerability assessments. The factors should be suitable for use with both EROS data and ground-level assessments. Methods to link historical data with advanced technologies should be considered.

- Develop a standard methodology, using an expert systems approach, to rate residential structures as fuels.

- Devise a methodology and provide training to local jurisdictions for use in the development of detailed, on-site wildfire risk and vulnerability assessments.

- Develop GIS-based wildfire hazard assessment tools for use by Federal, State, and local agencies. These tools should be configured to use both EROS data and locally collected data.

- Support development of advanced fire behavior modeling tools configured to run in the spatial context of GIS.

- Create a National Wildfire Mitigation Program and collect wildfire statistics for the past 10 to 20 years, estimates of current risk and exposure, and projections for all local jurisdictions.

- Test tools and methodologies by conducting a thorough wildfire risk and vulnerability assessment for a pilot project area. These data could then be provided to appropriate State and Federal agencies, and could be used for fine-filter ground-truthing of EROS data.

- Use the National Fire Information Reporting System for the collection, compilation, and reporting of comprehensive national wildfire statistics.

BIBLIOGRAPHY AND REFERENCES

Baden, W. 1995. National Fire Protection Association. ***National Wildland/Urban Interface Fire Protection Initiative***. Black Tiger Fire Case Study.

Boulder County Land Use Department. 1995. County of Boulder, CO. ***Wildfire Hazard Identification and Mitigation System (WHIMS) Maps.***

Burgan, R., and R. Hartford. 1993. ***Monitoring Vegetative Greenness with Satellite Data***. U.S. Forest Service, Intermountain Research Station, Missoula, MT.

California Governor's Office of Emergency Services. 1994. "East Bay Hills Fire Operations Review Group: A multi-Agency Review of the October 1991 Fire in Oakland/Berkley Hills" In: ***Report of the National Commission on Wildfire Disasters.*** Washington, DC.

Cortner, G., and Bridges. 1985. "Wildfire: Managing the Hazard in Urbanizing Areas." ***Journal of Soil and Water Conservation***.

Dodge, M. 1972. "Forest Fuel Accumulation: A Growing Problem." ***Science Magazine***, Vol. 177.

Federal Emergency Management Agency, Hazard Mitigation Survey Team Report. 1993. ***Southern California Firestorms***.

Federal Emergency Management Agency, Office of Civil Defense. 1990. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations***. FEMA 191. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Emergency Management. 1993. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations***. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, U.S. Fire Administration. 1992. ***Report to Congress, Fiscal Year 1991***. Washington, DC.

Federal Emergency Management Agency, U.S. Fire Administration, Wildfire Section. 1994. ***An Overview of Natural Hazards in the Vicinity of Boulder, CO***.

Federal Wildland Fire Management Policy and Program Review. 1995. ***Federal Register***. Vol. 60, No. 120, pp. 32492.

Gale, R., and H. Cortner. 1987. ***People and Fire at the Urban Wildland Interface***. U.S. Forest Service.

Gardner, P., H. Cartner, and J. Bridges. 1985. "Managing the Hazard in Urbanizing Areas." ***Journal of Soil and Water Conservation.*** Vol. 40, No. 4, P. 319.

Gardner, P., H. Cortner, and K. Widaman. 1987. "The Risk Perceptions and Policy Response Toward Wildland Fire Hazards by Urban Home-Owners." ***Landscape and Urban Planning***. No. 14, pp. 163-172.

Grant, C. 1995. "Pushed to the Limit." ***National Fire Protection Association Journal***.

International Fire Code Institute, Urban-Wildland Interface Code Committee. 1995 (draft). ***Urban-Wildland Interface Code***. Whittier, CA.

Kay, C. E. 1994. ***Aboriginal Overkill and Native Burning: Implications for Modern Ecosystem Management***. Salt Lake City, UT: Utah State University.

Loveland, T., and others. 1991. "Development of a Land-Cover Characteristics Database for the Conterminous U.S." ***Photogrametric Engineering & Remote Sensing***. Vol 57, No. 11, pp. 1453-1463.

MacCleary, D.W. 1994. ***Report of the National Commission on Wildfire Disasters***. Washington, DC.

Magill, A. Undated. ***Fire Managers Must Talk With People***. U.S. Forest Service, Wildland Recreation and Urban Culture.

McLean, H.E. 1994. "The Boise Quickstep" In: ***Report of the National Commission on Wildfire Disasters***. Washington, DC.

Mullenix, M. July 1995. "Preventing Wildfires." ***Firehouse***. Page 74.

Mutch, R. 1995a. "Prescribed Fire and the Double Standard." In ***Proceedings: Environmental Regulations and Prescribed Fire Conference***. Tampa, FL.

Mutch, R. 1995b. "Need for More Prescribed Fire." In ***Proceedings: Environmental Regulation and Prescribed Fire Conference***. Tampa, FL.

National Fire Protection Association. 1991. ***Wildfire Strikes Home***, 2nd Edition, pp. 59–60.

National Fire Protection Association. 1992. ***Report of the National Commission on Wildfire Disasters***, p.8.

National Fire Protection Association, Technical Committee on Forest and Rural Fire Protection. 1991. ***Standard for Protection of Life and Property***. NFPA 299.

National Wildland/Urban Interface Fire Protection Initiative. 1992. ***Fire Storm '91 Case Study***.

Peterson, G. 1992. ***Report of the Operation Urban Wildfire Task Force***. Federal Emergency Management Agency, Operation Urban Wildfire, p. 12.

Phillips. 1994. Personal Communication, excerpt from "Report of the National Commission on Wildfire Disasters," p. 9.

Pyne, S.J. 1982. ***Fire in America, A Cultural History of Wildland and Rural Fire***. Princeton, NJ: Princeton University Press.

Savage, M. 1989. ***Structural Dynamics of a Pine Forest in the American Southwest Under Chronic Human Disturbance***. Doctoral Thesis, Department of Geography. Boulder, CO: University of Colorado.

Shanks, Hammon, Jensen, Wallen, and Associates. 1992. "The Fire Next Time." ***Geo Info Systems***. Vol. 3, No. 2, p. 35.

Joffe, B. 1992. "Update from the Ashes: GIS Helps Oakland Organize to Rebuild." ***Geo Info Systems***. Vol. 3, No. 7, p. 43.

Sutphen, S. 1994. ***The California Fires of 1993: Coping in Orange County***. Working Paper 89. Boulder, CO: Natural Hazards Research and Applications Information Center, Institute of Behavioral Science, University of Colorado.

U.S. Department of Agriculture, U.S. Forest Service. 1997. ***Wildland Fire Assessment System***. [Online] Accessible at http://www.fs.fed.us./land/wfas.

U.S. Department of Agriculture, U.S. Forest Service, Fire Aviation Management. 1993. ***Fire Related Considerations and Strategies in Support of Ecosystem Management***. Washington, DC.

Veblen, T., and D. Lorenz. 1991. ***The Colorado Front Range: A Century of Ecological Change***. Salt Lake City, UT: University of Utah Press.

Veblen, T. 1994. ***Preliminary Report On: Fire Ecology in the Urban/Wildland Interface of Boulder County***. Boulder, CO: University of Colorado.

Part III

RISK ASSESSMENT APPROACHES

"The time has come to face the fact that this Nation can no longer afford the high costs of natural disasters. We can no longer afford the economic costs to the American taxpayer, nor can we afford the social costs to our communities and individuals."

James Lee Witt, Director, FEMA
Testimony before U.S. Congress
October 27, 1993

Introduction

Risk assessment is a process or application of a methodology for evaluating risk as defined by probability and frequency of occurrence of a hazard event, exposure of people and property to the hazard, and consequences of that exposure. Different methodologies exist for assessing the risk of natural hazard events, ranging from qualitative to quantitative.

FEMA is developing a methodology that can be applied throughout the nation by local, State, and regional officials. The results will be used to plan and stimulate efforts to reduce risks from natural hazards and the technological hazards that may be triggered by natural events. Preparations for emergency response and recovery can be tailored to address the consequences of expected events. The methodology will be flexible enough to integrate the unique components of individual hazards, while at the same time be applicable to multiple hazards.

Expected benefits of a standard risk assessment methodology include: consistency of approach; more economic use of available resources; improved sharing of knowledge; more consistent and standardized measurements of performance for mitigation efforts; more consistent and standardized measurements of progress in reducing specific and multiple hazards locally, regionally, and nationally; and more effective means for setting local, regional, and national priorities.

Chapter 24 summarizes the development and applications of the risk assessment or loss estimation methodology initially developed for earthquake hazards by the National Institute of Building Sciences (NIBS) under cooperative agreement with FEMA.

For comparison purposes, other risk assessment approaches are summarized in Chapter 25. They are less quantitative and detailed and do not estimate damage or losses.

CHAPTER

24

HAZUS: STANDARD RISK ASSESSMENT (LOSS ESTIMATION) METHODOLOGY

Chapter Summary

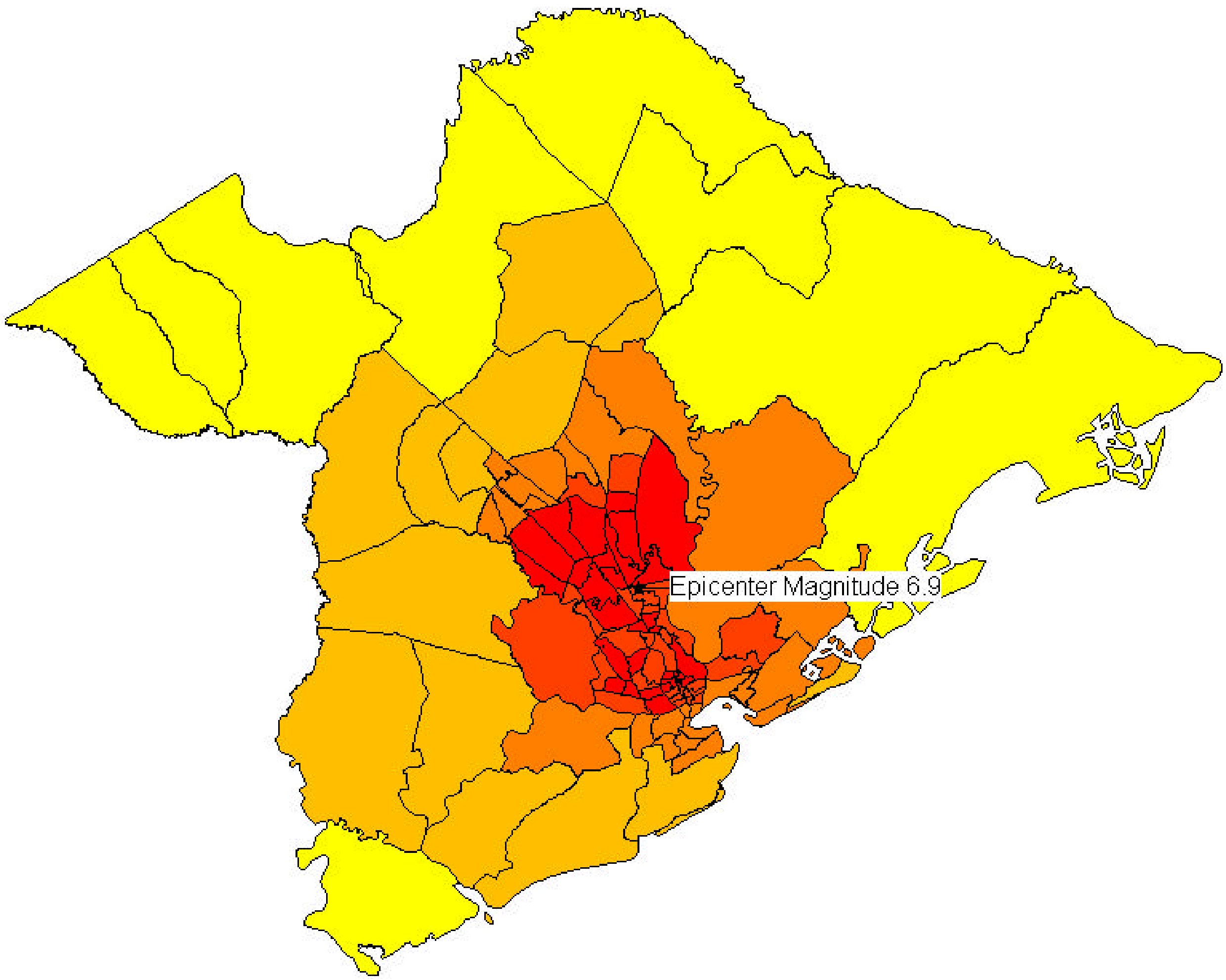
The standard risk assessment (loss estimation) methodology developed jointly by FEMA and the National Institute of Building Sciences (NIBS) is nationally applicable and standardized. As originally developed, the methodology, referred to as Hazard United States (HAZUS), is used to assess the risk of, and to estimate the potential losses from, earthquakes. It incorporates the better features of previously developed loss estimation methodologies and overcomes many shortcomings. When completed, HAZUS and numerous default inventory databases will be made available to State and local agencies.

HAZUS is an integrated geographic information system designed for the personal computer. It was developed based on several criteria: standardization; user-friendly design and display; accommodation of user needs; accommodation of different levels of funding; revisable results; state-of-the-art models and parameters; balance; flexibility in earthquake ground shaking intensities; and non-proprietary methods and data.

The HAZUS framework includes six major modules: Potential Earth Science Hazard; Inventory; Direct Damage; Induced Damage; Direct Losses; and Indirect Losses. The modules are interdependent: the output from one module acts as input to another. The modular approach allows estimates based on simplified models and limited inventory data. More refined estimates based on more extensive inventory data and detailed analyses can be produced. Limited studies can be conducted, which may be desirable because of budgetary and inventory constraints.

FEMA initiated development of HAZUS specifically for direct and indirect economic and social losses from earthquakes and secondary hazards triggered by earthquakes such as fires and floods due to dam or levee failure. FEMA plans to expand HAZUS to address other hazards such as floods and hurricanes, and to develop additional inventory databases to provide State and local users.

Photo: Red Cross


Epicenter Magnitude 6.9

BACKGROUND

The first task undertaken by FEMA and the National Institute of Building Sciences (NIBS) during development of HAZUS was an assessment of earthquake loss estimation methodologies (FEMA, 1994). Conducted jointly by the California Universities for Research in Earthquake Engineering and Risk Management Solutions, Inc., the assessment identified more than 1,000 individual references, from which approximately 150 studies were selected for detailed review.

The literature review revealed that, although numerous regional studies were carried out during the last two decades, potential users such as emergency response planners and local governments found them to be less useful than expected for a variety of reasons. The reasons included: the inability of a single study to meet the very different needs of users at different levels of government; the costs of collecting inventory data and performing studies; the stagnant nature of the results when compiled in report form; and the highly technical nature in which results were presented. In addition, final reports rarely contained documentation of the inventory used, and the output was often provided in a tabular format that provided little insight about the geographical distribution of damage and losses.

Many of the studies reviewed based loss estimates on a worst case scenario or a maximum size event. Using several scenarios of varying magnitudes and frequencies provides estimates of the range of losses and provides a better basis for preparedness and mitigation. The majority of studies reviewed used Modified Mercalli Intensity (MMI) and isoseismal maps to represent the level of potential ground motion hazards. Few researchers made an attempt to use a probabilistic description of ground motion.

Recognizing limitations of earlier studies, FEMA and NIBS incorporated into HAZUS the better features of the methodologies reviewed to overcome many shortcomings. HAZUS includes all the elements of risk assessment, the important concepts of which are:

- Applicability on different levels, depending on the efforts and interests of the user and the level of data available;

- Inventory databases that can be updated easily, such as building stock, critical facilities, lifeline systems, and levees and dams;

- State-of-the-art models for relating the magnitude of an event to damage;

- State-of-the-art models for estimating the probability or frequency of occurrence of a given magnitude event; and

- GIS technology to easily display the results and to evaluate different scenarios and assumptions.

HAZUS will be made available to State and local agencies along with many baseline inventory databases to support consistent risk assessments across all States and regions. FEMA plans to enhance and extend HAZUS to address other hazards.

OVERVIEW OF DEVELOPMENT EFFORT

Development and implementation of HAZUS in a GIS-based system are being completed by a consortium of natural hazard loss experts, including earth scientists, engineers, architects, economists, emergency planners, social scientists, and software developers. Technical direction for, and review of, methodology development are provided by an eight member Project Working Group with guidance from a Project Oversight Committee. The Project Oversight Committee represents user interests in the earthquake engineering and emergency planning communities.

The Project Working Group focuses on developing a useful tool for local, State, and regional officials to estimate regional losses, to provide the basis for planning emergency response and recovery, and to stimulate efforts to mitigate risks. With input from the Project Oversight Committee, the Project Working Group established a set of criteria, described below, to accomplish the project goals.

Standardization. To enable comparisons between different regions, standard practices were defined to:

- Collect inventory data based on site-specific or U.S. Census tract aggregation;
- Classify database maps for soil types, liquefaction susceptibility, and landslide susceptibility;
- Classify occupancy classes for buildings and facilities;
- Classify building structure type;
- Describe damage states for buildings and lifelines;
- Develop building damage functions;
- Group, rank, and analyze lifelines;
- Use technical terminology; and
- Provide output.

User Friendly Design and Display. HAZUS is implemented in an integrated geographic information system that can be run on a personal computer. This technology provides a powerful tool for displaying outputs and allows users to see the geographical distribution of effects from different earthquake scenarios and assumptions.

Interactive software provides the user with a Windows-oriented environment for entering and accessing data, and allows the overlaying of input and output data on color-coded maps of the study region. Different display colors permit rapid visual identification of areas with the potential for high loss, such as areas that have both significant ground shaking and a large number of vulnerable buildings.

Accommodation of User Needs. To accommodate a wide spectrum of potential users, HAZUS consists of modules that can be activated or deactivated by the user. The needs of most users are accommodated by the flexible approach. An advantage of the GIS technology is that once the inventory database is built, it can be used for other purposes, such as planning and public works. Conversely, some useable databases may already be available in other State and local agencies, or may be available commercially.

Accommodation of Different Levels of Funding. Resources vary from region to region and among government agencies. HAZUS is flexible enough to permit different levels of detail that may be dictated by funding. The modules allow users to perform rough estimates of damage and loss using default data that will be supplied by FEMA. More precise estimates require more extensive inventory information at additional costs to the user.

Revisable Results. Results of studies can be updated as inventory databases are improved, as the building stock or demographics of a region change, or if revised earthquake scenarios are proposed. Once the data are input, any number of scenario events can be evaluated. Databases can be updated readily and analyses can be run quickly with new information.

State-of-the-Art Models and Parameters. HAZUS incorporates state-of-the-art models and parameters based on recent earthquake damage and loss data. The methodology can evolve readily as research progresses, prompting modification of individual modules.

Balance. HAZUS provides balance between the different components of loss estimation. For example, a precise evaluation of casualties or reconstruction costs would not be warranted if estimates of building damage are based on an inferred inventory with large uncertainty. The methodology permits users to select methods (modules) that produce varying degrees of precision.

Flexibility in Earthquake Ground Shaking Intensities. HAZUS incorporates both deterministic (specific scenario earthquakes) and probabilistic descriptions of ground shaking intensities. User-supplied maps of earthquake shaking intensity can be an input.

Non-Proprietary Methods and Data. HAZUS includes only non-proprietary loss estimation methods and inventory data. The GIS technology, which must be purchased and licensed from a vendor, is non-proprietary to the extent permitted by software suppliers. Software costs are modest and comparable to commercially available database programs.

METHODOLOGY FRAMEWORK

HAZUS is designed to be flexible, to accommodate the needs of a variety of users and applications, and to provide the uniformity of a standardized approach. By framing the loss estimation methodology as a collection of modules, new modules or improvements to current models and data in existing modules, may be added without reworking the entire methodology. This approach facilitates the rapid transfer of information between the academic and research communities and the end user. The models may be modified to reflect local or regional needs or to incorporate new regional models and data.

The HAZUS framework includes the following major interdependent modules (Figure 24-1):

- Potential Earth Science Hazard (PESH);
- Inventory;
- Direct Damage;
- Induced Damage;
- Direct Economic/Social Losses; and
- Indirect Losses.

In general, each module is required for a comprehensive loss estimation study. However, the degree of required sophistication, and associated cost, varies greatly by user and application. It is necessary and appropriate that modules have multiple levels of detail or precision. Another advantage is that it enables users to limit studies to selected losses. For example, a user may wish to

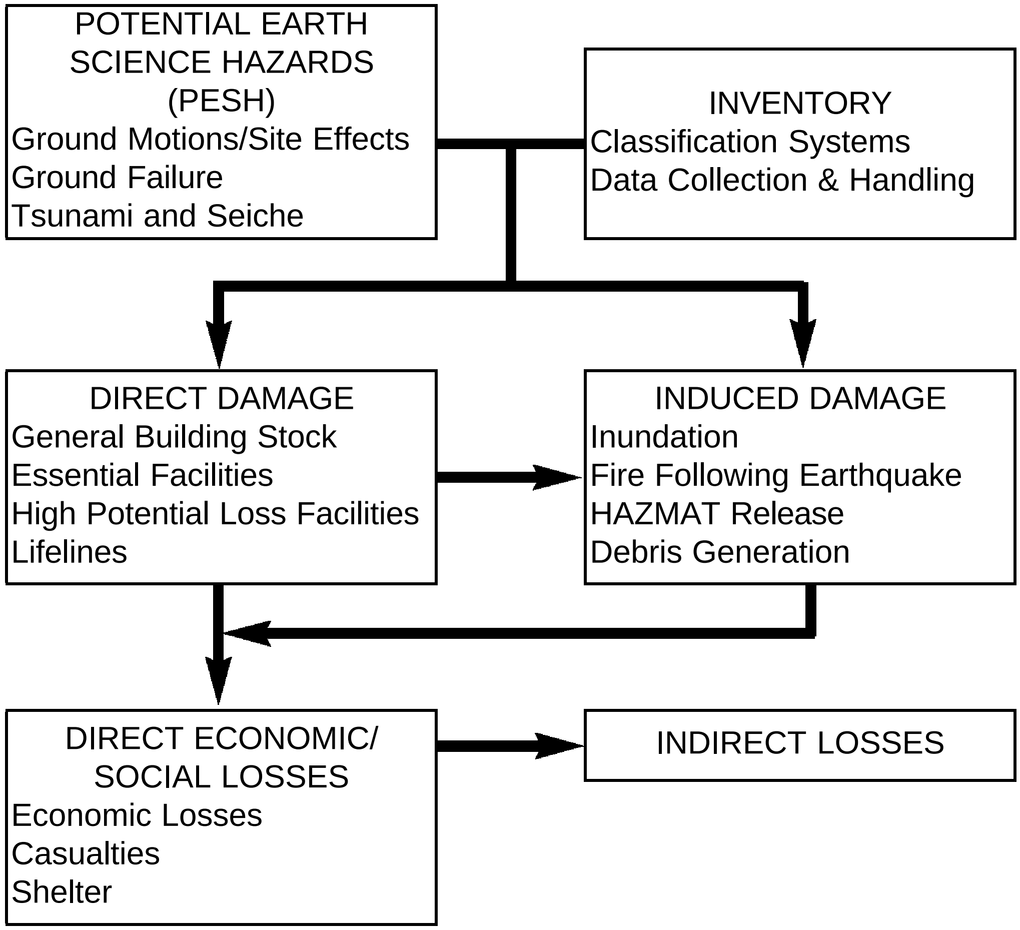


FIGURE 24-1.—Modules of HAZUS.

Source: *From Risk Management Solutions, 1996.*

ignore induced damage when computing direct losses, thus eliminating the need for certain corresponding input requirements. A limited study may be desirable for a variety of reasons such as budget and inventory constraints, or the need for answers to very specific questions.

The HAZUS modular framework also permits FEMA to extend the methodology to other hazards and to multiple hazards. Many of the inventory databases compiled for earthquake loss estimation, such as high hazard dam sites, HAZMAT storage sites, critical facilities, and lifelines, are necessary for other risk assessments. Additional inventory databases and damage relations may be added.

Because of the complexity of the earthquake damage and loss problem, HAZUS is complex and requires that the different modules interact in the calculation of impacts and losses. Detailed technical descriptions of the methods can be found in the technical manuals currently being prepared.

Potential Earth Science Hazard (PESH) Module

The PESH module generates estimates of ground motion and ground failure: landslides, liquefaction, and surface fault ruptures. Based on the location and size of an event and the local geology, ground motion demands are generated in terms of spectral acceleration, peak ground acceleration (PGA), and peak ground velocity (PGV). For ground failures, permanent ground deformation (PGD) and probability of occurrence are estimated. Related earth science hazards, such as tsunami and seiche inundation, can be used to assess potential impacts.

PESH Ground Motions/Site Effects. The use of integrated GIS software allows users to define graphically the scenario event and to quantify the associated ground shaking and ground failure hazards which serve as the basis for evaluating damage and losses.

The PESH module estimates site-specific ground shaking intensities and uses the values to estimate damage to buildings and lifeline inventories. Estimating the ground shaking intensities in the GIS-based program requires the three steps described below.

1. Select the scenario earthquake event. The methodology provides three approaches for characterizing an earthquake event: deterministic seismic events, probabilistic seismic hazards, or user-supplied ground shaking maps. A deterministic event is created using the supplied database of historical earthquakes, existing seismic source maps (source maps for California are provided), or a hypothetical event customized by the user.

   Users can generate annualized estimates of damage and loss based on the probabilistic spectral response contour maps developed by USGS for the NEHRP Provisions and other studies. Frequency-based hazard curves are created for the region and damage/losses are evaluated for eight discrete levels of shaking intensity.

   Users can replicate a scenario event by supplying a digitized map representing ground motion or shaking, intensities that occurred from, or are predicted to occur from, earthquakes. This option was created to allow users to develop scenarios that could not be adequately described by a theoretical attenuation relationship or to replicate a well-recorded past event.

2. Determine the input ground motion levels for the baseline site-soil conditions using attenuation relationships. The methodology provides five attenuation relationships (three for use in the Western United States, one for use in the Eastern States, and one for subduction events) to explicitly determine the spectral response for eight specific periods (0.5 second, 1.0 second, etc.) and peak ground shaking (PGA and PGV). Site-specific response spectra are generated by connecting the demands (shaking) at the eight discrete spectral periods.

3. Overlay high resolution geologic information and modify ground motion demands using site amplification factors based on local site conditions. To account for site effects, a user-supplied map of high-resolution geologic data may be overlaid on the baseline shaking demands to modify ground motion demands. If a user-supplied map does not exist, the model defaults to the soil information provided with the methodology.

PESH Ground Failure. Ground deformations due to liquefaction, landslides, and surface fault ruptures are quantified and the damage to buildings and lifelines is adjusted to account for the associated ground failures. Each type of ground failure is quantified in terms of median permanent ground deformation (PGD) and probability of occurrence. Using GIS, susceptibility maps and ground motion contour maps are evaluated to determine landslide and liquefaction consequences. The expected deformation is computed for surface fault rupture as a function of a scenario event, but not for probabilistic and user-supplied events. Users have the option to assume that all or part of a fault rupture does not extend to the surface, thus limiting the effects of displacements.

PESH Tsunami and Seiche. Damage, fatalities, and fires from inundation due to tsunami or seiche can be significant. Although a tsunami wave can be almost undetectable in the open ocean, it can grow to great heights when it reaches land. Seiches are waves in a lake or reservoir that are induced because of ground shaking. If the waves are large, facilities along the lake shore can be damaged or dams can be overtopped. Since models available for estimation of losses from these hazards are not well established, PESH is limited to assessment of inundation potential unless an expert analysis is involved.

Inventory Module

Development and collection of inventory data are the most time consuming and costly aspects of performing a loss estimation study, and are often a limiting factor in the development of a comprehensive study. Because many potential users have limited budgets, HAZUS is designed to accommodate different levels of resources.

An extensive amount of data is provided in the Inventory Module: buildings, essential facilities, lifelines, population, and economic conditions. Default data are supplied to assist users who may not have the resources to develop detailed inventory data specific to a community, region, or State. However, the default data are limited for certain areas, especially utility lifelines, and should be augmented or superseded by improved information whenever possible. Uncertainty will be associated with the resulting estimates.

Direct Damage Module

This module provides damage estimates for four distinct groups: general building stock; essential facilities; high potential loss facilities; and lifelines (transportation and utility systems). The groups are defined to address distinct inventory and modeling characteristics. Estimates are presented in the form of probabilities of being in a specific damage state given a specified level of ground motion and ground failure. Estimates of damage also include loss of function by facilities and lifelines, and the anticipated service outages for potable water and electric power.

Direct Damage - Buildings. In earlier loss estimation methodologies, the extent and severity of building damage typically were evaluated for generic groups of buildings using expert opinion and non-engineering parameters. In HAZUS, inelastic building capacity and site-specific response spectra are used to describe damage sustained by both structural and nonstructural components. A simple and practical procedure is used to estimate the inelastic seismic response of buildings, and it can be applied by the engineering community for specific structures, as well as for generalized groups of structures.

The predicted building response, in terms of PGD or PGA, is used to create fragility curves, which in turn are used to obtain probabilistic estimates of the extent and severity of damage. Damage estimates are expressed in terms of the probability that the building will be in one of five damage states: none, slight, moderate, extensive, complete. Although damage varies from none to complete as a continuous function of building response, it is impractical to describe a continuous function and discrete states are used for ease of description. For some cases, structural damage may not be directly observable if structural elements are hidden behind architectural finishes or fireproofing. Hence, the structural damage states often are described with reference to certain effects on nonstructural elements, which may be indicative of the structural damage state.

To adequately service all the needs of the methodology, the damage state definitions are descriptive and the user must glean the nature and extent of the physical damage to a building type from the damage prediction output. Life-safety, societal, and financial losses that result from the damage can be estimated.

Because damage to nonstructural building components such as architectural elements and mechanical/electrical systems affect losses differently than damage to structural components (i.e., gravity and lateral load resisting systems), HAZUS separately estimates structural and nonstructural damage. Damage to nonstructural components is considered to be independent of the building type, and descriptions of damage states are developed for common nonstructural systems rather than for building types. Whether part of a steel-frame building or concrete shear-wall building, such components as partitions, ceilings, and cladding are assumed to incur the same degree of damage when subjected to the same interstory drift or floor acceleration.

Damage to certain nonstructural components such as full-height drywall partitions, is primarily a function of interstory drift. For other components such as mechanical equipment, damage is a function of floor acceleration. Developing fragility curves for each possible nonstructural component is not practicable. Therefore, nonstructural components are grouped into drift-sensitive and acceleration-sensitive components.

The generalized method for predicting damage to buildings provides a mechanism to account for variations in structural characteristics and local soil conditions. The Direct Damage Module uses a five-step process to determine the damage state probability for a particular structure or class of structures at a given site.

1. The nonlinear building capacity incremental "pushover" curve of a building is computed based on its structural characteristics;

2. The site-specific elastic response spectra generated by the ground motion model are modified to account for the effects of both increased damping at higher response levels and durations;

3. The modified site-specific response spectra are overlaid on the nonlinear building capacity curve. The intersection point defines the expected building response (both roof displacement and acceleration);

4. For the expected building response, structural and nonstructural fragility curves are evaluated to determine damage state probabilities; and

5. The damage state probabilities are modified to account for site-specific probable ground deformations estimated by the ground failure model.

For both general building stock and essential facilities, damage state probabilities are determined for each facility or structural class. Then, based on the level of structural and nonstructural damage, the buildings are estimated to be fully functional, partially functional, or nonfunctional (closed). The output of the functionality models is a loss-of-function estimate expressed as a percent of capacity and an estimated time to recover to full capacity.

Damage and loss of function are key issues with respect to essential facilities, especially those involved with emergency response. Emergency facilities are treated as special structures that may or may not be designed to higher standards than the general building stock. The user can modify the performance of an essential facility to reflect the design and construction quality standards under which the facility was built.

Direct Damage - Lifelines. The amount of damage and restoration time are estimated for 13 transportation and utility systems. Fragility curves for lifeline system subcomponents such as airport fuel facilities, highway bridges, and water treatment plants, are combined using fault tree logic to develop an overall fragility curve for the lifeline component. Based on fragility curves, a method for assessing functionality of each component was developed.

The performance of the key components and simplified rules relating performance to damage, damage state probabilities for lifeline components. Damage states are qualified descriptions of damage that portray various levels of damage, such as shattered windows, broken pipes, and cracked drywall. Estimates of loss of function and time to restore are calculated for a given event.

Evaluation of direct damage to lifeline systems requires an understanding of the interactions between components and the potential for alternatives when certain components fail. The lifeline model provides estimates of service outages for electric power and potable water systems with limited input from lifeline operators.

Induced Damage Module

When estimates of direct damage are available, induced damage can be evaluated. Induced damage is defined as the consequences of a natural hazard event, other than damage due to the primary hazard, that lead to losses. This module includes inundation due to dam or levee failure, fire following earthquake, HAZMAT release, and debris generation.

Induced Damage - Inundation. The National Inventory of Dams database is used as default information. Dams are ranked according to their hazard potential and users can query the database to prioritize the impact potential for dams in a particular region.

Development of a dam failure inundation map typically requires the assistance of a technical expert. However, HAZUS users may use existing inundation maps which are available for many high hazard dams. HAZUS imports and overlays inundation maps with population and building inventory information to estimate exposure to potential inundation due to dam failure.

A recognized drawback to using existing dam-break inundation maps is that they may have been developed for different scenarios. The U.S. Bureau of Reclamation (USBR) developed a simplified approach to estimate peak discharge downstream of a dam considering the depth of water behind the dam and the configuration of the watercourse. This approach is included in the HAZUS technical manual.

Induced Damage - Fire Following Earthquake. Fires triggered by earthquakes can be a major problem that is well documented in historical events. The recent earthquake in Kobe, Japan, reinforced awareness of the potential threat. Estimation of the impacts from fires is an extremely complex problem.

HAZUS uses Monte Carlo simulation techniques to assess potential impacts. The model is separated into three major elements, described below.

1. Fire ignition is a function of the severity of the shaking, the type and age of construction, and the anchoring of equipment within structures. Based on empirical information from previous earthquakes, the number of fire ignitions is estimated from the size and type of inventory subjected to different levels of ground motion.

2. Fire spread is a function of the density of construction, the presence of wind, and the presence of fire breaks and low fuel areas such as parks, cemeteries, golf courses, wide streets, and lakes.

3. Fire suppression is a function of available fire fighting capabilities. If water service is interrupted or transportation systems are damaged, the response of fire suppression personnel is hindered.

The spread and suppression models use the damage and loss-of-function outputs of the essential facilities and lifeline modules to determine the response capabilities and effectiveness of fire suppression personnel. Thus, information about the number and location of strike teams, the average width of streets, the condition of lifeline systems, and the speed and direction of the wind is required to perform a fire-following-earthquake analysis. The combination of ignition, spread, and suppression determines a fire spread area and estimates the number of serious ignitions. Based on the fire spread area, the methodology determines the population and value of building stock exposed.

Induced Damage - HAZMAT Release. HAZUS is restricted to considering only regional incidents such as large toxic releases, fires, or explosions, the consequences of which could lead to a significant demand on health care and emergency response facilities. Therefore, the supplied database (USEPA Tri-Services Database) includes those chemicals that are considered highly toxic, flammable, or highly explosive, and is limited to those facilities where large quantities are stored.

Before this module was developed, an exhaustive search was made of existing literature for models that could be used to predict the likelihood of occurrence of HAZMAT releases during earthquakes (Tierney and others, 1990; Ravindra, 1992; Los Angeles County Fire Department, 1992). The identified models require significant expert input, including a walk-through inspection. Furthermore, such efforts typically are aimed at large complexes such as petrochemical facilities, and are not suitable for more general applications.

Because of the limitations of state-of-the-art HAZMAT release models, the Induced Damage-HAZMAT Release module is restricted to establishing a standardized method for classifying materials and developing a default database that can be used by local planners to identify those facilities that may be most likely to have significant releases in future earthquakes. A more general model that can be used by emergency preparedness officials at the local level is needed to allow determination of the potential for HAZMAT releases.

Induced Damage - Debris Generation. Limited research has been done in the area of estimating debris from earthquakes. Some of the early regional loss estimation studies (Algermissen and others, 1973; Rogers and others, 1976) included simplified models for estimating the amount of debris from unreinforced masonry structures. HAZUS adopts a similar empirical approach to two types of debris: debris that falls in large pieces, such as steel members or reinforced concrete elements that require special treatment to break into smaller pieces before hauling away; and debris that is smaller and more easily moved with bulldozers, including brick, wood, glass, building contents, and other materials.

HAZUS uses an approach where, for given damage states for structural and nonstructural components, debris estimates are based on: the results from the Direct Damage Module; tables that quantify debris generated from different structural and nonstructural building damage states; and the typical weights of structural and nonstructural elements. Aggregated estimates of generated debris are presented in terms of type (brick versus reinforced concrete and steel) and origin (structural versus nonstructural components).

Direct Economic/Social Losses Module

Both direct and induced damage can lead to direct economic or social losses. The Direct Economic/Social Losses Module evaluates two types of direct loss: the cost of repair and replacement of structures and lifeline systems, including structural and nonstructural damage and losses to contents and business inventory; and the consequence of building or lifeline loss-of-function, such as costs of relocation, income loss, and rental loss. Social losses are quantified in terms of casualties, injuries, displaced households, and short-term shelter needs.

Direct Losses - Economic Losses. Direct economic losses include the cost of repair or replacement of damaged structures. Structural and nonstructural damage, relocation costs, loss of business inventory, income losses, and rental losses also are direct economic losses. Relocation costs, income losses, and rental losses occur as a consequence of how long a business is inoperable, which is a function of the level of damage and the type of structure or facility.

Information from the Direct Damage Module is combined with regional economic data to compute direct economic losses. Examples of economic data used include the per square foot cost of construction by occupancy type, average per square foot rental rates, and gross sales. HAZUS accounts for regional variations in construction costs. Direct economic losses can be mapped or queried by census tract, by loss type, or by general/specific occupancy type.

Direct Losses - Casualties. HAZUS estimates earthquake-related casualties that are caused by building and bridge collapses, occupant entrapments, building and bridge damage, and nonstructural damage. A modifier is used to account for casualties that occur outside of buildings, such as debris falling on pedestrians.

HAZUS combines the output from the Direct Damage Module with building inventory and population data to quantify casualty estimates. Daily migration patterns and associated casualties are estimated for three representative times of day: 2:00 p.m. (office hours); 5:00 p.m. (commute time); and 2:00 a.m. (night).

Daily migration patterns are based on census data, land-use data, occupancy type, available inventory information, and transportation planning origin-destination data. For example, the model estimates the number of employees working at 2:00 p.m. in a retail commercial environment in a steel frame building. Combining these estimates with damage estimates from the Direct Damage Module yields the number and type of casualties resulting from building and bridge collapse or damage.

The output of the Direct Losses-Casualties Module contains estimates of four types of casualties by general occupancy and time, which are aggregated by U.S. Census tract. The casualty types range from "Stage 1: first aid level injuries not requiring hospitalization" to "Stage 4: instantaneously killed or mortally injured."

Users can display maps or tables of casualty estimates, which can be used to estimate the amount and type of medical attention that may be required. By combining casualty information with loss-of-function estimates for hospitals, alternate plans may be prepared for treatment of victims outside of an affected area.

Direct Losses - Shelter Needs. Homelessness caused by residential building damage results in two general shelter needs: short-term needs (up to 2 weeks) for which public shelters are provided by the American Red Cross and others; and long-term needs which are accommodated by leased housing units, importing mobile units, and constructing new public or private housing. Long-term needs are caused by extended or complete loss of housing units. Estimation of shelter needs is driven by damage information for residential units and the demographics of a region

HAZUS combines damage to residential building stock with utility service outage relationships to estimate the number of households that may be uninhabitable. The loss-of-function to utilities can drastically change the short-term shelter needs in severe climates. The uninhabitable household estimates are combined with demographic data to quantify the number and composition of the population that may require short-term sheltering. Currently, HAZUS does not estimate shelter needs associated with induced damage.

Indirect Losses Module

Long-term effects on regional economy due to earthquakes are evaluated by the Indirect Losses Module. Examples of indirect economic losses include increased unemployment rates, loss of tax revenue, loss of production, reduction in demand for products, and reduction in spending. Essentially, indirect economic losses are a consequence of direct economic effects, major interruption to lifelines, length of time to relocate, repair and rebuild, aid that flows into a region, and the ability of a region to adjust to changes in demand and supply. To estimate indirect economic losses, HAZUS users must supply social and economic information about a region, such as population, employment base, and nature of business activities.

HAZUS estimates indirect economic losses by multiplying output from the Direct Economic Loss Module with input-output multipliers. Multipliers, based on estimates for 80 U.S. counties, are provided as defaults for a given set of industrial sectors. Economic and social information provided by users is used to determine the appropriate multipliers for a particular region and industrial sector. For example, a multiplier of two for tourism would indicate that, for every dollar of tourist revenue lost, there will be an additional dollar of lost income to those in the tourist industry.

Outputs of the indirect economic module include income change, value added change, tax revenue change, and employment change by industrial sector aggregated on a county basis.

CONCLUSION

The HAZUS risk assessment (loss estimation) methodology was specifically developed to estimate losses from earthquakes and other hazards that are induced by earthquakes. Because of the modular nature of the methodology, FEMA plans to expand its use to other hazards and may provide loss algorithms and additional inventory databases in the future.

BIBLIOGRAPHY AND REFERENCES

Algermissen, S.T., M. Hopper, K. Campbell, W.A. Rinehart, D. Perkins, K.V. Steinbrugge, H.J. Lagorio, D.F. Moran, F.S. Cluff, H.J. Degenkolb, C.M. Duke, G.O. Gates, N.N. Jacobson, R.A. Olson, and C.R. Allen. 1973. ***A Study of Earthquake Losses in the Los Angeles, California Area.*** Washington, DC: National Oceanic and Atmospheric Administration.

Federal Emergency Management Agency. 1994. ***Assessment of the State of the Art Earthquake Loss Estimation Methodologies, Earthquake Hazards Reduction Series 70.*** FEMA 249. Washington, DC: National Institute of Building Sciences.

Los Angeles County Fire Department, Hazardous Materials Section, RMPP Unit. 1992. ***Seismic Assessment Guidelines for RMPP Studies.*** Los Angeles, CA: Los Angeles Fire Department.

Ravindra, M. 1992. "Seismic Assessment of Chemical Facilities under California Risk Management and Prevention Program." ***Proceedings, International Conference on Hazard Identification and Risk Analysis, Human Factors and Human Reliability in Process Safety.*** American Institute of Chemical Engineers, Center for Chemical Process Safety.

Risk Management Solutions, Inc. 1996. ***Development of a Standardized Earthquake Loss Estimation Methodology.*** Draft Technical Manual, Vil. I. Prepared for FEMA and the National Institute of Building Sciences. Menlo Park, CA.

Rogers, A.M., S.T. Algermissen, W.W. Hays, D.M. Perkins, D.O. Van Strien, H.C. Hughes, R.C. Hughes, H.J. Lagorio, and K.V. Steinbrugge. 1976. ***A Study of Earthquake Losses in the Salt Lake City, Utah Area.*** USGS Open-File Report 76-89. Washington, DC: U. S. Geological Survey.

Tierney, K.J., H.A. Seligson, and R.T. Eguchi. 1990. ***Chemical Hazards, Mitigation, and Preparedness in Areas of High Seismic Risk: A Methodology for Estimating the Risk of Post-Earthquake Hazardous Materials Releases.*** National Science Foundation and National Center for Earthquake Engineering Research.

CHAPTER

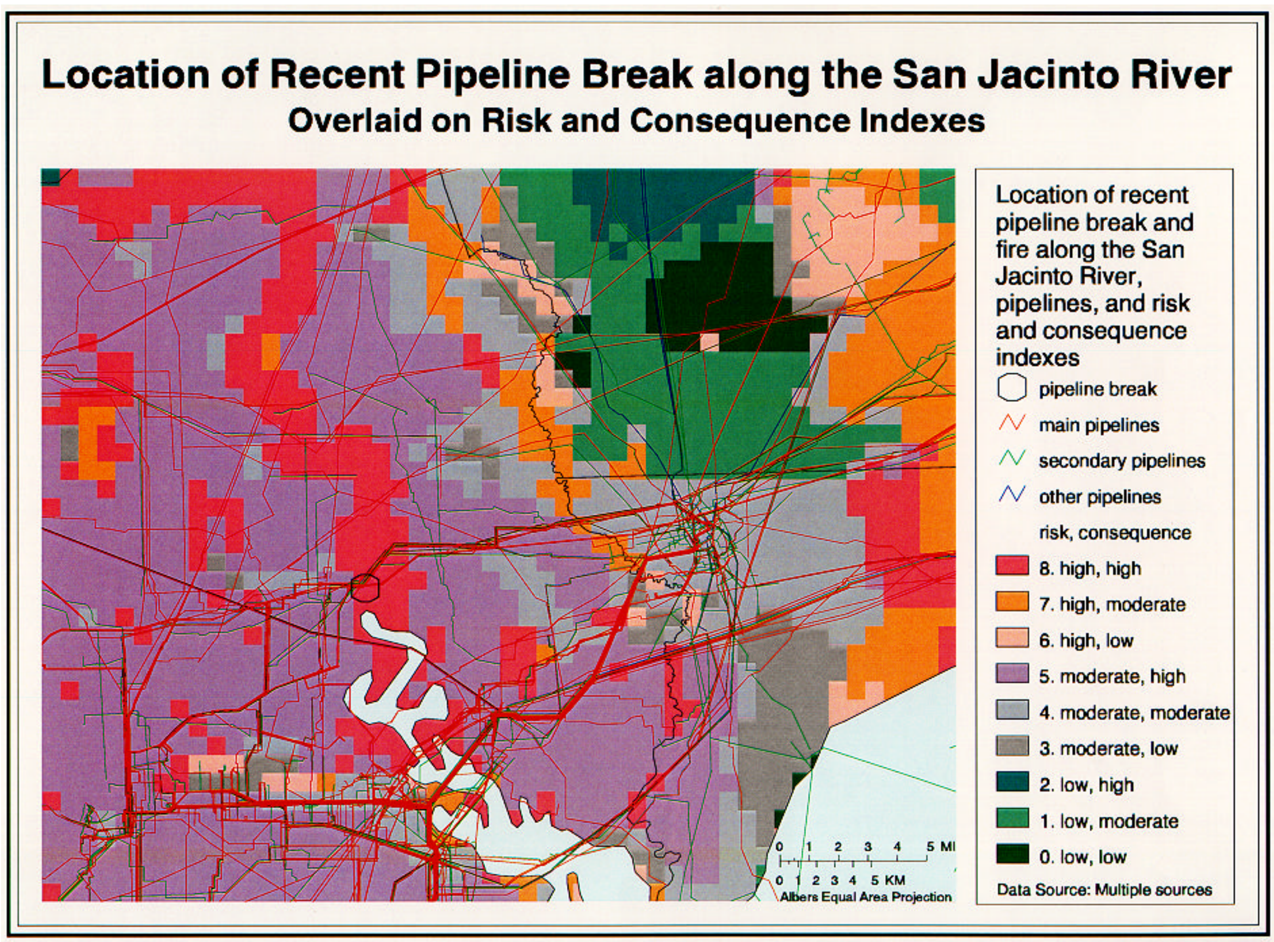
25

OTHER RISK ASSESSMENT APPROACHES

Chapter Summary

Risk assessment methodologies that estimate actual losses are vital tools for emergency managers and hazard mitigation specialists. There are other approaches that provide important information on the nature and level of risk in a given region but that do not yield loss estimates. This chapter presents five such approaches to risk assessment:

- **Risk Matrix Approach** to anticipate losses and to evaluate potential impacts;
- **Composite Exposure Indicator** based on public exposure to natural hazards using a principal components analysis of 14 demographic indicator variables;
- **Multiple Coastal Hazard** using quantitative and qualitative risk assessments associated with seven coastal factors;
- **Coastal Vulnerability Index** based on a complex set of coastal factors to identify the risk from permanent and episodic sea level rise; and
- **Multiple Hazard (Seismic-Hydrologic) Approaches**, focusing on land-use planning and understanding the multiple-hazard impact of a local Cascadia Subduction Zone earthquake and associated tsunami, ground failure, fault rupture, liquefaction, and landslides.



Example of Hazard Identification using geographic information system technology (GIS).

RISK MATRIX APPROACH

The practice of risk management permits decision-makers to anticipate losses and to evaluate potential impacts to facilitate effective planning and management. It requires recognition of risks, evaluation of the frequency of those events and the related magnitude of consequences or potential losses, and determination of appropriate measures for prevention or reduction of these risks from a cost/benefit point of view (Long and John, 1993).

The risk matrix approach, developed by Arthur D. Little, Cambridge, MA, involves several continuous steps (Figure 25-1):

1. **Identify and Characterize Hazards.** Define and describe hazards, measures of magnitude and severity, causative factors, and interrelations with other hazards;

2. **Screen Risk.** Rank, or order, the identified hazards as a function of the relative degree of risk;

3. **Estimate Risk.** Apply the process or methodology to evaluate risk;

4. **Assess Acceptability.** Determine whether risks that have been identified and estimated in the previous steps can be tolerated;

5. **Develop Alternatives to Reduce Risk.** Select cost-effective actions to reduce or mitigate unacceptable risks, including technological and management controls;

6. **Implement Necessary Mitigation Measures, Control, and Review.** Implement mitigation measures to control risk to acceptable levels.

7. **Control and Review.** Periodically monitor and review risks.

Regional Differentiation

Each region is unique because of such factors as climate, geography, and development. Therefore, the risks associated with hazards in each region are also relatively unique. Depending on the corresponding needs for risk assessment and associated costs, different levels of risk management can be conducted.

Levels of risk management can range from cursory risk screenings, where worst-case consequence assessments are assumed, to full-scale quantitative risk assessments which are very analytical, formal and vigorous techniques used to numerically evaluate all credible hazards. An intermediate approach is a semi-quantitative risk survey, which facilitates the categorization and prioritization of hazards as the basis for mitigation and/or emergency management.

Hazard Identification and Associated Risk

Both natural and technological hazard events can occur to various degrees. Defining categories for a risk matrix, and specifically for severity categories, is a catalyst for hazard definition (Long and John, 1993).

Criteria for severity categorization might include an examination of the potential for fatalities, injuries,

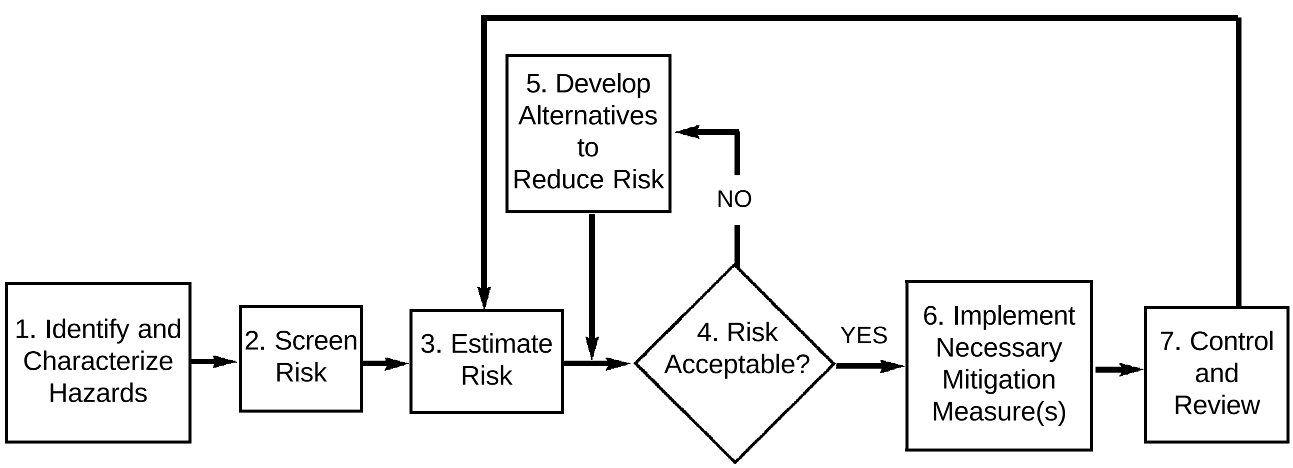


FIGURE 25-1.—A risk matrix approach.

Source: *Modified from Long and John, 1993.*

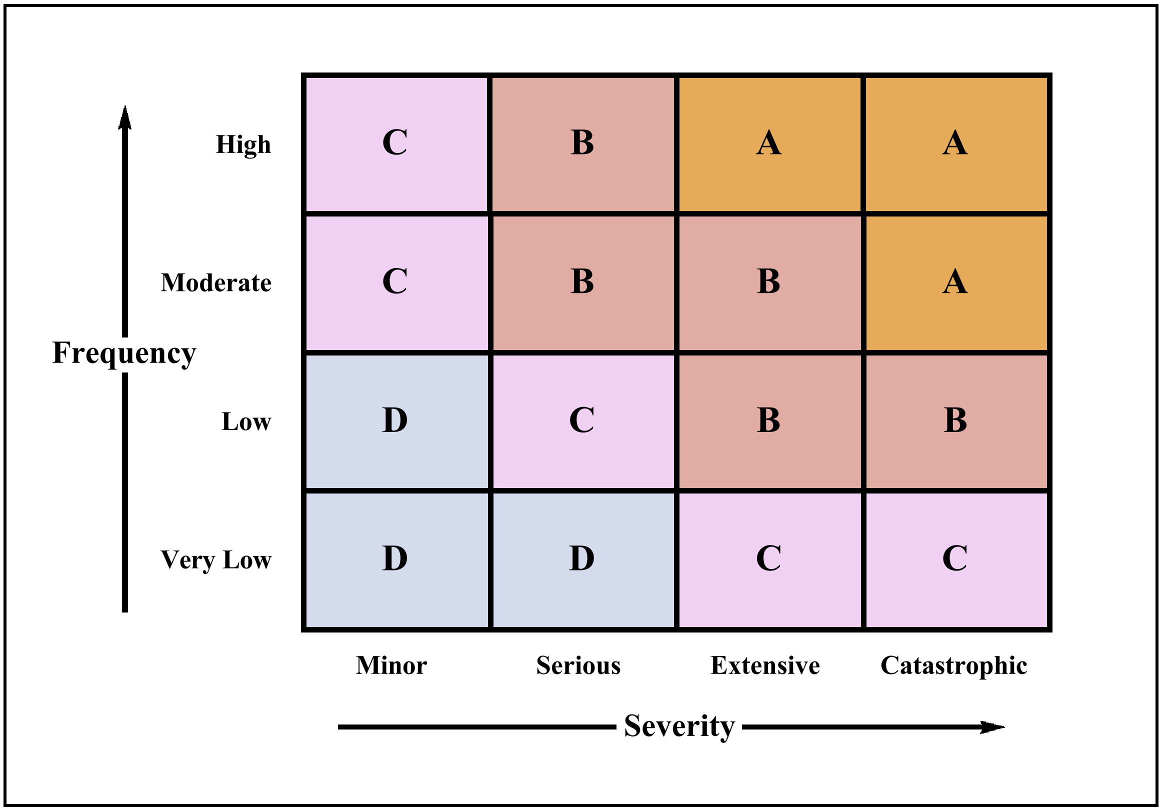


FIGURE 25-2.—Example of risk matrix.
Source: *Modified from Long and John, 1993.*

property damage, business interruption, and environmental and economic impacts, rated in categories ranging from catastrophic to minor.

Criteria for frequency categorization might include:

- High frequency: events that occur more frequently than once in 10 years ($>10^{-1}$/yr);
- Moderate frequency: events that occur from once in 10 years to once in 100 years (10^{-1} to 10^{-2}/yr);
- Low frequency: events that occur from once in 100 years to once in 1,000 years (10^{-2} to 10^{-3}/yr); and
- Very low frequency: events that occur less frequently than once in 1,000 years ($<10^{-3}$/yr).

In the risk matrix approach, both the magnitude and frequency of occurrence of a hazard are given a qualitative measure that permits the prioritization of risk among multiple hazards (Figure 25-2):

- Class A: High-risk condition with highest priority for mitigation and contingency planning (immediate action). Examples of losses: death or fatal injury, complete shutdown of facilities and critical services for more than one month, more than 50 percent of the property located in affected area is severely damaged;
- Class B: Moderate-to-high-risk condition with risk addressed by mitigation and contingency planning (prompt action). Examples of losses: permanent disability, severe injury or illness, complete shutdown of facilities and critical services for more than 2 weeks, more than 25 percent of the property located in the affected area is severely damaged;
- Class C: Risk condition sufficiently high to give consideration for further mitigation and planning (planned action). Examples of losses: injury or illness not resulting in disability, complete shutdown of facilities and critical services for more than one week, more than 10 percent of the property located in the affected area is severely damaged; and
- Class D: Low-risk condition with additional mitigation contingency planning (advisory in nature). Examples of losses: treatable first aid injury, complete shutdown of facilities and critical services for more than 24 hours, no more than 1 percent of property located in the affected area is severely damaged.

COMPOSITE EXPOSURE INDICATOR APPROACH

Another approach to assess the risk from a given hazard based on several indicator variables is the composite exposure indicator (CEI) method (Thomas and others, 1996). The output of this approach is a ranking of the potential for losses in a given region or area for single or multiple hazards. Actual losses are not estimated because the approach does not include a relationship between exposure and losses, and economic data are not used. The approach could be extended to provide estimates of losses.

Using databases provided by FEMA, 14 variables are quantified for 3,140 counties in the United States. The variables and their units of measure, expressed as densities (number or length per square mile), are defined in Table 25-1. The variables were chosen because they are readily available and indicative of exposure and potential damage from hazards. The approach is flexible and the list of indicator variables could be modified easily.

The mean, standard deviation, minimum, and maximum for the 14 indicator variables illustrate the variability of the data. All variables except population have a lower bound of zero. This implies that there is at least one county without at least one bridge, or one public water supply, or airport, or road, etc.

Many variables are highly correlated and are essentially measuring similar exposures. Using the correlation coefficients, several conclusions can be drawn:

- The number of hospitals and population are highly correlated;
- Hospitals and population are moderately correlated with the number of bridges;
- The number of public water supply systems and sewage treatment sites are strongly correlated;
- Public water supply systems and sewage treatment plants are moderately correlated with the length of pipelines and the number of dams; and

TABLE 25-1.—*Variables, units of measure, and summary statistics for exposure variables for 3,140 U.S. counties.*

Variable	Unit of Measure	Mean	Standard Deviation	Minimum	Maximum
Hospitals	#/ mi^2	0.005	0.028	0	1.297
Population	# persons / mi^2	213.767	1,519.663	0.053	62,245.000
Nuclear Power Plants	# plants / mi^2	0.000	0.001	0	0.010
Toxic Release Inventory	# sites / mi^2	0.059	0.228	0	4.913
Public Water Supplies	# / mi^2	0.005	0.077	0	4.276
Superfund Sites	# sites / mi^2	0.001	0.003	0	0.056
Sewage Treatment Sites	# sites / mi^2	0.014	0.056	0	2.460
Utility Lines	Ft / mi^2	647.161	404.752	0	2,756.591
Airports	# / mi^2	0.002	0.003	0	0.100
Roads	Ft / mi^2	665.084	443.725	0	11,633.116
Railroads	Ft / mi^2	420.221	361.616	0	4,624.799
Pipelines	Ft / mi^2	300.052	726.723	0	32,188.936
Dams	# / mi^2	0.012	0.031	0	1.246
Bridges	# / mi^2	0.270	0.591	0	13.767

Source: *Data from FEMA, Map Application Center, 1995.*

- The length of roads is moderately correlated with sewage treatment sites and the length of railroads.

Significant correlations between variables indicate similar variation in terms of exposure, suggesting the need for a multivariate analysis approach, such as the principal components analysis. In summary, the results indicate that the first and largest principal component is the transportation variables (road and rail) and the water-related variables (public water supply, sewage sites, dams, and bridges). The second (next largest) principal component is for hospitals and population which are highly correlated. Similar analogies can be made for the other principal components.

Principal components scores (one score for each of the five components) are computed for each of the 3,140 U.S. counties and combined into a single Composite Exposure Indicator (CEI) for each county. The CEI reflects the influence of all 14 original variables and is a measure of exposure of those 14 variables to various hazards. Larger CEI values imply that more people, critical facilities and lifelines are exposed to potential damages from various natural and technological hazards.

MULTIPLE COASTAL HAZARD ASSESSMENT APPROACH

A 1989 study and mapping performed by the Coastal Engineering Research Center and the University of Virginia for USGS (Anders and others, 1989) evaluated selected segments of U.S. coastline for risk and exposure to coastal hazards. The frequency of occurrence and intensity of coastal factors were depicted on a map (Chapter 13).

An overall hazard assessment identifying the risk from very low to very high was established and depicted for coastal segments of the U.S. mainland, Alaska, and Hawaii. A similar assessment for the Great Lakes region is underway.

The USGS mapping represents quantitative and qualitative risk assessments associated with coastal factors that are used to identify coastal hazards: shoreline change, overwash distance, storm surge, storm and wave damage, earth movements, and stabilization. The mapping includes onshore factors of coastal relief (a modified geomorphology and geology factor) and population demographics.

The population density for shoreline segments was not directly integrated in the assessment to allow a determination of overall exposure. The integration of onshore population demographics and other factors of risk could transform the hazard assessment study into a more useful tool to assess exposure.

The onshore factors needed for developing an overall assessment should include infrastructure, lifelines, and technological factors. The density of population, hospitals, schools, utility lines, roadways, railways, bridges, dams, airports, powerplants, and sewage treatment facilities in the hazard area increase the exposure. Increased exposure generally results in higher damage potential and disruption of economic health of a coastal area.

COASTAL VULNERABILITY INDEX APPROACH

A coastal hazard assessment performed by the Oak Ridge National Laboratory for DOE evaluated a complex set of coastal factors to identify the risk from permanent and episodic sea level rise for 4,557 coastal segments (Daniels and others, 1992; Gornitz and White, 1992; Gornitz, and others, 1994). The risk assessments were integrated into a Coastal Vulnerability Index (CVI).

The original CVI study used seven marine and land variables. An update to determine impacts of sea level rise expanded and revised the CVI to include six climatological variables, including tropical cyclone probabilities and intensities. For each of the 13 variables, the degree of risk was weighted based on the relative importance to the erosion or inundation risk determination.

In the 1994 publication on the CVI, Gornitz, and others, defined the high-risk coastlines as those having one or more of the following characteristics: low coastal elevations; erodible substrates; previous experience with subsidence; histories of extensive shoreline retreat; high wave/tide energies; and high probabilities of being hit by tropical or extratropical cyclones.

The CVI is composed of three major variable groups: permanent inundation, episodic inundation, and erosion. The inundation variables correlate the factors of coastal flooding as influenced by the geomorphology and geology of the coastal floodplain and topography.

The elevations of the landform and impacts of local subsidence due to sea level rise are considered permanent impacts. The episodic variables are tropical storm probability, hurricane probability, hurricane frequency-intensity, hurricane and tropical storm forward speed, extratropical cyclones (including nor'easters), storm surge, and tide range. The erosion variables are geomorphology and geology of the coastal floodplain and topography, geologic composition of the shoreline, landform elevation and shape, shoreline erosion rates, and wave heights.

The CVI identified ranges within each risk classification for the 13 variables and ranked them on a scale of increasing vulnerability, from 1 (very low risk) to 5 (very high risk). The percentage of shoreline within each risk class was determined for each variable. The weighting of each factor and the algorithm used to combine the factors into the CVI depended on the importance and combination of the 13 factors.

The vulnerability to coastal inundation was determined to constitute the greatest impact and was weighted higher than the erosion variables. The permanent inundation factor was the most significant of the two inundation factors, and was weighted more heavily than the episodic factors.

The sums of factors were assigned weights: permanent inundation (35 percent), episodic inundation (25 percent), and erosion potential factor (40 percent). Within the episodic inundation factor, the variables for tropical storm and hurricane probabilities were averaged with respective weights of 0.25 and 0.75, because of differences in the relative energies of the two storm intensities. Within the erosion potential factor, the geology and landform variables were averaged because in the Southeastern U.S. study area, the variables contain similar information (Gornitz and others, 1994).

The updated CVI assessment for sea level rise in the Southeastern United States from Texas to North Carolina determined that the Gulf Coast has 30 percent, and the Atlantic Coast has 15 percent, of the respective coastlines at very high risk and exposure to inundation or increased erosion.

The CVI assigned higher vulnerability rankings to the North Carolina barrier islands and low-lying barrier islands of Louisiana than to the Florida coastline. Florida is classified as being frequented more often by fewer severe storms and has a wave climate of lower wave heights than the Outer Banks of North Carolina.

The estimated 1993 Florida coastal population is 10.5 million and total insured property values for residential and commercial properties are the highest in both categories for all coastal States from Texas to Maine. North Carolina and Louisiana may have a higher CVI ranking and physically more vulnerable coastlines than Florida, but their economic and population factors are much lower than Florida's highly developed coastline.

The integration of the Oak Ridge National Laboratory's CVI ranking into a vulnerability assessment for demographics and economics may be a valuable tool for assessment of overall coastal vulnerability. Because the information is geocoded, the data can be incorporated into existing Geographic Information Systems and used to assist in determining erosion and inundation impacts from sea level rise, multiple coastal hazard impacts, and other impacts on natural and technological hazards, utilities, and lifelines.

MULTIPLE HAZARD (SEISMIC-HYDROLOGIC) APPROACHES

The potential for loss of life and property damage from a local tsunami event created by a Cascadia Subduction Zone earthquake is significant enough to warrant extensive regional planning efforts to prepare pre-disaster response and mitigation plans. Recent studies conducted for Grays Harbor, WA (Preuss and Hebenstreit, 1991), and Humboldt and Del Norte Counties, CA (Toppozada and others, 1995) included multiple-hazard assessments of risk and vulnerability.

Approach Developed by Preuss and Hebenstreit

Preuss and Hebenstreit (1991) developed and applied a methodology to assess the multiple hazard impacts of an earthquake and associated tsunami flood event. The report presents a risk-based urban planning approach designed to allow assignment of discrete risk factors for vulnerabilities on an individual community basis.

Tsunami high-hazard inundation zones were established along the vulnerable coastal areas. Areas subject to subsidence during an earthquake were delineated, with emphasis on the flood potential in these zones. Transportation lifelines were identified for susceptibility to flooding and landslide hazards. Local land-use patterns, population distribution, and population densities were used to delineate vulnerability zones in the model study area of Grays Harbor, WA. The secondary impacts of earthquake ground motion and the release of toxic and hazardous chemicals were identified

This multiple hazard assessment approach needs to be expanded to include more information on structures and local storage facilities. Community response to a Cascadia Subduction Zone earthquake event was determined to need improvement through public awareness campaigns. Expanded assessment and mapping programs have been recommended for implementation in other high risk communities of the Pacific Northwest coastline.

Approach Developed by Toppazada and Others

Toppozada and others (1995) describe an assessment of the vulnerability of infrastructure and lifelines in northwestern California to a major Cascadia Subduction Zone earthquake. The assessment integrates the seismic-geologic-hydrologic hazards, including tsunami waves, ground failure, fault rupture, liquefaction, and landslides.

The report includes mapping of the hazards and societal impacts (i.e., buildings and structures, transportation lifelines, utility lines) and addresses coastal community planning needs. The hazards, seismic and planning considerations, and planning scenarios are characterized with damage assessments.

The report addresses the areas in need of improvement to expand the application of the assessment methodologies. Identifying the generally vulnerable areas in the scenario presented in the report provides the tool to lead to other investigations, such as more detailed and site-specific models on tsunami flooding, landslides, or engineering design standards for seismic resistance and retrofitting needs of local structures. Integration of the assessment components, detailed modeling, and mapping data into a GIS database may expand its usefulness in other vulnerable coastal communities in the Pacific Northwest.

BIBLIOGRAPHY AND REFERENCES

Anders, F., S. Kimball, and R. Dolan. 1989. Map. ***Coastal Hazards: National Atlas of the United States.*** U.S. Geological Survey.

Daniels, R.C., V.N. Gornitz, A.J. Mehta, S.C. Lee, and R.M. Cushman. 1992. ***Adapting to Sea-Level Rise in the U.S. Southeast: The Influence of Built Infrastructure and Biophysical.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3915. Oak Ridge, TN.

Gornitz, V.M., and T.W. White. 1992. ***A Coastal Hazards Data Base for the U.S. East Coast.*** Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3913. Oak Ridge, TN.

Gornitz, V.M., T.W. White, and R.C. Daniels (ed.). 1994. ***A Coastal Hazards Data Base for the U.S. Gulf Coast.*** Oak Ridge Laboratory, Environmental Sciences Division, Publication No. 4101. Oak Ridge, TN.

Gornitz, V.N., R.C. Daniels, T.W. White and K.R. Birdwell. 1994. “The Development of a Coastal Risk Assessment Database: Vulnerability to Sea-Level Rise in the U.S. Southeast.” ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.*** Pp. 327-338.

Long, M.H., and J.I. John. 1993. ***Risk-based Emergency Response.*** Paper presented at the ER93 Conference on the Practical Approach to Hazardous Substances Accidents. St. John, New Brunswick, Canada.

McCuen, R.H. 1993. ***Microcomputer Applications in Statistical Hydrology.*** Englewood Cliffs, NJ: Prentice Hall.

Morrison, D.F. 1976. ***Multivariate Statistical Methods.*** 2nd ed. New York: McGraw-Hill.

Preuss, J., and G.T. Hebenstreit. 1991. ***Integrated Hazard Assessment for a Coastal Community: Grays Harbor.*** U.S. Geological Survey Open-File Report 91-441-M.

Thomas, W.O., Jr., B. Bonn, and A.V. Romano. 1996. ***Development of a Multivariate Vulnerability Indicator.*** Accepted for publication, Proceedings of the International Conference and Exposition on Natural Disaster Reduction ‘96, American Society of Civil Engineers, Washington, DC.

Toppozada, T., G. Borchardt, W. Haydon, M. Peterson, R. Olson, H. Lagorio, and T. Anvik. 1995. ***Planning Scenario in Humboldt and Del Norte Counties, California, for a Great Earthquake on the Cascadia Subduction Zone.*** California Department of Conservation, Division of Mines and Geology, Special Publication 115.

Part II

TECHNOLOGICAL HAZARDS

"Advancements in technology and the increased development and use of chemicals over the past decades have resulted in the rise of a new and wide range of threats. Estimates of some of these threats are often difficult because of a lack of experience with them or a thorough knowledge of the full range of their impact."

From **Principal Threats Facing Communities and Local Emergency Management Coordinators**, April 1993

Introduction

Technological hazards can affect localized or widespread areas, are frequently unpredictable, can cause property damage and loss of life, and can significantly affect infrastructure in many areas of the United States. FEMA recognizes that a comprehensive strategy to mitigate the nation's hazards can not address natural hazards alone.

FEMA and other disaster and mitigation experts have long acknowledged that natural events can trigger technological disasters. It is recognized that one technological event can lead directly to another. Recent events illustrate the effects of technological events:

- On April 13, 1992, the heart of the Business District in Chicago was immobilize by flooding in an old network of tunnels connecting major buildings in the Chicago Loop. Approximately 25,000 people were sent home while the subway system was shut down, and workers addressed the flood damage before vital power and fiber-optic communication lines in the tunnels could be affected.

- On June 30, 1992, a derailed train dumped 30,000 gallons of benzene and other petroleum additives into the Nemadji River. The resulting toxic vapor cloud covered an area of over 1,200 mi^2 (1,900 km^2). As a result, 25,000 people were evacuated from Superior, WI to Duluth, MN.

The following technological hazards have been identified in FEMA reports as warranting attention:

- **Dam failures -** collapses or failures of impoundment structures that cause downstream flooding (Chapter 20);

- **Fires -** uncontrolled burning in residential, commercial, industrial or other properties in rural or developed areas (not forest and wildfires) (Chapter 21);

- **Hazardous materials events -** uncontrolled releases of hazardous materials from fixed sites or during transport (Chapter 22);

- **Nuclear accidents -** uncontrolled releases of radioactive materials at commercial powerplants or other nuclear reactor facilities or during the shipment of materials (Chapter 23);

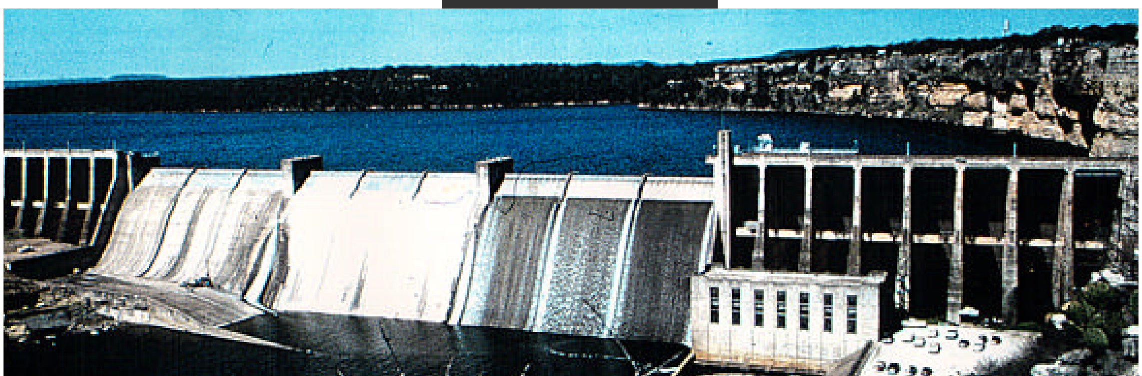
- **National security hazards -** hazards that come from actions by external hostile forces against the land, population, or infrastructure of the United States, such as ballistic missile attack, chemical and biological attack, civil disorder, nuclear attack, terrorism) ;

- **Power failures -** interruptions or losses of electrical service for extended periods of time (i.e., length of time sufficient to require emergency management organization response to health and safety needs); and

- **Telecommunications failures -** failures of data transfer, communications, or processing brought about either by physical destruction of computers or communications equipment or a performance failure of software.

CHAPTER

20



DAM FAILURES

Chapter Summary

The 1993-1994 National Inventory of Dams identifies 74,053 dams in the United States (FEMA and USACE, 1994). Thousands are classified as high or significant hazard dams whose failure would likely cause loss of life and/or substantial economic damage.

Dam failures can result from natural events, human-induced events, or a combination. Failures due to natural events such as hurricanes, earthquakes, or landslides are significant because there is generally little or no advance warning. The most common cause of dam failure is prolonged rainfall that produces flooding.

The deadliest dam failure in U.S. history occurred in Johnstown, PA, in 1889, 2,209 people. More recently, the 1972 failure in Buffalo Creek, WV, killed 125 people and left 3,000 homeless. A 1976 failure in Teton, ID, took 11 lives and cost $1 billion. A 1977 failure in Toccoa Falls, GA, resulted in 37 deaths and heavy property damage. In 1994, approximately 230 dams in Georgia were damaged by flooding caused by Tropical Storm Alberto.

As States move forward with dam safety programs, Emergency Action Plans (EAPs) have been prepared for approximately 6,500 dams. The plans, which are public documents, include evaluations of downstream inundation areas.

Since the initiation of the National Inventory of Dams in 1975, some Federal, State, and local governments and private owners have taken action to mitigate the potential for damage from dam failures. The Community Rating System of the National Flood Insurance Program provides reduced flood insurance premium rates based on activities that communities undertake to reduce flood losses. Credit points are awarded if a State's dam safety program meets the criteria of the Model State Dam Safety Program.

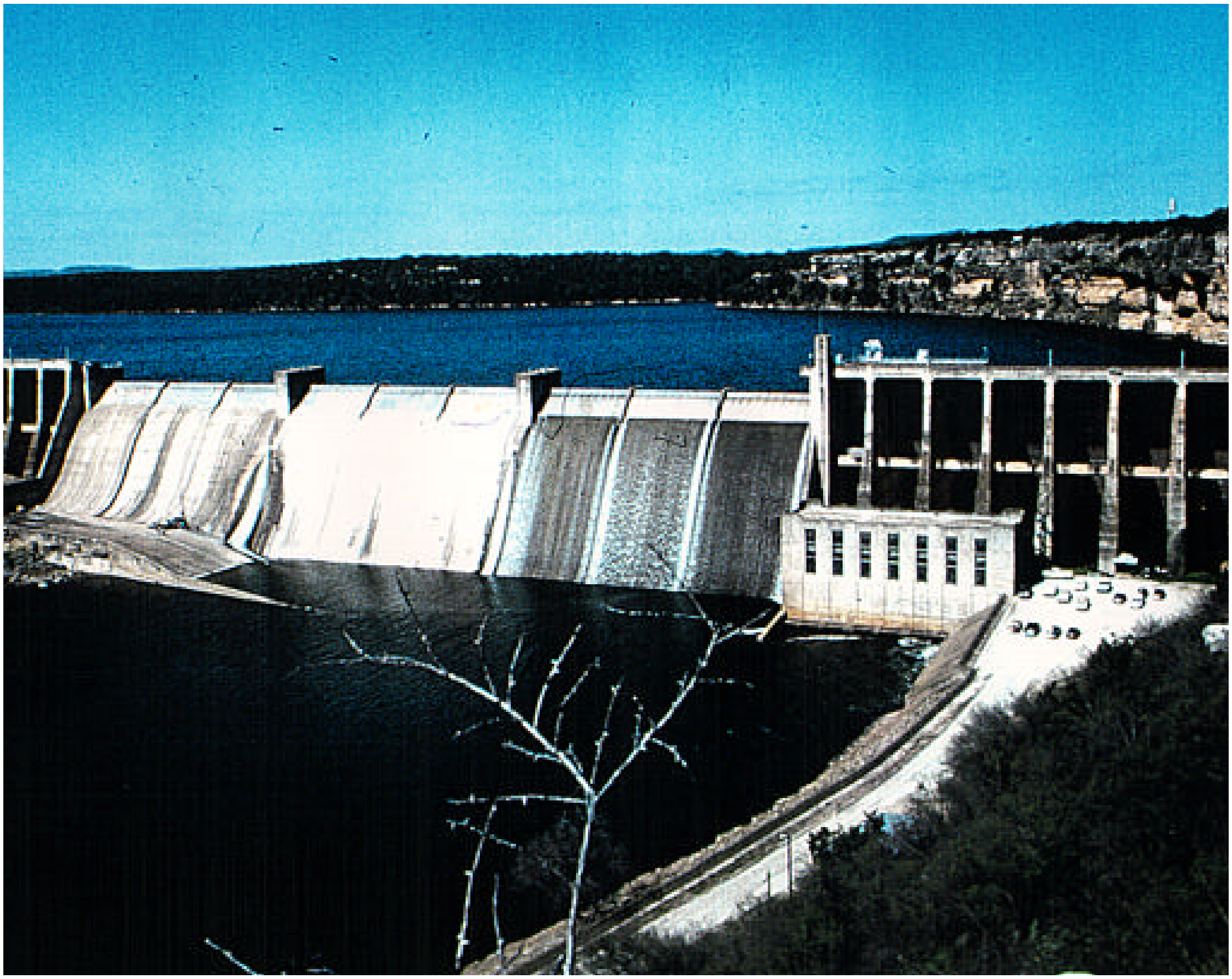


Photo: Michael Baker Corporation

HAZARD IDENTIFICATION

A dam is defined as a barrier constructed across a watercourse for the purpose of storage, control, or diversion of water. Dams typically are constructed of earth, rock, concrete, or mine tailings. A dam failure is the collapse, breach, or other failure resulting in downstream flooding.

A dam impounds water in the upstream area, referred to as the reservoir. The amount of water impounded is measured in acre-feet. An acre-foot is the volume of water that covers an acre of land to a depth of one foot. As a function of upstream topography, even a very small dam may impound or detain many acre-feet of water. Two factors influence the potential severity of a full or partial dam failure: the amount of water impounded, and the density, type, and value of development and infrastructure located downstream.

Of the 74,053 dams identified in the 1994 National Inventory of Dams, Federal agencies own 2,131; States own 3,627; local agencies own 12,078; public utilities own 1,626; and private entities or individuals own 43,656. Ownership of 10,935 dams is undetermined. The locations of the dams included in the Inventory are illustrated on Map 20-1. The Inventory categorizes the dams according to primary function:

- **Recreation** *(31.3 percent)*
- **Fire and farm ponds** (17.0 percent)
- **Flood control** (14.6 percent)
- **Irrigation** (13.7 percent)
- **Water supply** (9.8 percent)
- **Tailings and other** (8.1 percent)
- **Hydroelectric** (2.9 percent)
- **Undetermined** (2.3 percent)
- **Navigation** (0.3 percent)

Each dam in the Inventory is assigned a downstream hazard classification based on the potential for loss of life and damage to property should the dam fail. The three classifications are high, significant, and low. Map 20-2 shows the dams classified as posing high or significant hazards. With changing demographics and land development in downstream areas, hazard classifications are updated continually. The hazard classification is not an indicator of the adequacy of a dam or its physical integrity.

Dam failures typically occur when spillway capacity is inadequate and excess flow overtops the dam, or when internal erosion (piping) through the dam or foundation occurs. Complete failure occurs if internal erosion or overtopping results in a complete structural breach, releasing a high-velocity wall of debris-laden water that rushes downstream, damaging or destroying everything in its path.

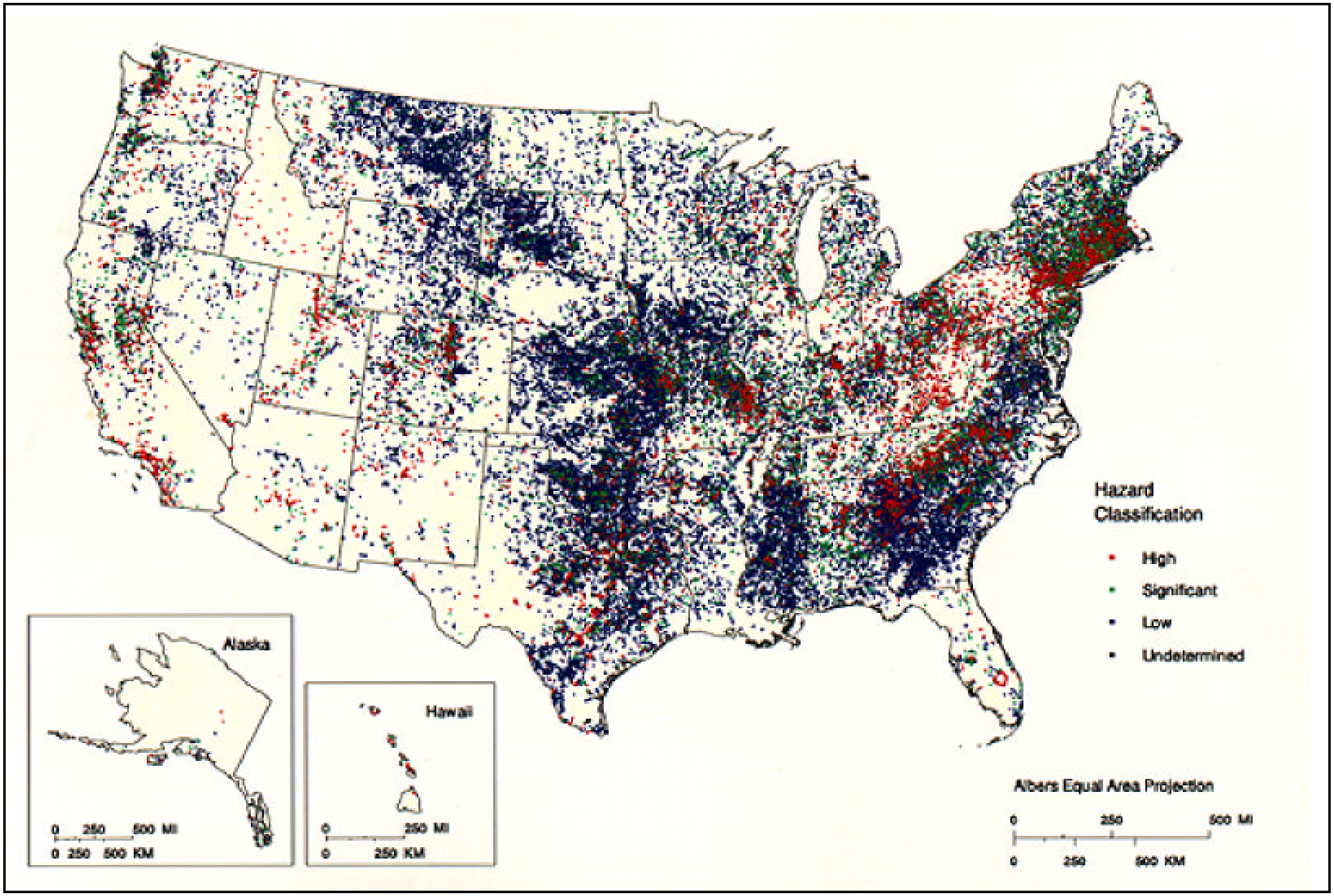
Dam failures can result from any one or a combination of the following causes:

- Prolonged periods of rainfall and flooding, which cause most failures;
- Inadequate spillway capacity, resulting in excess overtopping flows;
- Internal erosion caused by embankment or foundation leakage or piping;
- Improper maintenance, including failure to remove trees, repair internal seepage problems, replace lost material from the cross section of the dam and abutments, or maintain gates, valves, and other operational components;
- Improper design, including the use of improper construction materials and construction practices;
- Negligent operation, including failure to remove or open gates or valves during high flow periods;
- Failure of upstream dams on the same waterway;
- Landslides into reservoirs, which cause surges that result in overtopping;
- High winds, which can cause significant wave action and result in substantial erosion; and
- Earthquakes, which typically cause longitudinal cracks at the tops of embankments that weaken entire structures.

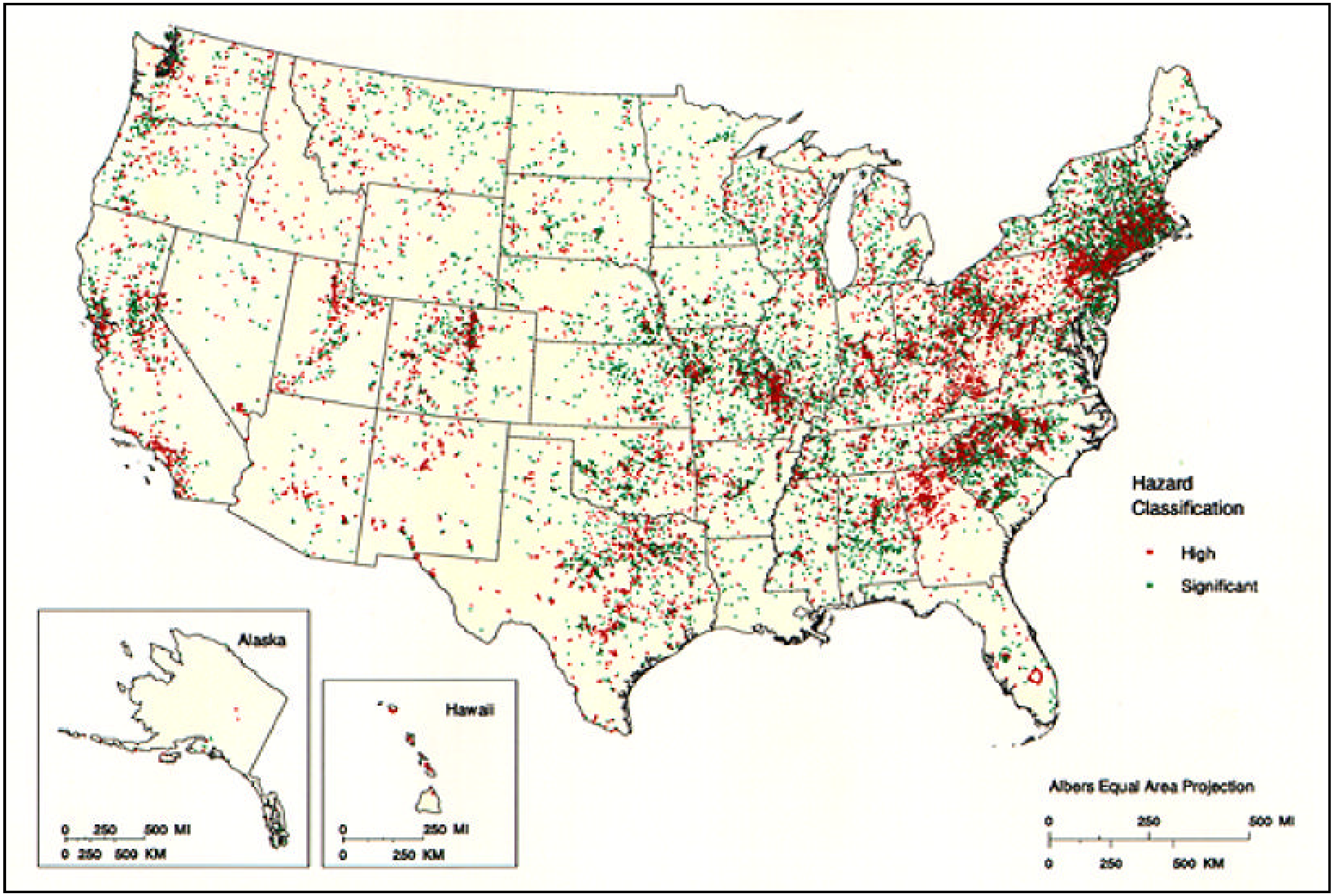
RISK ASSESSMENT

Exposure

People, property, and infrastructure downstream of dams could be subject to devastating damage in the event of failure. The areas impacted are delineated using dam breach analyses that consider both "sunny day" failures and failures under flood conditions. The



Map 20-1. Dams included in the National Inventory of Dams.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *FEMA, 1994.*



Map 20-2. Dams in the National Inventory of Dams classified as having high or significant hazard. Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *FEMA, 1994.*

downstream extent of impact areas and the height to which waters will rise are largely functions of valley topography and the volume of water released during failure. More than 3,300 high and significant hazard dams are located within 1 mi (1.6 km) of a downstream population center, and more than 2,400 are located within 2 mi (3.2 km).

Exposure is compounded in communities experiencing growth because the typical dam-break floodplain is more extensive than the floodplain used for regulatory purposes. Therefore, new development is likely occurring without full recognition of the potential hazard. Few States and local jurisdictions consider the hazard classification of upstream dams when permitting development.

Roads and linear infrastructure such as electric, gas, cable, water lines, and sewer lines that cross waterways are exposed to scour and damage during dam failures.

Consequences

Some of the worst U.S. dam failures in terms of lives lost from 1874 to 1995 are listed in Table 20-1. The most devastating failure in U.S. history occurred in Johnstown, PA, in 1889. An earthen dam above the City failed, resulting in the deaths of 2,209 people and widespread property destruction.

The 1952 earthquake in southern California weakened the South Haiwee, Dry Canyon, and Buena Vista Dams (Sherard, 1983). In 1959, the Hebgen Dam in West Yellowstone, MT, was impacted by an earthquake with an estimate MMI of 10 (Woodward, 1983). During the 1994 Northridge earthquake, a Los Angeles earthen replacement dam settled 3 ft (1 m) and began to leak. The leaking subsided, as was anticipated by Los Angeles officials after inspection (Emergency Preparedness News, 1995).

In 1972, the failure of a privately-owned slagheap dam at Buffalo Creek, WV, devastated a 16-mi (26-km) valley. Of the 6,000 residents, 125 were killed and more than 3,000 were left homeless. The dam was neither designed nor built to acceptable engineering standards. In 1976, the failure of a federally-owned earthen dam in Teton, ID, caused 11 deaths and more than $1 billion in losses. The 1977 failure of the Kelly Barnes Dam in Toccoa Falls, GA, resulted in 37 deaths and heavy damage to homes and property.

In 1994, approximately 230 dams in Georgia were damaged by flooding caused by Tropical Storm Alberto. The damage to dams attributable to saturation during and after rainfall ranged from partial to complete failure. This is believed to be the greatest number of dams damaged in a single event. However, according to the Center on the Performance of Dams at Stanford University, very few fatalities were attributed to the failures (McCann, 1995).

Dam failures often are cited as secondary effects of natural disasters and are not named as the primary hazard that causes the disaster declaration. Although wind-induced erosion occurred at the Point-of-Rocks Dam in northeastern Colorado, it did not fail

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Public concern stirred by the 1972 Buffalo Creek dam failure prompted the U.S. Congress to adopt the National Dam Inspection Act (P. L. 92-367) in 1972. The U.S. Army Corps of Engineers was authorized to inventory and inspect all non-Federal dams. In 1975, USACE published the first *National Inventory of Dams*.

Following the Teton and Kelly Barnes Dam failures, the U.S. Congress provided funding for USACE to begin inspecting the dams listed in the *Inventory*. The updated *Inventory* was established as a source of information for Federal, State, and local governments and other public and private owners to assist in the management of dams. Results of the initial inspection program were provided to each State's Governor.

In 1976, the President appointed an ad hoc committee to review safety programs for Federal dams. The committee developed the *Federal Guidelines for Dam Safety* in 1979, and FEMA became responsible for coordinating Federal dam safety efforts.

In 1981, FEMA commissioned the National Research Council (NRC) to study policy and technical issues related to dam safety. The first NRC report emphasized the importance of updating the *National Inventory of Dams*. A second report examined technical issues of dam safety, and proposed guidelines to achieve improvements.

In 1985, FEMA modified a cooperative agreement with the Association of State Dam Safety Officials (ASDSO) to update the *National Inventory of Dams* through electronic transfer of State data. In 1986, funds to maintain and periodically publish updated information were authorized with the enactment of the Water Resources Development Act of 1986 (P. L. 99-662). Funds could be used for State grants, research programs to develop improved techniques for dam inspections, and training for State dam safety inspectors.

In 1989, FEMA and USACE signed a Memorandum of Agreement in which FEMA accepted responsibility for updating the *National Inventory of Dams* with USACE funds.

TABLE 20-1.—*Selected Dam failures in the United States: 1874 - 1995*

Dam Name	Date	Fatalities
Mill River, MA	1874	143
South Fork (Johnstown), PA	1889	2209
Walnut Grove, AZ	1890	150
Mountjoy Hill Reservoir, ME	1893	4
Angles, CA	1895	1
Melzingah 1&2, NY	1897	7
Austin TX	1900	8
Bayless (Austin Dam), PA	1911	80
Lyman, AZ	1915	8
Lower Otay, CA	1916	30
Mammoth, UT	1917	1
St. Francis, CA	1928	450
Wagner, WA	1938	1
Schoellkopf Station, NY	1956	1
Baldwin Hills, CA	1963	5
Little Deer Creek, UT	1963	1
Moohegan Park (Spaulding Pond), CT	1963	6
Swift, MT	1964	19
Two Medicine (Lower), MT	1964	9
Skagway, CO	1965	2
East Lee (Mud Pond), MA	1968	2
Lee Lake, MA	1968	2
Virden Creek, IA	1968	1
Anzalduas, TX	1972	4
Black Hills, SD	1972	245
Buffalo Creek, WV	1972	125
Canyon Lakes, SD	1972	33
Lake O' the Hills, AK	1972	1
Lakeside, SC	1975	1
Asheville, NC	1976	4
Bear Wallow, NC	1976	4
Teton, ID	1976	11
Evans & Lockwood, NC	1977	2
Kelly Barnes, GA	1977	39
Laurel Run, PA	1977	40
Sandy Run, PA	1977	5
Lake Keowee Cofferdam, SC	1978	7
Swimming Pool, NY	1979	4
Eastover Mining Co., KY	1981	1
Lawn Lake, CO	1982	3
DMAD, UT	1983	1
Bass Haven, TX	1984	1
Little Falls, DC	1984	5
Kendall Lake, SC	1990	4
Shadyside, OH	1990	24
Timber Lake, VA	1995	2
Unnamed Dams		
Winston, NC	1904	9
Kansas River, KS	1951	11
Denver, CO	1965	1
Black Hills, SD	1972	245
Big Thompson River, CO	1976	144
Newfound, NC	1976	4
Kansas City, MO	1977	20
Texas Hill County, TX	1978	25
Austin , TX	1981	13
Northern, NJ	1984	2
Allegheny County, PA	1986	9
Americus, GA	1994	3

Source: *From McCann, 1995.*

Emergency Action Plans (EAPs) have been prepared for approximately 6,500 dams, allowing for evaluation of the downstream inundation areas. Delineation of inundation areas is a crucial step, without which public notification, warning and evacuation planning cannot occur. As States move forward with dam safety programs, dam classifications are amended when warranted by changing conditions, new development, and new information.

MITIGATION APPROACHES

Mitigation of hazards associated with dam failure differs depending on whether the hazard is associated with a new or existing dam. New dams can be designed to meet stringent safety criteria, including passage of extreme flood discharges and resistivity to earthquakes. Land downstream of new dams can be zoned or otherwise regulated to limit new construction and exposure.

Addressing hazards associated with existing dams often is problematic, especially when ownership cannot be determined. The primary mechanism is development of EAPs focused on evacuation of people and closure of roads. In some cases, high hazard dams that are deemed unsafe because of disrepair, poor maintenance, or changed design standards, can be retrofit. In extreme cases, removal of a dam may be the most efficient and cost-effective approach to mitigation of imminent danger and damage.

FEMA, working in concert with Federal and non-federal agencies, is continuing its efforts in the dam safety program, while considering improvements. One improvement under consideration would be to show dam-break inundation areas on NFIP maps to facilitate avoidance of hazards and emergency response.

Human intervention can play a significant role in averting dam catastrophes as illustrated by the following examples.

- A dam owned by Los Angeles County, CA, was severely damaged and considered destroyed by an earthquake in 1972. Fortunately for thousands of San Fernando Valley residents, dam operators were able to lower the water level to a safe elevation through the existing outlet structure, thus significantly reducing risks.

- Following the Mount St. Helens eruption in Washington in May 1980, a natural impoundment at Spirit Lake was in danger of failure. Because of the proximity of downstream communities combined with ash-laden streams, failure would have been devastating. Emergency pumping was accomplished to equalize the elevation of the lake, preventing a secondary disaster.

When FEMA was established in 1979, the position of Dam Safety Project Officer was created. The Dam Safety Project Officer serves as the chair of the Interagency Committee on Dam Safety (ICODS), a forum where Federal agencies initiate cooperative efforts and offer talent and resources to meet national dam safety needs. The ICODS member agencies are FEMA, DOD, NRC, DOE, TVA, U.S. Department of Agriculture, U.S. Department of the Interior, U.S. Department of Labor, Federal Energy Regulatory Commission, and the International Boundary and Water Commission.

FEMA coordinates with the Association of State Dam Safety Officials, which brings together State and local agencies and private sector representatives to provide a non-Federal voice on national dam safety issues. The United States Committee on Large Dams (USCOLD) represents the United States on the International Commission on Large Dams. USCOLD is dedicated to advancing the technology of dam design, construction, and operation and maintenance, and to promoting awareness of the role of dams in the beneficial development of water resources nationwide. Federal, State, and local governments and private owners have taken action since the initiation of the *National Inventory of Dams* to mitigate the potential for damage from dam failures. Activities have included the following:

- Develop a model dam safety program and database as a resource for States. States are now responsible for the safety of more than 95 percent of all dams, and all but three States have dam safety programs;
- Develop EAPs for dams that have high- and significant-hazard classifications. EAPs have been prepared for 35 percent of dams with high hazard classification, and 15 percent of dams with significant hazard classification.
- Hold dam safety engineering seminars, training sessions, and workshops, including the *EAP Development and Design Course* for all dam owners.
- Improve State dam safety programs as a part of the comprehensive hazard mitigation plan required after a disaster declaration.

RECOMMENDATIONS

Those States and communities that have not already done so should develop and adopt Dam Safety Programs. State and community officials should be encouraged to develop or update EAPs for the remaining structures classified as having high or significant downstream hazards. Unsafe dams present significant risks for people and property, and retrofit, repair, or removal should be considered in selected cases.

BIBLIOGRAPHY AND REFERENCES

Byrant, E. 1991. ***Natural Disasters***. New York, NY: Cambridge University Press.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Federal Emergency Management Agency. 1986. ***National Dam Safety Program: A Progress Report.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Civil Defense. April 1990. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** FEMA 191. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. April 1993. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency and U.S. Army Corps of Engineers. 1994. ***Water Control Infrastructure, National Inventory of Dams on CD-ROM, Updated Data.*** Washington, DC.

Federal Emergency Management Agency. 1987. ***State Non-Federal Dam Safety Programs-1985***. Washington, DC: U.S. Government Printing Office.

McCall, M. 1995. Unpublished data. National Performance on Dams Program, Center on Performance of Dams. 1995. Stanford, CA: Stanford University.

Tschantz, Bruce A. August 1989. ***1989 Report on Review of State Non-Federal Dam Safety Programs.*** Knoxville, TN: University of Tennessee.

CHAPTER

21

FIRES

Chapter Summary

Natural hazards represent a significant fire risk to the built-environment in the United States: lightning, high winds, earthquakes, volcanoes, and floods can trigger or exacerbate fires.

States with the largest populations tend to have the greatest number of fire-related fatalities, which are related to population density. During 1991, structural fires caused 4,465 civilian deaths and 21,850 injuries, and resulted in an estimated $8.3 billion in damage.

The National Fire Protection Association (NFPA) prepares data that assist in assessment of the frequency and severity of fires caused by natural events. These and other industry-specific data help to assess risk and to determine exposure.

Of the current mitigation approaches, the trend toward performance-based regulations in the fire and building code communities is evolving and is based on the development and use of fire safety engineering methods.

Photo: Red Cross

Photo: Red Cross

HAZARD IDENTIFICATION

Lightning is the most significant natural contributor to fires affecting the built-environment. Lightning can trigger structural fires, such as the $1.5 million loss of a historic mansion in Pennsylvania in 1994. Buildings with roof-top storage tanks for flammable liquids are particularly susceptible.

Wildfires are commonly the result of lightning strikes in outdoor areas, many of which have significant impacts to buildings. For example, a lightning strike near Dude Creek, AZ, resulted in six deaths in 1990. Wildfires are addressed in Chapter 19.

Prolonged warm winds can increase fire risks, especially in the more arid Western States. Sparks and embers are carried by winds, escalating fire spread. In 1985, a welder triggered a fire in a building under construction in Tennessee. The situation magnified in intensity when winds carried molten metal to an area with ordinary combustibles.

Significant seismic events often result in fires, particularly in areas where natural gas distribution systems can rupture, as was evident several years ago during the San Francisco earthquake. Floods can trigger fires, and volcanic events may involve multiple fires.

RISK ASSESSMENT

The National Fire Protection Association (NFPA) Technical Committee on Lightning Protection prepared a guide for the risk assessment of buildings subject to lightning events (NFPA, 1992). Factors considered include type of structure, type of construction, relative location, topography, occupancy and contents, and lightning frequency isoceraunic level. This general approach has been complemented by industry-specific studies. For example, Giese, Rohsler, and Schollhorn (1984) developed a lightning risk assessment methodology specific to a gas-insulated switchgear plants.

Probability and Frequency

To determine the frequency and severity of structural and outdoor fires caused by natural hazards, statistical data from the NFPA were analyzed and are summarized in Tables 21-1 through 21-4. The data are national estimates of fires reported to local fire departments. Fires and associated losses are given as annual averages based on 10 years of data (1984-1993). Estimates are

TABLE 21-1.—*Fires in the Northeast region* reported by U.S. public fire departments by type of natural condition: 1984 - 1993 annual average.*

Structure Fires Type of Natural Condition	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage
High wind	114	0	2	$1,170,000
Earthquake	4	0	0	11,000
Floods, high water	31	0	1	224,000
Lightning	999	1	12	16,128,000
Unclassified natural condition	183	0	4	1,315,000
Total	**1,330**	**2**	**18**	**$18,847,000**

Outdoor Fires Type of Natural Condition	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage
High wind	443	0	0	$64,000
Earthquake	4	0	0	0
Floods, high water	9	0	0	1,000
Lightning	480	0	0	261,000
Unclassified natural condition	575	0	1	22,000
Total	**1,512**	**0**	**1**	**$347,000**

*Northeast region consists of the following States: CT, MA, NH, NJ, NY, PA, RI, and VT.
Sums may not equal totals due to rounding.

Source: *Data from 1984-1993 NFIRS, NFPA Surveys*

TABLE 21-2.—*Fires in the North Central region* reported by U.S. public fire departments by type of natural condition: 1984 - 1993 annual average.*

Structure Fires Type of Natural Condition	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage
High wind	279	1	2	$2,971,000
Earthquake	8	0	0	20,000
Floods, high water	46	0	0	128,000
Lightning	3,601	5	28	51,202,000
Unclassified natural condition	409	0	9	3,265,000
Total	**4,343**	**7**	**38**	**$57,587,000**

Outdoor Fires Type of Natural Condition	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage
High wind	2,039	0	0	$234,000
Earthquake	10	0	0	25,000
Floods, high water	22	0	0	1,000
Lightning	3,486	0	0	1,464,000
Unclassified natural condition	1,151	0	1	148,000
Total	**6,708**	**0**	**1**	**$1,872,000**

*North Central region consists of the following States:
IA, IL, IN, KS, MI, MN, MO, ND, NB, OH, SD, and WI.
Sums may not equal totals due to rounding.

Source: *1984-1993 NFIRS, NFPA Survey*

based on data from the NFPA's annual stratified random sample survey and the National Fire Incident Reporting System (NFIRS) developed by the U.S. Fire Administration (USFA). The estimates were combined using statistical methods developed by analysts at NFPA, USFA, and the U.S. Consumer Product Safety Commission.

Tables 21-1 through 21-4 present information for four regions of the United States: Northeastern, North Central, Southern, and Western. Each table shows the type of natural condition that caused the fire, identified as Ignition Factors 80 through 89 in accordance with the 1976 Edition of NFPA 901, *Uniform Coding for Fire Protection.*

The 10-year annual average number of civilian deaths and civilian injuries are rounded to the nearest whole number, and figures for fire-related direct property damage are rounded to the nearest thousand dollars. Normally, figures for number of reported fires are rounded to the nearest hundred, however the number of fires caused by earthquakes and floods are too few for rounding.

Exposure

All areas of the United States are exposed to personal injury and property damage as a result of fires caused by natural hazards. Fires occur year-round, but the rate of residential fires in January is twice that of the summer months (FEMA, 1993). Fatalities tend to be distributed according to population density. In 1987, 52 percent of the recorded fires occurred in 10 States (FEMA, 1993).

The 16 States and the District of Columbia that make up the Southern Region experience the most fires triggered by natural hazards, and lightning is the largest contributor. In the Western Region, high winds account for more structure fires than lightning, and a high percentage (50 to 60 percent) of fires were caused by unclassified natural conditions.

Consequences

Fires, including large-scale fires, are well documented. For instance, the Great Chicago Fire of 1871 killed 1,152 people, burned 17,450 buildings, and caused an estimate $168 million in damage. It still ranks as one of the worst urban fires in U.S. history (FEMA, 1993).

TABLE 21-3.—*Fires in the Southern region* reported by U.S. public fire departments by type of natural condition: 1984 - 1993 annual average.*

Structure Fires Type of Natural Condition	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage
High wind	276	1	2	$2,857,000
Earthquake	11	0	0	141,000
Floods, high water	32	0	0	147,000
Lightning	3,034	3	34	43,505,000
Unclassified natural condition	260	1	4	4,464,000
Total	**3,613**	**4**	**41**	**$51,114,000**

Outdoor Fires Type of Natural Condition	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage
High wind	2,714	0	0	$93,000
Earthquake	70	0	0	2,000
Floods, high water	23	0	0	24,000
Lightning	6,135	0	3	2,085,000
Unclassified natural condition	1,869	0	2	161,000
Total	**10,811**	**0**	**7**	**$2,365,000**

*Southern region consists of the following States:
AL, AR, DC, DE, FL, GA, KY, LA, MD, MS, NC, OK, SC, TN, TX, VA, and WV.
Sums may not equal totals due to rounding.

Source: *1984-1993 NFIRS, NFPA Survey*

During 1991, structural fires caused 4,465 civilian deaths and 21,850 injuries and resulted in an estimated $8.3 billion in fire-related losses (FEMA, 1993).

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Friedman conducted an international survey of computer models for fire and smoke on behalf of the Forum for International Cooperation on Fire Research (Friedman, 1992). The survey identified 62 programs in 10 countries, including compartment fire models, fire-sprinkler interaction models, and submodels for fire endurance, building evacuation, thermal detector activation, fire spread on a wall, and smoke movement.

As directed by P.L. 93-498, the National Fire Data Center (NFDC), operated by FEMA's Office of Fire Data and Analysis, is responsible for selecting, analyzing, publishing, and disseminating information concerning the prevention, occurrence, control, and results of fires of all types. Its missions are to: provide accurate nationwide analysis of the fire problem; identify major problem areas; assist in setting priorities; determine possible solutions to problems; and monitor the progress of programs designed to reduce the loss of life and property due to fires (USFA, 1992). NFDC gathers and analyzes information on:

- Frequency, cause, spread, and extinguishment;
- Number of injuries and deaths, including the specific cause(s) and nature of the deaths and injuries;
- Property losses;
- Occupational hazards faced by firefighters, including the cause(s) of deaths and injuries;
- Types of firefighting activities, including inspection practices;
- Building construction practices and fire properties of materials;
- Fire prevention and control laws, systems, methods, techniques, and administrative structures used in other countries; and
- Causes, behavior, and best methods for control of structural, brush, forest, underground, oil-blowout, and water-borne fires.

With the cooperation of the National Fire Information Council (NFIC), the USFA maintains the National Fire Incident Reporting System (NFIRS). NFIRS data are analyzed to assess fire problems on national, regional, State, and local levels. Based on these analyses, the USFA develops and distributes reports describing problems and indicating targets for prevention and mitigation strategies. Of particular note is the NFDC's Technical Report Series, through which information on major or unusual fires is disseminated, stressing "lessons learned" from those incidents.

MITIGATION APPROACHES

The USFA provides an extensive continuing series of on- and off-campus educational programs through the National Fire Academy in Emmitsburg, MD. It provides information on an array of topics through the EENET videoconferencing network, and works with State and local fire officials to educate the public through school curricula and a variety of awareness publications and presentations.

The trend toward performance-based regulations in the fire and building code communities is evolving based on the development and use of fire safety engineering methods. Such regulations may have a significant impact on fire-caused damage in the future.

The mitigation measures available for lightning protection are well-known. As presented by the NFPA (1992), there are detailed requirements for ordinary structures, miscellaneous structures and special occupancies, heavy-duty stacks, and structures containing flammable vapors, flammable gases, or liquids that can give off flammable vapors. Conductors are specified in terms of design and construction as a function of the geometry of the structure protected.

RECOMMENDATIONS

While a risk assessment methodology exists for lightning hazards, additional methods for assessing the risk of fires due to other natural events have not been developed or were not identified during this research effort.

TABLE 21-4.—*Fires in the Western region* reported by U.S. public fire departments by type of natural condition: 1984 - 1993 annual average.*

Structure Fires

Type of Natural Condition	**Fires**	**Civilian Deaths**	**Civilian Injuries**	**Direct Property Damage**
High wind	368	1	5	$5,432,000
Earthquake	32	0	0	756,000
Floods, high water	22	0	1	180,000
Lightning	169	0	3	1,973,000
Unclassified natural condition	576	4	12	33,079,000
Total	**1,167**	**5**	**22**	**$41,420,000**

Outdoor Fires

Type of Natural Condition	**Fires**	**Civilian Deaths**	**Civilian Injuries**	**Direct Property Damage**
High wind	1,992	0	0	$3,218,000
Earthquake	23	0	0	10,000
Floods, high water	30	0	0	7,000
Lightning	2,019	0	3	285,000
Unclassified natural condition	5,706	0	6	2,211,000
Total	**9,770**	**0**	**10**	**$5,731,000**

*Western region consists of the following States:
AK, AZ, CA, CO, HI, ID, MT, NM, NV, OR, UT, WA, and WY.
Sums may not equal totals due to rounding.

Source: *1984-1993 NFIRS, NFPA Survey*

BIBLIOGRAPHY AND REFERENCES

Federal Emergency Management Agency. 1987. ***Fire in the United States: Deaths, Injuries, Dollar Losses, and Incidents.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Civil Defense. 1990. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** FEMA 191. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Emergency Management. 1993. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, U.S. Fire Administration. 1992. ***Report to Congress, Fiscal Year 1991.*** Washington, DC.

Friedman, R. 1992. "An International Survey of Computer Models for Fire and Smoke." ***Journal of Fire Protection Engineering.*** Vol. 4, No. 3, p. 81.

Giese, M., H. Rosler, and W. Schollhorn. 1989. "Lightning Protection of Gas Insulated Switchgear Plant - a Procedure for Assessing the Residual Failure Risk." ***Elektrizitactswirtschaft.*** Vol. 88, No. 11, p. 672.

National Fire Protection Association. 1976. ***Uniform Coding for Fire Protection, No. 901.***

National Fire Protection Association, Technical Committee on Lightning Protection. 1992. ***Lightning Protection Code, No. 780.***

Sundt, N. A. 1989. ***Budgetary Levels and Flexibility: The 1988 Fire Season and Beyond.*** U.S. Forest Service. Washington, DC: U.S. Government Printing Office.

CHAPTER

22

HAZARDOUS MATERIALS EVENTS

Chapter Summary

Cities, counties, and towns where hazardous materials (HAZMAT) fabrication, processing, and storage sites are located, and those where hazardous waste treatment, storage, or disposal facilities operate, are at risk for HAZMAT events.

Of the 6,774 HAZMAT events that occur on average each year, 5,517 are highway events, 991 are railroad events, and 266 are due to other causes. Transportation of HAZMAT on highways involves tanker trucks or trailers and certain types of specialized bulk-cargo vehicles. Because of the distances traveled, it is not surprising that trucks are responsible for the greatest number of HAZMAT events. Transportation routes and facilities may sustain damage, including pipelines, airports, highways, railroad routes, harbors, and related facilities.

An average of 280 HAZMAT releases and spills at fixed sites occurred each year between 1987 and 1990, according to the U.S. Coast Guard's National Response Center. Natural disasters, particularly earthquakes, can cause HAZMAT releases at fixed sites and can impact response. External events, including natural hazards, can contribute to transportation-related HAZMAT events.

Photo: Michael Baker Corporation

Rain, high winds, and fires can worsen conditions surrounding HAZMAT events, making it more difficult to contain releases and to mitigate the short- and long-term effects. Burning fuels or chemicals entering sewers or drains that are not completely filled with storm runoff have caused underground fires. Fires involving certain types of HAZMAT may generate more toxic gas or smoke than would otherwise normally evolve (FEMA, DOT, and EPA, 1989).

HAZMAT releases pose short- and long-term toxological threats to people and to terrestrial and aquatic plants and wildlife. Toxic materials affect people through inhalation, ingestion, or direct contact with skin.

Two programs specifically designed by FEMA to address potential HAZMAT releases are the Hazardous Materials Program and the Chemical Stockpile Emergency Preparedness Program. Additional supporting programs by other Federal agencies, the Chemical Manufacturers Association, and the American Institute of Chemical Engineers promote safety and development of plans to respond to HAZMAT events.

Photo: FEMA

Photo: Michael Baker Corporation

HAZARD IDENTIFICATION

Under the Emergency Planning and Right to Know Act of 1986, the U.S. Department of Transportation (DOT) identified as hazardous 308 specific chemicals from 20 chemical categories. Identified chemicals cover a wide range of toxicities, and in small doses many have minimal or no effect on humans. Another category of HAZMAT is the U.S. Army's stockpile of unitary chemical weapons, which are stored at eight sites in the continental United States.

To identify the extent of the hazard in a particular community or region, planning personnel and others must determine what types of HAZMAT are stored, handled, processed, or transported, and where and how those functions are performed. Storage, handling, and processing will usually take place at fixed sites: bulk chemical, petroleum processing, and other industrial facilities; hazardous waste disposal and water treatment facilities; public and private chemistry laboratories; and U.S. Army weapons depots.

For regulatory purposes, various U.S. and international organizations including USEPA, DOT, NFPA, and the International Maritime Organization, have defined HAZMAT lists or classes. USEPA sorts HAZMAT into the following categories: toxic agents (irritants, asphyxiants, anesthetics and narcotics, sensitizers); other types of toxic agents (hepatoxic and nephratoxic agents, carcinogens, mutagens); hazardous wastes; hazardous substances; toxic pollutants; and extremely hazardous substances.

During transportation, DOT classifies HAZMAT in one or more of the following categories: explosive; blasting agent; flammable liquid; flammable solid; oxidizer; organic peroxide; corrosive material; compressed gas; flammable compressed gas; poison (A and B); irritating materials; inhalation hazard; etiological agent; radioactive materials; and other regulated material (FEMA, DOT, and USEPA, 1989).

The 1986 Act requires that companies report releases of designated hazardous chemicals to USEPA, even if releases do not result in human exposure. Types of releases are:

- Air emissions of gases or particles from a pressure relief valve, smokestack, ruptured reaction vessel, broken pipe or other equipment at a chemical plant or other fixed-site facility; from broken, loose-fitting, or punctured equipment, containers, or cylinders on transportation vehicles; and from solid or liquid discharges onto ground or into water;
- Discharges into bodies of water from damaged ships, barges, underwater pipelines, and trucks or railroad cars that fall into the water;
- Discharges as outflows from sewer or drain outfalls, runoff from spills on land, runoff from water used to control fires, or contaminated groundwater;
- Discharges onto land;
- Solid waste disposal in onsite landfills;
- Injection of wastes into underground wells;
- Transfers of wastewater to public sewage plants; and
- Transfers of wastes to offsite facilities for treatment or storage.

Fixed-Site Facilities. HAZMAT is stored, processed, and handled at a range of facilities:

- Large refineries, chemical plants, and storage terminals;
- Moderate-sized industrial users, warehouses, and isolated storage tanks for water treatment; and

• Small quantity users and storage facilities, such as school laboratories, florists/greenhouses, and hardware/automotive stores.

Because of the wide range of facility types, accurate data are not available to make determinations concerning the magnitude of the potential hazard. HAZMAT releases result from storage tank and container ruptures or leaks, releases through safety and relief valves, piping ruptures and leaks, fire-induced releases, equipment failures, overfills and overflows of storage tanks, and human error (FEMA, DOT, and USEPA, 1989).

The chemical weapons stockpile represent another fixed-site category. The Department of Defense Authorization Act of 1986 (P.L. 99-145) mandated that the stockpile be destroyed, while directing the Secretary of Defense to provide for the protection of the environment, the general public, and the personnel involved in stockpile destruction activities.

Highway and Rail Transportation. Transportation of HAZMAT on the highway involves tanker trucks or trailers and specialized bulk-cargo vehicles. Average trip lengths are 28 miles for gasoline trucks and 260 miles for chemical trucks. Because of the distance traveled, it is not surprising that trucks are responsible for the greatest number of HAZMAT events (FEMA, DOT, and USEPA, 1989).

Two types of HAZMAT releases from railroad events are of most concern: collisions and derailments that result in large spills or discharges; and releases from leaks in fittings, seals, or relief valves, and improper closures or defective equipment. According to Harvey and others (1987), these releases account for 70 percent of the nearly 1,000 railroad-related events each year. Many of the more severe events occur in railyards and on sidings (Wolfe, 1984).

Marine Transportation. The primary vessels used for marine transport of HAZMAT are bulk liquefied gas carriers, chemical tankers, oil tankers, and tank barges. Bulk cargos may be found in smaller tanks on decks of vessels or in standard intermodal cargo containers (FEMA, DOT, and USEPA, 1989).

Air Transportation. Transportation of HAZMAT by air is generally limited to small packages. According to 1986 figures from the Office of Technology Assessment (March 1996), the annual tonnage shipped is between 200,000 and 300,000 tons. Only a few HAZMAT events involving air transportation occur each year, and those usually are due to violations of regulations.

Pipeline Transportation. U.S. pipelines are used primarily for the transport of petroleum liquids (crude oil, gasoline, and natural gas liquids) and energy gases (natural gas and liquefied petroleum gas). Some pipelines transport ethane, ethylene, liquefied natural gas, anhydrous ammonia, carbon monoxide, sour gas, and other chemicals.

Pipeline length from the source to the receiving site can be 1,000 ft (300 m), 1 mi (1.6 km), or hundreds of miles. Pipelines cross both rural and heavily populated areas. The capacity of a pipeline depends largely on its diameter. A pipeline may be buried or above-ground, and may contain pumps or compressors, cased sleeves under roadways or rail lines, and storage tanks.

Natural Hazards. Natural disasters, particularly earthquakes, can cause HAZMAT releases at fixed sites and complicate spill response activities. An earthquake may impair the physical integrity of a facility or may cause failure of multiple containers. When a HAZMAT event occurs during a natural disaster, access to facilities may be restricted, waterlines for fire suppression may be broken, and response personnel and resources may be limited. The potential threat of an event can be magnified by winds, thunderstorms, or floods, which can spread contamination quickly, threatening the local water supply, agriculture, and air.

Examples of natural hazards that may cause transportation-related HAZMAT events include:

• Heavy rainfall during thunderstorms and hurricanes cause slippery road conditions resulting in highway carrier accidents;

• Earthquakes destroy highways, bridges, and railways, resulting in damage to HAZMAT carriers;

• Earthquakes, land subsidence, avalanches, flood/scouring, lightning, fires, and severe winterstorms cause pipelines to fail;

• Snow, ice, and high-wind conditions during severe winterstorms cause traffic accidents; and

• High velocities and volumes of floodwaters wash out bridges, roads, and fixed HAZMAT manufacturing, handling, and storage facilities.

RISK ASSESSMENT

Probability and Frequency

An average of 280 HAZMAT releases and spills at fixed sites occurred each year between 1987 and 1990, according to the U.S. Coast Guard's National Response Center. In 1987, the first year of reporting, releases totaling 22.5 billion pounds occurred (FEMA 191, 1990). Facilities in the Gulf Coast, Great Lakes, and Middle Atlantic States and California have had the largest number of releases.

According to DOT, most HAZMAT events between 1982 and 1991 occurred during transport. The average number of HAZMAT events (6,774 each year) is broken down as follows: highway (5,517 or 81.4 percent); railroad (991 or 14.7 percent); and other events (266 or 3.9 percent).

The number of railroad accidents reported to the Federal Railroad Administration (FRA) decreased by a factor of three between 1979 and 1993, while total rail traffic increased by 5 percent over the same period. The number of accidental releases also declined, due both to the reduction in accidents and the application of protective measures. The design, construction, and use of railroad tank cars are regulated by the FRA and the American Association of Railroads.

Because of the slow speeds and extra precautions taken on marine vessels, the lowest number of HAZMAT events occurs on the water. However, due to the total tonnage of materials involved, events involving collisions with other vessels and groundings have the potential to be devastating. As with other modes of transportation, small leaks do occur as a result of problems with seals and other equipment integrity. However, the impact of such small leaks is minimized because of the physical separation of the vessels from the general population.

Pipeline failure rates have not declined in recent years. In fact, some specialists have suggested that, although the standards for new pipelines are improving, the likelihood of failure of older pipelines due to corrosion and aging has increased. A significant correlation exists between reported incidents involving loss of product and pipeline age. Besides corrosion, failures are caused by external impacts by farm or construction machinery, structural failures, mechanical defects, and natural hazards.

Exposure

All areas of the United States where DOT-designated chemicals are fabricated, processed, stored, or disposed at fixed sites may be exposed. USEPA catalogued existing HAZMAT sites and identified 1,225 Superfund sites. Every State has at least one Superfund site, but they are more prevalent east of the Mississippi River and most heavily concentrated in the Northeastern States (Map 22-1). New Jersey and Pennsylvania account for more than 18 percent of the sites.

Communities close to highway, railroad, pipeline, air, and water transportation systems are at risk from HAZMAT events that occur during transport. The Emergency Planning and Right to Know Act requires that USEPA be notified of releases. USEPA, DOT and the U.S. Coast Guard maintain spill data.

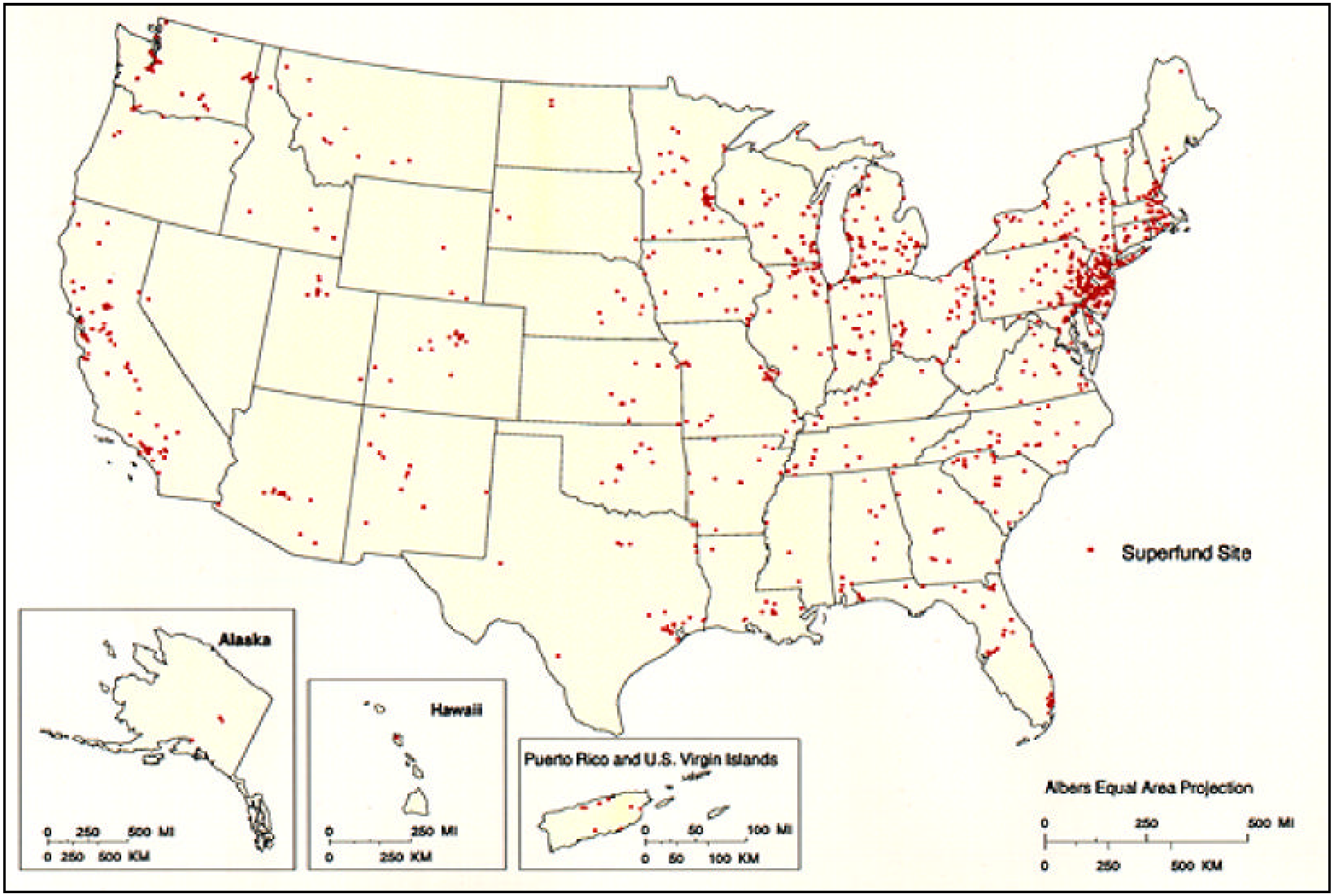
States and jurisdictions immediately surrounding unitary chemical weapon stockpile sites have the highest risk of exposure in the event of a storage or destruction accident:

- Aberdeen Proving Ground, Aberdeen, MD;
- Lexington-Blue Grass Army Depot, Lexington, KY;
- Anniston Army Depot, Anniston, AL;
- Pine Bluff Arsena, Pine Bluff, AR;
- Newport Army Ammunition Plant, Newport, IN;
- Pueblo Depot, Pueblo, CO;
- Tooele Army Depot, Tooele, UT; and
- Umatilla Depot, Umatilla, OR.

Consequences

HAZMAT releases pose short- and long-term toxological threats to humans and to terrestrial and aquatic plants and wildlife. Toxic materials affect people through one of three processes: inhalation, ingestion, or direct contact with skin. Inhalation exposures result from breathing gases that may have been vented from containers, liquid aerosols generated during venting of pressurized liquids, fumes from spilled acids, vapors created by evaporating liquids, and airborne dust. Ingestion exposures typically result from poor hygiene habits after handling contaminated materials or eating contaminated food, or the inhalation of insoluble particles that become trapped in mucous membranes. Skin may be affected by direct contact with gas, liquid, or solid forms of hazardous materials.

Since reporting began, highway transportation events have caused more than 100 deaths (averaging 11 per year) and 2,800 injuries (FEMA, 1993). Incidents asso-



Map 22-1. Superfund sites in the United States as of 1993.
Data not available for Pacific Territories.
Source: *Data from USEPA,1993.*

ciated with all other modes of transportation accounted for an average of less than one death per year. The estimated average annual damage from HAZMAT events is $22.4 million. This dollar figure does not account for multi-year losses such as the fishing industry losses from the 1991 chemical spill in the Sacramento River or the disruption caused by evacuations during the Nemadji River spill in Wisconsin.

RESEARCH, DATA COLLECTION, AND MONITORING

The Federal Railroad Administration's accident reporting system provides accurate data regarding accident incidences by cause, but it does not include natural hazards as a separate category. The Department of Transportation's Research and Special Programs Administration (RSPA) collects data on HAZMAT releases, but these data do not include information on accident causes. Efforts to match these data with natural hazard events have been only partially successful.

FEMA, USEPA, and DOT collect and disseminate extensive statistics on HAZMAT releases. Information is provided via the Hazardous Materials Information Exchange computerized bulletin board system maintained by FEMA and DOT.

With the publication of *Handbook of Chemical Hazard Analysis Procedures* in 1989, FEMA, USEPA, and DOT introduced a computer program that can be used by local emergency planning committees and other personnel to evaluate potentially hazardous facilities and activities. The Automated Resource for Chemical Hazard Incident Evaluation (ARCHIE) program was designed as a tool for local government officials to use "to conduct consequence analysis for postulated accident scenarios" involving HAZMAT (FEMA, DOT, and USEPA, 1989).

DOT has sponsored numerous research studies and demonstration projects related to planning for transportation-related HAZMAT events. A fairly comprehensive list is provided in Appendix E of the *Hazardous Materials Emergency Planning Guide*, published by the National Response Team in 1987. Additional studies are cited in the *Handbook of Chemical Hazard Analysis Procedures* (FEMA, DOT, and USEPA, 1989).

MITIGATION APPROACHES

Science and technology applications used to avoid HAZMAT events are of two types: physical adjustments and social adjustments. Physical adjustments for avoiding the impacts of natural hazards include:

- Planning and building HAZMAT facilities to withstand prevalent natural hazards;
- Identifying and avoiding sites where hazards are highly likely to occur;
- Predicting the occurrence of hazards; and
- Preventing or altering the characteristics of hazards.

Social adjustments for avoiding impacts associated with natural hazards include:

- Restricting the use of land and establishing minimum standards for avoiding hazardous sites and conditions;
- Implementing Local Emergency Planning Committees to enhance public awareness of hazardous materials in communities;
- Instituting public awareness campaigns in areas prone to hazards in the vicinity of HAZMAT sites;
- Initiating emergency preparedness and evacuation programs to protect life and property when warnings are issued or events occur;
- Establishing systems for notification of key individuals in the public and private sectors, including supervisory personnel of facilities requiring special notification, water users, supervisory personnel of water-treatment plants, utility companies, air traffic controllers, railroad dispatchers, and U.S. Coast Guard or harbor master facilities;
- Spreading the economic loss among a larger population through insurance, taxation, and monetary grants; and
- Reconstructing communities to be less vulnerable to future hazard events and HAZMAT releases.

As an example of social adjustments, in August 1994, community activists successfully lobbied to prevent the storage of tons of hazardous waste in Strawberry Canyon on the campus of the University of California. The site was located close to residential neighborhoods and in an area subject to fires, mudslides, and earthquakes that could damage a facility. Thus, the potential for a catastrophic HAZMAT event caused by a natural hazard was significant.

Two FEMA programs specifically designed to address the potential problem of HAZMAT releases are the Hazardous Materials Program and the Chemical Stockpile Emergency Preparedness Program (CSEPP).

FEMA's mission under the Hazardous Materials Program is to provide technical and financial assistance to State and local government agencies and to coordinate and cooperate with private-sector companies in developing, implementing, and evaluating HAZMAT emergency preparedness programs. This mission is accomplished through planning, training, exercising, information exchange, and intergovernmental coordination and cooperation.

FEMA's efforts under the CSEPP are based on a Memorandum of Understanding with the U.S. Army, under which FEMA assists States and local jurisdictions surrounding the eight stockpile sites. FEMA provides technical assistance with comprehensive planning, exercises, training, and emergency public information, and serves as the intermediary through which U.S. Army funding is provided to jurisdictions.

Standards in ANSI B31.8, *Code for Gas Transmission and Distribution Piping Systems* (1986), recognize the increased risk from pipeline failures in populated areas. Improved safety requirements are recommended, including progressive increases in pipe wall thickness with both increased population density and types of road and railroad crossings. The code recommends minimum safety distances to occupied buildings to reduce individual risk levels for pipelines carrying gas, volatile liquids and chemicals.

Corrosion can be reduced by the installation of cathodic protection systems. They are used in areas prone to corrosion and in the vicinity of metallic services (telephone, sewer, water, etc.). Regular inspection is required to ensure that high electrical currents are not being drawn so that early indication of the failure of the corrosion coatings is detected. Inspection devices travel internally along pipelines and measure the condition of pipe walls.

Railroad car design features have a significant influence on release probability. With proper design, the risk of release can be lowered if a natural event causes an accident. Resistance to head and shell puncture during impact is a function of shell thickness and material of construction, and whether the car is equipped with jacketed insulation (glass wool inside a steel jacket). Distortion of the jacket absorbs impact energy and reduces the severity of containment shell damage. Other measures reduce vulnerability to puncture and rupture in the event containers are uncoupled.

The Federal Government has a long record of concern about HAZMAT releases and the potential impact on U.S. citizens and the environment. Several Federal agencies, including USEPA, DOT, and FEMA, provide training, technical assistance, and guidance to State and local governments and industry in planning for, and responding to, HAZMAT releases.

With the publication of *Hazardous Materials Emergency Planning Guide* (March 1987), the National Response Team coordinated the Federal planning process. The National Response Team consists of 14 agencies with responsibilities for the environment, transportation, and public health and safety. The guide focused on the needs of State and local governments, while providing useful information for industrial planners (USEPA and USDOT, 1987).

The joint publication of *Technical Guidance for Hazards Analysis-Emergency Planning for Extremely Hazardous Substances* (USEPA and USDOT, 1987) fulfilled mandates of the Superfund Amendments and Reauthorization Act of 1986 by providing simplified guidance for hazard identification, vulnerability analysis, and risk analysis for fixed facilities that are subject to the 1986 reporting requirements.

Also issued by FEMA, DOT, and USEPA (undated), *The Handbook of Chemical Hazard Analysis Procedures* takes a more comprehensive approach to emergency planning and mitigation activities by including information on explosive, flammable, reactive, and otherwise dangerous chemicals. DOT has sponsored many research studies and demonstration projects related to planning for HAZMAT-related transportation emergencies. To assist emergency personnel at all levels, USEPA and FEMA published a variety of planning documents.

Federal agencies are not the only organizations involved in disseminating planning and mitigation information to the public and private sectors. The Chemical Manufacturers Association and the American Institute of Chemical Engineers have also undertaken ambitious programs to promote safety and the development of plans for HAZMAT response.

BIBLIOGRAPHY AND REFERENCES

American Institute of Chemical Engineers, Battelle Memorial Institute. 1985. ***Guidelines for Hazard Evaluation Procedures.*** New York, NY: Center for Chemical Plant Safety.

American Institute of Chemical Engineers. 1987. ***Guidelines for Safe Storage and Handling of High Toxic Hazard Materials.*** New York, NY: Arthur D. Little, Inc.

American Institute of Chemical Engineers. 1994. ***Guidelines for Evaluating the Characteristics of Vapor Cloud Explosion, Flash Fires, and BLEVEs.*** New York, NY: The Center.

Badolato, E.V. 1990. "Vulnerability of the Oil and Gas Transportation and Storage System." Paper presented at the ***Joint Government-Industry Symposium on Transportation***, Williamsburg, VA, March 21-22, 1990.

Bennett, G.F. and others. 1982. ***Hazardous Materials Spills Handbook.*** New York, NY: McGraw-Hill Book Company.

Chemical Manufacturers Association. 1985. ***Community Awareness and Emergency Response Program Handbook.*** Washington, DC.

Chemical Manufacturers Association. 1992 ***Community Emergency Response Exercise Program.*** Arlington, VA.

Chemical Manufacturers Association. 1992 ***Site Emergency Response Planning.*** Arlington, VA.

Deines, V., B.H. Garten, R. Jepsen, P.G. Joshi, J.P. Lambert, T.R. Mansfield, E.R. Russell, and J.J. Smaltz. 1986. ***Community Model for Handling Hazardous Material Transportation Emergencies: Executive Summaries.*** Office of the Secretary of Transportation, University Research Program. Manhatten, KS: Kansas State University.

Federal Emergency Management Agency. (undated). ***Guide for Development of State and Local Emergency Plans.*** Washington, DC.

Federal Emergency Management Agency. 1981. ***Disaster Operations: A Handbook for Local Governments.*** Washington, DC.

Federal Emergency Management Agency. 1984. ***Objectives for Local Emergency Management.*** Washington, DC.

Federal Emergency Management Agency. 1987. ***Digest of Federal Training in Hazardous Materials.*** Washington, DC.

Federal Emergency Management Agency, U.S. Department of Transportation, and U.S. Environmental Protection Agency. 1989. ***Handbook of Chemical Hazard Analysis Procedures.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Civil Defense. 1990. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** FEMA 191. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Emergency Management. 1993. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** Washington, DC: U.S. Government Printing Office.

Federal Railroad Administration, Office of Safety. 1990. ***Accident/Incident Bulletin No. 158, Calendar Year 1989.*** Washington, DC: U.S. Government Printing Office.

Federal Railroad Administration, Office of Safety. 1992. ***Accident/Incident Bulletin No. 160, Calendar Year 1991.*** Washington, DC: U.S. Government Printing Office.

Federal Railroad Administration, Office of Safety. 1987. ***Certain Fatalities Investigated by the Federal Railroad Administration, Third Quarter 1987.*** Washington, DC: U.S. Government Printing Office.

Federal Railroad Administration, Office of Safety. ***Certain Fatalities Investigated by the Federal Railroad Administration, Fourth Quarter 1987.*** Washington, DC: U.S. Government Printing Office.

Federal Railroad Administration, Office of Safety. 1987. ***Certain Fatalities Investigated by the Federal Railroad Administration, Third Quarter 1987.*** Washington, DC: U.S. Government Printing Office.

Federal Railroad Administration, Office of Safety. 1988. ***Certain Fatalities Investigated by the Federal Railroad Administration, Fourth Quarter 1987.*** Washington, DC: U.S. Government Printing Office.

Federal Railroad Administration, Office of Safety. (Various Calendar Years). ***Summary of Accidents Investigated by the Federal Railroad Administration.*** Washington, DC: U.S. Government Printing Office.

Harvey, A.E., P.C. Conlon, and T.S. Glickman. 1987. ***Statistical Trends in Railroad Hazardous Materials Transportation Safety.*** Association of American Railroads, Washington Systems Center. Publication No. R-640.

Hatayama, H.K. and others. 1980. ***A Method for Determining the Compatibility of Hazardous Wastes.*** EPA Report No. 600/2-80-76. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory. Cincinnati, OH.

Hildebrand, M.S. 1980. ***Disaster Planning Guidelines for Fire Chiefs - Final Report.*** Washington, DC: International Association of Fire Chiefs.

Lee, M.T., and P.G. Roe. 1981. ***Hazardous Materials Management System: A Guide for Local Emergency Managers.*** For Federal Emergency Management Agency. Portland, OR: Multnoma County Office of Emergency Management.

McGregor, G.I. (Ed.) 1983. ***Community Teamwork: Working Together to Promote Hazardous Materials Transportation Safety—A Guide for Local Officials.*** U.S. Environmental Protection Agency, Chemical Emergency Preparedness and Prevention Office. Cambridge, MA: Cambridge Systematics, Inc.

National Fire Protection Association. 1986. ***Fire Protection Guide on Hazardous Materials.*** Quincy, MA.

National Response Team. 1987. ***Hazardous Materials Emergency Planning Guide.*** Washington, DC.

National Transportation Safety Board. January 17, 1991. ***News Release S.B. 91.03.*** Washington, DC.

National Transportation Safety Board. 1981. ***Railroad/Highway Grade Crossing Accidents Involving Trucks Transporting Bulk Hazardous Materials.*** NTIS PB82-113432. Washington, DC: U.S. Government Printing Office.

National Transportation Safety Board. 1990. ***Safety Information.*** Washington, DC: U.S. Government Printing Office.

Office of Technology Assessment. 1986. ***Transportation of Hazardous Materials: State and Local Activities.*** OTA-SET-301. Washington, DC: U.S. Government Printing Office.

Office of Technology Assessment. 1986. ***Transportation of Hazardous Materials.*** OTA-SET-340. Washington, DC: U.S. Government Printing Office.

U.S. Environmental Protection Agency and U.S. Department of Transportation. 1987. ***Technical Guidance for Hazards Analysis—Emergency Planning for Extremely Hazardous Substances.*** Washington, DC: Federal Emergency Management Agency.

U.S. Department of Transportation and U.S. Environmental Protection Agency. 1985. ***Lessons Learned: A Report on the Lessons Learned from State and Local Experiences in Accident Prevention and Response Planning for Hazardous Materials Transportation.*** Washington, DC: ICF, Incorporated.

U.S. Department of Transportation. 1981. ***Risk Assessment Vulnerability - Users Manual for Small Communities and Rural Areas.*** Research and Special Programs. Washington, DC.

U.S. Environmental Protection Agency. 1988. ***Chemicals in Your Community: A Guide to the Emergency Planning and Community Right to Know Act.*** Department of Solid Waste and Emergency Response Office, Washington, DC.

U.S. Environmental Protection Agency. 1988. ***Technical Assistance Bulletin 1 of 3, A Guide Introduction to Exercises in Chemical Emergency Preparedness Program.*** Chemical Emergency Preparedness and Prevention Office, Washington, DC.

U.S. Environmental Protection Agency. 1988. ***Technical Assistance Bulletin 2 of 3, A Guide to Planning and Conducting Table-Top Exercises.*** Chemical Emergency Preparedness and Prevention Office, Washington, DC.

U.S. Environmental Protection Agency. 1988. ***Technical Assistance Bulletin 3 of 3, A Guide to Planning and Conducting Field Simulation Exercises.*** Chemical Emergency Preparedness and Prevention Office, Washington, DC.

U.S. Environmental Protection Agency. 1989. ***The Toxicss-Release Inventory: A National Perspective.*** Research and Special Programs Washington, DC.

U.S. Environmental Protection Agency. 1990. ***Toxics in the Community: 1988 National and Local Perspectives.*** Washington, DC.

Wolfe, K.E. 1984. "An Examination of Risk Costs Associated with the Movement of Hazardous Materials." ***Proceedings of the 26th Annual Transportation Research Forum.***

CHAPTER

23

NUCLEAR ACCIDENTS

Chapter Summary

Although the term "nuclear accident" has no strict technical definition, it generally refers to events involving the release of significant levels of radioactivity or exposure of workers or the general public to radiation. Most commercial nuclear facilities in the United States were developed in the mid-1960s and are designed to withstand aircraft attack. Therefore, they should withstand most natural hazards even though they may not have been specifically designed for those forces. In known seismic areas, significant protection was addressed during initial design.

Although the possibility of a nuclear accident caused by a natural hazard is remote, a variety of nuclear facilities in or adjacent to the United States could be affected. The United States and Canada conduct extensive reviews of design and safety records and require periodic exercises to ensure a high degree of safety.

The U.S. Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC) require safety analyses for all major nuclear facilities, including those associated with research. Furthermore, regulations administered by NRC, DOE, and the U.S. Environmental Protection Agency (USEPA) require facilities to calculate offsite radiation doses from routine, allowable releases.

Seventeen Federal agencies, including FEMA, have developed the Federal Radiological Emergency Response Plan (FRERP) to respond to actual, potential, or perceived peacetime radiological consequences. In response to a State request, during a major radiological occurrence DOE and FEMA will coordinate response efforts through establishment of the Federal Radiological Monitoring and Assessment Center (FRMAC). FEMA coordinates Federal offsite monitoring and assessment efforts to assist DOE and affected State and local authorities.

Photo: Michael Baker Corporation

HAZARD IDENTIFICATION

The NRC regulates 123 commercial nuclear power plants (Map 23-1). Nuclear accidents are classified in three categories, described below.

- **Criticality accidents** involve nuclear assemblies, research, production or power reactors, and chemical operations. While such accidents have been few, they have resulted in fatalities, radiation exposure, and release of radioactivity to the environment. To date, the NRC reports no deaths from radiation at NRC-licensed facilities, and natural hazards have not been associated with any criticality accidents.

- **Loss-of-coolant accidents** result whenever a reactor coolant system experiences a break or opening large enough so that the coolant inventory in the system cannot be maintained by the normally operating makeup system. Loss-of-coolant accidents have not been triggered by natural disaster events.

- **Loss-of-containment accidents** involve the release of radioactivity and have involved materials such as tritium, fission products, plutonium, and natural, depleted, or enriched uranium. Points of release have been containment vessels at fixed facilities or damaged packages during transportation accidents. Loss-of-containment accidents have not been caused by natural disaster events.

RISK ASSESSMENT

The Nuclear Regulatory Commission encourages use of Probabilistic Risk Assessments (PRA) to estimate quantitatively the potential risk to public health and safety considering the design, operations, and maintenance practices at nuclear powerplants. PRAs typically focus on accidents that can severely damage the core and that may challenge containment. In cooperation with FEMA and other federal interests, affected State and local governments formulate Radiological Emergency Response Plans (REPS) to prepare for radiological emergencies.

Probability and Frequency

Although the possibility of a nuclear accident caused by a natural hazard is remote, a variety of nuclear facilities in or adjacent to the United States could cause radiation releases during disasters. The probability of release would be related to the probability of occurrence of the triggering natural hazard.

An important difference between commercial nuclear powerplants and federal nuclear facilities is that the commercial facilities were built during the 1960s, 1970s, and 1980s and were subject to the NRC public licensing process. A facility safety analysis was conducted for each site. The analyses determine which plants must meet requirements to withstand low-probability natural hazards that would have high consequences if are damages occurred.

Most federal nuclear facilities were built under the requirements of national security with virtually no public review or involvement. Safety analysis reviews may have been performed either initially or after construction. Most of the weapons complexes are aging, and decommissioning and decontamination activities are planned. A recent DOE review of its plutonium operations and storage facilities identified potential problems (DOE, 1994).

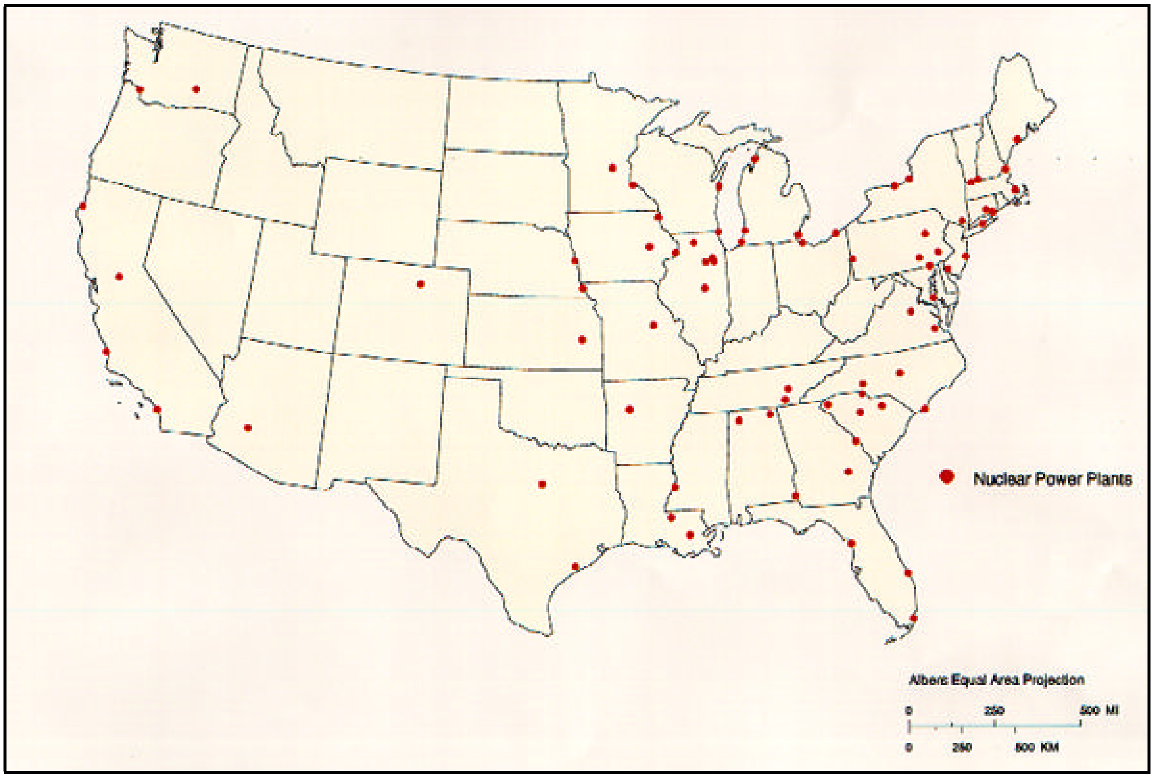
To date, no major nuclear accident has occurred as a result of natural hazards, either in the United States or abroad. However, people in the immediate vicinity of facilities could be exposed and air or waterborne contamination could expose people outside of the immediate facility planning area.

Consequences

Consequences associated with a nuclear accident triggered by a natural hazard would be a function of the nature of the hazard, the nature of the accident, and the population characteristics within the Emergency Planning Zone (EPZ) around the impacted facility. EPZs typically include a 10-mile Critical Risk Zone and a 50-mile Ingestion Pathway Zone.

In August, 1992, the Florida Power and Light Company's Turkey Point nuclear powerplant could have been severely impacted by Hurricane Andrew. At the peak of the storm, windspeeds of 140 mph (225 km/h), with gusts up to 152 mph (245 km/h), were measured at Turkey Point. Plant operators had adequate notice on the hurricane's estimated time of landfall, and brought the plant to a shutdown state. During the hurricane, both units lost offsite power.

In recognition of the potential for hurricanes and other factors that could interrupt power, Turkey Point was designed with emergency diesel generators to maintain shutdown cooling. Although communication between the facility and NRC was lost, it was restored quickly. Some facility damage was sustained but the basic reactor and the primary and secondary cooling loops were not damaged and radiation was not released.



Map 23-1. Nuclear powerplants in the United States as of 1993. Data not available for Pacific Territories. Note: there are no commercial reactors in Alaska or Hawaii.
(Source: Data from U.S. Department of Energy, 1993)

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

The NRC has developed an implementation plan to encourage use of Probabilistic Risk Assessments. Performance-based regulations may be developed based on improved knowledge of risks.

The Atomic Energy Commission performed numerous studies related to nuclear reactor accidents. The most notable were performed by Brookhaven National Laboratory in 1957, and the Massachusetts Institute of Technology (MIT). The MIT study included an assessment of accident risks at U.S. commercial nuclear powerplants. Through a fault tree analysis, this study evaluated quantitatively, the probability of a release, transport of radioactivity, dose consequence, and health effects to the public from a variety of causes. External accidents caused by natural hazards such as earthquakes, tornados, and floods were evaluated. NRC used the accident analysis to set many continuing, comprehensive research and experience requirements.

MITIGATION APPROACHES

The Nuclear Regulatory Commission and DOE require owners of major nuclear facilities to perform safety analyses relating to natural and technological hazards that may cause damage to facilities and could result in the release of radioactivity and radiation exposure to the public. If the probability is low, but the consequences are high, regulators require that facilities be designed to withstand the primary damage and thus eliminate secondary effects on the public. Commercial nuclear powerplant systems are designed for seismic events, with snubbers on essential cooling water and other critical systems to minimize damage.

Some U.S. facilities have experienced earthquakes and were safely shut down until further system inspections assessed potential damage.

RECOMMENDATIONS

Additional research to determine whether nuclear facilities could be damaged by low-probability natural hazards would be beneficial to determine the possibility of high-consequence impacts, and to facilitate emergency management response planning.

BIBLIOGRAPHY AND REFERENCES

American Nuclear Society. 1995. ***Nuclear News.*** Vol. 38, No. 3.

Federal Emergency Management Agency. 1987. ***Digest of Federal Training in Hazardous Materials.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1988. ***Federal Emergency Management Agency's Radiological Emergency Preparedness (REP) Program.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1991. ***Guidance for Developing State and Local Radiological Emergency Response Plans and Preparedness for Traffic Accidents.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency. 1985. ***Guide for the Evaluation of Alert and Notification Systems for Nuclear Power Plants.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Civil Defense. 1990. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** FEMA 191. Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency, Office of Emergency Management. 1993. ***Principal Threats Facing Communities and Local Emergency Management Coordinators: A Report to the United States Senate Committee on Appropriations.*** Washington, DC: U.S. Government Printing Office.

Federal Emergency Management Agency and U.S. Nuclear Regulatory Commission. 1987. ***Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Powerplants—Criteria for Utility Offsite Planning and Preparedness.*** Washington, DC: U.S. Government Printing Office.

U.S. Department of Energy. 1994. ***Plutonium Working Group Report No. EH-0415.*** Washington, DC: U.S. Government Printing Office.

U.S. Department of Energy, Office of Environmental Management. 1995. ***Closing the Circle on the Splitting of the Atom.*** Washington, DC: U.S. Government Printing Office.

U.S. Nuclear Regulatory Commission. 1992. ***Annual Report on Power Reactors.*** Washington, DC: U.S. Government Printing Office.

U.S. Nuclear Regulatory Commission. 1990. ***Report to Congress on Abnormal Occurrences, July-September 1989.*** Washington, DC: U.S. Government Printing Office.

Part IV

ACTIVITIES UNDER THE NATIONAL MITIGATION STRATEGY

"We want to develop pre-disaster mitigation incentives and opportunities, the intent being to help protect communities before disaster strikes by providing assistance to undertake a host of mitigation activities."

James Lee Witt, Director, FEMA
Testimony before U.S. Congress
January 19, 1993

Introduction

This Part includes brief reports on a wide range of mitigation actions undertaken by FEMA and its federal, State, local, and non-governmental partners. The concepts, opportunities, and programs that are collectively known as "mitigation" are changing to meet growing needs and awareness. This Part reflects activitites as of the end of 1995.

The FEMA Mitigation Directorate distributed the *National Mitigation Strategy, Partnerships for Building Safer Communities* (FEMA, 1995) to participants at the first National Mitigation Conference held in Washington, DC. FEMA recognizes that "a significant, sustained, long-term commitment to mitigation as the means for building safer communities requires a national dialog among all levels of government and the private sector that seeks to establish priorities and allocate burdens."

The appropriateness of a national strategy focused on hazard mitigation is supported by the United Nations' designation of the 1990's as the International Decade for Natural Disaster Reduction (IDNDR). The U.N. General Assembly formally launched IDNDR with Resolution 44/236 on December 22, 1989. Recognizing that the goals of IDNDR will have far-reaching worldwide ramifications, the U.S. Congress endorsed the concept by passing a resolution that declared the 1990's to be the "United States Decade for Natural Disaster Reduction."

FEMA has consulted and met with many partners: members and staff of the U.S. Congress; State and local elected officials; emergency and floodplain management, environmental, public works, utility, and planning officials; representatives of the building, banking, real estate, and insurance industries; academicians at public and private colleges and universities; volunteer organizations and public interest groups; and private citizens. The coordination effort included distributing over 15,000 questionnaires and conducting public Mitigation Forums in 11 communities across the United States during the spring of 1995.

FEMA has articulated national mitigation goals: to substantially increase public awareness of natural hazard risk so that the public demands safer communities in which to live and work; and to significantly reduce the risk of loss of life, injuries, economic costs, and destruction of natural and cultural resources that result from natural hazards. Five major elements have been identified:

- Hazard Identification and Risk Assessment (Chapter 26);
- Applied Research and Technology Transfer (Chapter 27);
- Public Awareness, Training, and Education (Chapter 28);
- Incentives and Resources (Chapter 29); and
- Leadership and Coordination (Chapter 30).

CHAPTER

26

HAZARD IDENTIFICATION AND RISK ASSESSMENT

Hazard identification and risk assessment together form important elements of any mitigation initiative. They establish both a starting point and the boundaries upon which mitigation plans and alternatives will be based. FEMA and others devote significant resources to hazard identification and risk assessment.

Examples of FEMA's hazard identification and risk assessment activities include identification and mapping of flood hazard areas under the NFIP, development of storm surge and wind-decay models to characterize the effects of hurricanes, preparation of maps depicting earthquake hazard zones, and maintenance of the National Inventory of Dams.

Activities undertaken by FEMA as of the end of 1995 include:

- Preparation of *Multi-Hazard Identification and Risk Assessment* to establish a summary baseline of information on hazard identification and risk assessment;

- Cooperation with the National Institute of Building Sciences to develop and test a nationally applicable, standardized methodology for estimating potential losses from earthquakes;

- Creation and distribution of NFIP maps in digital format for hundreds of counties;

- Performance of a shoreline mapping study in cooperation with NOAA’s National Ocean Service and the Massachusetts Coastal Zone Management Office, to include assessment of photogrammetric and Global Positioning System-based technologies to identify coastal high hazard areas;

- Initiation of numerous coastal erosion mapping studies in conjunction with State Coastal Zone Management programs, in response to the National Flood Insurance Reform Act of 1994 (NFIRA);

- Initiation of a study to determine the technical feasibility of mapping riverine erosion hazard areas, in response to NFIRA;

- Preparation, in cooperation with NWS and USACE, of hurricane evacuation studies for New Jersey, New York, and Connecticut, including a regional transportation analysis for the New York metropolitan area;

- Participation in a Federal-State working group formed to develop a statewide risk assessment for flood-related hazards in Illinois;

- Initiation of a seismic mapping project with the California Division of Mines and Geology to ensure land-use planning and seismic building measures are applied in affected areas of Los Angeles, Ventura, and Orange Counties; and

- Performance of a risk analysis of U.S. pipelines to identify areas that have high exposure to natural hazards and to assess the impact of pipeline rupture on people, commerce, and the environment.

CHAPTER

27

APPLIED RESEARCH AND TECHNOLOGY TRANSFER

Chapter Summary

Many techniques and tools for hazard identification, risk assessment, and mitigation have been developed through the application of research and technology. FEMA has participated in the development of many, including land-use planning, land-use management, engineering design, and building standards, codes, and practices.

In recent years, FEMA has placed greater emphasis on coordination and priority-setting for the development and implementation of mitigation tools and techniques, and the sharing of knowledge gained through applied research and the use of technology.

Problems associated with hazard identification, risk assessment, and developing mitigation solutions are inherently spatial in nature. New and emerging technologies make it feasible to automate labor-intensive tasks and to change dramatically the way emergency management is conducted.

The conceptual and theoretical roots of spatial information science's analytical methods are in the geographic and cartographic disciplines. The tools are found in the high technology areas of computer science, computer mapping, remote sensing, database management, systems modeling, and digital telecommunications. When these elements are combined and managed, the power of the modern computing system is extended beyond that of the traditional management information system. The result is a system that can handle all of the tasks normally accomplished by traditional emergency management systems, and that also answers "where?" questions, such as:

- Where did events happen?
- Where else can they happen?
- Where are the highest priority areas?
- Where is the situation changing?
- Where are the risks?
- Where are mitigation measures needed?
- Where are exposed populations?
- Where are evacuation routes and destinations?

Important emerging technologies include:

- **Geographic Information System (GIS)** technology, which allows users to collect, display, manage, and analyze large volumes of spatially referenced and associated attribute data to solve complex research, planning, and management problems;
- **Remote-sensing applications** designed to collect information about a target from either airborne or spaceborne sensors without physical contact between the data-gathering device and the target;
- **Computer models** developed by FEMA and others;
- **Databases and indices** prepared by FEMA and others that can be used for hazard identification and risk assessment; and
- **Digital communication technologies** for collectively sharing data resources, assuring the integrity of updates, and cooperative processing among responding Federal, State, and local agencies and the private sector.

Geographic Information Systems

GIS provides the integration vehicle for mapping, modeling, database management, and information analysis including topography, natural and cultural resources, land use and cover, infrastructure, and building types and densities.

Too often, GIS is viewed simply as a technology for map production. Implementation based on this objective results in separation of data and decision-making from spatial analysis resources. GIS also may be viewed simply from the perspective of hardware and software design. Such viewpoints result in highly capable systems that are rendered essentially ineffective through inattention to the acquisition and structuring of data for rapid retrieval and analysis.

GIS is designed to allow users to collect, manage, and analyze large volumes of spatially referenced and associated attribute data. GIS is used to solve complex research, planning, and management problems. The major components of systems are a user interface, system/database management capabilities, database creation/data entry capacity, spatial data manipulation and analysis packages, and display/product generation functions.

Spatial data used in GIS consist of the various features that are defined by geographic location and descriptive attributes. Features can have point, line, or areal characteristics that are visually discernible, such as building locations, roads, and water bodies, or invisible boundaries such as county boundaries, land-use zones, and school districts.

Geographic information systems typically are designed to handle either raster or vector data structures. However, this is changing rapidly, and increasingly capable products are developed to integrate raster-image data with vector information. Image processing systems, specifically those developed to manipulate remotely-sensed digital data from satellites (such as LANDSAT or SPOT) have many functions that are synonymous with a raster-based GIS.

Most Federal agencies have significant GIS efforts underway. Federal expenditures for hardware, software, and data are running into the hundreds of millions each year. To establish standards and coordinate efforts, the Federal Geographic Data Committee (FGDC) developed the Spatial Data Transfer Specification (SDTS) as a Federal Information Processing Standard (FIPS). The GIS Standards Laboratory of the National Institute for Standards and Technology (NIST) has primary responsibility for maintenance of the SDTS standard in close coordination with FEMA, USGS, and others.

A major focus of FEMA's GIS development efforts is situation assessment. The purpose of situation assessment is to provide timely and accurate information to decision makers in advance of, and in response to, natural disasters and catastrophic events. Performing a situation assessment requires identification of hazards (areal extent, magnitude, and frequency), as well as information about exposed populations, infrastructure, and property at risk. These data, when combined with damage prediction models, offer the means to estimate rapidly the type and scale of response needed. Aerial and ground assessment data, which become available as an event progresses, serve to ground-truth and refine damage models and to develop the planning database for comprehensive recovery operations and mitigation initiatives.

Data collected by FEMA as part of situation assessment efforts include:

- Baseline data to document pre-event geography, demographics, and economics;
- Risk data from scientific and technical studies conducted for hazard identification and risk assessment;
- Policy data on insurance coverage and exposure;
- Event data to document the type, nature, physical forces, and extent;
- Aerial assessment data to document the extent of the damage area and the intensity of damage using airborne reconnaissance resources; and
- Ground assessment data to provide information on a structure-by-structure basis about the magnitude of damage, including information on damage not evident from airborne reconnaissance.

GIS is a critical technology element for situation assessment. It facilitates management of spatial data, the analysis of geographic trends, statistics, and relationships, and the development of mapping products. However, GIS is most effective when operating in a network environment and supported by robust database management systems.

In the event of a reasonably predictable disaster, such as a hurricane or large riverine flood, initial situation assessments on a county level may be required several days prior to the expected event. Within hours of the event, as storm tracks and/or inundation patterns become increasingly predictable, detailed data may required. Immediately after passage of the storm or flood peak, detailed statistics are required for situation assessment. Air and ground assessments, combined with local government and utility data files, provide the information that can take the level of detail to the individual structure.

Through GIS analysis of U.S. Census factors such as age, ethnic group, and income, neighborhoods likely to require special attention can be identified. State and Federal agencies can use these data to direct priority specialized resources toward high concentrations of elderly, non-English speaking, and low-income areas.

FEMA and others have applied GIS technology in several program areas:

- Hundreds of NFIP maps have been converted or prepared in digital format.

- FEMA implemented the Emergency Support Team (EST) GIS as a result of the 1993 Midwest floods. The EST-GIS uses a large data store (24 GB), holding TIGER-class base maps and U.S. Census databases. Other point data are on-line, such as the National Inventory of Dams, USEPA Toxic Release Inventory, and Superfund site locations. The system is capable of producing ad hoc database analysis and mapping in direct support of needs in the post-disaster environment.

- FEMA and the U.S. Department of Transportation developed GIS database files on liquid and natural gas pipelines as part of a nationwide risk analysis of the impact of natural hazards on pipelines with high exposures. The site-specific geographic, demographic, climatic, infrastructure, and economic data are used to develop detailed scenarios for hypothetical pipe ruptures in 10 high exposure/high consequence areas.

- FEMA developed a GIS-driven database for repetitively flood damaged sites in North Dakota and South Dakota. The database will be used for short- and long-term planning by all governmental and planning agencies.

Remote-Sensing Applications

Remote-sensing may be defined as the collection of information about a target without physical contact between the data-gathering device and the target. Remote-sensing devices range from the simple, such as cameras, to the exceedingly complex, such as microwave systems based on satellite platforms.

Data collected by remote-sensing devices are typically either analog (such as a standard film recording) or digital. Analog data, including aerial photographs, offer simplicity for processing and interpretation. Digital recordings require more complex systems to collect and analyze the data. However, digital remote-sensing products are compatible with GIS technology.

Emergency managers and hazard specialists often use products generated by remote-sensing techniques to provide information on the location, severity, and extent of damage following a natural disaster. Remote-sensing offers a quick, low-cost means of collecting information. Applications are optimized when developed to support GIS analysis capabilities.

The primary remote-sensing systems available to support disaster response, recovery, and hazard mitigation efforts are either airborne (helicopter, airplane, and remote-piloted vehicle) or spaceborne (orbiting and geosynchronous satellites). Airborne sensors are categorized by image or data collection technology and separated into eight categories: electro-optical, infrared, radar, video, multispectral, Light Detection and Ranging (LIDAR), acoustic, and magnetic.

Many airborne sensors have excellent, long-term potential to support mitigation activities. Global Positioning System (GPS) receivers integrated with existing video or digital cameras can be used efficiently to count and identify structures, to detect change, and to delineate areal boundaries. GPS-augmented video is particularly inexpensive and can provide excellent relative horizontal location accuracies. It is especially advantageous for "ground-swath" or narrow-path data collection. Mature technologies exist for using this type of remote sensing for direct input into GIS environments and map update files. Video imagery can be used for three-dimensional viewing and medium-accuracy mensuration.

Airborne, high-resolution, multispectral imagery combined with "subpixel" analysis processing can offer input for change detection and precise mapping. The Interferometric Synthetic Aperture Radar (IFSAR) and LIDAR systems that are under development may provide opportunities for rapid collection of accurate elevation data. The post-processing of images must mature before either system will be widely operational. They depend on very disciplined calibration and correct processing of the associated GPS, inertial navigational data, and the airborne vehicle's attitude control information to derive relative vertical accuracies.

Spaceborne sensors are imaging and monitoring systems that are separated into categories: electro-optical; infrared; radar; multispectral; advanced very high resolution radiometric; and others, such as special purpose environmental sensing systems. Current estimates are for 60 additional spaceborne remote-sensing systems to be available by the year 2010.

SPOT and LANDSAT satellite imaging sensors have been used for many years, as have digital processing techniques needed to take full advantage of the imagery. SPOT panchromatic can be used for map scales of 1:24,000 for feature mapping. Elevation determination can be performed with Stereo-SPOT.

LANDSAT images are useful for area delineation, natural feature classification, and interpretation where features more than 30 meters in size are of interest. The emerging Canadian-launched RADARSAT, may be very beneficial for monitoring large features, such as a volcano soon after an eruption. A useful technology for monitoring an entire mountain area and measuring such factors as earth deformations is stereo Synthetic Aperture Radar (SAR) imagery. SAR penetrates atmospheric vapor and gives excellent nighttime and daytime imagery for measuring in all dimensions, analyzing data and providing image scenes that may support warnings about follow-on eruptions.

The two satellite remote-sensing systems that offer the most potential for hazard identification and risk assessment are: the existing, mature, classified electro-optical National Technical Means (NTM) sensor system, which was used during the Gulf War; and the emerging commercial electro-optical systems that are expected to be available by 1998. The NTM system will have advantages: a mature collection process; public domain processing tools; the ability to use higher resolution imagery; output that may be used as unclassified data; Digital Elevation Model (DEM) production satisfying FEMA requirements; fine-scale capabilities; narrow-swath and wide-area coverage; and predictable imagery acquisition costs. Emerging commercial satellite systems also have advantages, including their similarities to NTM imagery, their use in combination with other commercial remote-sensing systems, and their lower per square mile costs than airborne photography for many applications, especially digital orthophoto production.

Satellite-borne electro-optical sensors can be very helpful to precisely match geographic location coordinates of structures to local GIS data records or U.S. Census Bureau data, where available. This would facilitate local government participation in checking for at-risk structures.

FEMA, USACE, USGS, and the National Aeronautic and Space Administration (NASA) have undertaken a cooperative interagency assessment of methods to produce remotely-sensed, highly accurate digital elevation data. These data have the potential to reduce the cost of identifying flood hazard, storm surge, and dam break inundation areas, and for performing risk assessments of those areas.

Computer Models

FEMA's modeling resources have been applied to estimating expected damage from catastrophic hurricane, flood, and earthquake events. Efforts are underway to develop systems of models to address comprehensively damage assessment estimation needs. Other Federal agencies have been active in developing models.

Some of the models in use by FEMA and others are summarized below.

- The Automatic Lightning Detection System (ALDS) links an electronic detection device to a network of remote automated weather stations. Using computers, ALDS locates lightning strikes and predicts the probability of starting wildfires.

- The Federal Emergency Management Information System (FEMIS) was developed by Pacific Northwest Laboratories for FEMA and the U.S. Army initially for use in the Chemical Stockpile Emergency Preparedness Program. FEMIS is an automated decision-support system that integrates all phases of emergency management. Plans can be created under non-emergency conditions and executed during an actual emergency response. Emergency managers may use FEMIS to develop plans, respond to an emergency, conduct re-entry and recovery operations, and execute mitigation tasks.

- TTSURGE and FEMA SURGE are two-dimensional hydrodynamic models used to prepare the detailed hydraulic analyses of the relationship of tropical cyclone storm surge elevations, astronomical tides, shoreline configurations, and elevations through the generation of synthetic populations of storm data.

- The Sea Lake and Overland Surges from Hurricanes (SLOSH) model, a two-dimensional hydrodynamic model that predicts coastal and inland storm surge flooding potential at various time intervals, is used by the National Hurricane Center to help FEMA and USACE develop specific evacuation plans for urban centers along the Atlantic and Gulf Coasts.

- The Automated Coastal Engineering Software packages, developed by USACE, include coastal erosion models and wave runup models for coastal engineering applications.

- TSU2, a tsunami wave runup model developed by USACE, is used to determine the inundation limits of the 100-year tsunami wave based on incoming wave heights, beach and shoreline slope, and wave energy losses due to ground cover and friction coefficients.

- The Geophysical Fluid Dynamics Laboratory tropical cyclone forecasting models are used by the National Hurricane Center to predict and forecast the movement and intensity of hurricanes in the North Atlantic basin.

- HURISK, a model developed by the Science Applications International Corporation, analyzes tropical storm and hurricane behavior and risk for site-specific reaches of the Atlantic coastline.

- The SBEACH model developed by CERC is an empirically based, two-dimensional model used to predict storm-induced beach erosion and post-storm recovery.

- The Norwegian Geotechnical Institute's Statistical Avalanche Runout Model is used to predict avalanche runout zones using statistical procedures (multiple regression equations) and historical data on known avalanche paths and runout distances.

- The PCM Avalanche Dynamics Model, Swiss Avalanche-Dynamics Model, and a particle simulation model of avalanche motion are used to compute velocity, acceleration, runout distance, flow depth, deposit depth, and other flow characteristics along the avalanche path profile.

- The National Severe Storms Forecast Center, Severe Local Storms Unit's Tornado and Severe Thunderstorm Forecast Program is used to identify areas of severe weather and to issue watches to affected regional centers.

Databases and Indices

Extensive databases and indices prepared by FEMA and others can be used for hazard identification and risk assessment. Some of the better known and more widely used are summarized below.

- The ERMS database, derived from Federal civilian agencies to assess effects of a nuclear blast/radiation, is extractable by FIPS code and includes data organized into six groups: communications, economic affairs, energy, government, human services, and law-legal.

- The Oak Ridge Laboratory's Vulnerability Index is a geocoded coastal database capable of integration into existing GISs. The database includes variables for each coastal segment for seven physical land factors, seven marine factors, and six climatological factors.

- The Coastal Erosion Information System (CEIS) was created from data collected by Dr. Robert Dolan and others, and is maintained as a computerized database accessible through the University of Virginia. CEIS has shoreline rates of change and average annual erosion rates for various geographic regions of the United States, based on erosion data computed at 50-m (165-ft) intervals along the shoreline.

- The Dolan/Davis Nor'easter Scale rates extratropical cyclones and severe winterstorm intensity based on a "storm power index," with power defined as the maximum deep-water significant wave height squared, times the storm duration. The classification system was developed from measured storm data updated through 1992: storm locations, track directions, event durations, wave fetch lengths, and offshore wave heights.

Digital Communications Technologies

Many databases collected for analysis in spatial information systems are exceedingly large. Total databases required for managing a disaster over a county-wide area may be several billion bytes, or gigabytes, in size. Robust communication ability is required for collectively sharing data resources, assuring the integrity of updates, and cooperative processing among responding Federal, State, and local agencies and private companies and individuals.

In addition to the requirement to move large volumes of data rapidly, data compression tools and smart database management practices are required. Brute force transmission of massive databases should be performed when only necessary.

The digital telecommunications system is the backbone that enables distributed database management, client-server system architectures, and transactional processing. These are key technologies in enhancing the future operational performance of emergency managers.

With advances in telecommunications occurring almost daily, the ability of emergency management specialists, government officials, and even individuals, to share vital disaster and hazard information is enhanced. Some recent systems and services that will increase the likelihood that the technology-sharing objectives will be met are summarized below.

- The Internet, with 30,000 networks in 86 countries, is the best known and most widely used computer-mediated networking system. Although technical problems occasionally limit access, in the emergency management environment the Internet can be a valuable asset. It can provide a powerful platform for coordinating and integrating information processing activities between individuals, communities, States, and nations, as well as between the various professional disciplines and their highly functional associations.

- The World Wide Web is a global, multi-media information service accessible through the Internet to provide information about Federal agencies, as well as commercial, educational, and other governmental organizations. FEMA has made assorted natural hazard and mitigation information available on the World Wide Web and its associated Gopher service. Other Web sites that are of interest to hazard identification and mitigation specialists include: the National Hazards Research and Applications Information Center Home Page; Hazard Net, a demonstration project of the U.N. International Decade for Natural Disaster Reduction; National Geophysical Data Center Natural Hazards Data Page; USGS Home Page; National Hurricane Center Home Page; the Cascade Volcanoes Observatory Page; and many others.

- EPIX integrates a variety of services that were developed separately for the Internet into a single network for disaster- and mitigation-related information. EPIX has assembled a number of directories, databases, and tools concerning disaster-related topics and grouped them into an "encyclopedia" of resources for emergency managers.

- E-Mail was developed as an early electronic processing service. It is a primary vehicle for distributing documents and information about natural hazards, including information on research and emergency management activities. Some well-known e-mail subscription services include:

  - *Disaster Research*, an electronic newsletter maintained by the Natural Hazards Research and Applications Information Center, Boulder, CO, provides information about recent disaster events, current research projects, legislation, and new developments;

  - *Networks in Emergency Management* provides communications-related information;

  - *Local Emergency Planning Committee* distributes information on hazardous materials topics; and

  - *FireNet* provides information on wildland fires.

- FEMA FAX is a 24-hour fax-on-demand service with a voice mail menu. Much of FEMA's information made available through the Internet on the World Wide Web is also available through FEMA FAX. Information is available in several categories, including:

  - *Disaster Information* contains the latest information on current and open disaster activities nationwide, including a list of contacts at the various Disaster Field Offices, historical disaster profiles, and annual disaster activity reports.

  - *Emergency Preparedness Information* contains background information and fact sheets on what to do before, during, and after a disaster, as well as a list of available publications.

  - *Miscellaneous Issues, Topics, and Policy Information* contains policy papers, white papers, and other documents on topics related to FEMA and FEMA's mission, including relevant documents on hazard identification, risk assessment, and mitigation.

CHAPTER 28

PUBLIC AWARENESS, TRAINING, AND EDUCATION

Chapter Summary

FEMA works with other Federal agencies, State and local emergency managers, and professional associations to develop and implement public awareness, training, and education programs. These programs are designed to enhance awareness of natural and technological hazards and available mitigation solutions and alternatives. Individuals and organizations must be aware of the existence of a hazard and the risk posed by that hazard before they can make reasoned judgments for response and mitigation.

FEMA operates the Emergency Management Institute (EMI) in Emmitsburg, MD, which offers curricula on earthquake and flood hazards, mitigation, geographic information systems, and risk reduction techniques. FEMA training and public awareness activities also take place within the different geographic regions exposed to unique or multiple hazards. Many successful State and community training and education activities have been conducted to complement Federal programs.

RECENT FEDERAL TRAINING AND EDUCATION ACTIVITIES (1995)

As of the end of 1995, courses at EMI included:

- *Building for the Earthquake of Tomorrow: Complying With Executive Order 12699*, a non-technical discussion of earthquakes, seismic building design, and the requirements of the Executive Order, designed for local community officials;
- *Retrofitting Floodprone Residential Buildings*, a 4-1/2-day course on retrofitting techniques, designed for engineers, architects, and local community officials;
- *School Earthquake Safety Program Workshop*, a 4-½-day workshop covering such topics as hazard identification, nonstructural hazard mitigation, earthquake drills, post-disaster mitigation opportunities, and planning, designed for school administrators, PTA members, district facility managers, and local emergency managers;
- *Teacher Enhancement Workshop on Earthquakes*, a 4-½-day workshop providing a hands-on demonstration of classroom activities using the National Science Teacher Association's "EARTHQUAKES—A Teacher's Package for K-6," designed for elementary school teachers;
- *Seismic Sleuths Leadership Institute for Masters Teachers*, a 4-½-day program designed to introduce an interdisciplinary package on earthquakes to show how mathematics, social studies, and science can be applied to reduce seismic hazards;
- *Geographic Information System Training,* a course providing information on FEMA's Digital Flood Insurance Rate Maps, designed for State and local officials, other Federal agencies, and the American Red Cross;
- *Multi-Hazard Safety Program for Schools*, a 4-½-day program covering such topics as risk reduction techniques, post-disaster recovery and mitigation opportunities, and crisis counseling, designed for school board members, school administrators, safety coordinators, teachers, and PTA members; and
- *Multi-Hazard Building Design Summer Institute,* a summer-long program covering wind, flood, and earthquake mitigation design, designed to provide instructional materials for engineering and architecture professors;

Recent training activities that FEMA has participated in or conducted include:

- A workshop to present HAZUS, the earthquake loss estimation methodology (Chapter 24) and related software, and to solicit input on its applicability and ease of use;
- The first "pilot test" of the Earthquake Loss Estimation Methodology in Portland, OR, in cooperation with the Oregon Department of Geology and Mining Industries and the Portland METRO government;
- A technical seminar on seepage and piping of dams, conducted with the Interagency Committee on Dam Safety and attended by more than 100 Federal engineers;
- A training course on the development and implementation of Emergency Action Plans for dams, conducted in Denver, CO and Panama City, FL, for dam safety and emergency management officials, developed with FERC and the Association of State Dam Safety Officials;
- The final modules for Training Aids for Dam Safety, including *Dam Safety Process, Dam Safety Awareness,* and *Facilitator's Guide for Group Training*;
- A coastal hazard mitigation conference in Charleston, SC, co-sponsored with NOAA;
- Training programs in multi-hazard resistant construction for architects, in cooperation with the American Institute for Architects (AIA);
- Support for AIA's development of seismic-resistant construction workshops to promote mitigation at the local level;
- Technical support and guidance to three national model building code groups for their wind- and flood-resistant construction workshops;
- A home study version of the course *Building for the Earthquake of Tomorrow*, to be offered through the EMI Home Study Program;
- Training sessions on the economics of hazard mitigation for disaster response and recovery staff from State and Federal agencies;
- A pilot workshop on the implications of an earthquake in rural areas, held in Asheville, NC;

- A 1-day course entitled *Seismic Retrofit Training for Building Contractors and Inspectors* following the 1994 Northridge Earthquake, in cooperation with the California Office of Emergency Services and the Building Industry Association;

- The *Mitigation Operations Manual*, delivered at training sessions for FEMA reservist employees and others;

- A cooperative agreement with the International City/County Management Association to conduct a needs assessment and to develop materials for educating city and county administrators on benefits and implementation of mitigation alternatives at local level;

- A 1-day workshop, *Finding the Weak Links: Cascadia*, co-sponsored with the USGS and the Washington Department of Natural Resources as part of an effort to address earthquake hazards in the Puget Sound region;

- An annual series of educational teleconferences for fire service and emergency management audiences throughout the United States on subjects ranging from flammable gases and liquids to residential sprinklers; and

- A continuing series of educational programs at the National Fire Academy and EMI in Emmitsburg, MD.

RECENT NON-FEDERAL TRAINING AND EDUCATION ACTIVITIES (1995)

The resources and expertise available for directing research and implementing mitigation programs and activities vary considerably from State to State. Some States have had difficulty keeping emergency management high on the priority list of citizens, legislatures, and governors. State emergency management agencies coordinate Federal funds with State funds to accomplish their goals.

Some recent success stories in particular States and communities are summarized below.

- The New England States Emergency Consortium, the first multi-state emergency management organization in the United States, initiated the *Mitigation Makes Sense* project in cooperation with the Aubuchon Hardware Store chain. The project produced a "how-to" video guide providing homeowners with information for mitigating natural hazard risks.

- The New Hampshire Office of Emergency Management used radio and television announcements to increase public awareness of natural and technological hazards and to stimulate preparedness measures in communities, households, schools, civic groups, and businesses. The activities were funded in part by the Federal earthquake and hurricane programs, and additional funding was provided by the New Hampshire Association of Broadcasters.

- The Massachusetts Department of Environmental Management is developing a workbook to guide Massachusetts communities through the hazard mitigation planning process.

- State officials of New Hampshire and Rhode Island are updating Floodplain Management Handbooks to provide guidance to communities on the most current information on flood hazard mitigation.

- The Colorado Office of Emergency Management, in cooperation with the Center for Community Development and Design at the University of Colorado-Colorado Springs, developed a training program in floodproofing techniques. Students who received the training assisted homeowners threatened by rising floodwaters.

- Using a grant from FEMA, the State of California is developing seminars to encourage local government and industry leaders to adopt and enforce codes to deal with urban-wildland fire problems. Planned seminars topics include: wildland fuels and fire behavior; fuels management; defensible space; fire-fighting infrastructure; slope stabilization; codes, standards, and regulations; and coordinated planning, code adoption, and enforcement.

- Under a cooperative agreement with FEMA, the American Planning Association (APA) is preparing a report entitled *Pre-Disaster Planning for Post-Disaster Reconstruction and Recovery and Development*. The report is part of the Planning Advisory Service series, through which APA provides technical guidance and assistance to urban planning professionals. The report will contain guidance for incorporating mitigation approaches into ongoing land-use processes and decisions.

- FEMA worked with Federal and New York State agencies in a cooperative project known as the *Metropolitan New York Hurricane Transportation Study*. The results, which will be shared with other States, underscore the need for preparedness and mitigation, including, at a minimum, anticipating which public facilities must be closed during a hurricane, and developing a plan to allow for commuter and traditional evacuee movements.

- Under a partnership with FEMA, AIA provided training to the faculty of schools of architecture and to practicing architects on seismic and multi-hazard design, construction, and land use.

- Hazard mitigation education programs, funded by FEMA and other sponsoring Federal and State agencies, are being developed and implemented by the Natural Hazards Research and Applications Information Center, Earthquake Engineering Research Institute, National Center for Earthquake Engineering Research, Southern California Earthquake Center, and New Mexico Bureau of Mines and Mineral Resources, among others.

RECENT FEDERAL PUBLIC AWARENESS ACTIVITIES (1995)

During the early part of the 1990s, FEMA implemented many activities to make the general public more aware of hazards and how their effects can be mitigated. Some recent activities undertaken by FEMA are summarized below.

- FEMA's Associate Director for Mitigation appeared on television programs with Congressman Johnson of Texas and Congressmen Farr and Mineta of California; was a speaker on two panels at the 1995 Natural Hazards Conference in Boulder, CO; and was a speaker at a workshop during the National Conference of State Legislatures Annual Meeting (1995) in Milwaukee, WI.

- FEMA's Deputy Associate Director for Mitigation addressed a 3-day meeting of academicians and officials from the United States, Canada, and Mexico at the Workshop on Natural Hazards Risk Assessment held in Ontario, Canada.

- Using information gained from the damage inflicted by Hurricane Andrew, FEMA teamed with the American Red Cross, National Association of Home Builders, Georgia Emergency Management Agency, and the Home Depot Corporation to produce an information package entitled *Against the Wind*. The package, consisting of a 18-minute video and an 8-page brochure, provides information to help homeowners mitigate the effects of hurricane-related wind damage.

- Representatives of FEMA participated with the USACE and Congressman Horn of California in a discussion forum on Flood Restoration (AR) Zones, attended by homeowners, builders, government officials, environmental groups, and other interested groups.

- The FEMA staff assigned to the State Support Services Element of the Community Assistance Program worked with the 44 participating States, Puerto Rico, and the U.S. Virgin Islands to publish an assortment of public awareness documents concerning flood hazard reduction and floodplain management, including manuals for State and local officials, professional newsletters, and brochures for the general public.

- FEMA published and distributed a new publication, *Engineering Principles and Practices for Retrofitting Flood Prone Residential Buildings*. Prepared with contributions from floodproofing experts nationwide, it provides guidance to engineers, architects, and building officials on how to select the most cost-effective method of nonstructural flood protection for existing buildings. FEMA's cost-effectiveness software program for riverine and coastal A-zone floodplains is distributed with the publication.

- FEMA developed an Emergency Education Network production, *The Status of Dam Safety in the United States—The 1994 Georgia Flood*s, which aired on August 31, 1994.

- FEMA representatives participated in the Steel Buildings Project User's Workshop in Los Angeles, CA, which was attended by the professional community that has been involved in the rehabilitation and repair of steel buildings damaged during the Northridge Earthquake.

- FEMA developed and distributed a publication entitled *Mitigation Standards for Reconstructing or Retrofitting Non-Regulated Public Dams in the State of Georgia*.

- Under the Regional Education Outreach Initiative, representatives of FEMA Region I and State agencies visited Grade 1-5 classrooms. Through an interactive program, students discussed family emergency preparedness, developed a family disaster plan and supplies kit, and learned about the role of emergency management in daily life. The program involved more than 7,000 students and teachers.

- FEMA Regional Office staff in Atlanta, GA, initiated work on a video and reference booklet covering hurricane mitigation for hospital administrators, and distributed more than 1,000 hurricane-related videos to State and local officials, including *Against the Wind*, *Hurricane: Prepare to Survive*, and *Jason and Robin's Awesome Hurricane Adventure*.

- FEMA representatives participated in the National Flood Insurance Forum in Fargo, ND. As a result, the Regional Office in Denver, CO, has seen an increase in the number of requests for information on flood insurance and mitigation measures.

- FEMA Regional Office staff in Denver developed and distributed a video documenting the multi-objective flood hazard mitigation plan process as implemented in Vermillion, SD.

- FEMA distributed, with the help of Home Depot and Georgia Pacific, informational materials on hurricanes to residents of Atlanta and Florida.

- FEMA produced numerous earthquake-related documents for the public, including: *Earthquake Preparedness: What Every Childcare Provider Should Know; Identification and Reduction of Nonstructural Earthquake Hazards in Schools; and Seismic Retrofit Incentive Programs: A Handbook for Local Governments.*

- FEMA produced and distributed a poster for Grades K through 6 entitled *Earthquake Safety*.

RECENT NON-FEDERAL PUBLIC AWARENESS ACTIVITIES (1995)

Recent hazard-related public awareness activities undertaken by State and local government agencies, colleges and universities, and private-sector organizations are summarized below.

- The California State Senate generated numerous documents pertaining to natural hazards, including *Official Report of the Northridge Earthquake Task Force and School Site Preparedness for the Safety of California's Children K-12—Official Report of the Northridge Earthquake.*

- The State of Maryland developed a hurricane brochure for publication in *The Baltimore Sun*. The brochure highlighted property protection projects selected from the FEMA's video *Against the Wind*.

- The Virginia Department of Emergency Services developed a newspaper supplement, distributed during Hurricane Awareness Week, that included reprints from *Against the Wind* and provided specific protection recommendations for homeowners. VDES co-sponsored an all-day hurricane awareness exhibition at a regional mall and the construction of "The Hurricane House," built by vocational school students with advice and guidance from emergency management staff to demonstrate techniques for strengthening structures.

- The State of Delaware reprinted and distributed 30,000 hurricane preparedness and evacuation brochures as part of its public awareness program.

- The Connecticut NFIP State Coordinator's office developed and distributed *The Torrent*, a floodplain management newsletter for local officials and interested citizens, covering important NFIP and hazard mitigation issues.

- The Ohio Department of Natural Resources updated its floodplain management handbook to include information on mitigation and Federal agencies that provide mitigation assistance.

- The Indiana Department of Natural Resources is producing a video focusing on the relocation of a community in southern Indiana that was devastated by flooding.

- The Wisconsin Department of Natural Resources developed a mitigation planning document to assist local officials and planners in developing local mitigation plans and programs.

- The American Red Cross prepared, and continues to distribute videos, brochures, and coloring books designed to make the public more aware of the need to be prepared for and to mitigate the effects of disasters, including:

  - *Preparing Your Home for a Hurricane*, a 44-page booklet for homeowners in hurricane-prone areas;

  - *Before the Wind Blows*, a package that includes a 12-minute video and a 34-page booklet designed for areas where hurricane evacuations are likely;

  - *Hurricane Information Guide for Coastal Residents*, a 17-minute video detailing one family's preparations for a hurricane;

  - Atlantic Hurricane and Pacific Hurricane/Typhoon Tracking Posters; and

  - Coloring books, produced in English and Spanish, covering activities related to earthquakes, floods, tornadoes, and fires.

- The State of Colorado, in conjunction with Federal agencies, volunteer organizations, and private industry, conducted a Wildfire Preparedness and

Awareness Campaign and distributed 50,000 brochures in high-risk areas throughout the State.

- Architects, engineers, and builders involved in mitigation efforts following the 1994 Northridge Earthquake developed full-scale models illustrating structural and nonstructural mitigation measures as a tool for informing local residents about such measures. Information was provided in eight languages.

- The University of Wisconsin-Extension prepared a handbook, *The Disaster Handbook for Extension Agents*, including chapters on floods, fires, tornadoes, severe winterstorms, and drought.

- The Weather Channel produced *Sky on Fire*, a 15-minute video and associated brochure documenting the characteristics of lightning and how to plan for lightning events.

CHAPTER

29

INCENTIVES AND RESOURCES

Before effective hazard mitigation measures can be developed and applied, stable funding sources and effective incentives must be established to encourage participation by the private and public sectors. FEMA's efforts are undertaken through existing FEMA programs, and through partnerships with each State.

PERFORMANCE PARTNERSHIP AGREEMENTS

Initiated in 1995, Performance Partnership Agreements (PPAs) will strengthen Federal-State relationships by setting mutual objectives and allowing States to determine how they will achieve those objectives. Prior to 1995, the financial assistance relationships between FEMA and the States were defined by Combined Cooperative Agreements (CCAs).

PPAs provide the framework to improve capabilities in emergency management and to reduce losses from disasters. The agreements define long-term objectives and the annual financial and technical assistance required to achieve those objectives. Through the PPA, FEMA consolidates programs and funding streams, eliminates micro-management of programs, devolves decision-making through national goal setting and added flexibility for local mitigation strategies, and encourages new funding mechanisms and incentives to reward progress towards those goals.

Accomplishing PPA objectives will help build and enhance State and local abilities to address hazards effectively, and will ensure that Federal, State, and local governments operate together efficiently during a major disaster or other emergency situation. The PPA will focus all participants' efforts to achieve the goals of the partnership.

Initially, FEMA will provide financial assistance to States on an annual basis, coincident with the Federal fiscal year through cooperative agreements that identify negotiated outcomes that contribute to the long-term goals and objectives. FEMA will seek changes to allow for multiyear agreements with multiyear funding, and a period of performance that is consistent with a State's fiscal year.

EXISTING FEMA PROGRAMS (1995)

Programs administered by FEMA under which resources and incentives are provided to State and local emergency management efforts are summarized below.

- **Emergency Management Assistance Program**. FEMA provides partial funding for salaries of State and local emergency managers, and fully funds population protection planners, radiological defense officers, and facility surveyors.

- **Community Assistance Program.** Funded by the NFIP, cost-shared funds to meet agreed-upon objectives for flood-hazard reduction are provided to States to support technical assistance to communities participating in the NFIP. The goal is to identify, prevent, and resolve floodplain management issues in NFIP communities before a flood occurs, or before poor performance or non-compliance warrant enforcement and intervention by FEMA.

- **Community Rating System (CRS) for Floodprone Communities.** A voluntary program, CRS rewards NFIP communities that exceed the minimum criteria of the NFIP. A primary goal is to encourage, through the use of flood insurance premium adjustments, community and State activities to reduce flood losses by reducing damage to insurable buildings, preventing increases in flood damage to new construction, protecting public health and safety, reducing the risk of erosion damage, and protecting natural and beneficial floodplain functions.

- **Community Volunteer Fire Prevention Program.** FEMA awards grants for local fire prevention and education projects.

- **Emergency Management and Assistance Grants.** Under the Stafford Act (P.L. 93-288), FEMA provides grants to States, with pass through to communities, to improve and update State and local disaster assistance plans and capabilities.

- **Disaster Preparedness Improvement Grants.** FEMA provides grants to States to enhance preparedness activities, including hazard mitigation planning.

- **Federal Disaster Assistance Program.** Encompassing post-disaster assistance, this program is designed to supplement the resources of State and local governments and voluntary relief organizations. The President's declaration of a "major disaster" or an "emergency" authorizes the use of supplemental Federal assistance under the Stafford Act (P.L. 93-288, as amended) and triggers other Federal disaster relief programs as well.

- **Hazard Mitigation Grant Program (HMGP).** FEMA provides grants to States and local jurisdictions to implement long-term hazard mitigation measures following major disaster declarations. To be eligible, projects must permanently reduce losses from natural hazards, comply with environmental requirements, be identified in the State Hazard Mitigation Plan, and be cost-effective. Examples of projects that can be funded include: property acquisition or structure relocation with conversion of land to public open space; elevation-in-place of flood-prone buildings; flood retrofit or seismic rehabilitation of existing buildings; training for architects, engineers, building officials, and other professionals on implementation of mitigation standards and codes; and initial implementation of vegetation management programs intended to reduce exposure of high-risk structures to wildfire hazards.

- **Hurricane Program Property Protection Mitigation Grants.** FEMA provides funds to hurricane-prone States for implementation of mitigation activities. Projects funded by FEMA Regional Offices include retrofitting of existing structures, evaluation of new building projects for mitigation measures, training of building code enforcement officials, and education and public awareness efforts.

- **Individual and Family Grant Program.** Post-disaster, FEMA provides small grants to individuals and families to meet disaster-related necessary expenses or serious needs when those affected are unable to meet such needs through other programs or by other means. Minimum protective measures such as elevating furnaces or installing sump pumps may be funded.

- **National Earthquake Technical Assistance Contracts.** FEMA supports the needs of the National Earthquake Hazard Reduction Program (NEHRP) through this program. Activities include economic impact analyses of earthquakes, exposure assessments for schools and hospitals, and development and training on nonstructural mitigation measures.

- **Public Assistance Program.** FEMA provides assistance to State and local governments following major disaster declarations. Assistance may fund a variety of actions, including: debris clearance; emergency protective measures; and repair and replacement of infrastructure, structural water control facilities, public facilities and buildings, recreational facilities, and eligible educational and health-care facilities. Eligible applicants or subgrantees for assistance are the States, political subdivisions of the States, Indian tribes or authorized tribal organizations, Alaska Native villages or organizations, and qualifying private non-profit institutions within designated disaster areas. In approving projects under this program, mitigation solutions are sought and encouraged.

- **State Earthquake Hazard Reduction Program.** FEMA provides funds to States for the development of comprehensive risk reduction programs at the State and local levels. The program funds technical assistance by States to local governments in the areas of structural and nonstructural mitigation, building codes, and land-use planning ordinances. States are expected to advocate earthquake risk reduction and to encourage the placement of earthquake mitigation on public and political agendas.

- **State Hurricane Program.** FEMA provides financial and technical assistance to State and local governments in support of efforts to plan for and to mitigate hurricane damage.

- **Flood Mitigation Assistance Program.** Authorized by the National Flood Insurance Reform Act of 1994, FMAP grants will assist State and local governments by cost-sharing in cost-effective projects to reduce or eliminate long-term risk of flood damage to buildings and other insurable structures. FMAP provides both planning and project grants, and eligible projects include acquisition, relocation, elevation, and minor structural projects. In order to receive a grant, communities or States must have a FEMA-approved Flood Mitigation Plan that identifies a comprehensive strategy for mitigation in affected areas.

- **Increased Cost of Compliance Under the NFIP.** Included in flood insurance policies issued by the NFIP, increased cost of compliance coverage is intended to cover the cost of compliance with land use and control measures that are part of the NFIP. Insured properties that sustain substantial damage or repetitive flood damage will be eligible for additional claim payments to assist with paying the cost of complying with local floodplain management ordinances.

RECENT ACTIVITIES SUPPORTED BY FEMA FUNDING (1995)

The largest mitigation project to date is the buyout of properties in the Midwest after the Great Flood of 1993. Using funds from the Hazard Mitigation Grant Program combined with funds from other Federal, State, local, and private sources, approximately 9,000 structures have been or are expected to be purchased in more than 200 communities. Structures are bought and removed, and the land is retained permanently in public ownership as open space or for compatible uses such as parkland.

Examples of other recent mitigation activities funded by FEMA, in whole or in part, under the programs discussed above are summarized below.

- The State of California offers seminars to encourage local government and industry leaders to adopt and enforce codes to deal with urban-wildland fire problems. The seminars address wildland fuels and fire behavior; fuels management; defensible space; firefighting infrastructure; slope stabilization; codes, standards, and regulations; and coordinated planning, code adoption, and enforcement.

- The final portion of the "inland wind decay model" is being developed and hurricane evacuation studies will be digitized using funds provided by the National Hurricane Program.

- FEMA developed and continues to maintain the NEHRP Recommended Provisions, in conjunction with the Building Seismic Safety Council. The provision are a resource that is widely used by practicing design professionals and building officials. They have been used in revising the seismic requirements of all three major model building codes.

- The University of Nevada at Reno is constructing two 14-foot by 14-foot movable "shake tables" to conduct earthquake research. The tables will simulate the force of an earthquake measuring 7.5 on the Richter scale.

- The Vermont Emergency Management Agency, FEMA, USACE, and local officials developed an ice-jam mitigation project on the Lamoille River in Hardwick, VT.

- As part of Project Blue Sky, a public building in Charleston, SC, will be retrofit to improve resistance to hurricane and tropical storm hazards and will be used for demonstration purposes.

- The State of New Jersey and the Rutgers University Institute of Marine and Coastal Sciences are developing a process to assist communities in applying risk reduction strategies within the framework of shoreline management. The project will include the design, creation, and testing of a beach-dune template for several storm scenarios.

- The State of Illinois teamed with FEMA Regional Office staff to develop and present a prototype local mitigation plan to be used by communities in the State. As a result, several communities have adopted mitigation plans.

- A statewide integrated storm warning system that uses a network of stream gages, precipitation gages, weather radar, and computer models to predict impending flooding and severe conditions is being developed in Ohio.

- Floodproofing projects were completed for public facilities in Breckenridge, MN, including the lift station, water treatment plant, and electric substation.

- Because of flood damage from the fall 1994 floods in southeastern Texas, 577 residential structures are being acquired and removed from the floodway at a cost of more than $19 million.

- As a result of flood damage from the 1993 disaster, 35 mitigation projects totaling more than $35 million were undertaken in North Dakota and South Dakota.

- Twenty statewide grants, totaling approximately $55 million, will be made available to qualified applicants in California, where the 1995 flooding produced major flood and landslide damage in all 58 counties.

CHAPTER

30

LEADERSHIP AND COORDINATION

The Federal Government, and FEMA in particular, must support and encourage mitigation activities at the State and local levels by providing leadership and coordination. FEMA has focused on supporting and encouraging hazard identification, risk assessment, and mitigation activities at the State and local levels. FEMA also must lead by example, by adopting and practicing the best mitigation techniques for all actions affecting its facilities and employees. FEMA must continue to lead coordination activities by initiating and forming partnerships with Federal, State, and local agencies and with private sector organizations.

In addition to numerous partnerships, FEMA staff participate in several interagency task forces, including the Federal Interagency Floodplain Management Task Force, Federal Interagency Mitigation Task Force, and the Interagency Committee on Seismic Safety in Construction.

EXISTING FEDERAL PROGRAMS (1995)

The programs under which FEMA has and will continue to provide leadership and coordination are summarized below.

- **Chemical Stockpile Emergency Preparedness Program (CSEPP).** Under CSEPP, FEMA assists State and local jurisdictions to prepare for incidents related to the storage and destruction of the U.S. Army's chemical weapons stockpile. Based on a Memorandum of Understanding with the U.S. Army, FEMA provides technical assistance with comprehensive planning, exercises, training, and public information for the States and local jurisdictions surrounding eight stockpile sites.

- **Civil Defense Program.** FEMA works with State and local agencies to provide the basic elements (personnel, hardware, facilities, communications) for an integrated, all-hazard emergency management capability. During natural disasters, FEMA operates the National Warning System and the Emergency Broadcast System.

- **Empowerment Zone/Enterprise Community (EZ/EC) Program.** FEMA launched an initiative with the U.S. Departments of Agriculture and Housing and Urban Development to include mitigation considerations in the EZ/EC program. Communities are encouraged to perform a comprehensive analysis of the natural hazards which is used to incorporate mitigation techniques into development and redevelopment strategies.

- **Hazard Mitigation Technical Assistance Program Contract (HMTAP).** HMTAP was established to provide FEMA with response capability for various post-disaster mitigation opportunities. The contractor has the capability to: (1) evaluate construction science techniques and practices, including build codes; (2) prepare environmental assessments or impact statements and historic preservation reviews and assessments; (3) conduct biological assessments and surveys; (4) conduct surveys, assessments, and reviews of other areas of impact such as water quality and wetland delineation; (5) conduct benefit/cost, social science, and public administration assessments; (6) conduct post-event assessments to identify mitigation opportunities; (7) provide post-disaster land surveying, mapping services and cost estimates using GIS, GPS, and remote sensing; (8) perform floodplain analyses; (9) conduct hazard identification and risk assessment to confirm accuracy and specific actions or methodologies needed for disaster areas; (10) document estimated flood elevations to guide reconstruction and to compute flood frequency; and (11) provide training for benefit/cost analysis, retrofit options, the Hazard Mitigation Grant Program, and National Environmental Policy Act.

- **Hazard Mitigation Grant Program (HMGP).** Under HMGP, FEMA helps States and local jurisdictions to implement long-term hazard mitigation measures following major disaster declarations. Examples of projects that are supported include:property acquisition or structure relocation and conversion of vacated land to public open space; elevation-in-place of floodprone buildings; flood retrofit or seismic rehabilitation of existing buildings; training for architects, engineers, building officials, and others on implementation of State or local mitigation standards and codes; and initial implementation of vegetation management programs intended to reduce susceptibility of high-risk buildings to wildfire hazards.

- **Hazardous Materials Program.** FEMA's mission under this program is to provide technical and financial assistance to States and local jurisdictions and to coordinate with public and private sector entities to develop, implement, and evaluate HAZMAT emergency preparedness programs. FEMA supports State and local agencies in the design, implementation, and evaluation of HAZMAT-related training and planning exercises, and cooperates with the U.S. Department of Transportation in the maintenance of electronic bulletin boards to provide the latest information on HAZMAT planning, training, exercises, and conferences.

- **National Earthquake Hazard Reduction Program (NEHRP).** Under NEHRP, FEMA leads efforts, in cooperation with the US Geological Survey, National Institute for Standards and Technology, and the National Science Foundation, to carry out fundamental and applied research, and technology and information dissemination. The primary activities include: development of improved seismic design and construction practices for adoption by Federal agencies, State and local governments, and the private sector; provision of financial and technical assistance to State and local governments for implementation of comprehensive earthquake hazard reduction programs; development of public education and awareness programs; and planning for and coordination of adequate Federal capability to respond to seismic disasters.

  Under FEMA's leadership, NEHRP agencies work with end users to identify research gaps and to promote the transfer of knowledge. A variety of vehicles are used, including the National Earthquake Information Service for Earthquake Engineering at the California Institute of Technology and University of California at Berkeley; National Earthquake Information Center in Golden, CO; National Hazards Information Center in Boulder, CO; Information Service of the National Center for Earthquake Engineering Research in Buffalo, NY; and the Earthquake Hazards Reduction Publications series.

- **National Earthquake Technical Assistance Program.** FEMA provides technical assistance, support, and expertise to State and local agencies in the evaluation of earthquake hazards and implementation of projects to reduce vulnerability to earthquakes.

- **National Flood Insurance Program (NFIP).** As part of the NFIP, FEMA works with States and communities to identify special flood hazard areas and to assess risks associated with certain magnitudes of flooding. Flood hazards are depicted, on a community or county-wide basis, on Flood Insurance Rate Maps. FEMA works with States and communities to implement floodplain management regulations that are designed to prevent new development from increasing flood hazards and to protect new and existing buildings from anticipated floods. More than 18,000 communities participate in the NFIP.

- **National Hurricane Program.** Under this program, FEMA coordinates ongoing hurricane-related planning and mitigation activities of the U.S. Army Corps of Engineers, the National Hurricane Center, the National Weather Service, and NOAA's Office of Ocean and Coastal Resource Management.

- **Radiological Emergency Preparedness Program (REPP).** FEMA's mission under REPP is to enhance integrated emergency planning and response for all types of radiological emergencies. The primary emphasis is on planning and preparedness for commercial and nuclear powerplants, nuclear fuel cycle and material license holders, transportation accidents, and incidents at the facilities of the U.S. Departments of Defense.

- **U.S. Fire Administration (USFA).** Through the USFA, FEMA administers a nationwide program to enhance fire prevention and control activities and to reduce significantly the loss of life and property caused by fires. Programs are carried out by: National Fire Academy; Office of Fire Prevention and Arson Control; Office of Firefighter Health and Safety; Office of Fire Data and Analysis; Office of Federal Fire Policy and Coordination; Office of National Emergency Training Center Operations and Support, and Office of Educational Technology.

TASK FORCE AND COMMITTEE PARTICIPATION (1995)

FEMA participates in several interagency task forces, including those summarized below.

- **Federal Interagency Floodplain Management Task Force.** This Task Force, chaired by FEMA and comprising 10 Federal agencies, was formed in 1975 to prepare reports for the President to transmit to the U.S. Congress. The Task Force produced *A Unified National Program for Floodplain Management*, which provides a conceptual framework for floodplain management nationwide and the 1994 update report identified goals and objectives for the next 25 years.

- **Federal Interagency Mitigation Task Force.** Recognizing that the successful implementation of the National Mitigation Strategy will require the cooperation of all Federal agencies, FEMA led the formation of this Task Force. Members include all Federal agencies with programs that support or encourage mitigation actions at the State and local levels. The ultimate goal of the Task Force is to develop a Federal Mitigation Plan to encourage partnerships for pre- and post-disaster hazard mitigation actions between Federal agencies and with State, local, and private sector partners.

  One of the most significant early Task Force recommendations is the establishment of a National Multi-Hazard Mitigation Council which would: identify, develop, and propose a coordinated agenda; identify appropriate sources of funding for ongoing public and private risk mitigation efforts; and define and recommend specific task-oriented projects.

- **Interagency Committee on Seismic Safety in Construction (ICSSC).** FEMA has had significant involvement with the ICSSC in the preparation of the Inventory of Federal Buildings, which provides guidance to Federal agencies to conduct building inventories and to estimate the cost of seismic rehabilitations.

RECENT LEADERSHIP AND COORDINATION ACTIVITIES (1995)

Selected activities in which FEMA staff from Headquarters and Regional Offices have participated are described below.

- In May 1995, FEMA conducted an exercise "RESPONSE 95," which involved simulation of a Category 4 hurricane in the Gulf of Mexico. The exercise involved more than 3,000 participants from 27 Federal departments and agencies, two U.S. Army areas, Mississippi, Alabama, private relief organizations, and several private companies.

- FEMA continues to work with and fund the activities of three multi-state groups to facilitate information exchange and technology transfer concerning seismic hazards and the reduction of risk from those hazards. The groups are the Central United States Earthquake Consortium, the New England States Earthquake Consortium, and the Western States Seismic Policy Council.

- FEMA continues to work closely with the Earthquake Engineering Research Institute, the Southern California Earthquake Center, and the National Center for Earthquake Engineering Research to conduct conferences, workshops, and earthquake-related studies.

- FEMA worked with the Rhode Island Emergency Management Agency and the University of Rhode Island Coastal Resources Center to develop a coordinated State and local hazard mitigation strategy that links State and local agencies early in the planning process.

- FEMA Regional Office staff participates in the Hazard Mitigation Policy Committee chartered by the New York State Office of Emergency Management.

- FEMA Regional Office staff work with USEPA, HUD, and State agencies to develop and implement the "Gateway Plan" in an effort to increase urban open space and greenbelts in East St. Louis, MO.

- FEMA Regional Office staff assisted in the development of a manual, *Flood Hazard Mitigation in Northern Illinois*, intended as guidance for the development of local hazard mitigation plans.

- FEMA Regional Office staff worked with the Texas Floodplain Management Association and the Building Officials Association of Texas to develop an innovative approach for assessing flood-caused damage quickly and consistently.

Part V

SUMMARY AND CONCLUSIONS

"For the first time in the history of Federal disaster assistance, mitigation - sustained action taken to reduce or eliminate long-term risk to people and their property from hazards and their effects - has become the cornerstone of emergency management."

From Mitigation: Cornerstone for Building Safer Communities,
Report of FEMA's Mitigation Directorate for Fiscal year 1995.

Introduction

A primary objective of this report is to provide reference information on what is known and what needs to be done in the area of hazard identification and risk assessment for natural and technological hazards in the United States. A vast amount of knowledge and information is available to characterize many natural and technological hazards, and yet its use may fall short in applications for risk assessment.

One conclusion is that there is a significant need for Federal, State, local, and private entities to work together in applying a national model for risk assessment in order to better use and to prioritize the use of resources. Other significant conclusions include the need for individuals and entities involved in emergency management, risk assessment, and hazard mitigation to focus on the development and implementation of specific actions, including:

- Consistent definitions, characterizations, and detailed information about natural and technological hazards that threaten various regions of the United States and its territories;

- A model risk assessment methodology to assess the potential impacts and exposure of people, key resources, critical facilities, and infrastructure, and for that methodology to be applicable nationally; and

- A uniform technique for quantifying risk and prioritizing the administration of mitigation programs and funding.

CHAPTER

31

SUMMARY AND CONCLUSIONS

SUMMARY

Identification of hazards and assessment of risks affecting the United States and its territories are important steps in the process of reducing the impacts of disasters. These steps help lay the foundation for the judicious allocation of finite resources to support mitigation initiatives. HAZUS, The national risk assessment (loss estimation) methodology under development by FEMA in cooperation with the National Institute for Building Sciences, is intended to achieve this objective.

Based on the hazard identification and risk assessment research and evaluation conducted for this report, the findings include:

- Improvements are needed in the characterization of all hazards because there are inconsistencies in the amount and quality of data available for each hazard;
- Hazards must be better defined because of inconsistencies in definitions used by Federal, State, and local government agencies and private-sector entities involved in evaluating and mitigating hazards;
- A model methodology for risk assessment for all hazards should be established, and the level of sophistication associated with current methodologies should be enhanced;
- A more uniform technique to quantify numerically the risk of each hazard, on an annual-percent-chance exceedance basis, should be developed to allow for a more equitable comparison of risks for multiple hazards;
- The results of risk assessments should serve as the basis for the prioritized administration of mitigation programs and funding; and
- Methods for evaluating the benefits and costs of mitigation programs should be enhanced to include quantitative and qualitative elements.

CONCLUSIONS: NATURAL HAZARDS

Many conclusions can be derived from the investigations and findings of other researchers and agencies. The most significant conclusions are listed below for each category of natural hazard.

Atmospheric

- Associated with the most severe natural catastrophes in U.S. history, hurricanes account for over 67 percent of insured property losses. Hurricane Andrew was the worst disaster in U.S. history, with over $15.5 billion in insured losses and total damage of $25 billion.
- Hurricanes present one of the greatest potentials for substantial loss of life and property because an estimated 36 million people live in the coastal areas that are most exposed. The large influx of people to coastal areas over the past 30 years has resulted in thousands of residents unaware of the hurricane hazard and the flood risks of the coastal high hazard zone. The continued implementation of public education and awareness programs is worthwhile.
- In the immediate shorefront area affected by tropical cyclones, relocation of exposed utility lines, water mains, sewer lines, and roadways has been effective in mitigating damage. Land-use controls and regulatory setback programs in coastal high hazard zones can be difficult because of intense development pressure and high property values.
- The recent deployment of Doppler radar, wind profilers, and networks of automated surface observation systems across the United States will significantly improve understanding of strong winds and can be used to support a nationwide program for mitigating wind-related hazards. Continued modernization and improvement in weather warning systems and implementation of the NEXRAD systems have improved predictions of severe weather phenomena.
- Knowledge about thunderstorms and lightning could be improved, and new research and monitoring are necessary for effective mitigation measures.
- Increased development and other activities in avalanche hazard zones (including winter recreation activities, resort facilities, residences, highways, telecommunication lines, utilities, and mining) have increased the exposure of people and property to snow avalanches.

Geologic

- Current risk assessment methodologies for geologic hazards do not quantify or qualify the frequency of occurrence. An opportunity exists to create a strong national program for hazard identification, risk assessment, and mitigation activities for geologic hazards.

- Geologic hazards generally occur infrequently or slowly over time. As a result, the resources and time expended to address them are not proportionate to the estimated annual damage.

Hydrologic

- In addition to having an impact on traffic, power transmission, and the general population, severe low-pressure systems and winter coastal storms can cause flooding, erosion, and property loss.

- The overwash component of storm surge from coastal storms can cause significant coastal erosion, loss of upland structures and recreational facilities, damage to infrastructure, degradation of water quality, interruption of lifelines and communication networks, injury, and loss of life.

- The severe storms and fluctuating water levels of the Great Lakes have caused hundreds of millions of dollars of erosion and flood damage to shorelines and residential, recreational, and industrial facilities. Episodic events of high lake levels have increased bluff erosion rates and caused the collapse or submergence of structures and beaches.

- Coastal erosion and shoreline change can be a function of multi-year erosion impacts, long-term climatic changes such as sea-level rise, or other natural or human-induced factors that reduce sediment influx, alter littoral processes, influence a shoreline retreat, and threaten large geographic areas and coastal floodplain development.

- Widespread and damaging effects of short- and long-term coastal erosion have had the greatest impact on coastal communities in southern California, Texas, Florida, South Carolina, Maryland, New Jersey, and New York because of intense residential and commercial development.

- National standards do not exist for defining the onset of drought because there are several types of drought and several indices that attempt to characterize them. Development of standards is further complicated by the fact that droughts occur gradually and are characterized by intensity, duration, frequency, and spatial variability.

- Even with adjustment for population and inflation, flood damage is increasing. Approximately 9.6 million U.S. households and property valued at $390 billion are at risk from the 1-percent-annual-chance flood.

- The National Flood Insurance Program has probably been the most dominant positive influence on floodplain management over the past 15 years. However, the majority of buildings exposed to identified flood hazards remain uninsured.

Seismic

- Although the literature indicates significant advancements have been made in most components of earthquake loss estimation, recent regional studies are similar in approach and methodology to studies performed in the 1970s. Application of earthquake loss estimation must be enhanced to match the development of available technology.

- HAZUS, the FEMA/NIBS risk assessment (loss estimation) methodology currently under development provides a standard approach that is user-friendly and utilizes state-of-the-art models for frequency and damage analyses.

- Programs coordinated by FEMA with support from the Building Seismic Safety Council and other agencies have been successful in adopting building codes and regulations to reduce seismic hazards to new and existing buildings. Cooperative programs are a good mechanism for obtaining input from all relevant public and private interests for developing and promulgating regulatory provisions to address earthquake hazard mitigation.

- The processes and trends of recurrent tsunami wave hazards must be understood better before specific, effective mitigation measures can be implemented. The economic impacts of regulatory setback and development-control practices must be evaluated at the national, regional, and local levels.

- Although tsunami events have not been declared disasters in the United States during the past 20 years, the risk to the Pacific Basin coastal zone warrants continued research and investigation.

Volcanic

- Losses resulting from eruptions can be reduced in several ways, including using information on past eruptive activity to define potential for and severity of future eruptions, establishing monitoring systems, and developing and implementing disaster preparedness and emergency evacuation plans.

- Significant improvements have been made in technology for detecting, monitoring, and providing warnings of volcanic eruptions.

- Improved methods are needed to track the movement of ash away from a volcano and to provide information to the airline industry on wind direction and speed around eruptive volcanoes and airborne ash.

Wildfires

- Wildfire mitigation in the urban/wildland interface is primarily the responsibility of homeowners who choose to live is this vulnerable area, and the city and county officials who are responsible for implementing and enforcing emergency management programs and land-use, building, and zoning regulations.

- Historical statistics on the impact of wildfires, including resource and property losses, are available for specific large incidents. Reporting is incomplete, and national statistics are not compiled. Therefore, accurate assessments of the economic impact of wildfires cannot be made.

- Most of the tools, data, and methodologies necessary for an accurate national assessment of the risk posed by wildfires are not yet in place.

CONCLUSIONS: TECHNOLOGICAL HAZARDS

A study of technological hazards is an integral part of the multi-hazard approach to risk assessment. Numerous studies and reports identify and assess the risk of technological hazards. A variety of government agencies and private entities are actively involved in risk assessment and mitigation planning.

This report intentionally focused on the link between natural hazards and technical hazards. Extensive discussion of hazard identification and risk assessment for technological hazards independent of natural hazards is beyond its scope.

For technological hazards that are caused by natural hazards, it is clear that mitigation of natural hazards can minimize the impact of technological hazards. The mitigation procedures and recommendations discussed have important applications for reducing the risk of technological hazards.

CONCLUSIONS: LOSS-REDUCTION OPPORTUNITIES

Many mitigation opportunities are available to reduce losses from natural hazard events. Several categories of opportunities that have been or could be effective are summarized below.

- Zoning as a form of land-use management and control can help regulate populations and residential, commercial, and industrial development in hazard-prone areas. It can be used to control building density, adjust the timing of development plans, and better define "allowable" development. As a first step, maps that identify high-hazard areas should be adopted and used to guide, restrict or limit development. Examples are Flood Insurance Rate Maps used to define floodplains and maps that restrict development in coastal areas.

- Control or protective structures may be useful in protecting life and property in certain circumstances. Examples include levees and dams to control floods and structures to divert or control landslides and snow avalanches.

- Building codes designed to improve construction, reinforcement, and anchoring of buildings and grading codes and practices may be effective in dealing with many hazards. A nationwide hazard-based code may help to ensure implementation of standards appropriate for hazard- and damage-resistant structures. Examples of progress in this area are the recommended provisions for seismic regulations for new and existing buildings that have been developed cooperatively by the Building Seismic Safety Council and FEMA, and land-use zoning measures in the Los Angeles area that reduce losses from landslides.

- Evacuation planning and preparedness programs are helpful in protecting residents in areas subject to imminent danger. Examples of effective programs can be found in areas exposed to tropical cyclones, storm surges, volcanic eruptions, and floods. In general, evacuation saves lives but does not result in significant damage reduction.

- Warnings and forecasts are useful for alerting communities and citizens to an impending hazard event. Both real-time, and longer range forecasts should be provided. Warnings and forecasts are issued in preparation of possible evacuations and to prompt property protection measures. Examples include warnings for floods, debris flows, tropical cyclones, and volcanic eruptions.

- Education and awareness efforts provide hazard information to the public in a non-technical manner to make them aware of the impacts of possible hazards. Informative publications are available for land subsidence, volcanic eruptions, earthquakes, floods, tropical cyclones, and coastal hazards. Information can include, but is not limited to, graphic depictions of hazard areas and evacuation routes, and simple, effective mitigation actions.

- Research on hazard processes and model development are needed to understand hazards and their consequences. This approach has been successful for the development of improved rainfall-runoff models for predicting floods, research on inland wind field models for hurricanes and other tropical cyclones, interdisciplinary research on atmospheric-ocean interrelations, and understanding the processes leading up to volcanic eruptions and earthquakes. Dedicated hazard-specific research facilities could coordinate research efforts with academic institutions and international organizations.

- Monitoring and data collection are necessary to support research, to provide affected communities and citizens with better warnings and forecasts, to understand hazards, and to develop loss reduction methodologies. Examples include the monitoring of coastal water levels, erosion rates, streamflow, and volcanic and seismic activity.

- Buyout, relocation, and demolition of damaged or high risk structures have been effective in reducing exposure of buildings to some hazards, notably flooding, erosion, debris flows, and lava flows.

- Modification of certain hazards may yield benefits. Examples of where people have successfully altered a hazard include detention of floodwaters, triggering snow avalanches, and excavation of expansive soils.

- Relocation of utilities and transportation routes out of extremely high risk areas can be beneficial. Such measures have proven effective in eroding coastal areas and where above-ground utilities have been buried to reduce damage by high wind and severe winterstorms.

- Hazard delineation and mapping are necessary for implementation of land-use controls, zoning, and regulatory setback programs which are effective in dealing with some hazards. Models to identify hazard areas need to be developed or tested to verify accuracy. Hazards that are mapped include floods, lava flows and ashfalls around active volcanoes, snow avalanche paths, earthquake risk zones, landslides, and land subsidence.

- Insurance does not directly reduce physical losses associated with hazards. However, it provides some economic protection through pre-payment and distribution of losses among a wider population. The National Flood Insurance Program is the only program that provides nationwide coverage for flood hazards. Private insurance for other hazards may be available in selected regions, and some States are participating in high risk areas.

- Legislation at all levels of government may be necessary to increase mitigation activity and to promote sound land-use and building practices in hazard-prone areas. Coordinated legislative efforts may support national approaches to the implementation of a model hazard identification and risk assessment methodology for all hazards. Examples that have created effective programs include the statutes for the NFIP and the Earthquake Hazards Reduction Act.

- State, Regional and Federal coordination between and among various agencies and programs encourages loss-reduction opportunities. Specific recommendations have been made for drought mitigation and tropical cyclone evacuation, but other hazards could benefit from coordination as well.

- Enhancement and integration of Federal programs by combination of resources merits consideration. FEMA and other Federal agencies can provide leadership to promote and improve hazard identification and risk assessment programs at the State and local levels.

APPENDIX

A

ACRONYMS AND ABBREVIATIONS

ACRONYMS

AFM	Acoustic Flow Monitor
AIA	American Institute for Architects
ALDS	Automatic Lightning Detection System
AMOL	Atlantic Meteorological and Oceanographic Laboratory
APA	American Planning Association
ASCE	American Society of Civil Engineers
ASDSO	Association of State Dam Safety Officials
ASFPM	Association of State Floodplain Managers
ASOS	Automated Surface Observing System
ATC	Applied Technology Council
ATCF	Automated Tropical Cyclone Forecast (system)
BOCA	Building Officials and Code Administrators
BSSC	Building Seismic Safety Council
CEGS	Code Effectiveness Grading Schedule (for buildings)
CEIS	Coastal Erosion Information System
CERC	Coastal Engineering Research Center
CEI	Composite Exposure Indicator
CRS	Community Rating System
CSEPP	Chemical Stockpile Emergency Preparedness Program
CVI	Coastal Vulnerability Index
DEM	Digital Elevation Model
DFO	Disaster Field Office
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
EAP	Emergency Action Plan
EIS	Emergency Information System
EMI	Emergency Management Institute
EOC	Emergency Operations Center
EPA	Effective Peak Acceleration
EPV	Effective Peak Velocity
EPIX	Emergency Preparedness Information Exchange
EPV	Effective Peak Velocity
EROS	Earth Resources Observation System
ESF	Emergency Support Function

FEMA	Federal Emergency Management Agency
FEMIS	Federal Emergency Management Information System
FERC	Federal Energy Regulatory Commission
FGDC	Federal Geodigital Data Committee
FHWA	Federal Highway Administration
FIA	Federal Insurance Administration
FIDO	Fire Incident Data Organization
FIPS	Federal Information Processing Standard (code)
FRA	Federal Railway Administration
FRERP	Federal Radiological Emergency Response Plan
FRMAC	Federal Radiological Monitoring and Assessment Center
GAO	General Accounting Office
GIS	Geographic Information System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HAZMAT	Hazardous Material(s)
HCDN	Hydro-Climatic Data Network
HMGP	Hazard Mitigation Grant Program
HMTAP	Hazard Mitigation Technical Assistance Program
IACWD	Interagency Advisory Committee on Water Data
ICBO	International Conference of Building Officials
ICMA	International City/County Management Association
ICODS	Interagency Committee on Dam Safety
ICOLD	International Commission on Large Dams
ICSSC	Interagency Committee on Seismic Safety in Construction
IDNDR	International Decade for Natural Disaster Reduction
IFSAR	Interferometric Synthetic Aperture Radar
IGIS	Integrated Geographic Information System
IILPR	Insurance Institute for Property Loss Reduction
IRC	Insurance Research Council
IWR	Institute for Water Resources
JTWC	Joint Typhoon Warning Center
LIDAR	Light Detection and Ranging (system)
LRM	Loss-Reduction Measure
MIS	Management Information System
MIT	Massachusetts Institute of Technology
MMI	Modified Mercalli Intensity

NAS	National Academy of Sciences
NASA	National Aeronautic and Atmospheric Administration
NBS	National Bureau of Standards
NCDC	National Climatic Data Center
NEHRP	National Earthquake Hazard Reduction Program
NEMA	National Emergency Management Association
NEP	National Earthquake (Loss Reduction) Program
NEPEC	National Earthquake Prediction Evaluation Council
NESEC	New England State Emergency Consortium
NESW	National Earthquake Strategy Working (Group)
NEXRAD	Next Generation Radar (system)
NFDC	National Fire Data Center
NFIC	National Fire Information Council
NFIP	National Flood Insurance Program
NFIRA	National Flood Insurance Reform Act of 1994
NFPA	National Fire Protection Association
NFIRS	National Fire Incident Reporting System
NGDC	National Geophysical Data Center
NHC	National Hurricane Center
NHRAIC	Natural Hazards Research and Applications Information Center
NIBS	National Institute of Building Sciences
NIST	National Institute for Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council or Nuclear Regulatory Commission
NSF	National Science Foundation
NSTC	National Science and Technology Council
NTM	National Technical Means
NWS	National Weather Service
PESH	Potential Earth Science Hazards (module)
PGA	Peak Ground Acceleration
PGD	Permanent Ground Deformation
PGV	Peak Ground Velocity
PI	Plasticity Index
PMEL	Pacific Marine Environmental Laboratory
PPA	Performance Partnership Agreement
PRA	Probabilistic Risk Assessment
PTWC	Pacific Tsunami Warning Center

RAWS	Remote Automatic Weather Station
RERP	Radiological Emergency Response Plan
RSAM	Real-time Seismic Amplitude Measurement (system)
RSPA	Research and Special Programs Administration (DOT)
SAIC	Science Applications International Corporation
SAR	Synthetic Aperture Radar
SBCCI	Southern Building Code Congress International
SCS	U.S. Soil Conservation Service
SHMO	State Hazard Mitigation Officer
SLOSH	Sea Lake and Overland Surge from Hurricane (model)
SSAM	Seismic Spectral Amplitude Measurement
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USCOLD	United States Committee on Large Dams
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFA	U.S. Fire Administration
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
USWRC	U.S. Water Resources Council
WERC	Wind Engineering Research Center
WES	Waterways Experiment Station
WIMS	Weather Information Management System

ABBREVIATIONS

C	Celsius
cm	centimeter/centimeters
cm^2	square centimeter/centimeters
cm^3	cubic centimeter/centimeters
F	Fahrenheit
ft	foot/feet
ft/s	feet per second
ft^2	square foot/feet
ft^3	cubic foot/feet
ha	hectare/hectares
in	inch/inches
in^2	square inch/inches
in^3	cubic inch/inches
km	kilometer/kilometers
km/h	kilometers per hour
km^2	square kilometer/kilometers
km^3	cubic kilometer/kilometers
Hz	Hertz
lb/ft^2	pounds per square foot
m	meter/meters
m/s	meters per second
m^2	square meter/meters
m^3	cubic meter/meters
mi	mile/miles
mi^2	square mile/miles
mi^3	cubic mile/miles
mph	miles per hour
MW	megawatt
MWe	megawatt electric
P.L.	Public Law

APPENDIX

B

METRIC CONVERSION TABLE

Length

1 in	2.54 cm
1 ft	0.3048 m
1 mi	1.6093 km

Area

1 in^2	6.452 cm^2
1 ft^2	0.0929 m^2
1 mi^2	2.59 km^2
1 acre	0.4047 ha
1 ha	10,000 m^2

Volume or capacity

1 in^3	16.39 cm^3
1 ft^3	0.0283 m^3
1 mi^3	4.1682 km^3
1 gal	0.13368 ft^3
OR	3.7854 l
1 acre/ft	43,560 ft^3

Speed or Velocity

1 ft/s	0.3048 m/s
1 mph	1.6093 km/h, 0.4470 m/s

PROVIDING COMMENTS ON

MULTI-HAZARD IDENTIFICATION AND RISK ASSESSMENT, A CORNERSTONE OF THE NATIONAL MITIGATION STRATEGY

July, 1997

The information in the report entitled *Multi-Hazard Identification and Risk Assessment, A Cornerstone of the National Mitigation Strategy*, is intended to serve as a baseline summary for natural and technological hazards. It is a reference document for use and enhancement by Federal, State, and local specialists and other users. The report is a living document. FEMA encourages all readers to contribute to its enhancement and expansion for subsequent editions.

If you or your organization would like to share additional hazard-specific or general information, we request that you complete the reverse and submit this sheet (or similar information) along with your contributions to:

Ms. Anne Flowers, Program Manager
Mitigation Directorate
Federal Emergency Management Agency
500 C Street, SW.
Washington, DC 20472

FAX (202) 646-4596
anne.flowers@fema.gov

OR

Ms. Rebecca Quinn, Project Manager
Michael Baker Jr., Inc.
3601 Eisenhower Avenue, Suite 600
Alexandria, Virginia 22304

FAX (703) 960-9125
rcquinn@mbakercorp.com

You may contact Ms. Flowers at (202) 646-2748, or Ms. Quinn at (703) 317-6298 if you wish to discuss your comments and concerns.

COMMENT FORM

MULTI-HAZARD IDENTIFICATION AND RISK ASSESSMENT
July, 1997

PLEASE TELL US WHO YOU ARE

Your Name and Title: ______________________________

Name of Organization You Represent: ______________________________

Mailing Address: ______________________________

____

Telephone Number (Optional): ______________________________

FAX/Internet Number (Optional): ______________________________

Date of Comments: ______________________________

Special Area of Interest or Expertise: ______________________________

PLEASE DESCRIBE WHAT YOU ARE PROVIDING

- ☐ Information on a Specific Natural or Technological Hazard(s).
  Please Specify Hazard: ______________________________
- ☐ General Information on Identifying Natural and Technological Hazards
- ☐ Information To Assist in Developing Risk Assessment Methodologies
- ☐ Other. Please Specify: ______________________________

PLEASE DESCRIBE THE FORMAT OF YOUR INFORMATION:

☐ Report, Paper, or Article	☐ Hard Copy	☐ Digital
☐ Maps or Graphics	☐ Hard Copy	☐ Digital
☐ Photograph(s)	☐ Hard Copy	☐ Digital

☐ Other Format. Please Specify: ______________________________

PLEASE ATTACH ADDITIONAL PAGES AS NEEDED.