Primer on NATURAL HAZARD MANAGEMENT in Integrated Regional Development Planning

DEPARTMENT OF REGIONAL DEVELOPMENT AND ENVIRONMENT
EXECUTIVE SECRETARIAT FOR ECONOMIC AND SOCIAL AFFAIRS
GENERAL SECRETARIAT
OF THE ORGANIZATION OF AMERICAN STATES

With Support from the
OFFICE OF FOREIGN DISASTER ASSISTANCE
UNITED STATES AGENCY FOR INTERNATIONAL DEVELOPMENT

A Contribution to the International Decade
for Natural Disaster Reduction

Cover:
Casma, Peru, following the May 31, 1970 earthquake

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Department of Regional Development and Environment
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With support from the Office of Foreign Disaster Assistance
United States Agency for International Development

Washington, D.C.
1991

This report was produced by the Natural Hazards Project of the Department of Regional Development and Environment with support from the Office of Foreign Disaster Assistance/U.S. Agency for International Development. AID does not necessarily share all the views expressed, but welcomes this publication as a means of encouraging further discussion of natural hazard issues in development planning.

PRIMER ON NATURAL HAZARD MANAGEMENT IN INTEGRATED REGIONAL DEVELOPMENT PLANNING

Contents

PREFACE

Following the El Niño occurrence of 1982-83, the member states of the Organization of American States (OAS) expressed the need for technical cooperation in natural hazard management. In response, the Department of Regional Development and Environment (DRDE) initiated the Natural Hazard Project with support from the Office of Foreign Disaster Assistance (OFDA) of the U.S. Agency for International Development (AID). OAS by that time had been providing services in regional development planning for over twenty years and in 1984 published *Integrated Regional Development Planning: Guidelines and Case Studies from OAS Experience*. In keeping with the principles set forth in that book, the OAS approach incorporates natural hazard management issues into the development planning process.

The services of technical cooperation, training, and technology transfer focus on hazard assessment and mitigation as elements of the processes of environmental assessment, natural resource evaluation, and project formulation. The technical cooperation concentrates on hazard and vulnerability assessments, inclusion of hazard mitigation measures in the formulation of investment projects, use of geographic information systems for mapping and analysis, and urban watershed planning for hazard and resource management. Training includes workshops and formal courses in a variety of aspects of disaster mitigation and integrated development planning. Personnel from virtually every member state have been trained in new hazard management skills. Technology transfer to date has focused on the establishment of geographic information and emergency information management systems, including provision of equipment and training of personnel. The effectiveness of reducing the impact of disasters by including natural hazard management as an element of development planning has been confirmed by the recipient countries and by other international organizations.

The need for this book became clear through field work and discussions with planning agency counterparts and representatives of other development assistance agencies. Great strides were made in the past two decades in emergency preparedness and response, but up to now insufficient attention has been paid to reducing the vulnerability of existing and planned development. After seven years of field work, it is now possible to prepare this synthesis of OAS experience with this neglected subject.

The material comes with a broad set of objectives, a reflection of the breadth of the issues involved in hazard mitigation. At the policy level, it is hoped that national planning ministries, development agencies, and international financing institutions will be encouraged to systematically include analyses of natural hazards in their economic development programs. Specifically, it is hoped that the experience will persuade:

- development agencies in the member states to incorporate natural hazard considerations into the process of integrated development planning;

- international technical cooperation and financing agencies to incorporate hazard considerations into the formulation of investment projects at the earliest stages;

- governments and financing agencies to place more emphasis on risk awareness in evaluating investment projects, and to assume a stance of risk avoidance rather than risk neutrality; and

- bilateral and multilateral aid donors to re-evaluate the distribution of their disaster relief funds, increasing the proportion for prevention activities.

At the operational level, it is hoped that development practitioners can be provided with some of the tools for conducting natural hazard assessments and implementing mitigation measures.

To reach both policy-makers and practitioners, the OAS has prepared complementary documents, each for a distinct audience. The first, *Disasters, Planning, and Development: Managing Natural Hazards to Reduce Loss*, is directed at policy-level personnel in the member states, international development banks, and development assistance agencies. The document in hand, *Primer on Natural Hazard Management in Integrated Regional Development Planning*, is a technical compendium directed at planners and other development practitioners. Its main intent is to establish two ideas: (1) that the best way to reduce the growing impact of natural hazard events is in the context of integrated development planning; and (2) that there are means available to reduce economic loss caused by disasters.

This document includes much of the material in *Disasters, Planning, and Development* and provides much greater depth on the specific hazards and assessment techniques. A compilation and analysis of experience not available from other sources, it complements the 1984 case book on integrated regional development planning. Its contents have been and will continue to be used as training materials. The term "primer" in the title indicates that this book is meant to be a first reader. Undoubtedly, many of the methods and much of the information presented here will be improved upon, giving rise to subsequent editions and to the preparation of similar documents for other regions and audiences.

The text is divided into three parts:

- Part I is an introduction to integrated development planning and natural hazard management, showing how the impact of natural hazards can be reduced by including hazard considerations in development planning and project formulation.

- Part II describes the technical tools used for hazard assessment, including geographic information systems, remote sensing, and special mapping techniques.

- Part III consists of a series of chapters on the most significant natural hazards in Latin America and the Caribbean, presenting new approaches to their assessment and mitigation in the context of integrated development planning.

It is hoped that these principles, guidelines, and technical approaches will help planners and decision-makers gain an understanding of the relationship between natural hazard mitigation and the development planning process in Latin America and the Caribbean. These publications come at a time when the region is facing the challenge presented by the International Decade for Natural Disaster Reduction, which was established by the United Nations General Assembly for the 1990s. These documents demonstrate that reducing the impact of natural hazards can only be done by changing the way development takes place. They have been prepared to contribute in some small way to that change.

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December, 1990

ACKNOWLEDGMENTS

The execution of a task as large and complex as the preparation of this book involved the collaboration of a number of institutions and a great many individuals. To all of them a well deserved thank you is extended.

Support for the Natural Hazards Project, which produced the Primer, has come from the Office of Foreign Disaster Assistance of the U.S. Agency for International Development. Oliver R. Davidson, Barry N. Heyman, Paul F. Krumpe, and Alan G. Swan offered helpful suggestions and encouragement during the preparation of this book.

The Regional Seismological Center for South America (CERESIS) in Lima, Peru, and the U.S. National Oceanographic and Atmospheric Administration made available valuable information. The U.S. Geological Survey not only provided much information but was also generous in donating staff time for its preparation.

Chapter 1 was prepared by Stephen O. Bender, who designed and directed the preparation of the Primer and acted as general editor. Contributions to that chapter were made by Arthur M. Heyman, John Horberry, Milagros Nanita-Kennett, and Jan C. Vermeiren. Chapter 2 was prepared by Ana Lea Florey and Randall A. Kramer, with contributions from Boris E. Utria. Richard E. Saunier prepared Chapter 3, and Chapter 9, with contributions from Carlos López Ocaña, Random Dubois and John L. Thames. Chapter 4 was prepared by Stephen J. Gawarecki, with contributions from Rose Mary García-Spatz, and was reviewed by Morris Deutsch and Donald R. Wiesnet. Chapter 5 was prepared by Enrique E. Bello and Ernest Hardy. William J. Kockelman prepared Chapters 6 and 7, which were reviewed by David Perkins, Robert Alexander, and Jeanne Perkins. Mr. Kockelman also prepared material for Chapters 1 and 3. Morris Deutsch and Donald Wiesnet prepared Chapter 8. Chapter 10 was prepared by Jerome DeGraff, with contributions from Earl E. Brabb and Allen P. King. Chapter 11 was prepared by Arthur Heyman, with contributions from William R. McCann, Stewart P. Nishenko, and Randall A. White, and was reviewed by Alberto A. Giesecke. Chapter 12 was prepared by Rose Mary García-Spatz and Jan Vermeiren.

Critical comments, ideas, and substantive editing were contributed by Enrique Bello, Arthur Heyman, and Claudio R. Volonté, who accompanied the Primer through its preparation; and by Lynn Filderman, Catherine Healy, Rose Mary García-Spatz, and Betty Robinson. Enrique Bello also directed the production of the manuscript with support from Claudio Volonté, Viviana Aliaga, Vivian Bacarreza, Jean Cho, Mariana Ferrari, Lili Getsztain, Jet Ledgard, Jeffrey Mendelsohn, Laura Meszaros, Mark Mercready, and Robert Sterner.

To the many other, unnamed people who contributed through their insights and comments, a debt of gratitude is expressed which, hopefully, is partially repaid by the completion of this book.

HOW TO USE THIS PRIMER

This Primer has been prepared as reference document for practitioners in the field, to guide integrated development planning teams in Latin America and the Caribbean in the use of natural hazard information during the different stages of the planning process. The information presented here is specifically oriented toward regional planning studies, whether the area in question is a few hundred or a few hundred thousand square kilometers, and complements other planning information that is typically gathered and analyzed during the course of the study. The methods have been selected for their utility in the regional planning process.

In some cases the information and methods are to be used "as is" during the study; in other cases, the Primer offers guidance on the acquisition of information or the selection of methods, presenting questions to be asked and decisions to be made by the planning team.

The Primer is divided into three parts, each covering a specific subject area and complementary to the others. Each part, with the chapters contained therein, is meant to provide the planning team sufficient guidance in that subject area for it to proceed with the task at hand. There is extensive cross referencing between chapters. Since the book is intended for reference, each chapter is complete within itself (even though this results in some redundancy), with its own detailed table of contents, a short summary, a statement of its objective, and complete references.

If there is an unevenness to the contents of the these parts, it is a reflection of the incipient state of natural hazard assessment in the integrated development planning process. In subject areas where assessment techniques, information, and/or planning study methods are generally available, the Primer so informs the user without necessarily presenting the technique, information, or method. In other instances, the contribution of the Primer is to present to the planning team heretofore unavailable elements, or to propose and explain the use of elements specifically created for integrated regional planning purposes.

All readers should start with Part I. The core of Chapter 1 is the section "Hazard Management and Development Planning," which describes the process of integrated development planning as practiced by the OAS and indicates the hazard management activities associated with each stage of that process. A second feature is the description of how to conduct natural hazard assessments for selected economic sectors. The chapter ends with a set of strategies for development assistance agencies interested in implementing the recommendations. Chapter 2 is vital to all practitioners who formulate investment projects: it explains how to include natural hazard risk consideration as an integral aspect of project preparation. Taking as a point of departure that the most effective way to persuade decision-makers to include hazard mitigation measures in a development project is to demonstrate the cost-effectiveness of the proposal, the chapter briefly presents principles of economic analysis, then provides guidelines for conducting various kinds of economic analyses appropriate for different levels of available information. While the rest of the book deals with the issue of how human activities can mitigate or exacerbate the impact of natural hazards, Chapter 3 shows that one of the services provided by ecosystems is the natural mitigation of hazards until that service is undermined by environmental degradation.

The chapters of Part II can be read when the need arises. Planners, particularly those working in large study areas, should be aware of the great variety of remote sensing devices, mounted in both airplanes and satellites. Chapter 4 gives a general orientation on the applications, limitations, and costs of the main remote sensing techniques and tells where to look for additional detail. Any modern planner or development practitioner should be aware of the great power of

geographic information systems (GIS) in storing and analyzing data. Chapter 5 explains the applications of a GIS for natural hazard management and development planning in general. It also gives a brief orientation on how to decide if an agency should invest in such a system and how to select one and put it into operation. Chapters 6 and 7, on multiple hazard mapping and critical facilities mapping, are more specialized, but any planner involved in natural hazard mitigation should be aware of these techniques.

Part III gives detailed guidelines on how to conduct assessments of flood hazards, desertification, landslides, geologic hazards (earthquakes, volcanic eruptions, and tsunamis), and hurricanes. Previously it was thought that conducting such assessments would be too expensive and time-consuming to be accommodated in a development planning study, but these five chapters offer new approaches that are compatible with development planning. They can be read in any order. A specialist might be interested only in one particular hazard, but planners and team leaders should be familiar with all the techniques. In the interest of promoting interdisciplinary activity, it is useful for all the members of a planning team to have at least a general idea of the work and information needs of the other team members. In this sense it is useful for all prospective members of a planning team to skim quickly the chapters of subordinate interest to them. Appendix A offers a concise compendium of sources of information applicable to all these chapters.

EXECUTIVE SUMMARY

The United Nations declared the 1990s the International Decade for Natural Disaster Reduction. The 1990s is also a time when for many developing countries coping with disasters is becoming virtually synonymous with development: the cost of rehabilitation and reconstruction in the wake of disasters is consuming available capital, significantly reducing the resources for new investment.

The toll is appalling. Since 1960 earthquakes, hurricanes, floods, droughts, desertification, and landslides in the Latin American and Caribbean region have killed 180,000 people, disrupted the lives of 100 million more, and caused more than US$54 billion in property damage. Rates of destruction increase decade after decade. The adverse effects on employment, balance of trade, and foreign indebtedness continue to be felt years after the occurrence of a disaster. Activities intended to further development often exacerbate the impact of natural hazards. Worst of all, the poorest countries and the poorest segments of their populations feel the severest impact. International relief and rehabilitation compensates the stricken countries for only a small part of their losses.

The good news is that, of all the global environmental problems, natural hazards present the most manageable of situations: the risks are most readily identified; effective mitigation measures are available; and the benefits of vulnerability reduction may greatly outweigh the costs. Moreover, experience shows that the impact of natural hazards can be reduced. Improved warning and evacuation systems have cut the death toll of hurricanes dramatically. Combinations of structural and non-structural mitigation measures have been shown to alleviate the effects of earthquakes, landslides, floods, and droughts.

Yet the countries of the region are slow to undertake actions of vulnerability reduction or to request financing for them, development financing and donor agencies are reluctant to finance them, and most development cooperation agencies provide little service in this subject area. Despite the cost-effectiveness of preventive measures, more than 90 percent of international funding for natural hazard management in the region is spent on disaster preparedness, relief, rehabilitation, and reconstruction, leaving less than 10 percent for prevention before a disaster.

There are reasons for this seemingly anomalous situation. More important, actions can be taken to change it. This book, a synthesis of the natural hazard experience of the Department of Regional Development and Environment of the Organization of American States (OAS/DRDE), argues that **the most effective approach to reducing the long-term impact of natural hazards is to incorporate natural hazard assessment and mitigation activities into the process of integrated development planning and investment project formulation, and their implementation.**

Guidelines for incorporating natural hazard considerations into development planning and project formulation can be summarized as follows:

HAZARD MITIGATION STRATEGIES FOR DEVELOPMENT PLANNING

Natural hazard management is often conducted independently of integrated development planning. It is important to combine the two processes. Of the many components of hazard management, the following techniques are the most compatible with the planning process:

- **Natural hazard assessment**: an evaluation of the location, severity, and probable occurrence of a hazardous event in a given time period.

- **Vulnerability assessment**: an estimate of the degree of loss or damage that could result from a hazardous event of given severity, including damage to structures, personal injuries, and interruption of economic activities and the normal functions of settlements.

- **Risk assessment**: an estimate of the probability of expected loss for a given hazardous event.

Integrated development planning is a multidisciplinary, multisectoral process that includes the establishment of development policies and strategies, the identification of investment project ideas, the preparation of projects, and final project approval, financing, and implementation. The OAS/DRDE version of this project cycle consists of four stages: Preliminary Mission, Phase I (development diagnosis), Phase II (project formulation and preparation of an action plan), and Project Implementation. The development planning and hazard management activities in each of these stages are summarized in the diagram on the next page.

The advantages of incorporating hazard management into development planning include the following:

- Vulnerability reduction measures are more likely to be implemented as part of development projects than as stand-alone mitigation proposals.

- The cost of vulnerability reduction is less when the measure is a feature of the original project formulation than when it is incorporated later.

- The planning community can help set the science and engineering research agenda to focus more on the generation of data suitable for immediate use in hazard mitigation.

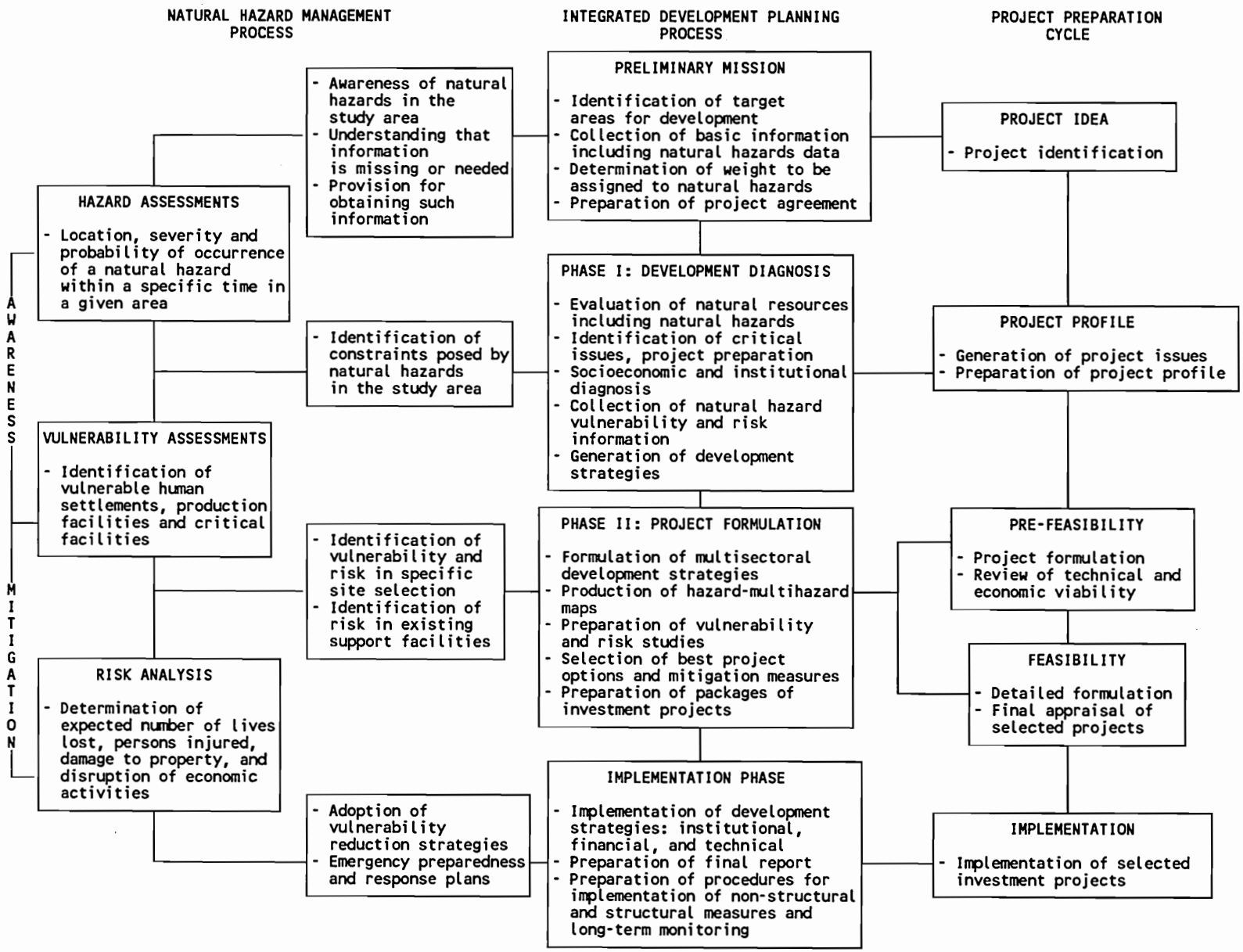
- Building vulnerability reduction into development projects benefits the poorest segments of the population.

HAZARD MITIGATION STRATEGIES FOR PROJECT FORMULATION

Examples of structural measures that can mitigate the effects of natural hazard events include building codes and materials specifications, retrofitting of existing structures to make them more hazard-resistant, and protective devices such as dikes. Non-structural measures concentrate on identifying hazard-prone areas and limiting their use. Examples include land-use zoning, tax incentives, insurance programs, and the relocation of residents away from the path of an event. A strong case can be made for emphasizing non-structural mitigation in developing countries, since structural mitigation measures often have a high direct cost that must be added to the costs of a project. Non-structural measures may have some capital and/or operating costs but these are usually less than structural costs.

Several questions enter into the issue of risk vis-a-vis investment projects:

Should risk be considered in the evaluation of investment projects? Governments may argue that they should be indifferent between high-risk and low-risk public sector projects that have the same expected net present value because the risks, being widely shared throughout the society, are negligible to each individual. But this ignores governments' obligation to consider the opportunity cost of each investment. International financing agencies can be indifferent to risk because the country will be obligated to repay the loan whether or not the structure


NATURAL HAZARD MANAGEMENT PROCESS
INTEGRATED DEVELOPMENT PLANNING PROCESS
PROJECT PREPARATION CYCLE
AWARENESS
MITIGATION
HAZARD ASSESSMENTS
- Location, severity and probability of occurrence of a natural hazard within a specific time in a given area
VULNERABILITY ASSESSMENTS
- Identification of vulnerable human settlements, production facilities and critical facilities
RISK ANALYSIS
- Determination of expected number of lives lost, persons injured, damage to property, and disruption of economic activities
- Awareness of natural hazards in the study area
- Understanding that information is missing or needed
- Provision for obtaining such information
- Identification of constraints posed by natural hazards in the study area
- Identification of vulnerability and risk in specific site selection
- Identification of risk in existing support facilities
- Adoption of vulnerability reduction strategies
- Emergency preparedness and response plans
PRELIMINARY MISSION
- Identification of target areas for development
- Collection of basic information including natural hazards data
- Determination of weight to be assigned to natural hazards
- Preparation of project agreement
PHASE I: DEVELOPMENT DIAGNOSIS
- Evaluation of natural resources including natural hazards
- Identification of critical issues, project preparation
- Socioeconomic and institutional diagnosis
- Collection of natural hazard vulnerability and risk information
- Generation of development strategies
PHASE II: PROJECT FORMULATION
- Formulation of multisectoral development strategies
- Production of hazard-multihazard maps
- Preparation of vulnerability and risk studies
- Selection of best project options and mitigation measures
- Preparation of packages of investment projects
IMPLEMENTATION PHASE
- Implementation of development strategies: institutional, financial, and technical
- Preparation of final report
- Preparation of procedures for implementation of non-structural and structural measures and long-term monitoring
PROJECT IDEA
- Project identification
PROJECT PROFILE
- Generation of project issues
- Preparation of project profile
PRE-FEASIBILITY
- Project formulation
- Review of technical and economic viability
FEASIBILITY
- Detailed formulation
- Final appraisal of selected projects
IMPLEMENTATION
- Implementation of selected investment projects

is destroyed by an earthquake. But this ignores the agencies' efforts to inculcate fiscal responsibility. Economic arguments notwithstanding, it simply makes common sense to include natural hazard risk in project evaluation just as the risk of market loss is considered.

How should competing project objectives be evaluated? This question should be addressed even before the search for project ideas begins. One approach to incorporating societal goals and priorities into the selection of projects is multicriteria analysis. This involves convening a meeting of a cross-section of a society's interest groups to array important social and economic objectives and agree on discriminatory weights for each. Projects can then be evaluated in terms of their capacity to fulfill the stated goals. Reducing vulnerability to natural hazards can be established as one of the goals.

How can the conflicting demands of different interest groups for the use of the same natural good or service, such as naturally occurring mitigation, be resolved? This is the classic problem that often goes under the misnomer "environmental impact." A feature of good planning is the identification of potential competition over the use of natural goods and services and seeking resolutions to these conflicts that are reasonably satisfying to all parties.

What are objective measures for evaluating natural hazard risk as an element of overall investment project evaluation? Two kinds of methods are available: those based on the availability of limited information and those based on probabilistic information. The application of the techniques in each category vary with type of natural hazard and the conditions under which proposed project is being evaluated.

STRATEGIES FOR SPECIFIC HAZARDS

How do planners incorporate natural hazards into an integrated study for the development of an area? First, they must determine which hazards, if any, pose a serious threat. Next, they must prepare an assessment of any threatening hazards. Up to now planners have relied largely on existing information because conducting hazard assessments was too costly and time-consuming to fit comfortably into a development planning study. Using techniques developed by the OAS, it is now possible to conduct assessments and introduce hazard mitigation measures in the context of a development study.

Hurricanes

Hurricanes occur in well-defined belts in the Caribbean basin and on the west coast of Central America. If a study area lies within these belts, the planner can proceed to determine risks and seek mitigation measures. Since storm surge (a rise in sea level due to the low barometric pressure of the storm) is by far the most damaging hurricane hazard, lowland areas close to the sea are the most jeopardized. Storm monitoring and improved warning and evacuation measures are the most effective mechanisms for saving lives. Some low-cost structural mitigation measures can reduce damage (e.g., ensuring that roofs are tied down, covering large glass panels, and removing projections that can easily be blown off). Small towns and villages must depend largely on their own resources to defend against hurricanes. This requires preparing community leaders and establishing a national program for training and maintaining communication with local personnel.

Desertification

This human-induced hazard is defined as the creation or spread of desert-like

conditions beyond desert margins. Desertification occurs in narrowly circumscribed arid or semiarid areas; the text classifies the status of desertification for political subdivisions of South America and Mexico. Development actions that could cause or exacerbate desertification in these areas should be avoided. If a development study covers an affected area a more detail hazard assessment can be prepared quickly using four available parameters: precipitation, soil texture, slope, and the ratio of precipitation to evapotranspiration. The technique defines 16 mappable units, each with a set of characteristics that indicate preferred management practices. Once the problem is identified, appropriate mitigation and rehabilitation measures for animal husbandry, dry-land agriculture, soil erosion, and salinization can be applied.

Geologic hazards

Enough scientific information exists to determine whether earthquakes, volcanic eruptions, or tsunamis constitute a significant threat in virtually any area of Latin America and the Caribbean. It was not readily accessible up to now, but this document assembles the information and puts it into a form suitable for use in planning. Areas that have a high probability of a large earthquake in the next 20 years are listed by political subdivision. All volcanoes that have erupted in Latin America and the Caribbean in the last 10,000 years are categorized as having long- or short-term eruption intervals: any study area within 30 km of a volcano having short-term periodicity must be considered as being under threat of an eruption. Large tsunamis strike only on the west coast of Latin America, and so rarely that mitigation measures can be economically justified only for the most vulnerable large urban concentrations. A list of all cities threatened shows the maximum likely height of a tsunami.

Floods

The existing information is rarely sufficient for evaluating flood potential in a study area, but using remote sensing interpretation, a flood hazard assessment can be prepared that fits the time and budgetary constraints of a development planning study. Such an assessment is useful for designing both new projects and identifying mitigation measures for existing development threatened by floods.

Landslides

As with flooding, the existing information is rarely sufficient for evaluating landslide potential in a study area, but new techniques make rapid analysis of the potential possible. Past landslides can be located on aerial photographs or satellite imagery, and a landslide zonation map can be compiled showing the relationship of landslides to causative factors--bedrock, slope, and moisture conditions.

STRATEGIES FOR SELECTED ECONOMIC SECTORS

Economic sectors such as energy, tourism, agriculture, and transport can benefit from an analysis to determine their vulnerability to natural hazards. Conclusions synthesized from sector vulnerability studies to date include the following:

- Vulnerability reduction measures can be cost-effective, either as stand-alone projects or, more commonly, as components of overall sector development programs.

- Sectoral studies reveal previously unrecognized linkages between disasters and development.

TOOLS AND TECHNIQUES FOR NATURAL HAZARD ASSESSMENTS

Geographic Information Systems (GIS)

A GIS, a systematic means of geographically referencing information about a unit of space, can facilitate the storage, retrieval, and analysis of data in both map form and tables. It can be a manual system, but most GIS are computerized, as dictated by the overwhelming number of pieces of information needed for natural hazard management, particularly in the context of development planning. A GIS can be surprisingly inexpensive; it can multiply the productivity of a technician; its use can give higher quality results than can be obtained manually regardless of the costs.

Remote Sensing in Natural Hazard Assessments

Remote sensing refers to the process of recording information from sensors mounted either on aircraft or on satellites. These techniques can be used to reveal the location of past occurrences of natural events and/or to identify the conditions under which they are likely to occur, so that areas of potential exposure can be distinguished and applicable mitigation measures can be introduced into the planning process. Aerial and satellite remote sensing techniques appropriate for the preparation of assessments will vary with the type of natural hazard and the stage of a development study under consideration.

Special Mapping Techniques

Multiple-hazard maps combine assessments of two or more natural hazards on a single map. Such a product is excellent for analyzing vulnerability and risk since the combined effects of natural phenomena on an area can be determined and mitigation techniques suitable for all can be identified. Critical facilities--transport and communication facilities, utilities, large auditoriums, hospitals, police and fire stations, etc.--must also be mapped as a part of the process of emergency planning. Combining critical facilities mapping with multiple hazard mapping provides information to guide the identification of projects and mitigation measures.

STRATEGIES FOR DEVELOPMENT ASSISTANCE AGENCIES

Activities that technical cooperation agencies can undertake to promote natural hazard assessment and mitigation include:

- Strengthening planning institutions' ability to incorporate natural hazard considerations into the planning process.

- Supporting pilot projects of natural hazard assessments.

- During relief and reconstruction efforts in the aftermath of a disaster, stimulating the interest of the government and development assistance agencies in natural hazard assessment and mitigation.

- Building natural hazard assessments into sector planning.

- Including in the preparation and evaluation of investment projects the costs and benefits of incurring vs. avoiding the impacts of natural hazards.

- Preparing case studies of noteworthy experiences that show how funding activities can be made more responsive to natural hazards.

A strategy to promote lending and donor agency interest in hazard assessment and mitigation consists of three elements:

- **Change the context in which the lenders and donors perceive governments and technical cooperation agencies to be addressing natural hazard issues.** Recipient countries can show their capacity to deal with natural hazards by focusing on priority hazards and sectors; by choosing simple, practical information collection and analysis systems; and by demonstrating a commitment to implementing study findings. Technical cooperation agencies can make study outputs appeal to lenders and donors by seeking practical and cost-effective solutions to recurrent problems and can identify mechanisms of cooperation with financing agencies such as pooling technical resources, exchanging experiences, and joint staff training in natural hazard issues.

- **Establish incentives for analysis.** Development financing agencies will be more willing to incorporate natural hazard considerations into project preparation and evaluation if minimum change in existing procedures is required. Ways to promote this include providing reusable information, integrating hazard concerns into existing review mechanisms, promoting proven mitigation measures in relation to specific types of projects, incorporating appropriate costs and benefits of hazard mitigation into economic appraisal, and sensitizing staff members.

- **Assign accountability for loss.** Bank directors and staff should be made more aware that projects they plan or fund may suffer losses from natural disasters. Losses from natural disasters should be evaluated in the context of the lender's program area and its project design and repayment performance. The inclusion of techniques to deal with natural hazards management issues in the professional standards of bank staff should be promoted.

INTRODUCTION

Natural hazards, like natural resources, are part of the offering of our natural systems; they can be considered negative resources. In every sense natural hazards are an element of the "environmental problems" currently capturing so much public attention: they alter natural ecosystems, heighten the impact of those ecosystems' degradation, reflect the damage done by humans to their environments, and can affect large human populations.

While virtually every book about natural hazards contains a chronicle of death and destruction, a similar accounting of damage avoided is almost never included. But the effects of the disasters caused by natural hazards can be greatly reduced by action taken in advance to reduce vulnerability to them. Industrialized countries have made progress at reducing the impacts of hurricanes, floods, earthquakes, volcanic eruptions, and landslides. For example, Hurricane Gilbert, the most powerful hurricane ever recorded in the Western Hemisphere, was responsible for 316 fatalities, though less forceful hurricanes killed thousands of people earlier in the century. A combination of zoning restrictions and improved structures together with new prediction, monitoring, warning, and evacuation systems made the difference. Latin American and Caribbean countries have reduced loss of life from some hazards, principally through disaster preparedness and response; they now have the opportunity to reduce economic losses through mitigation in the context of development to a much greater extent than they have to date.

The disasters caused by natural hazards generate a demand for enormous amounts of capital to replace what is destroyed and damaged. The development community should address this issue because it affords, among all environmental issues, the most manageable of situations: the risks are readily identified, mitigation measures are available, and the benefits that accrue from vulnerability reduction actions are high in relation to costs.

THE TOLL

With depressing regularity, natural disasters become international headlines. Each year one or more hurricanes strike the Caribbean region. Particularly destructive ones, such as Gilbert in 1988 and Hugo in 1989, can cause billions of dollars of damage. Flooding, too, occurs annually, but no reliable estimates are available of the cost in human lives and property. Earthquakes and volcanic eruptions occur unpredictably with disastrous effects: the mudslide precipitated by the eruption of Volcán Ruiz in Colombia in 1985 killed 21,800 people, and earthquakes in Mexico (1985) and El Salvador (1986) together killed more than 10,000. Landslides are limited in area, but occur so frequently that they account for hundreds of millions of dollars in damage every year. While not as spectacular, drought can be more harmful to agricultural production than hurricanes. After the 1971 drought, for example, banana production in Saint Lucia did not recover fully until 1976. Disaster aid, however, is scarce in the region for this type of pervasive, slow-onset hazard.

Over the past 30 years the average annual costs of natural disasters to Latin America and the Caribbean were 6,000 lives, adverse effects on 3 million people, and US$1.8 billion in physical damage and economic losses. Moreover, the impacts are increasing: during the 1960s approximately 10 million people were killed, injured, displaced, or otherwise affected; the number for the 1970s was six times larger, and for the 1980s, three times larger.

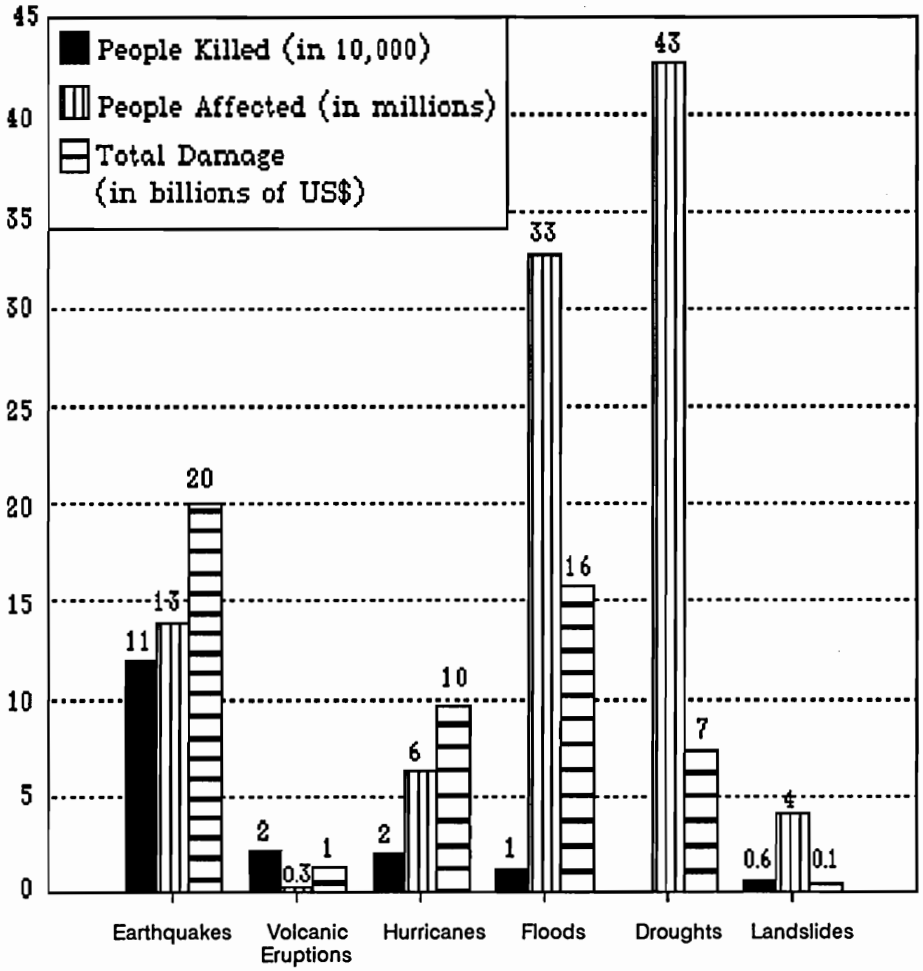
A conservative estimate of the impact of disasters on the region from 1960 to 1989 is given in Figure 1. It can be seen that droughts and floods affect the largest number of people; earthquakes account for the most deaths; and earthquakes, floods, and hurricanes cause the most financial damage. Hurricanes are the most devastating natural hazard in the Caribbean region, earthquakes in the Mexico-Central America region. Floods, droughts, volcanic eruptions, and earthquakes are all very destructive in South America. Figure 2 summarizes the effects of some of the worst disasters of the period.

In addition to the direct social and economic impact, natural disasters can affect employment, the balance of trade, and foreign indebtedness for years after their occurrence. After Hurricane Fifi struck Honduras in 1974, for example, employment in agriculture decreased by 70 percent (World Bank, 1979). Funds intended for development are diverted into costly relief efforts. These indirect but profound economic effects and their drain on the limited funds now available for new investment compound the tragedy of a disaster in a developing country. Furthermore, international relief and rehabilitation assistance has been insufficient to compensate countries for their losses; during the period 1983-1988, reconstruction assistance amounted to only 13 percent of the estimated value of losses.

Yet natural hazards appear to generate little constituency for their prevention.

Figure 1

IMPACT OF NATURAL DISASTERS IN LATIN AMERICA AND THE CARIBBEAN: 1960-1989



Source: Office of Foreign Disaster Assistance/United States Agency for International Development. Disaster History. Significant Data on Major Disasters Worldwide, 1900-Present. July, 1989 (Washington, D.C.: OFDA/USAID, 1989).

NATURAL HAZARDS AND DEVELOPMENT

The losses are a concern not only for the countries in which they occur but also for international lending agencies and the private sector which are interested in protecting their loans and investments. The investments are often at risk of both natural hazards and the side effects of development projects that exacerbate these hazards. For example, excessive erosion and siltation reduces the useful life of large multipurpose dams. Many smaller dams in the region also experience this type of damage: accelerated erosion caused by a hurricane filled half the storage capacity of a reservoir in the Dominican Republic virtually overnight. As a result of these concerns, one important lender, the Inter-American Development Bank, is studying the process of evaluating dam projects on the grounds that more realistic methods of estimating life expectancy and cost-benefit ratios will have to be introduced if the problem of erosion and siltation cannot be resolved satisfactorily for any project.

While the development efforts of the past have brought economic advancement to many parts of the world, they have also brought unwise or unsustainable uses of the natural resource base. Indeed, in recent years, the United Nations specialized conferences on the human environment, desertification, water management, deforestation, and human settlements all

Figure 2

LATIN AMERICA AND THE CARIBBEAN: SELECTED NATURAL HAZARD EVENTS (1983-1989)[a/]

Country	Year	Event type	Number of fatalities	Affected population[b/] (thousands)	Economic losses (million US$)	International assistance[c/] (million US$)
Antigua & Barbuda	83	Drought	0	75.0	- -	0.44
Argentina	83	Floods	0	5,580.0	1,000.0	1.74
Bolivia	83	Floods	250	50.0	48.4	1.85
	83	Drought	0	1,583.0	417.2	71.41
	84	Drought	0	1,500.0	500.0	0.53
Brazil	83	Floods	143	3,330.0	12.0	0.18
	83	Drought	0	20,000.0	- -	9.48
	84	Floods	27	250.0	1,000.0	0.10
	85	Floods	100	600.0	200.0	- -
	88	Floods	289	58.6	1,000.0	0.65
Chile	85	Earthquake	180	980.0	1,500.0	9.98
Colombia	83	Earthquake	250	35.0	410.9	3.76
	85	Volcano	21,800	7.7	1,000.0	22.65
	88	Hurricane Joan	26	100.0	50.0	- -
Ecuador	83	Floods	307	700.0	232.1	12.68
	87	Earthquake	300	150.0	- -	11.30
El Salvador	86	Earthquake	1,100	500.0	1,030.0	308.68
Eastern Caribbean Islands [d/]	89	Hurricane Hugo	21	50.0	- -	11.67
Haiti	88	Hurricane Gilbert	54	870.0	91.3	3.32
Jamaica	86	Floods	54	40.0	76.0	3.41
	88	Hurricane Gilbert	49	810.0	1,000.0	102.41
Mexico	85	Earthquake	8,776	100.0	4,000.0	21.70
Nicaragua	88	Hurricane Joan	120	300.0	400.0	- -
Paraguay	83	Floods	0	100.0	82.0	0.56
Peru	83	Floods	364	700.0	988.8	83.81
	83	Drought	0	620.0	151.8	18.05
Venezuela	87	Landslide	96	15.0	0.8	0.03

a/ Information for all columns but International assistance was obtained from the United States Agency for International Development/Office of Foreign Disaster, Disaster History, Significant Data on Major Disasters Worldwide, 1900-Present, August 1990 (Washington, D.C.: USAID/OFDA, 1990). Damage estimates may be preliminary and therefore, other sources may show different figures.

b/ Excluding fatalities.

c/ Information obtained from United States Agency for International Development/Office of Foreign Disaster Assistance, OFDA Annual Report FY 1983, 1984, 1985, 1986, 1987, 1988, and 1989 (Washington, D.C.: USAID/OFDA, 1983-1989). Disaster assistance figures do not include contributions from international reconstruction loans and grants.

d/ Information obtained from a preliminary report from the United States Agency for International Development/Office of Foreign Disaster Assistance (USAID/OFDA), "After-Action Report of the Hurricane Hugo OFDA Disaster Relief Team" (Washington, DC: OFDA, 1990).

- - Information not available.

point to environmental degradation brought about by development, and the corresponding reduction in the capacity of an ecosystem to mitigate natural hazards.

Nevertheless, development agencies often continue to operate as though their activities and natural disasters were separate issues. As Gunnar Hagman (1984) points out in *Prevention Better than Cure*:

> When a disaster has occurred, development agencies have regarded it as a nuisance and tried to avoid becoming involved; or even worse, the risk of existing or new potential hazards has been over-looked in the planning and implementation of some development activities. It is now being observed that intensive development may be the cause of many new disasters in poor countries.

Until quite recently, in fact, many practitioners believed that development efforts themselves would spontaneously provide solutions to problems posed by natural hazards. In 1972 the United Nations Conference on the Human Environment in Stockholm declared:

> Environmental deficiencies generated by the conditions of underdevelopment and natural disasters pose grave problems and can best be remedied by accelerated development through the transfer of financial and technological assistance as a supplement to the domestic effort of the developing countries.

In the intervening eighteen years enormous amounts of financial aid and sustained technical assistance have been provided, but far from reducing the effects of natural disasters, development has contributed to disaster vulnerability in areas where the presence of hazards was not properly assessed.

While the link between natural disasters and development has been demonstrated repeatedly, governments and lending agencies do not yet systematically integrate the consideration of natural hazards into project preparation. Past losses and the vulnerability of infrastructure have reached such levels that in some areas development assistance consists almost entirely of disaster relief and rehabilitation. When loan proceeds are routinely programmed for reconstruction, little remains for investment in new infrastructure or economic production. Thus, recurrent disaster relief and reconstruction needs have brought about a reassessment of economic development programs in Bolivia, Colombia, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Peru, the Paraguay River Basin, and several Caribbean island countries.

There is a growing awareness that natural hazard management is a pivotal issue of development theory and practice. The United Nations has declared the 1990s the "International Decade for Natural Disaster Reduction" (IDNDR) and calls on developing countries to participate actively in reducing disaster vulnerability. The OAS has endorsed the IDNDR and made natural hazard management a priority technical assistance area.

PREVENTION VERSUS RECONSTRUCTION

A key element to be addressed in this decade is the distribution of resources between disaster prevention and post-disaster efforts. Prevention, which includes structural measures (e.g., making structures more hazard-resistant) and non-structural measures (e.g., land-use restrictions), is a cost-effective means of reducing the toll on life and property. Post-disaster relief and reconstruction measures are important for humanitarian reasons, and may include improvements that are designed to prevent or mitigate future disasters. This is increasingly the case in projects funded by development financing organizations. Nevertheless, post-disaster measures are disproportionately costly for each life saved and each building reconstructed. Moreover, preventive measures in developing countries can reduce the human tragedy and the incalculable costs of lost jobs and production associated with natural disasters.

It is useful in this regard to distinguish between hazard management and disaster management. Both include the complete array of pre-event and post-event measures, but they differ in their focus. Disaster management is concerned with specific events that destroy lives and property to such an extent that international assistance is often needed. Hazard management addresses the potentially detrimental effects of all natural hazardous events, whether or not they result in a disaster; it is the more inclusive of the two terms, seeking to incorporate consideration of natural hazards in all development actions, regardless of the severity of the impact. It thus concentrates more on the analysis of hazards, the assessment of the risk they present, and the prevention and mitigation of their impact, while disaster management tends to concentrate more on preparedness, alert, rescue, relief, rehabilitation, and reconstruction.

Despite the clear economic and humanitarian advantages of prevention, it is relief and reconstruction measures that typically enjoy political appeal and financial support. Donor nations quickly offer sophisticated equipment and highly trained personnel for search and rescue missions. Politicians of a stricken nation gain more support from consoling disaster victims than from requesting taxes for the undramatic measures that would have avoided the disaster. Short-term efforts to address immediate needs usually take precedence over long-term disaster

recovery and prevention activities, particularly given the visibility attached to the relief phase of disaster by the mass media. It is not surprising, therefore, to find that of all funds spent on natural hazard management in the region, more than 90 percent goes to saving lives during disasters and replacing lost investment; less than 10 percent goes to prevention before disasters.

The situation is similar with respect to science and technology. Increasingly, investment is directed toward prediction, monitoring, and alert technologies as opposed to basic information on the location, severity and probability of events--the data that provide the basis for prevention measures. A sound balance must be sought between obtaining additional scientific information and applying existing information to institute mitigation measures resting chiefly on economic and political organization and process.

THE MESSAGE OF THIS BOOK

From the seven years of experience the Organization of American States through its Department of Regional Development and Environment (OAS/DRDE) has had in assisting its member states with natural hazard management and reduction of vulnerability to natural disasters, several related principles have emerged:

The impact of natural hazards can be reduced. The information and methods exist to minimize the effects of even the most sudden and forceful of hazardous events and prevent them from causing a disaster. While in some cases the event itself cannot be avoided, construction measures and location decisions can save lives and prevent damage. In other cases, such as flooding, the integration of hazard mitigation measures into development planning and investment projects may make it possible to avoid the event altogether.

Hazard mitigation pays high social and economic dividends in a region with a history of natural disasters. Mitigation measures should be seen as a basic investment, fundamental to all development projects in high-risk areas, and not as a luxury that may or may not be affordable. The vulnerability of many areas of Latin America and the Caribbean to hurricanes, earthquakes, volcanic eruptions, flooding, or drought is widely recognized. Planners should not ask themselves whether these events will occur, but what may happen when they do.

Hazard management is most effective in the context of integrated development planning. Traditional single-sector planning cannot maximize the benefits of mitigation techniques and may, in fact, increase the risk exposure of people and their property. Because the traditional development project often represents an isolated intervention into complex and long-standing natural and socioeconomic processes, an advance in one sector may not be accompanied by needed change in another. When natural events subsequently exert pressure, the fruits of the project may be lost to a disaster caused by the deterioration of the natural and human environment related, in turn, to the project itself.

Integrated development planning, in contrast, means a multisectoral approach. It accounts both for a change in associated sectors that share a defined physical space and for the changing relationships between sectors as the result of an intervention. Underlying the integrated approach is the assumption that change is organic and that an initiative in one sector affects the region as a whole. In its development work the OAS applies this philosophy by preparing packages of interrelated projects that reflect a balance between investment in infrastructure, productive activities, service provision, and resource management.

Natural hazard considerations should be introduced at the earliest possible stage in the development process. If a site lies in a fault zone subject to earthquakes, that should be known before it is planned for urban development. If an area considered for an irrigation project is subject to flooding, that should be taken into consideration in the formulation of the project. As natural hazard risk is identified earlier in the planning process, fewer undesirable projects will be carried forward simply on their own momentum. Mitigation measures should be introduced early, and non-structural mitigation, the most cost-effective mechanism, requires particularly early recognition of the need for land-use restrictions. Like an environmental impact statement conducted on a project already formulated, an after-the-fact natural hazard evaluation has much less value than an evaluation conducted in time to influence the original formulation of the project.

One of the roles of technical cooperation agencies such as the OAS is the identification and preliminary formulation of investment projects which later may be funded by international lending agencies for more advanced study and implementation. It is important that technical cooperation agencies incorporate hazard considerations into their part of the development process since it becomes progressively more difficult to do so in later stages.

Use Common Sense. People know the kinds of hazards that occur in their home areas. They may not know how to quantify these dangers or the best ways to mitigate them, but they understand something must be done about them.

This book is a guide to natural hazard management in the context of integrated development planning based on the accumulated experience of the OAS. It is in no sense comprehensive, but rather is confined to the experiences of the recent past in development planning in this hemisphere. Readers should also be aware that it focuses on broad strategies and methodologies, rather than specific instructions for all possible particular cases. But it is about what has proved useful in actual field work.

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PART I

INTEGRATED DEVELOPMENT PLANNING AND NATURAL HAZARDS

CHAPTER 1

INCORPORATING NATURAL HAZARD MANAGEMENT INTO THE DEVELOPMENT PLANNING PROCESS

CHAPTER 1

INCORPORATING NATURAL HAZARD MANAGEMENT INTO THE DEVELOPMENT PLANNING PROCESS

Contents

List of Figures

INCORPORATING NATURAL HAZARD MANAGEMENT INTO THE DEVELOPMENT PLANNING PROCESS

SUMMARY

This chapter defines natural hazards and their relationship to natural resources (they are negative resources), to environment (they are an aspect of environmental problems), and to development (they are a constraint to development and can be aggravated by it). The chapter demonstrates that the means of reducing the impact of natural hazards is now available. The factors that influence susceptibility to vulnerability reduction--the nature of the hazard, the nature of the study area, and institutional factors--are discussed. The core of the chapter explains how to incorporate natural hazard management into the process of integrated development planning, describing the process used by the OAS--Study Design, Diagnosis, Action Proposals, Implementation--and the hazard management activities associated with each phase. The chapter goes on to show how the impact of natural hazards on selected economic sectors can be reduced using energy, tourism, and agriculture as examples. Finally, the significance of a hazard management program to national and international development institutions is discussed.

The planning process in development areas does not usually include measures to reduce hazards, and as a consequence, natural disasters cause needless human suffering and economic losses. From the early stages, planners should assess natural hazards as they prepare investment projects and should promote ways of avoiding or mitigating damage caused by floods, earthquakes, volcanic eruptions, and other natural catastrophic events. Adequate planning can minimize damage from these events. It is hoped that familiarizing planners with an approach for incorporating natural hazard management into development planning can improve the planning process in Latin America and the Caribbean and thereby reduce the impact of natural hazards.

A. What Are Natural Hazards?

A widely accepted definition characterizes natural hazards as "those elements of the physical environment, harmful to man and caused by forces extraneous to him" (Burton, 1978). More specifically, in this document, the term "natural hazard" refers to all atmospheric, hydrologic, geologic (especially seismic and volcanic), and wildfire phenomena that, because of their location, severity, and frequency, have the potential to affect humans, their structures, or their activities adversely. The qualifier "natural" eliminates such exclusively manmade phenomena as war, pollution, and chemical contamination. Hazards to human beings not necessarily related to the physical environment, such as infectious disease, are also excluded from consideration here. Figure 1-1 presents a simplified list of natural hazards, and the boxes on the following pages briefly summarize the nature of geologic hazards, flooding, tsunamis, hurricanes, and hazards in arid and semi-arid areas.

1. HOW NATURAL ARE NATURAL HAZARDS?

Notwithstanding the term "natural," a natural hazard has an element of human involvement. A **physical event**, such as a volcanic eruption, that does not affect human beings is a **natural phenomenon** but not a natural hazard. A natural phenomenon that occurs in a populated area is a **hazardous event**. A hazardous event that causes unacceptably large numbers of fatalities and/or overwhelming property damage is a **natural disaster**. In areas where there are no human interests, natural phenomena do not constitute hazards nor do they result in disasters. This definition is thus at odds with the perception of natural hazards as unavoidable havoc wreaked by the unrestrained forces of nature. It shifts the burden of cause from purely natural processes to the concurrent presence of human activities and natural events.

Figure 1-1

POTENTIALLY HAZARDOUS NATURAL PHENOMENA

ATMOSPHERIC	HYDROLOGIC
Hailstorms	Coastal flooding
Hurricanes	Desertification
Lightning	Salinization
Tornadoes	Drought
Tropical storms	Erosion and sedimentation
	River flooding
SEISMIC	Storm surges
Fault ruptures	
Ground shaking	VOLCANIC
Lateral spreading	Tephra (ash, cinders, lapilli)
Liquefaction	Gases
Tsunamis	Lava flows
Seiches	Mudflows
	Projectiles and lateral blasts
OTHER GEOLOGIC/HYDROLOGIC	Pyroclastic flows
Debris avalanches	
Expansive soils	WILDFIRE
Landslides	Brush
Rock falls	Forest
Submarine slides	Grass
Subsidence	Savannah

Although humans can do little or nothing to change the incidence or intensity of most natural phenomena, they have an important role to play in ensuring that natural events are not converted into disasters by their own actions. It is important to understand that **human intervention can increase the frequency and severity of natural hazards.** For example, when the toe of a landslide is removed to make room for a settlement, the earth can move again and bury the settlement. **Human intervention may also cause natural hazards where none existed before.** Volcanoes erupt periodically, but it is not until the rich soils formed on their ejecta are occupied by farms and human settlements that they are considered hazardous. Finally, **human intervention reduces the mitigating effect of natural ecosystems.** Destruction of coral reefs, which removes the shore's first line of defense against ocean currents and storm surges, is a clear example of an intervention that diminishes the ability of an ecosystem to protect itself. An extreme case of destructive human intervention into an ecosystem is desertification, which, by its very definition, is a human-induced "natural" hazard.

All this is the key to developing effective vulnerability reduction measures: **if human activities can cause or aggravate the destructive effects of natural phenomena, they can also eliminate or reduce them.**

2. ENVIRONMENT, NATURAL HAZARDS, AND SUSTAINABLE DEVELOPMENT

The work of the OAS/DRDE is focused upon helping countries plan spatial development and prepare compatible investment projects at a prefeasibility level. In a general sense, these tasks may be called "environmental planning"; they consist of diagnosing the needs of an area and identifying the resources available to it, then using this information to formulate an integrated development strategy composed of sectoral investment projects. This process uses methods of systems analysis and conflict management to arrive at an equitable distribution of costs and benefits, and in doing so it links the quality of human life to environmental quality. In the planning work, then, the environment--the structure and function of the ecosystems that surround and support human life--represents the conceptual framework. In the context of economic development, the environment is that composite of goods, services, and constraints offered by surrounding ecosystems. An ecosystem is a coherent set of interlocking relationships between and among living things and their environments. For example, a forest is an ecosystem that offers goods, including trees that provide lumber, fuel, and fruit. The forest may also provide services in the form of water storage and flood control, wildlife habitat, nutrient storage, and recreation. The forest, however,

Earthquakes

Earthquakes are caused by the sudden release of slowly accumulated strain energy along a fault in the earth's crust . Earthquakes and volcanoes occur most commonly at the collision zone between tectonic plates. Earthquakes represent a particularly severe threat due to the irregular time intervals between events, lack of adequate forecasting, and the hazards associated with these:

- Ground shaking is a direct hazard to any structure located near the earthquake's center. Structural failure takes many human lives in densely populated areas.
- Faulting, or breaches of the surface material, occurs as the separation of bedrock along lines of weakness.
- Landslides occur because of ground shaking in areas having relatively steep topography and poor slope stability.
- Liquefaction of gently sloping unconsolidated material can be triggered by ground shaking. Flows and lateral spreads (liquefaction phenomena) are among the most destructive geologic hazards.
- Subsidence or surface depressions result from the settling of loose or unconsolidated sediment. Subsidence occurs in waterlogged soils, fill, alluvium, and other materials that are prone to settle.
- Tsunamis or seismic sea waves, usually generated by seismic activity under the ocean floor, cause flooding in coastal areas and can affect areas thousands of kilometers from the earthquake center.

Volcanoes

Volcanoes are perforations in the earth's crust through which molten rock and gases escape to the surface. Volcanic hazards stem from two classes of eruptions:

- Explosive eruptions which originate in the rapid dissolution and expansion of gas from the molten rock as it nears the earth's surface. Explosions pose a risk by scattering rock blocks, fragments, and lava at varying distances from the source.
- Effusive eruptions where material flow rather than explosions is the major hazard. Flows vary in nature (mud, ash, lava) and quantity and may originate from multiple sources. Flows are governed by gravity, surrounding topography, and material viscosity.

Hazards associated with volcanic eruptions include lava flows, falling ash and projectiles, mudflows, and toxic gases. Volcanic activity may also trigger other natural hazardous events including local tsunamis, deformation of the landscape, floods when lakes are breached or when streams and rivers are dammed, and tremor-provoked landslides.

Landslides

The term landslide includes slides, falls, and flows of unconsolidated materials. Landslides can be triggered by earthquakes, volcanic eruptions, soils saturated by heavy rain or groundwater rise, and river undercutting. Earthquake shaking of saturated soils creates particularly dangerous conditions. Although landslides are highly localized, they can be particularly hazardous due to their frequency of occurrence. Classes of landslide include:

- Rockfalls, which are characterized by free-falling rocks from overlying cliffs. These often collect at the cliff base in the form of talus slopes which may pose an additional risk.
- Slides and avalanches, a displacement of overburden due to shear failure along a structural feature. If the displacement occurs in surface material without total deformation it is called a slump.
- Flows and lateral spreads, which occur in recent unconsolidated material associated with a shallow water table. Although associated with gentle topography, these liquefaction phenomena can travel significant distances from their origin.

The impact of these events depends on the specific nature of the landslide. Rockfalls are obvious dangers to life and property but, in general, they pose only a localized threat due to their limited areal influence. In contrast, slides, avalanches, flows, and lateral spreads, often having great areal extent, can result in massive loss of lives and property. Mudflows, associated with volcanic eruptions, can travel at great speed from their point of origin and are one of the most destructive volcanic hazards.

like any physical resource, also has its constraints. It requires a fixed period of time in which to reproduce itself, and it is vulnerable to wildfires and blights. These vulnerabilities, or natural hazards, constrain the development potential of the forest ecosystem.

A survey of environmental constraints, whether focused on urban, rural, or wildland ecosystems, includes (1) the nature and severity of resource degradation; (2) the underlying causes of the degradation, which include the impact of both natural phenomena and human use; and (3) the range of feasible economic, social, institutional, policy, and financial interventions designed to retard or alleviate degradation. In this sense, too, natural hazards must be considered an integral aspect of the development planning process.

Recent development literature sometimes makes a distinction between "environmental projects" and "development projects." "Environmental projects" include objectives such as sanitation, reforestation, and flood control, while "development projects" may focus on potable water supplies, forestry, and irrigation. But the project-by-project approach is clearly an ineffective means of promoting socioeconomic well-being. Development projects, if they are to be sustainable, must incorporate sound environmental management. By definition, this means that they must be designed to improve the quality of life and to protect or restore environmental quality at the same time and must also ensure that resources will not be degraded and that the threat of natural hazards will not be exacerbated. In short, good natural hazard management is good development project management.

Indeed, in high-risk areas, sustainable development is only possible to the degree that development planning decisions, in both the public and private sectors, address the destructive potential of natural hazards. This approach is particularly relevant in post-disaster situations, when tremendous pressures are brought to bear on local, national, and international agencies to replace, frequently on the same site, destroyed facilities. It is at such times that the pressing need for natural hazard and risk assessment information and its incorporation into the development planning process become most evident.

To address hazard management, specific action must be incorporated into the various stages of the integrated development planning study: first, an assessment of the presence and effect of natural events on the goods and services provided by natural resources in the plan area; second, estimates of the potential impact of natural events on development activities; and third, the inclusion of measures to reduce vulnerability in the proposed development activities. Within this framework, "lifeline" networks should be identified: components or critical segments of production facilities, infrastructure, and support systems for human settlements, which should be as nearly invulnerable as possible and be recognized as priority elements for rehabilitation following a disaster.

3. THE IMPACT OF NATURAL HAZARDS CAN BE REDUCED

Experiences both in and out of Latin American and the Caribbean show that the record of hazard mitigation is improving. The installation of warning systems in several Caribbean countries has reduced the loss of human life due to hurricanes. Prohibition of permanent settlement in floodplains, enforced by selective insurance coverage, has significantly reduced flood damage in many vulnerable areas.

In the field of landslide mitigation, a study in the State of New York (U.S.A.) showed that improved procedures from 1969 to 1975 reduced the cost of repairing landslide damage to highways by over 90 percent (Hays, 1981). Experience of the city of Los Angeles, California, indicates that adequate grading and soil analysis ordinances can reduce landslide losses by 97 percent (Petak and Atkisson, 1982).

A study in the San Fernando Valley, California, after the 1971 earthquake showed that of 568 older school buildings that did not satisfy the requirements of the Field Act (a law stipulating design standards), 50 were so badly damaged that they had to be demolished. But all of the 500 school buildings that met seismic-resistance standards suffered no structural damage (Bolt, 1988). The Loma Prieta earthquake in 1989 was the costliest natural disaster in U.S. history, but provisions in local zoning and building codes kept it from being even worse. In the San Francisco Bay area post-1960 structures swayed but stayed intact, while older buildings did not fare nearly as well. Unreinforced masonry structures suffered the worst damage. Buildings on solid ground were less likely to sustain damage than those constructed on landfill or soft mountain slopes (King, 1989).

Mitigation techniques can also lengthen the warning period before a volcanic eruption, making possible the safe evacuation of the population at risk. Sensitive monitoring devices can now detect increasing volcanic activity months in advance of an eruption. Still more sophisticated assessment, monitoring, and alert systems are becoming available for volcanic eruption, hurricane, tsunami, and earthquake hazards.

Sectoral hazard assessments conducted by the OAS of, among others, energy in Costa Rica and agriculture in Ecuador have demonstrated the savings

Flooding

Two types of flooding can be distinguished: (1) land-borne floods, or river flooding, caused by excessive run-off brought on by heavy rains, and (2) sea-borne floods, or coastal flooding, caused by storm surges, often exacerbated by storm run-off from the upper watershed. Tsunamis are a special type of sea-borne flood.

a. Coastal flooding

Storm surges are an abnormal rise in sea water level associated with hurricanes and other storms at sea. Surges result from strong on-shore winds and/or intense low pressure cells and ocean storms. Water level is controlled by wind, atmospheric pressure, existing astronomical tide, waves and swell, local coastal topography and bathymetry, and the storm's proximity to the coast.

Most often, destruction by storm surge is attributable to:

- Wave impact and the physical shock on objects associated with the passing of the wave front.
- Hydrostatic/dynamic forces and the effects of water lifting and carrying objects.

The most significant damage often results from the direct impact of waves on fixed structures. Indirect impacts include flooding and undermining of major infrastructure such as highways and railroads.

Flooding of deltas and other low-lying coastal areas is exacerbated by the influence of tidal action, storm waves, and frequent channel shifts.

b. River flooding

Land-borne floods occur when the capacity of stream channels to conduct water is exceeded and water overflows banks. Floods are natural phenomena, and may be expected to occur at irregular intervals on all stream and rivers. Settlement of floodplain areas is a major cause of flood damage.

Tsunamis

Tsunamis are long-period waves generated by disturbances such as earthquakes, volcanic activity, and undersea landslides. The crests of these waves can exceed heights of 25 meters on reaching shallow water. The unique characteristics of tsunamis (wave lengths commonly exceeding 100 km, deep-ocean velocities of up to 700 km/hour, and small crest heights in deep water) make their detection and monitoring difficult. Characteristics of coastal flooding caused by tsunamis are the same as those of storm surges.

Hurricanes

Hurricanes are tropical depressions which develop into severe storms characterized by winds directed inward in a spiraling pattern toward the center. They are generated over warm ocean water at low latitudes and are particularly dangerous due to their destructive potential, large zone of influence, spontaneous generation, and erratic movement. Phenomena which are associated with hurricanes are:

- Winds exceeding 64 knots (74 mi/hr or 118 km/hr), the definition of hurricane force. Damage results from the wind's direct impact on fixed structures and from wind-borne objects.
- Heavy rainfall which commonly precedes and follows hurricanes for up to several days. The quantity of rainfall is dependent on the amount of moisture in the air, the speed of the hurricane's movement, and its size. On land, heavy rainfall can saturate soils and cause flooding because of excess runoff (land-borne flooding); it can cause landslides because of added weight and lubrication of surface material; and/or it can damage crops by weakening support for the roots.
- Storm surge (explained above), which, especially when combined with high tides, can easily flood low-lying areas that are not protected.

Hazards in Arid and Semi-Arid Areas

a. Desertification

Desertification, or resource degradation in arid lands that creates desert conditions, results from interrelated and interdependent sets of actions, usually brought on by drought combined with human and animal population pressure. Droughts are prolonged dry periods in natural climatic cycles. The cycles of dry and wet periods pose serious problems for pastoralists and farmers who gamble on these cycles. During wet periods, the sizes of herds are increased and cultivation is extended into drier areas. Later, drought destroys human activities which have been extended beyond the limits of a region's carrying capacity.

Overgrazing is a frequent practice in dry lands and is the single activity that most contributes to desertification. Dry-land farming refers to rain-fed agriculture in semiarid regions where water is the principal factor limiting crop production. Grains and cereals are the most frequently grown crops. The nature of dry-land farming makes it a hazardous practice which can only succeed if special conservation measures such as stubble mulching, summer fallow, strip cropping, and clean tillage are followed. Desertified dry lands in Latin America can usually be attributed to some combination of exploitative land management and natural climate fluctuations.

b. Erosion and Sedimentation

Soil erosion and the resulting sedimentation constitute major natural hazards that produce social and economic losses of great consequence. Erosion occurs in all climatic conditions, but is discussed as an arid zone hazard because together with salinization, it is a major proximate cause of desertification. Erosion by water or wind occurs on any sloping land regardless of its use. Land uses which increase the risk of soil erosion include overgrazing, burning and/or exploitation of forests, certain agricultural practices, roads and trails, and urban development. Soil erosion has three major effects: loss of support and nutrients necessary for plant growth; downstream damage from sediments generated by erosion; and depletion of the water storage capacity, because of soil loss and sedimentation of streams and reservoirs, which results in reduced natural stream flow regulation.

Stream and reservoir sedimentation is often the root of many water management problems. Sediment movement and subsequent deposition in reservoirs and river beds reduces the useful lives of water storage reservoirs, aggravates flood water damage, impedes navigation, degrades water quality, damages crops and infrastructure, and results in excessive wear of turbines and pumps.

c. Salinization

Saline water is common in dry regions, and soils derived from chemically weathered marine deposits (such as shale) are often saline. Usually, however, saline soils have received salts transported by water from other locations. Salinization most often occurs on irrigated land as the result of poor water control, and the primary source of salts impacting soils is surface and/or ground water. Salts accumulate because of flooding of low-lying lands, evaporation from depressions having no outlets, and the rise of ground water close to soil surfaces. Salinization results in a decline in soil fertility or even a total loss of land for agricultural purposes. In certain instances, farmland abandoned because of salinity problems may be subjected to water and wind erosion and become desertified.

Inexpensive water usually results in over-watering. In dry regions, salt-bearing ground water is frequently the major water resource. The failure to properly price water from irrigation projects can create a great demand for such projects and result in misuse of available water, causing waterlogging and salinization.

in capital and continued production that can be realized with very modest investments in the mitigation of natural hazard threats through vulnerability reduction and better sectoral planning.

However, much remains to be done. The overall record of hazard management in Latin America and the Caribbean is unimpressive for a number of reasons--among them lack of awareness of the issue, lack of political incentive, and a sense of fatalism about "natural" disasters. But techniques are becoming available, experiences are being analyzed and transmitted, the developing countries have demonstrated their interest, and the lending agencies are discussing their support. If these favorable tendencies can be encouraged, significant reduction of the devastating effects of hazards on development in Latin America and the Caribbean is within reach.

B. Susceptibility to Vulnerability Reduction

1. THE NATURE OF THE HAZARD

a. Rapid Onset vs. Slow Onset

The speed of onset of a hazard is an important variable since it conditions warning time. At one extreme earthquakes, landslides, and flash floods give virtually no warning. Less extreme are tsunamis, which typically have warning periods of minutes or hours, and hurricanes and floods, where the likelihood of occurrence is known for several hours or days in advance. Volcanoes can erupt suddenly and surprisingly, but usually give indications of an eruption weeks or months in advance. (Colombia's Volcán Ruiz gave warnings for more than a year before its destructive eruption in 1985.) Other hazards such as drought, desertification, and subsidence act slowly over a period of months or years. Hazards such as erosion/sedimentation have varying lead times: damage may occur suddenly as the result of a storm or may develop over many years.

b. Controllable Events vs. Immutable Events

For some types of hazards the actual dimensions of the occurrence may be altered if appropriate measures are taken. For others, no known technology can effectively alter the occurrence itself. For example, channelizing a stream bed can reduce the areal extent of inundations, but nothing will moderate the ground shaking produced by an earthquake.

c. Frequency vs. Severity

Where flooding occurs every year or every few years, the hazard becomes part of the landscape, and projects are sited and designed with this constraint in mind. Conversely, in an area where a tsunami may strike any time in the next 50 or 100 years, it is difficult to stimulate interest in vulnerability reduction measures even though the damage may be catastrophic. With so long a time horizon, investment in capital intensive measures may not be economically viable. Rare or low-probability events of great severity are the most difficult to mitigate, and vulnerability reduction may demand risk-aversion measures beyond those justified by economic analysis.

d. Mitigation Measures to Withstand Impact vs. Mitigation Measures to Avoid Impact

Earthquake-resistant construction and floodproofing of buildings are examples of measures that can increase the capacity of facilities to withstand the impact of a natural hazard. Measures such as zoning ordinances, insurance, and tax incentives, which direct uses away from hazard-prone areas, lead to impact avoidance.

2. THE NATURE OF THE STUDY AREA

The high density of population and expensive infrastructure of cities makes them more susceptible to the impacts of natural events. Mitigation measures are both more critically needed and more amenable to economic justification than in less-developed areas. Urban areas are likely to have or are able to establish the institutional arrangements necessary for hazard management.

For small towns and villages non-structural mitigation measures may be the only affordable alternative. Such settlements rely on the government to only a limited extent for warning of an impending hazard or assistance in dealing with it. Thus organizing the local community to cope with hazards is a special aspect of hazard management.

The physical characteristics of the land, land-use patterns, susceptibility to particular hazards, income level, and cultural characteristics similarly condition the options of an area in dealing with natural hazards.

3. THE PARTICIPANTS IN THE DRAMA

Among the "actors" involved in the process of hazard management are planning agencies, line ministries, emergency preparedness and response centers, the scientific and engineering community, local communities, technical assistance agencies, development finance agencies, and non-governmental organizations, not to mention the equally diverse list of private-sector players. Each has its own interests and

approach. These varied and sometimes conflicting viewpoints can add to the constraints of planning and putting into operation a hazard management program, but having advance knowledge of the difficulties each may present can help the practitioner deal with them.

Planning agencies are often unfamiliar with natural hazard information, or how to use it in development planning.

Line ministries similarly have little familiarity with natural hazard information or with the techniques of adapting it for use in planning. Projects for the development of road, energy, telecommunications, irrigation systems, etc., often lack hazard mitigation consideration. Furthermore, ministries tend to have little experience in collaborating with each other to identify the interrelationships between projects or to define common information requirements so that information that suits the needs of many users can be collected cooperatively.

The ***emergency preparedness community*** has tended to view its role exclusively as preparing for and reacting to emergencies and has therefore neglected linking preparedness to long-term mitigation issues. Furthermore, emergency centers have paid insufficient attention to the vulnerability of their own infrastructure. When these lifeline facilities are wiped out, disaster victims have nowhere to turn. Emergency preparedness policies are beginning to change. For example, international emergency relief organizations such as the International League of Red Cross and Red Crescent Societies have stated that they will devote more effort in developing countries to prevention.

The ***scientific and engineering community*** often sets its agenda for research and monitoring on the basis of its own scientific interests without giving due consideration to the needs of vulnerability reduction or emergency preparedness. For example, a volcano may be selected for monitoring because of its scientific research value rather than its proximity to population centers. Valuable information on hazards is often published in scientific journals in abstruse language. The scientific community should ensure that data are translated into a form suitable for use by hazard management practitioners.

Local communities are jarringly aware of the impact of natural hazards. But they usually have little opportunity to participate in the preparation of large infrastructure and production projects that impinge on them, and even less in setting agendas for natural hazard assessment and vulnerability reduction.

Technical cooperation agencies do not normally include natural hazard assessment and vulnerability reduction activities as a standard part of their project preparation process. "Hazard impact statements" that, like environmental impact statements, are conducted after the project is formulated, are not adequate. Hazard considerations must be introduced earlier in the process so that projects are prepared with these constraints in mind.

Development financing agencies engage actively in post-disaster reconstruction measures, yet do not insist on hazard assessment, mitigation, and vulnerability reduction measures in their ordinary (non-disaster-related) development loans, and are reluctant to incorporate such considerations into project evaluation.

Other institutional considerations: Knowledge of and experience with hazard management techniques are rare commodities in most agencies in Latin America and the Caribbean. Thus, if a technical cooperation agency proposes to incorporate these ideas into planning and project formulation, it invariably has to overcome the skepticism of the relevant local personnel. This adds to the cost of formulating a project, but the extra cost can pay high dividends.

Greater consideration should be given to the private sector, as is pointed out by Andrew Natsios (1990) in "Disaster Mitigation and Economic Incentives." Natsios, following Charles Schultze, claims that policy-makers can change social behavior more effectively by changing the incentives of the marketplace, i.e., the public use of private interest, than by regulation. For example, casualty insurance companies could offer a large premium differential for earthquake- and hurricane-resistant construction. He suggests that governments should specify the desired outcome of policy, but leave the method of achieving that outcome to the economic actors.

At the national level, giving a single entity total responsibility for hazard management tends to cause other agencies to see it as an adversary. Instead, each agency that formulates projects as part of its standard activities should appreciate the importance of introducing hazard considerations into the process of project formulation. Planning agencies should take an advocacy position on hazard management and on introducing non-structural mitigation strategies early in the planning process. Such agencies should have personnel trained for these functions.

Similarly, at the project level responsibility for mitigating the impact of natural hazards does not lie with a single individual or component but is an overall responsibility of the project, requiring the cooperation of all components.

Post-disaster reconstruction activities often lack support for hazard assessments intended to ensure

that the impact of the next event is less destructive. The problem lies with both the lender and the recipient: the stricken country rarely includes this item in its request, but when it does, the lending agencies often reject it. Reconstruction projects, especially when they are very large, are often managed by newly created implementation agencies. This results in a drain of the already limited supply of technical personnel from the existing agencies and complicates coordination between long-term development and short-term rehabilitation.

C. Hazard Management and Development Planning

For purposes of this discussion, development planning is considered the process by which governments produce plans--consisting of policies, projects, and supporting actions--to guide economic, social, and spatial development over a period of time. The hazard management process consists of a number of activities designed to reduce loss of life and destruction of property. Natural hazard management has often been conducted independently of development planning. A distinctive feature of OAS technical assistance is the integration of the two processes.

1. HAZARD MANAGEMENT ACTIVITIES

The natural hazard management process can be divided into pre-event measures, actions during and immediately following an event, and post-disaster measures. In approximate chronological order these are as follows:

1. Pre-event Measures:
   a. Mitigation of Natural Hazards:
      - Data Collection and Analysis
      - Vulnerability Reduction
   b. Preparation for Natural Disasters
      - Prediction
      - Emergency Preparedness (including monitoring, alert, evacuation)
      - Education and Training

2. Measures During and Immediately After Natural Disasters:
   a. Rescue
   b. Relief

3. Post-disaster Measures:
   a. Rehabilitation
   b. Reconstruction

a. Disaster Mitigation

An accurate and timely prediction of a hazardous event can save human lives but does little to reduce economic losses or social disruption; that can only be accomplished by measures taken longer in advance. Included in the concept of disaster mitigation is the basic assumption that the impact of disasters can be avoided or reduced when they have been anticipated during development planning. Mitigation of disasters usually entails reducing the vulnerability of the elements at risk, modifying the hazard-proneness of the site, or changing its function. Mitigation measures can have a structural character, such as the inclusion of specific safety or vulnerability reduction measures in the design and construction of new facilities, the retrofitting of existing facilities, or the building of protective devices. Non-structural mitigation measures typically concentrate on limiting land uses, use of tax incentives and eminent domain, and risk underwriting through insurance programs.

Many countries are making efforts to introduce mitigation measures in hazard-prone areas. For example, the coastal area of Ecuador and the northern area of Peru are often affected by severe floods caused by "El Niño" or the El Niño Southern Oscillation (ENSO) phenomenon, which recurs approximately every 3 to 16 years. Between November 1982 and June 1983, heavy rains created the most dramatic series of floods reported this century, affecting 12,000 square kilometers in this region, with total losses estimated at US$1,200 million. Subsequently, Peru transferred six of the most affected villages to higher elevations (a non-structural mitigation measure), and introduced special adobe-building techniques to strengthen new constructions against earthquakes and floods (a structural mitigation measure).

Disaster mitigation also includes the data collection and analysis required to identify and evaluate appropriate measures and include them in development planning. The data collection involves essentially three kinds of studies:

Natural Hazard Assessments

Studies that assess hazards provide information on the probable location and severity of dangerous natural phenomena and the likelihood of their occurring within a specific time period in a given area. These studies rely heavily on available scientific information, including geologic, geomorphic, and soil maps; climate and hydrological data; and topographic maps, aerial photographs, and satellite imagery. Historical information, both written reports and oral accounts from long-term residents, also helps

characterize potential hazardous events. Ideally, a natural hazard assessment promotes an awareness of the issue in a developing region, evaluates the threat of natural hazards, identifies the additional information needed for a definitive evaluation, and recommends appropriate means of obtaining it.

Vulnerability Assessments

Vulnerability studies estimate the degree of loss or damage that would result from the occurrence of a natural phenomenon of given severity. The elements analyzed include human population/capital facilities and resources such as settlements, lifelines, production facilities, public assembly facilities, and cultural patrimony; and economic activities and the normal functioning of settlements. Vulnerability can be estimated for selected geographic areas, e.g., areas with the greatest development potential or already developed areas in hazardous zones. The techniques employed include lifeline (or critical facilities) mapping and sectoral vulnerability analyses for sectors such as energy, transport, agriculture, tourism, and housing. In Latin America and the Caribbean vulnerability to natural hazards is rarely considered in evaluating an investment even though vulnerability to other risks,such as fluctuating market prices and raw-material costs, is taken into account as standard practice.

Risk Assessments

Information from the analysis of an area's hazards and its vulnerability to them is integrated in an analysis of risk, which is an estimate of the probability of expected loss for a given hazardous event. Formal risk analyses are time-consuming and costly, but short-cut methods are available which give adequate results for project evaluation. Once risks are assessed, planners have the basis for incorporating mitigation measures into the design of investment projects and for comparing project versus no-project costs and benefits.

b. Natural Hazard Prediction

Even short notice of the probable occurrence and effects of a natural phenomenon is of great importance in reducing loss of life and property. The prediction of a natural event is a direct outcome of scientific investigation into its causes and is aimed at establishing the probability of the next occurrence in terms of time, place, and range of severity. Increasingly sophisticated monitoring stations, both manned and remote, collect information of potentially hazardous events for more accurate prediction.

Some hazards, such as hurricanes and floods, can be forecast with high accuracy, but most geologic

VULNERABLE ELEMENTS THAT SHOULD BE CONSIDERED IN THE DEVELOPMENT PLANNING PROCESS

Human Settlements:
Human population and associated housing and services.

Critical Facilities:
(1) Essential services, such as telecommunications, water, energy, and sanitation; (2) emergency medical services, fire and police stations, and disaster organizations; and (3) local, national, and international transportation facilities and carriers.

Economic Production Facilities:
Major sources of livelihood of the population, such as industries, banking and commerce buildings, public markets, agroprocessing plants and areas of agricultural production, livestock, forestry, mines, and fisheries production.

Public Assembly Sites:
Buildings such as schools, churches, auditoriums, theatres, public markets, and public and private office buildings.

Cultural Patrimony:
Buildings of significant cultural and community value or use, and buildings of architectural importance.

events cannot. Alert systems for some kinds of disasters suffer from a very short lead time. In the case of tsunamis, for example, the Pacific Warning Center, which constantly monitors the oceans, provides advance notice that varies from ten minutes to a few hours. At best, these warnings provide enough time to withdraw the population, but not to take other preventive measures.

Although world-wide efforts to anticipate earthquakes persist, their prediction is still an incipient science. Few forewarnings have been as successful as the one made in February 1975 when the people of Haicheng, China, were evacuated six hours before a magnitude M.7 earthquake struck. Other predictions have been disastrous, as was the case with the erroneous warning of an imminent earthquake in Peru in 1981. Thousands of people fled, causing some deaths and long-term disruption of investment and tourism.

c. Emergency Preparedness

Emergency preparedness is aimed at minimizing the loss of life and property during a natural event. Preparedness includes actions taken in anticipation of the event and special activities both during and immediately after the event.

Two levels of preparedness can be identified: public safety information and hazard awareness planning. The first includes a number of efforts aimed at increasing the amount of information disseminatedto the public and at promoting cooperation between the public and the authorities in case of an emergency. In the course of an event, or in its aftermath, social and public behavior undergoes important changes. This results in new organizational responsibilities for the public sector. Hazard information and education programs can improve public preparedness and social conduct during a disaster.

Hazard awareness planning is concerned about improving the ability of a particular area, region, or nation to respond to natural disasters. Disaster preparedness promotes the development of a system for monitoring known hazards, a warning system, emergency and evacuation plans, emergency routes, and the formulation of educational programs for public officials and professionals. Many Latin America and Caribbean countries are developing and adopting emergency plans in order to identify and effectively mobilize human and national resources in case of a disaster.

d. Disaster Rescue and Relief

After a natural calamity, local residents usually undertake the first relief activities. However, their efforts must usually be complemented with those of national or regional authorities. The keystones of post-disaster relief are the preparation of lifelines or critical facilities for emergency response, training, disaster rehearsals, and the identification and allocation of local and external resources.

Relief activities are affected by broad-scale planning decisions, but they are not a part of the mainstream national and regional planning processes. Although relief and disaster preparedness receive the most resources at the international, national, regional, and local levels, cost-effective mitigation measures are not adequately considered. This lack of forethought exacerbates the effects of natural disasters in terms of loss of life and property. Meanwhile, natural disasters continue to occur worldwide, and the number of people affected is increasing faster than the population growth rate.

e. Post-Disaster Rehabilitation and Reconstruction

Concurrent with or immediately after relief activities, post-disaster rehabilitation is carried out to restore the normal functions of public services, business, and commerce, to repair housing and other structures, and to return production facilities to operation. However, mitigation is often ignored in this phase: rehabilitation proceeds without any measures to reduce the chances of the same impact if the event happens again. In developing countries, road systems that are flooded or blocked by landslides year after year are commonly rebuilt at the same site and with similar design specifications.

In considering reconstruction costs, existing development policies and sectoral projects need to be reevaluated. In many cases, they are no longer appropriate or do not coincide with the best use of natural resources. For this reason, the natural hazard management process must examine any changes in the resources, goals, objectives, and products of development plans and incorporate these factors into subsequent planning activities.

f. Education and Training Activities

Education and training, both formal and informal, prepare people at all levels to participate in hazard management. Universities, research centers, and international development assistance agencies play the leading formal role in preparing individuals in a variety of skill levels such as natural hazards assessment, risk reduction, and natural phenomena prediction. These activities are also carried out by operational entities such as ministries of agriculture, transportation, public works, and defense.

Informal learning can be delivered through brochures, booklets, and audio and video tapes

prepared by national and international agencies involved in disaster preparedness and mitigation programs, and through the national media. Additionally, courses, workshops, conferences, and seminars organized by national and international disaster assistance agencies disseminate great amounts of information on natural hazard management strategies.

Finally, direct observation after a disaster has proved to be one of the most effective means of learning. Post-disaster investigations describe the qualitative and quantitative aspects of natural hazards, often improving on information produced by modelling and conjecture by indicating areas where development should be extremely limited or should not take place. A direct outcome of the learning process is (1) the improvement of policies and program actions, building codes, standards, construction and design skills; (2) the development of legislation to mandate the adoption of these policies and the strengthening or creation of new disaster organizations; (3) the improvement of the key logistical aspects of disaster prevention, such as communication and warning systems; and (4) the establishment of community and resource organizations to confront future disasters.

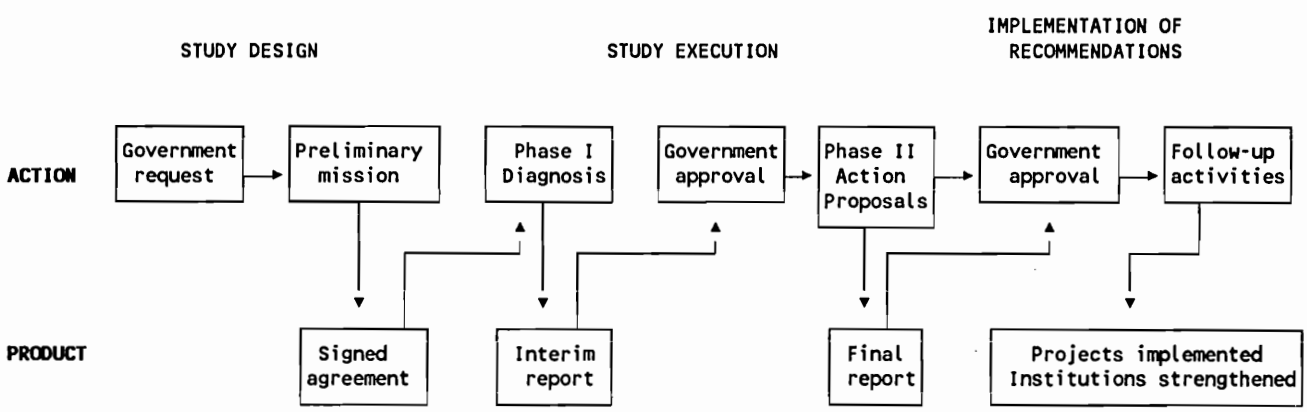
2. INCORPORATING MITIGATION MEASURES INTO THE STAGES OF AN INTEGRATED DEVELOPMENT PLANNING STUDY

Integrated development planning is a multidisciplinary, multisectoral approach to planning. Issues in the relevant economic and social sectors are brought together and analyzed vis-a-vis the needs of the population and the problems and opportunities of the associated natural resource base. A key element of this process is the generation of investment projects, defined as an investment of capital to create assets capable of generating a stream of benefits over time. A project may be independent or part of a package of projects comprising an integrated development effort. The process of generating projects is called the project cycle. This process proceeds from the establishment of development policies and strategies, the identification of project ideas, and the preparation of project profiles through prefeasibility and feasibility analyses (and, for large projects, design studies) to final project approval, financing, implementation, and operation.

While the process is more or less standardized, each agency develops its own version. The development planning process evolved by the OAS/DRDE consists of four stages: Preliminary Mission, Phase I (development diagnosis), Phase II (project formulation and preparation of an action plan), and Implementation. Because the process is cyclical, activities relating to more than one stage can take place at the same time. The main elements of the process are shown in Figure 1-2, and a synthesis of the activities and products of each stage is shown in Figure 1-3. A comprehensive set of guidelines for executing a study following this process is given in *Regional Development Planning: Guidelines and Case Studies from OAS Experience.*

Figure 1-2

KEY ELEMENTS IN THE PROCESS OF OAS ASSISTANCE FOR INTEGRATED REGIONAL DEVELOPMENT PLANNING



Source: OAS. Integrated Regional Development Planning: Guidelines and Case Studies from OAS Experience (Washington, D.C.: OAS, 1984).

Figure 1-3

SYNTHESIS OF THE OAS INTEGRATED DEVELOPMENT PLANNING PROCESS

COMPONENTS	STUDY DESIGN	STUDY EXECUTION		IMPLEMENTATION OF THE RECOMMENDATIONS
		PHASE I Development Diagnosis	PHASE II Project Formulation and Preparation of Action Plan	
Activities:	Receipt and analysis of request for cooperation Preliminary Mission - pre-diagnosis - cooperation agreement preparation	Diagnosis of the region - sectoral analysis - spatial analysis - institutional analysis - environmental analysis - synthesis: needs, problems, potentials, constraints Relation to national plans, strategies and priorities Development strategies - formulation and analysis of alternatives - identification of project ideas, preparation of project profiles	Project formulation (pre-feasibility or feasibility) and evaluation - production sectors (agriculture, forestry, agroindustry, industry, fishing, mining) - support services (marketing, credit, extension) - social development (housing, education, labor training, health) - infrastructure (energy, transportation, communications) - urban services - natural resource management Action plan preparation - formulation of project packages - determination of policies for priority areas and sectors - enabling and incentive actions - investment timetable - evaluation of funding sources - institutional development and training - promotion	Assistance for specific programs and projects Assistance in incorporating proposed investments into the national budget Advisory services for private sector actions Support to executing agencies Support in the inter-institutional coordination
Products:	Signed agreement - definition of the study products - financial commitments of participants - preliminary workplan	Interim Report (Phase I) - diagnosis of the region - preliminary development strategy - identified projects	Final Report - development strategy - action plan - formulated projects - supporting actions	Execution by government of - final design studies - project implementation - changes in legislation and regulations Improved operational capability of institutions
Time Frame:	3 to 6 months	9 to 12 months	12 to 18 months	Variable

This presentation of the procedures of an integrated study features the incorporation of hazard management considerations at each stage. The relationships of the integrated development planning process, the hazard management process, and the project cycle are summarized in Figure 1-4.

Generally, planners depend on the science and engineering community to provide the required information for natural hazard assessments. If the information available is adequate, the planner may decide to make an assessment. If it is not adequate, the planner usually decides that the time and cost of generating more would be excessive, and the assessment is not made. While the information available on hurricanes and geologic hazards is often adequate for a preliminary evaluation, the information on desertification, flooding, and landslide hazards rarely is. The OAS has developed fast, low-cost methodologies that make these evaluations possible in the context of a development study. The differences in treating the various hazards in each stage of the process are highlighted in the following discussion.

a. Preliminary Mission: Designing the Study

The first step in the process of technical assistance for an integrated development planning study is to send a "preliminary mission" to consult with officials in the interested country. Experience has shown that this joint effort of OAS staff and local planners and decision-makers is frequently the most critical event in the entire study. They take action to:

- Determine whether the study area is affected by one or more natural hazards. For example, the National Environmental Study of Uruguay conducted by the OAS with financial support from the Inter-American Development Bank determined in the preliminary mission that natural hazards were an important environmental problem, and consequently an assessment of all significant hazards, to be conducted by reviewing existing information, was programmed for Phase I.

- Identify the information available for judging the threat posed by those hazards in the study area:

FRAMEWORK FOR THE INCORPORATION OF NATURAL HAZARD ASSESSMENT INTO PROJECT PREPARATION STRATEGIES DURING THE PRELIMINARY MISSION

QUESTIONS PLANNERS NEED TO ASK:

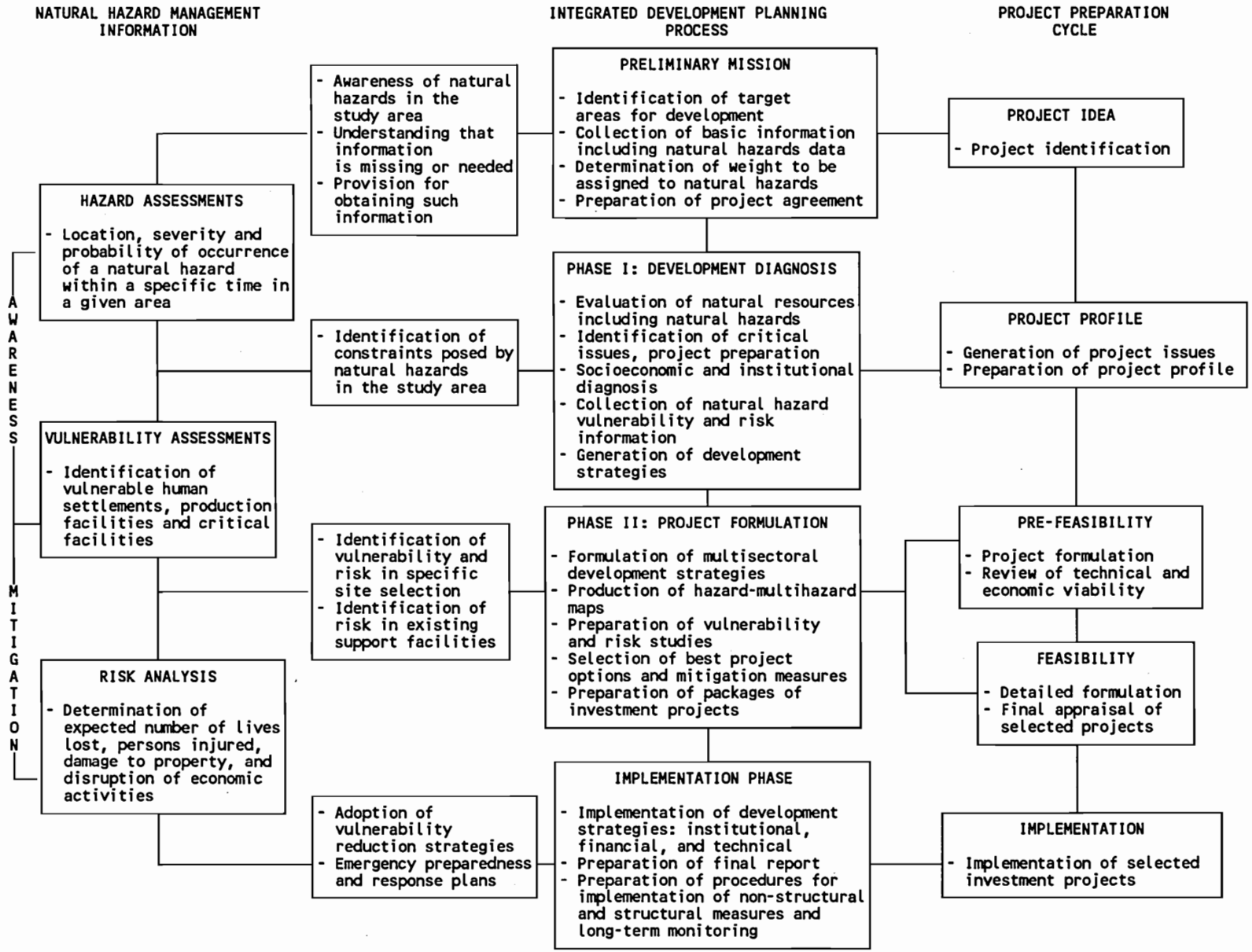
- Is there a history of significant natural hazards in the study area?
- What is the likelihood of occurrence of natural hazard phenomena during the time frame of the development project?
- If hazards pose a threat, what is their expected severity, frequency, and the demarcation of the affected zone?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Natural hazards are (or are not) a threat in the study area and therefore consideration of hazards should (or should not) be included in the development planning process.
- Natural hazards identified in the study should be considered in the definition and design of the planning framework, spatial context, study goals, and project procedures management.
- The workplan should include the financial and personnel resources needed for obtaining the appropriate hazard information in the various stages of project design and formulation.
- If natural hazard phenomena are found to constitute a significant threat to the study area, mitigation efforts should be built into the study design or alternatives to development should be proposed.
- If the information available is insufficient for a recommendation on the above decisions in the Preliminary Mission, Phase I should include the necessary data collection effort so that appropriate recommendations can be made.

Figure 1-4

INTEGRATED DEVELOPMENT PLANNING PROCESS, NATURAL HAZARD MANAGEMENT, AND THE PROJECT CYCLE



FRAMEWORK FOR INCORPORATING INFORMATION ON VULNERABILITY TO NATURAL HAZARDS IN THE PREPARATION OF PROJECT PROFILES DURING PHASE I

QUESTIONS PLANNERS NEED TO ASK:

- Is the project area vulnerable to natural hazards? Which ones?
- Do natural hazards currently constitute a significant constraint in determining a development strategy and identifying projects?
- Are modifications in the project study needed at this stage? Which ones?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Can non-structural mitigation measures be included as part of the development strategy? Which ones?
- Is it likely that structural mitigation measures will have to be considered?
- What mechanism will be used to incorporate the vulnerability assessment information into the overall study activities?
- Would mitigation measures hinder project implementation? What is the social cost of a decision of this nature? How can such an outcome be avoided?
- How and by whom can the assessment information be summarized for project formulation and action plan preparation?
- Is more information on hazardous events and critical facilities in the project area needed for the next stage of project formulation? How will this information be collected?
- Should the design of the planning framework, spatial context, and management structure be reevaluated and mitigation strategies incorporated into project formulation and action plans?

history of hazardous events; disaster and damage reports; assessments of hazards, vulnerability, risk; maps and reports on natural resources and hazards; topographic maps, aerial photographs, satellite imagery.

- Determine whether the available data are sufficient to evaluate the threat of hazards. If they are not, determine what additional data collection, hazard assessment, remote sensing, or specialized equipment will be needed for the next stage of the study. For example, in preliminary missions in Dominica, Saint Lucia, and St. Vincent and the Grenadines, landslides were determined to be a serious problem, and landslide assessments were included in the work plan for Phase I.

- Determine whether the studies required would serve more than one sector or project. If so, establish coordination.

- Establish coordination with the national institution responsible for disaster planning.

- Prepare an integrated work plan for Phase I that specifies the hazard work to be done, the expertise needed, and the time and cost requirements.

b. Phase I: Development Diagnosis

In Phase I, the team analyzes the study region and arrives at detailed estimates of development potentials and problems of the region and selected target areas. From this analysis a multisectoral development strategy and a set of project profiles are prepared for review by government decision-makers. Phase I also includes a detailed assessment of natural hazards and the elements at risk in highly vulnerable areas which facilitates the early introduction of non-structural mitigation measures. During this phase the team will:

- Prepare a base map.

- Determine the goods, services, and hazards of the region's ecosystems. Identify cause-and-effect relationships between natural events and between

natural events and human activity. In the hilly Chixoy region of Guatemala, for example, it was found that inappropriate road construction methods were causing landslides and that landslides, in turn, were the main problem of road maintenance. In Ecuador, the discovery that most of the infrastructure planned for the Manabí Water Development Project was located in one of the country's most active earthquake zones prompted a major reorientation of the project.

- Evaluate socioeconomic conditions and institutional capacity. Determine the important linkages between the study region and neighboring regions.

- Delineate target areas of high development potential, followed by more detailed natural resource and socioeconomic studies of these areas.

- In planning the development of multinational river basins or border areas where a natural disaster could precipitate an international dispute, make an overall hazard assessment as part of the resource evaluation. Examples of such studies include those for the development of the San Miguel-Putumayo River Basin, conducted in support of the Colombia-Ecuador Joint Commission of the Amazon Cooperation Project, and for the Dominican Republic and Haiti Frontier Development Projects.

- Conduct assessments of natural hazards determined to be a significant threat in the study region. For hurricanes and geologic hazards, the existing information will probably suffice; if the information on geologic hazards is inadequate, an outside agency should be asked to conduct an analysis. For flooding, landslides, and desertification, the planning team itself should be able to supplement the existing information and prepare analyses. The studies of the Honduran departments of Atlántida and Islas de la Bahía included flood hazard assessment as part of the coastal area development plan and landslide hazard assessments for some of the inland areas.

- Conduct vulnerability studies for specific hazards and economic sectors. Prepare lifeline maps, hazard zoning studies, and multiple hazard maps as required. The study of the vulnerability of the Ecuadorian agriculture sector to natural hazards and of ways to reduce the vulnerability of lifelines in St. Kitts and Nevis, for example, both generated project ideas which could be studied at the prefeasibility level in Phase II. The study of the Paraguayan Chaco included flood and desertification assessments and multiple-hazard zoning. The execution of these hazard-related activities did not distort the time or cost of the development diagnosis.

- Identify hazard-prone areas where intensive use should be avoided.

- Prepare a development strategy, including non-structural mitigation measures as appropriate.

- Identify project ideas and prepare project profiles that address the problems and opportunities and that are compatible with political, economic, and institutional constraints and with the resources and time frame of the study.

- Identify structural mitigation measures that should be incorporated into existing facilities and proposed projects.

- Prepare an integrated work plan for the next stage that includes hazard considerations.

c. Phase II: Project Formulation and Action Plan Preparation

At the end of Phase I a development strategy and a set of project profiles are submitted to the government. Phase II begins after the government decides which projects merit further study. The team now makes prefeasibility and feasibility analyses of the projects selected. Refined estimates are made of benefits (income stream, increases in production, generation of employment, etc.) and costs (construction, operation and maintenance, depletion of resources, pollution effects, etc.). Valuative criteria are applied, including net present value, internal rate of return, cost-benefit ratio, and repayment possibilities. Finally, the team assembles packages of investment projects for priority areas and prepares an action plan. More detail on this phase is given in the section on Hazard Mitigation Strategies for Development Projects, but broadly speaking the team must:

- Examine the human activities that could contribute to natural hazards (e.g., irrigation, plowing in the dry season, and animal husbandry could cause or exacerbate desertification) and the social and cultural factors that could influence project vulnerability during and after implementation.

- Determine the levels of technology, credit, knowledge, information, marketing, etc., that it is realistic to expect will be available to the users of the land, and ensure that the projects formulated are based on these levels.

KEY PROPOSITIONS FOR THE INCORPORATION OF VULNERABILITY INFORMATION ON SELECTED AREAS DURING PROJECT FORMULATION IN PHASE II

QUESTIONS PLANNERS NEED TO ASK:

- To what degree do hazards pose a significant risk to existing or proposed development projects?
- Is the information resulting from Phase I sufficient to proceed with investment project formulation? If not, will additional assessment activities take place within or outside of the planning study?
- Which areas should be included in any additional assessment?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Who will be responsible for incorporating additional information in project formulation activities?
- Are there certain non-structural mitigation measures that should be included in the formulation of investment projects, such as regulation of land use, warning systems, and the creation of hazard-oriented organizations?
- Should structural mitigation measures be considered as part of project investment? How much would they cost? Are they economically, socially, and politically feasible?
- Who will carry out the mitigation measures identified in the project?
- How and by whom will risk information be incorporated into study documents?
- What complementary activities should the study team carry out to maximize the use of the hazard assessment and mitigation information by potential funders and disaster-oriented institutions?

- Prepare site-specific vulnerability and risk assessments and appropriate vulnerability reduction measures for all projects being formulated. For example, the multimillion-dollar program for the development of the metropolitan area of Tegucigalpa, Honduras, featured landslide mitigation components. Flood alert and control projects were central elements in the comprehensive Water Resource Management and Flood Disaster Reconstruction Project for Alagoas, Brazil.

- Mitigate the undesirable effects of the projects, avoid development in susceptible areas, recommend adjustments to existing land use and restrictions for future land use.

- Examine carefully the compatibility of all projects and proposals.

- Define the specific instruments of policy and management required for the implementation of the overall strategy and the individual projects; design appropriate monitoring programs.

d. Implementing the Study Recommendations

The fourth stage of the development planning process helps implement the proposals by preparing the institutional, financial, and technical mechanisms necessary for successful execution and operation. Efforts made to consider hazards in previous stages will be lost unless mitigation measures are closely adhered to during the projects' execution. Either the planning agency or the implementing agency should:

- Ensure that suitable hazard management mechanisms have been included in all investment projects; provide for monitoring of construction to insure compliance with regulations, and for on-going monitoring to ensure long-term compliance with project design.

- Ensure that national disaster management organizations have access to the information generated by the study. Point out hazardous situations for which the study did not propose vulnerability reduction measures.

PROJECT IMPLEMENTATION

QUESTIONS PLANNERS NEED TO ASK:

- How are mitigation and risk information be used in project funding approval and implementation activities?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- How and by whom will mitigation and risk information be integrated into the project funding and implementation of activities?
- Which institutions are responsible for the update, control, and dissemination of new and existing information?

- Arrange for the continuing collection of hazard data and the updating of information of planning and emergency preparedness agencies.

- Prepare legislation mandating zoning codes and restrictions, building and grading regulations, and any other legal mechanisms required.

- Include adequate financing for hazard mitigation measures.

- Involve the private sector in the vulnerability reduction program.

- For community-based vulnerability reduction programs, establish national training and hazard awareness programs for town and village residents, a feature of OAS technical assistance programs for Saint Lucia and Grenada.

- Generate broad-based political support through the media, training programs, and contacts with community organizations. Use products of the studies (photos, maps, charts, etc.) for mass communication. Use personnel who participated in the studies in public meetings to promote the concept of vulnerability reduction.

- Accelerate the implementation of projects that include hazard mitigation considerations; if budget cutbacks occur, reduce the number of projects rather than dropping the hazard mitigation components.

3. ADVANTAGES OF INTEGRATED DEVELOPMENT PLANNING FOR HAZARD MANAGEMENT

Even though integrated development planning and hazard management are usually treated in Latin America and the Caribbean as parallel processes that intermix little with each other, it is clear that they should be able to operate more effectively in coordination, since their goals are the same--the protection of investment and improved human well-being--and they deal with similar units of space. Some of the advantages of such coordination are the following:

- There is a greater possibility that vulnerability reduction measures will be implemented if they are part of a development package. The possibility increases if they are part of specific development projects rather than stand-alone disaster mitigation proposals. Furthermore, including vulnerability reduction components in a development project can improve the cost-benefit of the overall project if risk considerations are included in the evaluation. A dramatic example is the case study on vulnerability reduction for the energy sector in Costa Rica.

- Joint activities will result in a more efficient generation and use of data. For example, geographic information systems created for hazard management purposes can serve more general planning needs.

- The cost of vulnerability reduction is less when it is a feature of the original project formulation than when it is incorporated later as a modification of the project or an "add-on" in response to a "hazard impact analysis." It is even more costly when it is treated as a separate "hazard project," independent of the original development project, because of the duplication in personnel, information, and equipment.

- Exchanging information between planning and emergency preparedness agencies strengthens the work of the former and alerts the latter to

elements whose vulnerability will not be reduced by the proposed development activities. In the Jamaica study of the vulnerability of the tourism sector to natural hazards, for example, solutions were proposed for most of the problems identified, but no economically viable solutions were found for others. The industry and the national emergency preparedness agency were so warned.

- With its comprehensive view of data needs and availability, the planning community can help set the research agenda of the science and engineering community. For example, when a planning team determines that a volcano with short-term periodicity located close to a population center is not being monitored, it can recommend a change in the priorities of the agency responsible.

- Incorporating vulnerability reduction into development projects builds in resiliency for the segment of the population least able to demand vulnerability reduction as an independent activity. A clear example of this situation was the landslide mitigation components of the metropolitan Tegucigalpa study: the principal beneficiaries were the thousands of the city's poor living in the most hazard-prone areas.

D. Hazard Management in Selected Economic Sectors

The managers of public and private sectoral agencies share a concern about the vulnerability of their sectors to hazardous events: What hazards threaten which services? Where are the weak links? How much damage might be done? How would the damage affect sector investment, income, employment, and foreign currency earnings? What is the impact of losing *x* service in *y* city for *z* days? What investment in mitigation would resolve that problem? What is the cost/benefit of that investment? In the experience of the OAS the sectors that can benefit most from vulnerability assessments are energy, transport, tourism, and agriculture, since these sectors typify problems of disaster impact faced by developing countries.

Presented below are case studies of hazard assessments for the energy sector, the tourism sector, and the agriculture sector. The section ends with some strategies for conducting such assessments for selected economic sectors.

1. ENERGY IN COSTA RICA

In 1989 the Costa Rican Sectoral Directorate of Energy asked the OAS to assist in analyzing the vulnerability of the energy sector to natural hazards. The study first defined the nature of possible impacts. These included:

- Loss of infrastructure; associated investment losses
- Loss of income to the sector from forgone energy sales
- Effect on the production of goods and services; associated losses of employment income
- Loss of foreign exchange
- Negative impact on the quality of life

It was clear that the study would have to cover not only the energy subsectors, but also the service and economic sectors that could affect or be affected by energy supply. Thus it included the electric power system, the hydrocarbon system, railroads, roads, telecommunications, the metropolitan aqueduct, and the major economic production sectors. Existing information was analyzed for earthquakes, volcanic eruptions, landslides, hurricanes, flooding, drought, and erosion.

To evaluate the vulnerability of each facility, the study used two methods simultaneously: field examination and the preparation of a geographic information system which could overlay each hazard with each energy and service system. Figure 1-5 shows one of the GIS overlays: landslide threats to transmission lines. Matrices prepared to show impacts were rated as follows:

- No impact
- Potential threat, major or minor
- Confirmed threat, major or minor

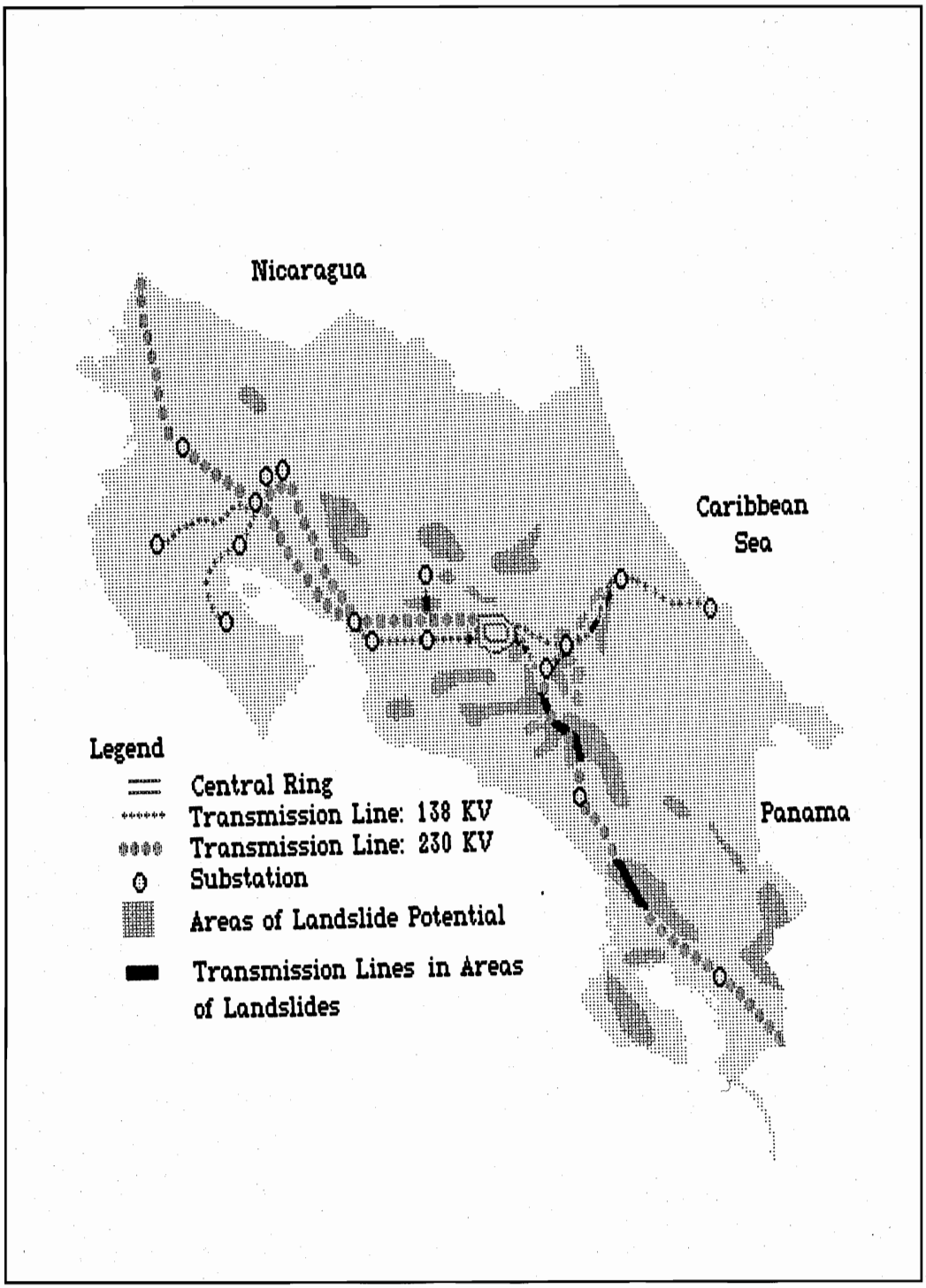
A rapid examination of the threats yielded a number of serious problems. The confirmed major impacts caused by each hazard in each sector are shown in Figure 1-6. The most important problems were studied in greater detail and actions to deal with them were recommended. Some examples follow.

- The worst event would be a strong earthquake or volcanic eruption that breached Arenal dam or crippled the Arenal and Corobici hydroelectric plants, cutting off half of the hydropower in the country. The probability of such an event is low, but the magnitude of the catastrophe is so great it has to be planned for. The report recommended contingency plans for emergency generation and the establishment of new power plants outside the Arenal system.

- Two critical substations and two transmission lines are threatened by earthquakes, landslides, volcanic eruptions, flooding, and severe windstorms. The

Figure 1-5

COSTA RICA: ENERGY SECTOR VULNERABILITY TO LANDSLIDE HAZARDS



Source: Adapted from Departamento de Desarrollo Regional/Organización de los Estados Americanos (OEA) and Dirección Sectorial de Energía/Ministerio de Recursos Naturales, Energía y Minas de Costa Rica (MIRENEM). Amenazas Naturales y la Infraestructura Energética de Costa Rica (San José, Costa Rica: unpublished report, 1989).

Figure 1-6

NUMBER OF CONFIRMED MAJOR IMPACTS OF NATURAL HAZARDS ON ENERGY FACILITIES IN COSTA RICA

	Electric Power Subsector				Oil and Gas Subsector[a]		Transport Sector	
	Hydropower plants	Thermal plants	Transmission lines	Substations	Refinery	Pipelines	Railroads	Roads
Earthquakes	--	--	--	15	--	1	--	3
Landslides[b]	--	--	15	8	--	4	6	15
Hurricanes								
Flooding	--	1	4	4	--	--	4	--
Wind	--	--	4	2	1	--	4	--
River flooding	1	1	4	2	--	--	7	1
Erosion	--	--	--	--	--	--	2	--

[a] No confirmed major impacts on port or substations
[b] Caused by earthquakes, volcanic eruptions, flooding, hurricanes

Source: Adapted from Departamento de Desarrollo Regional/Organización de los Estados Americanos (OEA) and Dirección Sectorial de Energía/Ministerio de Recursos Naturales, Energía y Minas de Costa Rica (MIRENEM). Amenazas Naturales y la Infraestructura Energética de Costa Rica. (San José, Costa Rica: unpublished report, 1989).

multiple hazards make the probability of occurrence moderate, and the loss of any of these components would cut off power from the Arenal system to the central region. The report recommended building an alternate transmission line that would bypass the four components.

- Landslides periodically damage one segment of the railroad that carries heavy petroleum derivatives from the refinery on the Atlantic Coast to a critical substation in San José. Since having the substation out of commission for a long time would be a major catastrophe for the region and rerouting the railroad would be too expensive, the report recommended equipping a West Coast port with facilities for handling a substitute supply which could be trucked to San José.

The Government found the recommendations valid and is now seeking financing for feasibility studies of the most critical ones. It is noteworthy that so many serious problems could be identified in a three-month study and, more importantly, that many were amenable to mitigation by relatively modest investments.

2. TOURISM IN JAMAICA

The geographic and climatic setting of the Caribbean and the siting of tourism projects on or near the beaches combine to make Caribbean tourism especially vulnerable to disruption from natural disasters. In the island countries hurricanes are the most damaging hazard, but land-based flooding, landslides, earthquakes, and wildfires also exact a toll.

Direct damage caused by Hurricane Gilbert to property and equipment of the tourism industry amounted about US$85 million. The indirect damage was much greater. In foreign exchange alone the cost from September to December 1988 was US$90 million --a particularly painful loss since the foreign exchange was needed to finance recovery programs. The temporary closing of hotels for repairs meant fewer visitors to the island, causing other indirect effects such as loss of income for the national airline and reduction in employment and the purchase of local goods and services.

The vulnerability of the tourism industry is not confined to its own capital stock, as was demonstrated by the Jamaican experience. Damage to roads, utilities, airports, harbors, and shopping centers also affected the industry. Conscious of the need to minimize damage from future events, the Government of Jamaica requested OAS technical cooperation in preparing an assessment of the vulnerability of the tourism sector to natural hazards and recommending mitigation actions.

The assessment disclosed that much of the damage to tourism facilities, as to other buildings, was due to lack of attention to detail in construction and maintenance, particularly in roof construction. Roof sheeting was poorly interlocked. Tie-downs of roof structures were inadequate. Nail heads were rusted off. Timber strength was reduced by termites, and metal strength by corrosion. Much glass was needlessly blown out because of faulty installation and poor design criteria, but also because windows were not protected from flying debris. Drains clogged with debris caused excessive surface runoff, resulting in erosion and scouring around buildings. Local water shortages developed because the lack of back-up generators prevented pumping. Although a major contributor to the damage, faulty building practices and maintenance deficiencies are easy to correct: it was calculated that proper attention to these matters would have increased the cost of construction less than 1 percent.

Long-term mitigation measures were also identified. The study recommended the protection of beach vegetation, sand dunes, mangroves, and coral reefs, all of which help to protect the land from wave and wind action. New construction sites should be evaluated for susceptibility to hazards. Setback distance from the shore should be enforced, and the quality of sewage outfall should be maintained to protect live coral formations.

In short, the preliminary study, conducted in one month, identified a number of possible actions that would substantially reduce the impact of future hurricanes and other natural hazards. The preliminary analysis indicated that many of these actions would have a high cost-benefit ratio. Subsequently, Jamaica requested IDB financing to undertake feasibility analyses of these proposals and to implement them. The ultimate objective of this work is for the tourism sector to arrive at a "practical and effective loss reduction strategy and program in response to the risks posed by natural disasters to the industry."

3. AGRICULTURE IN ECUADOR

In Ecuador, as in most Latin American and Caribbean countries, agriculture is one of the most important sources of income, employment, investments, and foreign exchange earnings. However, it is perhaps the most vulnerable and least protected sector in terms of infrastructure and institutional support to cope with natural hazards. In the floods caused by the El Niño phenomenon in 1982-83, for example, the agricultural sector suffered 48 percent of the US$232 million in damage. Furthermore, besides generating inflationary pressures on domestic prices, the disaster had a significant impact on the balance of payments due to the loss of export crops and the need to import basic food products to compensate for domestic production losses (ECLAC, 1983).

In 1990, the Ministry of Agriculture asked the OAS to assist in evaluating the vulnerability of the agricultural sector to natural hazards and identifying appropriate mitigation strategies to reduce it to acceptable levels. These strategies would be identified as project ideas or project profiles, some of which would be selected by local officials to be further studied and evaluated to determine their economic and technical viability.

The study, conducted at the national level, first defined 14 of the most important crops, grouped in three categories: basic food crops, strategic crops, and export crops. Key infrastructure support elements for the production, processing, storage, transportation, and distribution of agricultural products were also defined and geographically located. This information was overlaid in a geographic information system (GIS; see Chapter 5) with information on drought, erosion, floods, landslides, volcanic eruptions, and seismic hazards.

By relating province-level socioeconomic data to potential affected areas, the study was able to determine the impacts of natural events in terms of sectoral income, employment, investments, foreign exchange earnings, and national food security. On the basis of these criteria, 49 different situations were selected as the most critical. It was found, for example, that erosion hazards in Carchi Province would affect in the medium to long run 11,750 ha of the potato-growing area, which accounts for more than 43 percent of the national production and for 40 percent and 80 percent, respectively, of the employment and income produced by the sector in the province.

The most serious problems according to each of the five criteria were identified, and policy options that would achieve the best gains were established. It was determined, for example, that policies oriented to avoid unemployment should seek to mitigate flood hazards in Guayas Province and erosion hazards in Tungurahua Province. To protect foreign exchange

earnings, the most effective actions would be to protect banana production in El Oro Province against drought hazards and to mitigate flood hazards in Guayas Province, especially in areas used for coffee and banana production.

Possible mitigation strategies were also identified as part of the study and planned or on-going programs and projects in the Ministry of Agriculture and other institutions were identified as suitable for carrying out some of these mitigation strategies and more detailed studies. A report describing the major findings and recommendations was prepared and submitted to the government for review. Based on these recommendations a US$317,000 technical cooperation proposal for hazard mitigation activities within the sector has been prepared by the Government and is to be presented to outside agencies for financing.

4. STRATEGIES DERIVED FROM THE CASE STUDIES

The following observations are common to many sectors. Of course, many additional strategies apply to individual sector studies.

Sectors are useful units of analysis for examining hazard assessment and vulnerability reduction issues. Sectors are recognizable and legitimate program subjects. Banks make loans on the basis of sectors. A sectoral approach fits the organizational structure of both international finance agencies and national governments. The knowledge and experience of most technical professionals is built around a sectoral approach. Information for the development diagnosis (Phase I of an integrated development planning study) is collected and analyzed on a sectoral basis. Sectoral studies need not be restricted to economic sectors: urban and rural sectors and the poor also make valid units of study.

Vulnerability reduction measures can be cost-effective, either as stand-alone projects or, more commonly, as component elements of overall sector development programs. Including such measures can improve the cost-benefit ratio of investment projects.

Sector vulnerability studies are a new approach which can be considered for inclusion in development diagnosis (Phase I) studies. Initial national-level studies allow for a quick and low-cost assessment of policies and projects at a profile level that can be examined in greater detail later.

Sectoral studies reveal previously unrecognized linkages between disasters and development. Often a sector is unaware of its role in the lifeline or critical facilities network. In many cases it has no strategy for dealing with abnormal situations resulting from any exogenous event. The complex interrelationships among the components of some sectors make it difficult to cope with the impact of a natural event. This is particularly true when the sector is more concerned with one set of components, such as the production or generation of power, than with another set such as transmission, distribution, and storage. Furthermore, sectors usually do not have an adequate understanding of the effect a curtailment of service can have on other sectors.

A sector may have to select between competing objectives to arrive at a vulnerability reduction strategy. Criteria that define those competing objectives include investment in the sector, income stream, export earnings, employment, and sector security. The cost of a component may be disproportionate to the impact of its loss as measured by one of these criteria.

E. Implementing the Recommendations: Strategies for Development Assistance Agencies[1/]

The different categories of development assistance agencies (technical cooperation agencies, bilateral and multilateral lending agencies) each have a potential role in supporting the assessment and mitigation of natural hazards. Technical cooperation agencies such as the OAS support institution-building, research, planning, and project formulation as requested. Their financial impact and their political or technical leverage are limited. But their contribution to natural hazard assessment and mitigation in regional and sectoral planning, project identification, and prefeasibility studies is important.

Bilateral agencies such as AID, CIDA, and the members of the OECD Development Assistance Committee provide funds for projects as well as for technical cooperation. Most bilateral funds are concessional, and financial returns are less important to these agencies than to the development banks. They can exert considerable leverage over projects they fund.

1/ This section is largely extracted from a previous OAS document, "Incorporating Natural Hazards Assessment and Mitigation into Project Preparation," published by the Committee of International Development Institutions on the Environment (CIDIE) in 1989.

The multilateral development banks, mainly the World Bank and the regional development banks, fund development projects but are also increasingly involved in sector policies, institutional strengthening, program lending, and structural adjustment. The domina nt factors that shape their lending programs are the financial and economic soundness of an investment and the creditworthiness of the borrowing institutions. Within these parameters they can significantly influence hazard mitigation issues.

The conditions for increasing national and international attention to disaster mitigation issues may be stated as follows:

- The more developed a country's planning institutions and processes, the more easily natural hazards assessment and mitigation issues can be adopted.

- The more experience a country has gained in hazards assessment and mitigation issues can be adopted.assessing specific hazards, often following a major disaster, the more likely it will be to request assistance for continuing such assessments.

- The more scientific, engineering, and prevention-related information available to countries and to donors, the easier it will be to apply natural hazards assessment and mitigation to individual programs and projects.

- The more experience governments and donors have concerning the kinds of mitigation measures that are most cost-effective and implementable, the less reluctant they are to include such measures in projects.

- The more experience and confidence there is in evaluating mitigation measures at various decision points in the project cycle, the more likely it is that the staffs of both the national and the assistance agencies will be prepared to undertake the analysis.

1. TECHNICAL COOPERATION AGENCIES

For technical cooperation agencies such as the OAS, the activities that should be included in a strategy for promoting natural hazards assessment and mitigation are:

- ***Support for national planning institutions.*** Unless they have the institutional capacity to incorporate natural hazards information into the planning process on an inter-sectoral basis, governments are not likely to show any enthusiasm about looking at individual investment projects from this perspective.

- ***Support for pilot projects.*** By initiating natural hazards assessments on a pilot basis, it is possible to demonstrate how to do them and what mitigation measures can be proposed, and thereby generate further demand when governments request project funding from donors.

- ***Support for establishing an information base.*** Once the information necessary for natural hazard assessments is available, its implications for individual investment projects become difficult to ignore.

- ***Linkage with relief and reconstruction efforts.*** In the aftermath of disasters it is easier than it would otherwise be to interest governments and development assistance agencies in natural hazards assessment and mitigation.

- ***Hazards assessment in sector planning.*** By building natural hazards assessment into the planning of the agriculture, energy, housing, tourism, transportation, and other sectors, it should be possible to focus attention on hazards in relation to various types of projects before specific investments are identified.

- ***Inclusion of financial and economic aspects of hazards in project preparation methods.*** Estimating the benefits of avoiding direct losses from natural hazards and the costs of appropriate non-structural mitigation measures will make it easier to examine their true importance in individual investment projects. An awareness of the investment losses and repair costs to governments and the private sector, and the distribution of these costs and damages, is likely to increase sensitivity to the issue among all concerned.

- ***Case studies of project design principles or components aimed at natural hazard mitigation.*** Examples of relevant experiences--liability and insurance schemes for investments, property rights designed to create incentives for hazard mitigation, subsidies for mitigation measures, institutional responsibility for coordinating disaster relief with hazard assessment and mitigation, etc.--will show how funding activities can be made more responsive to natural hazards.

The OAS has initiated programs in all these activity areas though direct technical cooperation, training, applied research, and participation in international conferences and workshops. But the need for such activities is much greater than present

resources allow. Financing agencies must also become more involved.

2. CONVINCING FINANCING AGENCIES

A strategy to promote natural hazards assessment and mitigation must also find means of inducing the cooperation of the agencies that actually fund the investment projects. **There are three elements that may offer this inducement: (1) a change in the context in which the donors perceive the governments and collaborating technical cooperation agencies to be addressing natural hazard assessment and mitigation issues; (2) incentives for analysis; and (3) the assignment of accountability for losses.**

a. A Change in Context

Changing the context in which lending and donor agencies perceive natural hazard assessment and mitigation to be taking place includes most of the activities that the OAS is already promoting: assisting governments in regional planning, pilot natural hazards assessments, assistance for information systems, increasing the quality of project identification, and building the appropriate mitigation measures into pre-investment activities. Further development of these activities raises three strategic questions: What can be done that is most cost-effective in terms of improving both the commitment and the technical and institutional capacity for hazard assessment in a country? What outputs can be generated that are most likely to appeal to donors and therefore bridge the gap between hazard assessment and project preparation? What cooperative mechanisms can be developed between the technical assistance and donor agencies that will help reach the first two goals?

In response to the first question, implementation of the following ideas seems necessary:

- *Focus on priority hazards.* Efforts should be concentrated on assessing hazards that are sufficiently urgent to generate the necessary cooperation. Trade-offs must be made between the need for specific information and broad research interests.

- *Focus on priority sectors.* Losses in some sectors are likely to have greater immediate significance to governments and economic interests than in others, and it seems prudent to try to generate institutional support for attention to these.

- *Choose simple and practical information collection and analysis systems.* The burden of data collection and management often consumes all available technical and institutional capacity and resources, leaving none for decision-making and implementation. Information systems should reflect realistic priorities for hazards and the development activities that are affected.

As to the second question, the following guides should be used:

- *Early identification and integration of mitigation issues.* Mitigation measures built into projects from the earliest preparation stages are more likely to receive adequate review.

- *Practical and cost-effective solutions to recurrent problems.* For certain types of projects such solutions are less likely to be rejected if it can be shown that situations to which they are applicable are common.

- *Commitment to implementation.* Confidence in hazard mitigation is higher if governments appear committed to carrying it out.

As to the third question, the following ideas are suggested:

- *Pooling of resources.* Donor and technical assistance agencies should make their professional staff available for joint missions at varying stages of the project cycle.

- *Exchange of experiences.* Technical assistance agency representatives should periodically present case-study and other training material on the design and implementation of natural hazard assessment and mitigation techniques in project formulation taken from real field experiences. In turn, as their capability in this area improves, the donor agency staffs should present their policies, programs, and project evaluation criteria.

- *Government institutional support.* Natural hazard assessment and mitigation should be routinely included in staff development and training programs in conjunction with project formulation activities.

b. Incentives for Analysis

The project staff of a development financing agency will resist any requirement to incorporate natural hazards into project preparation and analysis unless it fits into the existing review mechanisms and appraisal methods. Various ways to promote this consistency exist:

- *Provide reusable information.* Agencies should set guidelines to alert their staffs to specific

hazards, and give them examples of appropriate mitigation measures and implementation requirements. This approach depends on the institution of mechanisms to ensure that the guidelines are followed routinely.

- ***Integrate hazard concerns into existing review mechanisms such as programming missions, project identification reports, reconnaissance surveys, and project appraisal.*** Hazards will inevitably be one of many factors to be taken into account, and there is a danger that they will be overlooked if they are not made part of the standard format.

- ***Promote proven mitigation measures in relation to specific types of projects.*** Design standards, insurance schemes, diversification of crops, feasibility of hazard-resistant crops or designs are examples. Project staffs are more likely to become enthusiastic about positive project opportunities than about review mechanisms.

- ***Incorporate the costs and benefits of hazards mitigation into economic appraisal.*** This makes sense to the extent that decisions are made on the basis of economic returns, that the information on which to base the economic calculations is available, and that the analysis is geared towards improving project design. It is hard to generate support for a new activity unless it can be justified on the basis of financial and economic returns. From this point of view, it is an advantage to be able to show that hazard mitigation can save financial and economic costs in the conventional cost-benefit framework.

- ***Sensitize project staff members.*** This is especially important for project staff responsible for hazard-prone regions and sectoral advisers responsible for hazard-sensitive sectors. Training, cooperation, and publicity can contribute to making project staff more aware of the issue. This, probably more than any other factor, can offset the institutional and financial resistance to hazard assessment and mitigation on the part of governments and the development financing agencies alike.

c. Assignment of Accountability for Losses

The concern of development financing agencies for natural hazard assessment and mitigation depends on the degree to which projects they help plan or fund suffer losses from natural disasters. There are number of ways to assign accountability:

- Evaluate losses from natural hazards not only in the context of the creditworthiness of the government or a particular sector, but also of the donor's program area and its project design and loan repayment performance.

- Study, discuss, and publish evaluations in instances where losses have been incurred for projects that failed to consider or evaluate hazard mitigation measures.

- Promote professional standards on the part of the engineers, agronomists, or others responsible for planning and executing development projects that include natural hazards assessment and mitigation.

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CHAPTER 2

NATURAL HAZARD RISK REDUCTION IN PROJECT FORMULATION AND EVALUATION

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Contents

List of Figures

NATURAL HAZARD RISK REDUCTION IN PROJECT FORMULATION AND EVALUATION

SUMMARY

This chapter discusses natural hazards and the preparation of investment projects within the context of the agricultural sector in Latin America and the Caribbean. It includes a summarized review of key concepts and policy issues and of selected project formulation and appraisal methods which can be used to incorporate natural hazard information into investment project preparation.

A review of existing investment projects in Latin America and the Caribbean indicates that those in the agricultural sector are generally undertaken with little or no consideration of natural hazards. Hazards affect agricultural projects more than any other sector. Considering the estimated US$670 billion in investments that will be necessary in this sector between 1980 and the year 2000 (FAO, 1981), there is a great need for an improved understanding of natural hazards, their assessment, and their management.

A combination of geographic location, climatic conditions, and limited capabilities for natural hazard assessment and disaster mitigation makes Third World nations more susceptible to the disasters natural hazard events pose than post-industrialized nations. Furthermore, the agricultural sector in these countries is often the most vulnerable and least able to cope with natural hazards in terms of infrastructure and institutional support.

In the following discussion, emphasis is placed on the need to apply the methods described in the formulation stage of new investment projects, rather than in the review of already prepared projects.

A. Natural Hazards in Perspective

1. HISTORICAL DISASTERS AND AGRICULTURAL LOSSES

Data from a variety of sources indicate that approximately 90 percent of all natural disasters worldwide occur in developing countries (Long, 1978). Recent Latin American and Caribbean examples illustrate the magnitude of the problem. When Hurricanes David and Frederick struck the Dominican Republic in 1979, they caused an estimated US$342 million in damage to the agricultural sector (UNDRO, 1980), destroying 80 percent of all crops and 100 percent of the banana crop. As a result, agricultural production fell 26 percent in 1979 and continued to be down 16 percent in 1980. Agriculture accounts for 37 percent of the country's gross domestic product and employs 40 percent of the labor force (USAID/OFDA, 1982). In 1984, the worst floods in Colombia in a decade caused an estimated US$400 million in damage to crops and livestock, while floods in Ecuador in 1982 and 1983 shrank the value of the banana crop by US$4.3 million (UN/ECLA, 1983).

In short, from 1960 to 1989 natural disasters caused over US$54 billion in physical damage in Latin America and the Caribbean. While the information available on the amount of national and international funds committed to reconstruction in response to each disaster is limited, the need to redirect funds to post-disaster work curtailed the availability of funds otherwise targeted for new investment.

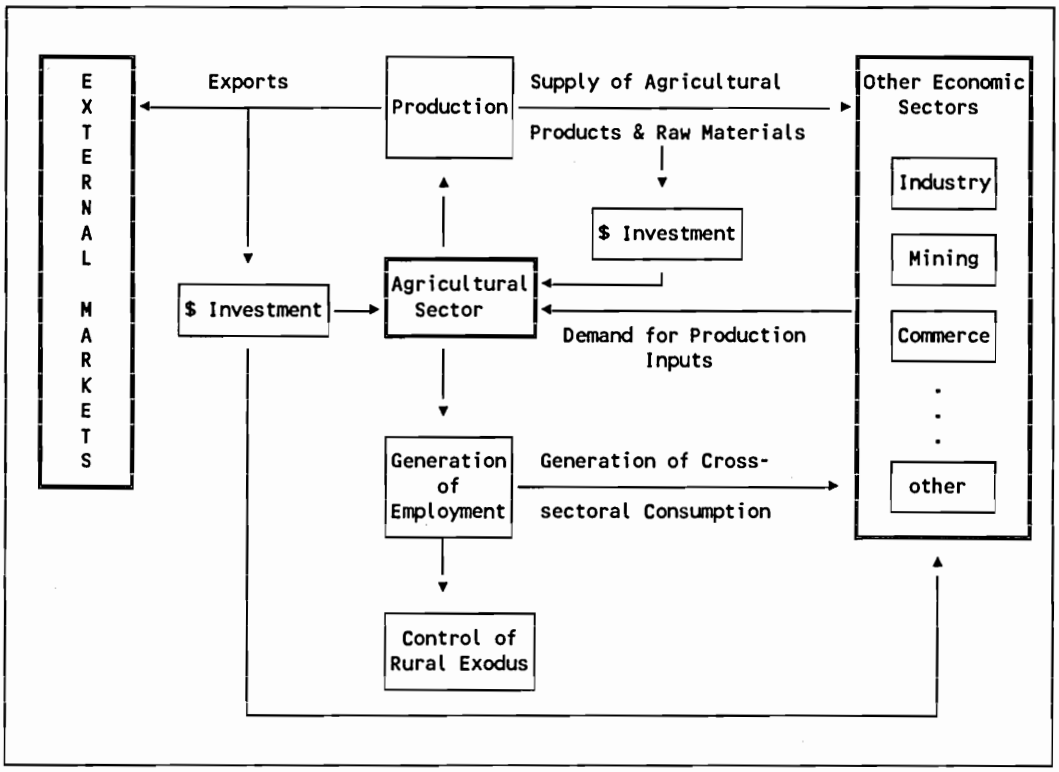
2. ECONOMY-WIDE EFFECTS OF DISASTERS

Besides the indirect social and economic impacts on a given region or sector, disasters can affect employment, the balance of trade, foreign indebtedness, and competition for scarce development investment funds. It has even been said that "the effect of natural disasters in disaster prone developing countries tends to cancel out real growth in the countries" (Long, 1978).

Figure 2-1 shows, in simplified fashion, the impact natural disasters in the agricultural sector can have on the entire economy. Internally, farm products provide food for the urban population and primary inputs to industry. Externally, they are exported and earn foreign exchange. Earnings from internal and external markets provide capital for new investment in the

Figure 2-1

POTENTIAL ECONOMY-WIDE IMPACTS OF NATURAL HAZARDS
IN THE AGRICULTURAL SECTOR IN LATIN AMERICA AND THE CARIBBEAN



economy. Furthermore, the sector's operation generates an important demand for products from other sectors (e.g., fertilizers, equipment, and machinery). Finally, agricultural employment generates an increased demand for consumption goods and services from urban sectors. Urban growth and rural exodus are important considerations in the management of natural hazards, since they result in overcrowding of peripheral urban areas and increase the probability of disasters in these areas as a result of floods, landslides, earthquakes, and other hazards.

3. NATURAL HAZARDS AND DEVELOPMENT ISSUES

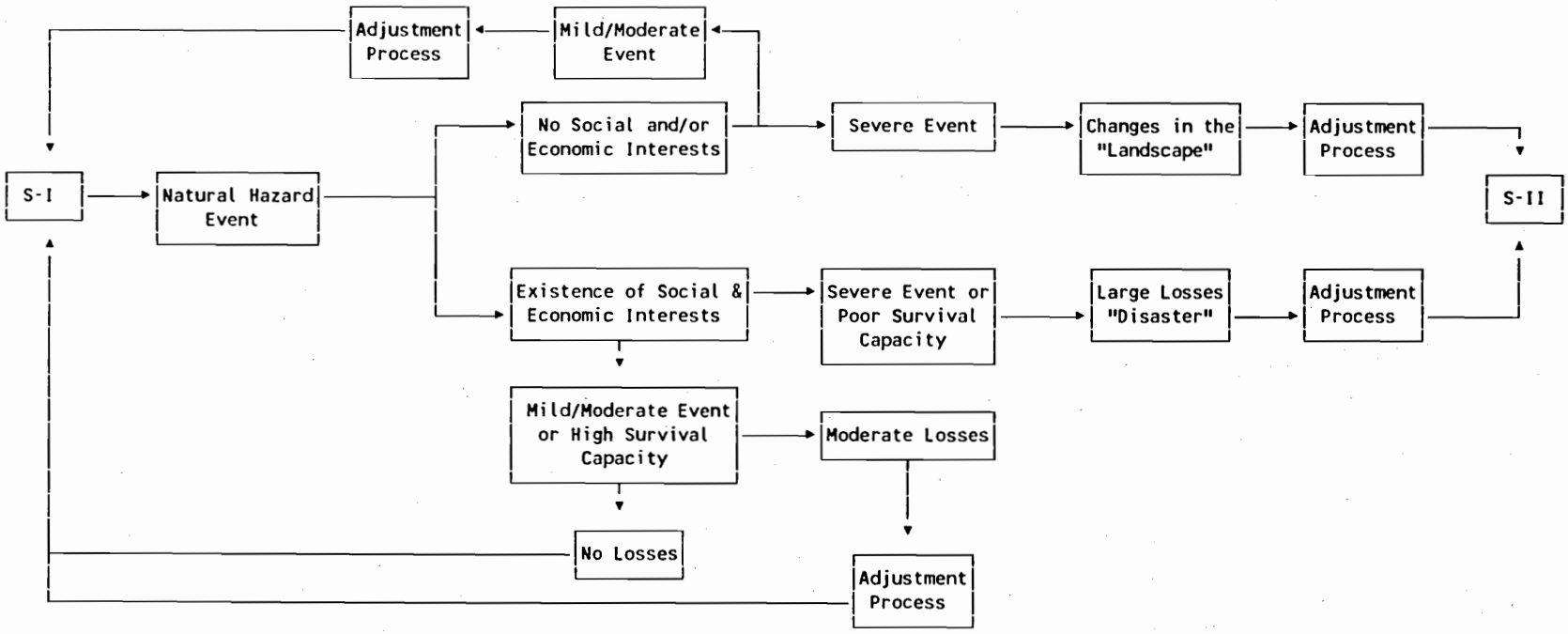
Notwithstanding the term "natural," a natural hazard has an element of human involvement. A **physical event**, such as a volcanic eruption, that does not affect human being is a **natural phenomenon** but not a natural hazard. A natural phenomenon that occurs in a populated are is a **hazardous event**. A hazardous event that causes unacceptably large numbers of fatalities and/or overwhelming property damage is a **natural disaster**. In areas where there are no human interests, natural phenomena do not constitute hazards nor do they result in disasters. This definition is thus at odds with the perception of natural hazards as unavoidable havoc wreaked by the unrestrained forces of nature. It shifts the burden of cause from purely natural processes to the concurrent presence of human activities and natural events.

Figure 2-2 illustrates this approach incorporating another argument into the discussion: the relationship of human and economic losses to the severity of an event and the degree of vulnerability (or survival capability) of human and economic interests.

The survival capability of projects depends on many factors. Losses from a severe event may be no worse or even less than those from a milder event if the former occurs in an area where both the population is adequately prepared to respond and the physical structures are designed and built to withstand its impact. One of the main differences between losses suffered by industrialized and less developed countries is the extent to which natural hazards and mitigation measures have been considered in the development planning process.

Figure 2-2

NATURAL HAZARD EVENTS IN THE CONTEXT OF HUMAN AND ECONOMIC INTERESTS



Planning systems and planners in developing countries cannot always be held fully responsible for the inadequacy of the natural hazard assessment and mitigation measures implemented (see Chapter 1). There are several reasons for this. First, much development is based on already existing hazard-prone scenarios. Second, planners depend on the availability of hazard information. And last, the planning process takes place within the prevailing economic, political, social, technological, and cultural parameters of a society. Mexico City's vulnerability to earthquakes is a good illustration. The sprawling city rests on precarious and deteriorating geological foundations. In spite of a well documented history of seismic activity, economic and technological constraints and complex political, social, cultural, and demographic elements impede the introduction of non-structural mitigation measures.

On the other hand, planning systems and planners are responsible for some serious shortcomings of investment projects in hazard-prone areas. Irrigation systems, roads, reservoirs, dams, and other infrastructure facilities are prime examples. In these cases, where the system of constraints and parameters is less complex than in urban planning, planners should be able to incorporate more information and have greater control over decision-making. But even where sufficient hazard risk information was available, projects have been undertaken without minimum mitigation measures. It is not uncommon for an area periodically devastated by hurricanes or earthquakes to be rebuilt again and again in the same way. Other disasters occur routinely as a direct consequence of improper human intervention in areas with previously stable ecosystems. The following box lists the key elements for incorporating natural hazards into agricultural investment projects.

Survival capability depends on many factors, and mitigation can make a substantial difference in minimizing the effects of disasters. While planners and planning systems are not responsible for some problems associated with natural hazards, they can exert influence in correcting some of the shortcomings. The following section discusses the process of integrating natural hazard information into the preparation of investment projects.

B. Basic Concepts: Natural Hazards and Investment Projects

To facilitate the understanding of the subsequent sections, several key concepts are defined and explained below.

1. PROBABILITY

Probability is the likelihood of occurrence of a particular event. This is often based on historical frequency. For example, the probability of a hurricane in any given year could be 0.1, or 10 percent, if hurricanes have struck in two of the past 20 years. For the purpose of decision-making, however, probabilities are rarely based strictly on historical information but are usually adjusted to take account of currently available information may be then referred to as subjective probabilities. For example, the observation that tropical storms have recently occurred in other parts of the world can result in the assignment of a higher subjective probability to a local storm than would be indicated by the historical frequency.

2. RISK

Risk is generally defined as the probability of loss. In economic terms, this refers to a decline in income due to losses resulting from a natural hazard. Here risk will be used more generally to refer to uncertainty in the variables used in economic planning. For instance, in assessing the benefits and costs of a planned irrigation project, prices and yields of agricultural crops may fluctuate during the life of the project. These fluctuations can be caused by natural hazard events, but can also be caused by changing market conditions and weather cycles.

3. RISK AVERSION

Risk aversion refers to an individual's attitude toward risk. Most people are risk-averse; that is, they are willing to incur some cost to avoid risk. But there is a wide range in degrees of risk aversion (Binswanger, 1980, and Young, 1979). In other words, to avoid a given level of risk, some people will pay more than others.

4. RISK ASSESSMENT

Risk assessment refers to the quantification of a risk. It requires a determination of both the consequences of an event and the likelihood of its occurrence. For example, a risk assessment of the potential economic effects of an earthquake on an agricultural project would require an estimate of its impact on farming activities and structural components, and of the probability of earthquakes in the region during the life of the project.

5. RISK MANAGEMENT

Risk management refers to actions taken to reduce the consequences or probability of unfavorable events. Similarly, natural hazard management refers to

KEY PROPOSITIONS FOR INCORPORATING NATURAL HAZARD INFORMATION INTO AGRICULTURAL INVESTMENT PROJECTS

- Natural hazard risk information is rarely considered in the preparation of investment projects in the agricultural sector.
- Agricultural projects can sustain severe losses from natural hazards. Losses can have serious sectoral and intersectoral economic implications.
- An adequate consideration of natural hazard issues in the preparation of projects, particularly during the formulation stage, can greatly reduce the vulnerability of investments and minimize human and economic losses.
- While basic natural hazard information is generally available, more specific and sophisticated risk and vulnerability information can be generated economically and used in the different project planning stages.
- Several analytical methods are available for incorporating natural hazard risk information into the evaluation of agricultural investment projects.

activities undertaken to reduce the negative effects of natural hazards. For example, a farmer may choose to plant a windbreak along a field to reduce the chances that wind will damage his sugar crops. While this may reduce his average income if he has to remove land from production, he may still do it to mitigate against an uncertain but potentially damaging storm.

6. INVESTMENT PROJECT

An investment project is the use of capital to create assets capable of generating a stream of benefits over time. Agricultural investment projects include land settlement, agricultural extension, irrigation, and soil conservation. Projects can be independent or part of an integrated regional development package.

C. The Use of Natural Hazard Information in Investment Project Preparation

Minimizing the effects of natural hazards on the agricultural sector, and on an entire economy, can reduce the vulnerabilities and increase the ability to survive natural disasters. This can be achieved by incorporating natural hazard information into the preparation of agricultural investment projects. How it is done, and its relationship to an integrated development study, are discussed in this section.

Integrated development planning is a multisectoral and multidisciplinary approach to generating plans and proposals for economic and social development. It brings together issues concerning various sectors and analyzes them in an integrated fashion vis-a-vis the needs of the population and the characteristics of the natural resource base. Appropriate natural resource use along sound environmental management guidelines seeks to maximize development opportunities while minimizing environmental conflicts (see Chapter 3). The creation of an integrated development planning study is a complex process, within which the preparation of investment projects is only one step. The preparation of planning studies and investment projects is very similar. That similarity is often a source of confusion.

An integrated development planning study is composed of four basic stages: the Preliminary Mission, Phase I or the Development Diagnosis, Phase II or Project Formulation and Action Plan, and Implementation. (See Chapter I for a detailed discussion of the four stages of integrated development planning.) The preparation of investment projects within the development planning study also entails four steps: Project Profile, Prefeasibility Analysis, Feasibility Analysis, and Implementation. The information needs of the four development planning study stages are described in the box below.

Although most institutions do not require risk information in project preparation guidelines except at the engineering design stage, both integrated development planning studies and investment project

THE USE OF NATURAL HAZARD INFORMATION IN THE PREPARATION OF INVESTMENT PROJECTS WITHIN AN INTEGRATED DEVELOPMENT PLANNING STUDY

- Natural hazards should be considered throughout the entire development study.

- Preliminary Mission: Natural hazard information should be collected and analyzed at this time. This information should be used to define the study area, the objectives and characteristics of the study, and the preparation of the intended work program.

- Phase I: Hazardous event information and risk maps should be used in the development diagnosis for the identification of hazard-prone areas, land-use zoning, and preliminary identification of mitigation measures.

- Phase II: Vulnerability information can be used to refine project costs and benefits at the prefeasibility level. Risk considerations can be incorporated into the different project formulation studies (market, size and location, engineering, etc.); and structural and non-structural mitigation measures can be selected. At the feasibility analysis level, available information can be complemented by specific hazard assessments and used to further refine cost and benefit calculations. More sophisticated probabilistic evaluation methods can be used by generating probabilistic risk distributions.

- Implementation: The implementation of an integrated development strategy and of individual projects should include monitoring of construction procedures to ensure compliance with engineering standards of buildings and structural mitigation measures. Long-term monitoring for ensuring compliance with designed non-structural mitigation measures should also be programmed.

preparation are improved when analysts incorporate natural hazard information into all stages of development planning. Guidelines for the use of natural hazard information in project preparation are listed in Figure 2-3 and discussed below.

1. PRELIMINARY MISSION

Risk information should be introduced at the earliest stages of project planning. (See Appendix A for more details on the types of available natural hazard information.) When this information is included at the Preliminary Mission stage, the design of the integrated study and the investment projects can accommodate risk factors; if the risks are too great, alternative overall development strategies can be considered. When risk information is not included until the feasibility analysis stage, it is usually too late for anything but remedial actions.

2. PHASE I - DEVELOPMENT DIAGNOSIS

Natural hazard issues should be considered further in the development diagnosis stage. Risk maps and hazard event frequencies should be consulted in order to identify the area's problems and opportunities. For example, a floodplain map produced by remote sensing techniques would depict areas that are prone to severe flooding. From the start of the project planning process, planners might want to avoid designating these areas for agricultural activities requiring extensive capital investment and propose instead an alternative land use less sensitive to flooding. Or planners might want to consider hazard mitigation practices to reduce the risk to acceptable levels. (See Chapter 8 for a discussion of flood hazard assessments and remote sensing techniques.)

The design of investment projects begins at this stage with the development of alternative project

PRELIMINARY MISSION (STUDY DESIGN)

QUESTIONS PLANNERS NEED TO ASK:

- What type of natural hazard information is available for the study area, and what additional information is needed?
- What are the benefits of incorporating natural hazard information at this stage?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- What values will be assigned to natural hazard issues as they relate to defining characteristics of a potential project(s), e.g., its area, objectives, target population?
- These values having been specified, what are the definitions of the defining characteristics?

PHASE I: DEVELOPMENT DIAGNOSIS (STRATEGY FORMULATION AND PROJECT IDENTIFICATION)

QUESTIONS PLANNERS NEED TO ASK:

- What type of information needs to be used?
- How can planners complement non-probabilistic hazard information in order to evaluate project uncertainty?
- Are natural hazards a significant variable in the identification of investment projects?
- Can mitigation measures be included as part of the development strategy? Which ones?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- What is an acceptable level of risk for the affected population and the investment project?
- What are the relevant natural hazard issues in the project area? What priority should be given to each?
- Are modifications of the project profile needed?
- Will additional hazard assessment studies be needed for investment project formulation?

profiles. A project profile should include project objectives and principal characteristics, rough estimates of costs and benefits, and a preliminary identification of alternatives for design and implementation. These activities should reflect the natural hazard information collected between the Preliminary Mission and the Development Diagnosis stages of the integrated development planning study.

3. PHASE II - PROJECT FORMULATION AND DEFINITION OF ACTION PLAN

In Phase II, investment projects are generated and selected. This phase includes prefeasibility and feasibility analyses and is based on a standardized project formulation methodology. The prefeasibility analysis involves a preliminary evaluation of the

Figure 2-3

THE USE OF NATURAL HAZARD INFORMATION IN INVESTMENT PROJECT PREPARATION WITHIN THE CONTEXT OF INTEGRATED DEVELOPMENT PLANNING STUDIES

INTEGRATED DEVELOPMENT PLANNING STUDY STAGES	INVESTMENT PROJECT PREPARATION PROCESS	SPECIFIC NATURAL HAZARDS RELATED ACTIVITIES
PRELIMINARY MISSION Determination of study areas and interest. Preparation of project agreement. →	Generation of investment project ideas	* Collection of basic information including natural hazards issues. * Determination of the weight to be assigned to natural hazards within the integrated development study.
PHASE I: DEVELOPMENT DIAGNOSIS Regional needs and resources diagnosis. Identification of critical issues and of institutional settings. →	PROJECT PROFILE Preparation of project profiles	* Identification of natural hazards situation in the project area. * Determination of socially acceptable risk for each hazard. * Collection/preparation of specific natural hazard risk and vulnerability information.
PHASE II: PROJECT FORMULATION & ACTION PLAN Formulation of regional development strategy including institutional, legal & fiscal support programs. Formulation of investment projects. →	PREFEASIBILITY Project formulation. Review of technical & economic viability FEASIBILITY Detailed formulation and final appraisal of selected projects	* Identification and technical analysis of mitigation measures within the formulation of projects. * Appraisal of mitigation measures. * Project(s) appraisal at prefeasibility level. * Selection of best project options and most suitable mitigation measures. * Final economic appraisal considering risk. * Final project(s) design including mitigation measures (structural and non-structural).
IMPLEMENTATION Implementation of the integrated development strategy: institutional, legal & fiscal programs, & investment projects. →	IMPLEMENTATION Implementation of selected investment projects	* Monitoring of construction procedures and compliance with engineering design of buildings and structural mitigation measures. * Monitoring of implementation of non-structural mitigation measures. * Design of long-term monitoring to guarantee operation of mitigation measures implemented.

technical and economic viability of a proposed project: alternative approaches to various elements of it are compared, the best are recommended for further analysis, and investment and operating costs are estimated. The feasibility analysis constitutes the final determination of the viability of the project, reexamining every aspect of it and refining the estimate of its benefits (income stream, increases in production, generation of employment, etc.), costs (construction, operation and maintenance, depletion of resources, pollution effects, etc.), and valuative criteria (net present value, internal rate of return, benefit-cost ratio, and repayment probabilities).

The design of individual investment projects should, but in current practice ordinarily does not, incorporate the following types of natural hazard information:

- Incidence of hazard risks in the project area
- Incidence of hazard risks in the project's market areas and commercialization routes
- Vulnerability of the supply and/or cost of production inputs (e.g., raw materials, equipment, energy resources) to natural hazard events
- Vulnerability of the project's output prices to natural hazard events

PHASE II - PROJECT FORMULATION AND ACTION PLAN DEFINITION

QUESTIONS PLANNERS NEED TO ASK:

- Which components of a project formulation study should include natural hazard considerations?
- Is the available hazard information adequate to formulate investment projects?
- What type of mitigation measures should be considered during the project formulation stage?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- How will the identification and technical analysis of natural hazard mitigation measures take place?
- How will the best project options and most suitable mitigation measures be determined?

- Vulnerability of physical structures and production processes to natural hazard events
- Existence of current and/or proposed legislation that establishes guidelines for natural hazard risk mitigation in project design
- Effectiveness and cost of alternative natural hazard mitigation measures

The critical factor for the successful incorporation of natural hazard considerations into the project formulation phase is the ability of project planners to use hazard information in the design. The identification of cost-effective mitigation measures that will significantly reduce risks is of crucial importance. Not every mitigation measure should be implemented--only those whose benefits exceed their costs.

Mitigation measures may be structural or non-structural. Structural mitigation includes physical measures or standards such as building codes, materials specifications, and performance standards for new buildings; the retrofitting of existing structures to make them more hazard-resistant; and protective devices such as dikes. Non-structural measures typically concentrate on identifying hazard-prone areas and limiting their use. Examples include land-use zoning, the selection of building sites, tax incentives, insurance programs, relocation of residents to remove them from the path of a hazard, and the establishment of forecasting and warning systems. Figure 2-4 presents some examples of structural and non-structural mitigation measures relevant to the agricultural sector. For a more detailed discussion of mitigation measures related to specific hazards, see Chapters 8 through 12.

A strong case can be made for emphasizing non-structural measures in developing countries. Essentially, all structural mitigation measures have a direct cost that must be added to the project under consideration. Given the prevailing lack of awareness of risks from natural hazards, additional costs will appear unjustified vis-a-vis expected costs and benefits. This does not mean that non-structural mitigation measures will add no cost to projects or society, but that in an area subject to flooding, for example, the economic and social costs of measures such as zoning policies and crop insurance are likely to be much lower than those of large-scale flood control systems in terms of initial cost, operation, and maintenance. Furthermore, the agricultural activities that have been the most affected by natural hazards are large-scale agricultural development projects.

When project characteristics impede the adoption of non-structural mitigation measures, more costly structural mitigation systems should be explored as a way to reduce risks to a socially acceptable and economically feasible level.

4. PROJECT IMPLEMENTATION

The Implementation stage begins once the investment projects and the action plan of a development planning study have been determined. Depending on the nature and scope of the overall study and of the individual projects selected, implementation can be simultaneous with or preceded by the implementation of sectoral and regional support programs and the development of legal and institutional frameworks.

Figure 2-4

MITIGATION MEASURES FOR THE AGRICULTURAL SECTOR

MITIGATION MEASURES	STRUCTURAL MITIGATION MEASURES										NON-STRUCTURAL MITIGATION MEASURES									
	Afforestation	Coastal Fortifications	Construction and Protection of Retention Basins	Dam Construction and Inspection	Livestock Shelters	Reinforcement of Structures	Slope Stabilization	Stream Channelization	Terracing	Wind-Breaks (natural & artificial)	Coastal Wetlands Protection	Countour Farming	Crop Diversification	Crop and Livestock Insurance	Forecasting and Warning	Improved and Resistant Crop Varieties	Land Use Zoning	Maintenance of Natural Runoff	Deforestation Prevention	Relocation
NATURAL HAZARDS																				
Desertification	X						X	X	X			X	X	X	X	X	X	X	X	X
Drought	X							X	X			X	X	X	X	X	X	X	X	X
Earthquake						X								X	X		X			X
Flood	X		X	X		X		X	X			X	X	X	X	X	X	X	X	X
Hurricane	X	X	X		X	X				X	X		X	X	X		X	X	X	X
Landslides	X		X			X	X		X			X		X	X		X		X	X
Tsunami		X				X					X			X	X		X			X
Volcanic Eruptions					X									X	X		X			X
Winds	X				X	X			X	X		X	X	X	X	X			X	X

PROJECT IMPLEMENTATION

QUESTIONS PLANNERS NEED TO ASK:

- Do natural hazard considerations enter into the project implementation phase? Which ones?
- What actions can be taken to ensure that the implementation of projects complies with the specified engineering standards and that mitigation measures are adequately put in place?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Does the final project design include the necessary mitigation measures?
- Are monitoring and maintenance procedures established for the implementation of mitigation measures within a project's implementation phase?

The implementation of investment projects is a critical phase in the successful incorporation of natural hazard considerations into the development planning process. All the efforts made in the previous stages will be lost unless the projects are carefully monitored throughout the implementation process to ensure that structural mitigation measures are adhered to and non-structural mitigation measures have been selected and adopted.

D. Incorporating Natural Hazards into Planning and Decision-Making in the Public Sector

1. ATTITUDES TOWARD THE RISKS FROM NATURAL HAZARDS

While risk aversion at the individual level is well documented, the question of whether or not government institutions should be risk-neutral has been the subject of controversy. Should risk be considered in the analysis of public sector projects?

It has been argued that although individuals are risk-averse, governments should take a risk-neutral stance because, given that project benefits and costs are spread over a large number of individuals in the society, the risk faced by each one is negligible. This implies that governments should be indifferent between a high-risk and a low-risk project provided that the two have the same expected net present value (NPV) (Arrow and Lind, 1970).

This argument is valid only up to a point. The reality of developing countries suggests otherwise. Governmental decisions should be based on the opportunity cost to society of the resources invested in the project and on the loss of economic assets, functions, and products. In view of the responsibility vested in the public sector for the administration of scarce resources, and considering issues such as fiscal debt, trade balances, income distribution, and a wide range of other economic, social, and political concerns, governments should must not be risk-neutral.

Suppose there are two projects under consideration in a coastal area of a developing country. The NPV of Project A is US$2 million, and of Project B US$1.5 million. Because Project A has the higher NPV, it would be selected if risks were ignored. However, Project A is vulnerable to floods and its actual NPV, depending on their frequency and severity, could be between US$0.5 and US$2.5 million. Project B is less susceptible to flood damage, and therefore has an NPV range of US$1.3 to US$1.7 million. Since the returns on Project B are more stable, the participants directly involved might prefer the project with the lower NPV. Furthermore, they would probably be unimpressed by arguments about the merit of societal risk sharing, since the risk (the variation in NPV) that their community directly bears from these projects is rather large.

In practice, most Latin America and Caribbean governments and their planning agencies lack awareness of the need to reduce the vulnerability of investment projects to natural hazards, and tend to disregard it in their evaluations. Some of the reasons for this lack of awareness are listed in the following box.

PRINCIPAL CAUSES FOR THE LACK OF AWARENESS OF THE NEED TO REDUCE PUBLIC INVESTMENT PROJECT LOSSES

- The magnitude of the risks and potential savings of mitigation are perceived as low.
- Political and financial pressures make it unappealing to take careful steps now to avoid losses in the future.
- If losses occur, international agencies will provide assistance.
- Natural hazards are accepted as inevitable and little is known about non-structural mitigation.
- The burden of analysis, institution-building, and implementation discourages the effort of assessment.
- Political, financial, economic, and social costs of natural hazard assessments and mitigation may not always be less than their benefits.
- The costs of undertaking natural hazard assessments and mitigation fall on government institutions that cannot recapture directly the benefits of preventing losses in the future.
- The property rights surrounding the investments do not necessarily provide a strong incentive for preventing losses from hazards.

National and international banking institutions also tend toward neutrality in the treatment of risks from natural hazards. They are generally more concerned with how macroeconomic and political factors may affect a government's overall repayment ability than with the effect of risk factors on cost recovery. As a result, loans are routinely made with little or no risk assessment. While this attitude makes sense for the bank because it grants loans against overall government credit worthiness and does not share the risk of any individual project, it does not necessarily make sense for borrowing nations.

2. ESTABLISHING EVALUATION CRITERIA AND PRIORITIES

In dealing with governmental and societal attitudes toward natural hazards, planners can benefit from multicriteria analysis or, as it is sometimes called, multiple conflicting objectives analysis. This method has been used in environmental assessments and is gaining increasing acceptance for the incorporation of societal goals and priorities into the selection of investment projects.

Multicriteria analysis entails the establishment of a set of objectives and a subset of attributes representing alternative social, economic, political, and environmental goals which are to be fulfilled by specific projects. The relevant social groups (government, interest groups, community leaders, etc.) participate in establishing the objectives and attributes and placing discriminatory weights on them. Projects can then be evaluated in terms of their capacity to fulfill the stated goal. If the establishment of the objectives and attributes is properly oriented, natural hazard vulnerability criteria can be introduced into the analysis along with the other goals (Vira and Haimes, 1983; Haimes et al., 1978; Keeney and Raiffa, 1976).

It is important to remember that regardless of the methods used in project evaluation, it is not planners but decision-makers who will ultimately rule on public investment options. Multicriteria analysis forces decision-makers to state their evaluation criteria explicitly. While most decision-makers will give low vulnerability a high priority in project selection for economic or political reasons, natural hazards will not always be considered in the final decision.

Multicriteria analysis can be applied throughout the project cycle, from the profile stage to the feasibility study, but since it is effective in the early identification of more desirable projects and project components, its use at the beginning stages of project planning maximizes its benefits.

E. Principles of Economic Analysis

Economic or cost-benefit analysis is a method that evaluates the efficiency of public sector activities, permitting a comparison of the merits of different government projects over time. A number of

techniques are available, and analysts should choose the one best suited to each case.

When private individuals consider whether or not to make an investment, they consider only the benefits that have a direct personal impact on them; this is financial analysis. In economic analysis the societal perspective is taken, incorporating all benefits and costs affecting society.

Another important aspect of economic analysis is the "with-and-without" criterion: what the state of affairs would be with versus without the project in place. The "with-and-without" analysis helps to sort out the benefits and costs of a project. Suppose an irrigation project is being considered for an area where crop yields are increasing. The project will raise them even more. The assessment of potential benefits would be erroneous if it attributed all the increase to the project, since some of it would have occurred anyway (Howe, 1971). In areas that are growing rapidly, it is particularly important to ensure that benefits and costs are properly accounted for and do not include changes that would have taken place without the project.

The economic appraisal of projects can be organized into four main steps:

- Identification and computation of all the costs of the proposed projects;
- Identification and computation of all the benefits of the proposed project;
- Discounting future net benefits and expressing them in current dollar terms; and
- Evaluation of the net project flow of proposed projects.

While these steps may appear simple, a thorough analysis requires considerable effort. The economist or planner carrying out the analysis should work with other specialists such as agronomists, engineers, and hydrologists to ensure that all relevant factors are taken into account and that technical and institutional relationships are properly reflected. This integrated, interdisciplinary approach to planning has been advocated by the OAS (OAS, 1984).

1. MEASURING COSTS

In measuring the costs of a project, it is important that all of them be accurately reflected, including those that may not be immediately apparent. There are, of course, the direct costs. Materials and administration are among these, as is the use of natural resources. The costs of natural hazard vulnerability reduction, both structural--canal systems, dams, dikes, windbreaks--and in some cases non-structural are direct costs. Additionally, there are indirect costs. For example, if a new project will draw water resources from nearby farmland, any decline in agricultural production in that area should be counted as a project cost. And then there are the "opportunity costs"--the loss of the benefits that would accrue from some alternative use of the resources that are being devoted to the project.

The analyst must also be aware that, owing to market distortions, the prices of inputs may not reflect their true valuation by society. In such cases, prices should be adjusted to correct for these distortions. If a government subsidy lowers the cost of the fertilizer used in the project, the economic analysis must add the amount of the subsidy to the market price of the fertilizer to reflect its true cost to society. Adjusted prices are referred to as "shadow prices."

2. MEASURING BENEFITS

Direct benefits of an agricultural project can result from an increase in the value or quantity of farm output and from a lowering of production costs. The benefits from natural hazard mitigation can be measured in terms of income losses avoided. Projects generate indirect benefits as well. For example, an irrigation project might have the "spillover" benefit of increasing the productivity of land adjacent to the land actually being irrigated by the project.

An evaluation of the benefits of a project should include only real increases in output. A flood control project may raise the value of farmland in the protected area, but since this higher value reflects the increased output potential of the land, counting it as a benefit would result in counting the benefits of the project twice.

The consideration of natural hazard risks requires differentiating between the concepts of income stream and benefit stream of a project. While the income generated by a project is a major component of the benefits, it does not reflect certain essential variables. For instance, income and job stability from the project and associated enterprises might be severely affected by a hazardous event, but merely adjusting the income stream to the uncertainty associated with natural hazard events will not reflect the economic and social losses that would accrue from income and job disruption. The benefit stream reflects these losses. In the case of a project that includes mitigation measures, the economic analysis should include the added benefit of avoiding losses. A proper identification of the benefit stream of a project allows analysts to evaluate the net effect of introducing mitigation measures into the project design, since both the direct cost of these measures and their expected benefit will be included in the evaluation process.

3. DISCOUNTING NET PROJECT FLOWS

The third step in project analysis is to discount the future benefits and costs. This is done by using a discount rate to convert future values into present values. The need to discount future costs and benefits arises because a given amount of money is worth more today than in the future: money today can earn interest between now and then. An investment of US$100 at an annual interest rate of 10 percent will be worth US$121 at the end of two years. Future benefits and costs must be discounted in order to express them with a common denominator--today's dollars or present value.

The project analyst must choose the discount rate, and often more than one rate is used in a project. For financial analysis, the discount rate is usually the rate at which the firm for which the analysis is being done is able to borrow money. In economic analysis, three alternatives for the discount rate are suggested: the opportunity cost of capital, the borrowing rate, and the social time preference rate (Gittinger, 1982). Probably the best is the opportunity cost of capital, which is the rate that will result in the utilization of all the capital in the economy if all possible investments that yield as much or more in return are undertaken. The opportunity cost of capital cannot be known with certainty, but in most developing countries is considered to be between 8 and 15 percent in real terms.

The borrowing rate is most commonly proposed when the country expects to borrow from abroad for investment projects. Financial rates of interest, however, are generally too low to justify their use in economic analysis, and may even be negative in real terms when the rate of inflation is high. The social time preference rate differs from the opportunity cost of capital in that it assigns a different (usually lower) discount rate for public projects than for private ones, given that society has a longer time horizon.

4. PROJECT EVALUATION

The discounted or net present value (NPV) of a project is represented mathematically as:

$$\Sigma B_t/(1 + r)^t - \Sigma C_t/(1 + r)^t \quad \text{for } t = 1,2,\ldots\ldots,n$$

where B = benefits, C = costs, r = discount rate, t = time period, n = life of the project in years, and Σ = summation operator. After benefits and costs are evaluated and a discount rate is selected, this equation will indicate the NPV of the project under consideration. The economic criteria used to determine the value of a project are (a) whether the NPV is positive and (b) whether the NPV is higher than that of alternative projects. Another way to compare benefits and costs is to set the equation equal to zero and solve for the value of r. This value is referred to as the "internal rate of return" (IRR).

The equation is often rearranged as a benefit-cost ratio in order to facilitate comparison of projects:

$$\frac{\Sigma B_t/(1 + r)^t}{\Sigma C_t/(1 + r)^t} \quad \text{for } t = 1,2,\ldots\ldots, n$$

The higher the NPV of the project, the higher the ratio will be. A benefit-cost ratio greater than one indicates that the discounted benefits exceed the discounted costs.

F. Incorporating Natural Hazards into the Economic Analysis of Investment Projects

Several methods are available for evaluating the natural hazard components in the economic analysis of a project. Some can be applied when little hazard information is available, others are appropriate when information on probability distributions can be obtained. All can be used to compare different projects or alternatives within a project. The methods used when limited information is available can be applied at the project profile and prefeasibility levels of analysis. Those using probabilistic information are usually used in feasibility studies, but may also be used at the prefeasibility stage. In all cases the methods should be applied as early as possible in the project cycle.

1. DECISION CRITERIA WITH LIMITED INFORMATION

Four methods of risk evaluation compensate for a lack of information: cut-off period, discount rate adjustment, game theory, and sensitivity analysis.

a. Cut-off Period

The crudest procedure for incorporating risk into economic analyses is the use of a cut-off period (Mishan, 1982). It is primarily used by private investment agencies interested in capital return rather than in long-term development. Under this method, economically feasible projects must accrue enough benefits to surpass project costs in relatively few years.

For very risky projects, the cut-off period might be set as low as two or three years, whereas for low-risk projects it would be much longer, say 30 years. The underlying logic is that the benefits and costs are so uncertain beyond the cut-off date that they can be ignored in determining project feasibility. The cut-off period should be determined at the prefeasibility stage of project preparation.

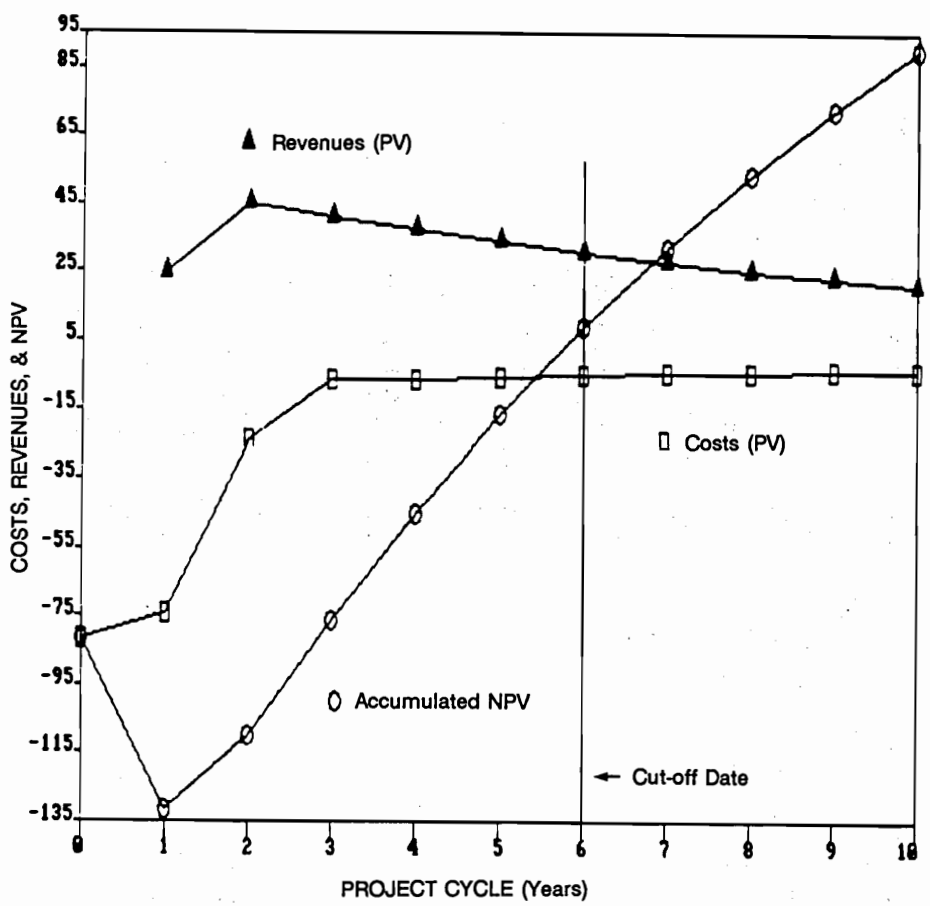
Some information is necessary to determine the relative risk of the project. The most useful data are a list of historical natural disasters or episodic information, meteorological records, land-use maps, agricultural crop maps, and previous damage assessments. This information provides economists with a rough idea of the inherent risks. In addition, satellite photography of the impacts of natural hazards can be useful in deciding on a cut-off period. In many cases it is not too difficult to obtain this type of information for short periods of time.

A cut-off period should only be considered when few records are available and the nature and magnitude of the hazards can potentially pose a great risk to development, e.g., severe storms and floods. It is more difficult to establish a cut-off period in the case of slow-onset hazards such as droughts or desertification.

As an example, the cut-off period method could be applied to a ten-year, large-scale vegetable and livestock farming project. This project may have a high risk if the area is subject to periodic flooding, which would damage crops and destroy livestock. In this case, a four- or six-year cut-off period might be chosen. Figure 2-5 illustrates this example.

Figure 2-5

CUT-OFF-PERIOD METHOD



While this approach considers the effects of risks, it does have some limitations. Too short a cut-off date can ignore economic information associated with much of the project's life, since it discards all information beyond the cut-off period. This may be particularly important when considering the sustainability of economic returns from a project as resources, renewable or non-renewable, are depleted after the cut-off period. If benefits and costs are highly variable beyond the cut-off date, there are more appropriate methods which can address the risk of benefit-cost variability.

b. Discount Rate Adjustments

Another ad hoc way to reflect uncertainty in project analysis is to add a risk premium to the discount rate. The effect of increasing the discount rate is to give less weight to the increasingly uncertain costs and benefits in future time periods (Anderson et al., 1977). This is consistent with what has been observed in the private sector: managers generally require higher internal rates of return for riskier investments. A variation of this is to add a premium to the discount rate for the benefits and subtract a premium for the costs, a procedure consistent with the fact that hazards decrease benefits and increase costs.

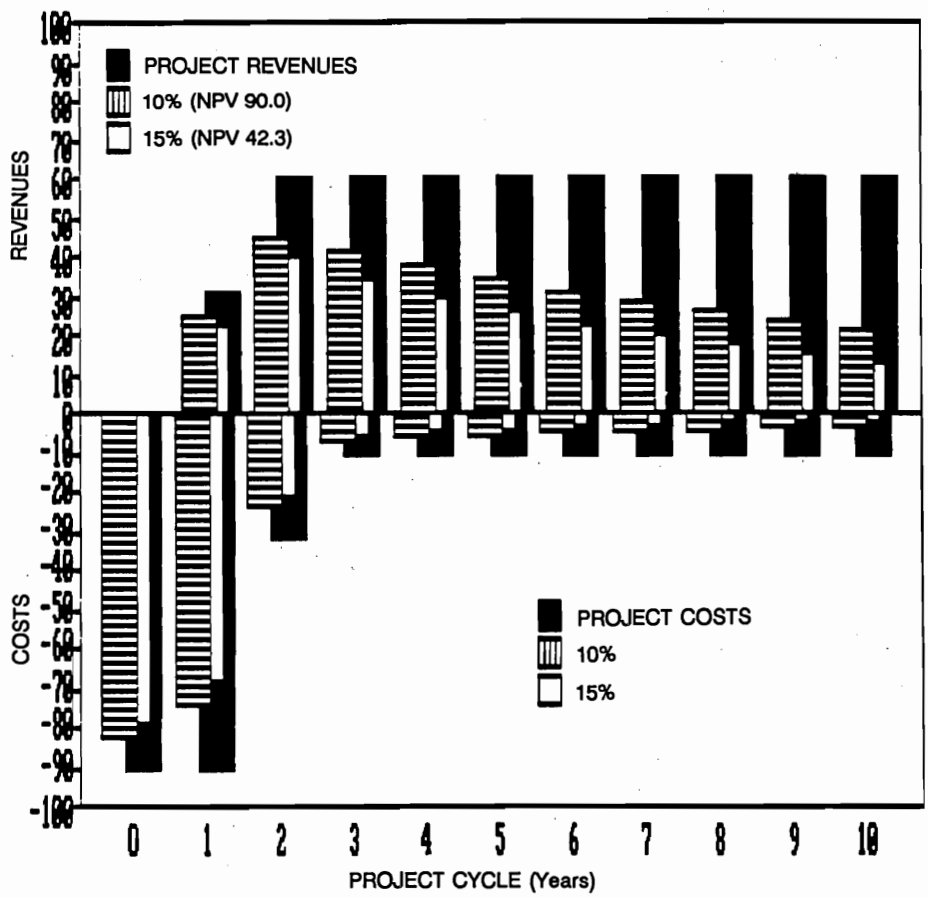
This technique is based on a subjective decision as to the risk premium to be added to and/or subtracted from the discount rate. The same type of information that is useful for a cut-off period can be used to determine the discount rate. This information should be available by the prefeasibility stage of project planning.

A subjective decision on the discount rate can incorporate the information available on the possibility of a slow-onset hazard in addition to short-term, immediate impact hazards such as severe storms and flash floods. Once again, this method should be employed when the information is limited.

In the previous farming example, any indication of flooding increases the risk of the project. If normally a discount rate of 10 percent for benefits is used, the discount rate might be increased to 12 or 15 percent, as shown in Figure 2-6.

Figure 2-6

DISCOUNT RATE ADJUSTMENT METHOD



This approach is preferable to the cut-off-period method because it includes information about the future benefits and costs. However, the risk adjustment of the discount rate is arbitrary, and the approach does not recognize risk differences across project components. More rigorous and defensible approaches which are capable of quantitatively assessing the uncertainty of benefits and costs over time are discussed below.

c. Game Theory Approaches

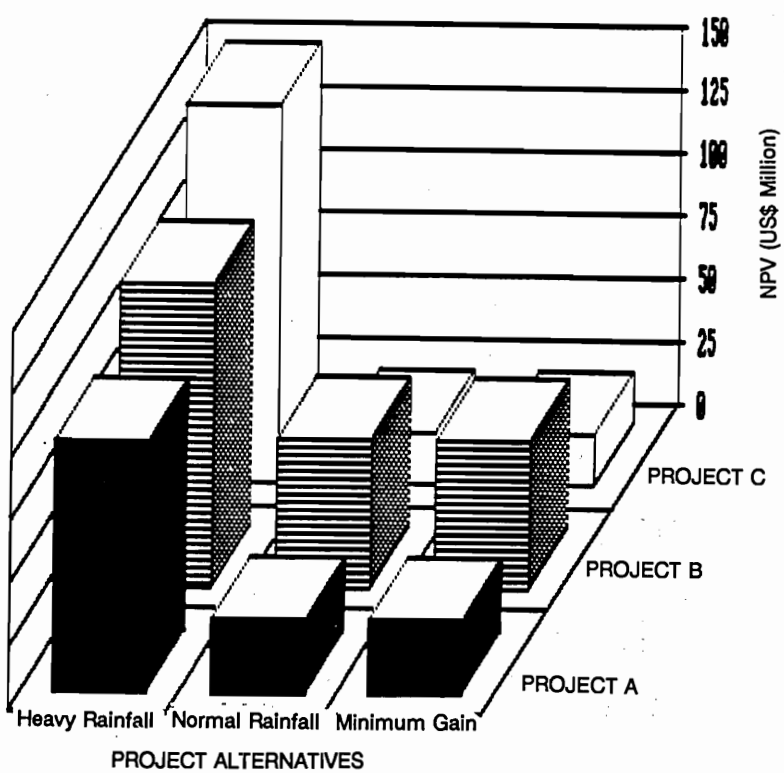
When there is no reliable information on probability distributions of hazards, two strategies from game theory can be useful: the maximin-gain strategy and minimax-regret strategy. Both can be applied in the early stages of project formulation as the necessary minimum of information--records of historical events, climatological and meteorological data, and previous natural hazard damage records--becomes available. From this information it is possible to estimate the comparative benefits of equivalent alternatives under varying degrees of natural hazard severity. Game theory approaches are better suited for short-term, immediate-impact hazards which can be easily divided into least/most-damage scenarios.

Maximin-Gain Strategy

To illustrate the maximin-gain approach, which derives its name from maximizing the minimum, suppose that a decision has been made to augment the previously discussed farming project with a structural mitigation measure aimed at reducing the effects of potential flooding. Three alternative flood control projects, Projects A, B, and C, equal in cost, are under consideration (Anderson and Settle, 1977). For convenience, it is assumed that there are two possible scenarios--heavy rainfall and normal rainfall. If heavy rainfall occurs, the NPV of benefits from the three projects are: Project A = $100 million, Project B = $120 million, and Project C = $150 million. If the rainfall is normal, the projects will provide irrigation and other discounted benefits of $30 million, $60 million, and $20 million, respectively. The benefits will be greater in the case of heavy rainfall, because the primary benefit is the prevention of flood damage. The different outcomes are summarized below and shown in Figure 2-7.

Figure 2-7

MAXIMIN-GAIN STRATEGY



	Benefits	
	Heavy rainfall	Normal rainfall
Project A	$100 million	$30 million
Project B	$120 million	$60 million
Project C	$150 million	$20 million

The maximin-gain strategy would result in choosing Project B, since its minimum benefit is $60 million, as compared to $30 million for Project A and $20 million for Project C. The maximin-gain strategy is based entirely on security and has the drawback of being very conservative: even if the benefits of A and C were 10 times larger than those of B under heavy rainfall conditions, Project B would still be selected. Thus, it can lead to the selection of projects which most people would agree are inferior.

Minimax-Regret Strategy

An alternative approach is the minimax-regret strategy. This consists in minimizing the maximum regret or loss that could be realized. Using the same example as above, if heavy rainfall does occur Project C would result in the greatest benefit, $150 million. If Project A was selected, the regret or forgone benefits from not selecting C would be $50 million ($150 million minus $100 million) and from not selecting B would be $30 million ($150 million minus $120 million). If the rainfall is normal instead of heavy, Project B would produce the most benefits, $60 million. In that case the forgone benefits would be $40 million for Project C and $30 million for Project A. Now considering both possible weather conditions, heavy and normal rainfall, the maximum regret would be $50 million, $30 million, and $40 million respectively for Projects A, B, and C. Therefore, the minimax-regret strategy would lead to a choice of B since it has the smallest maximum regret, as is shown in Figure 2-8.

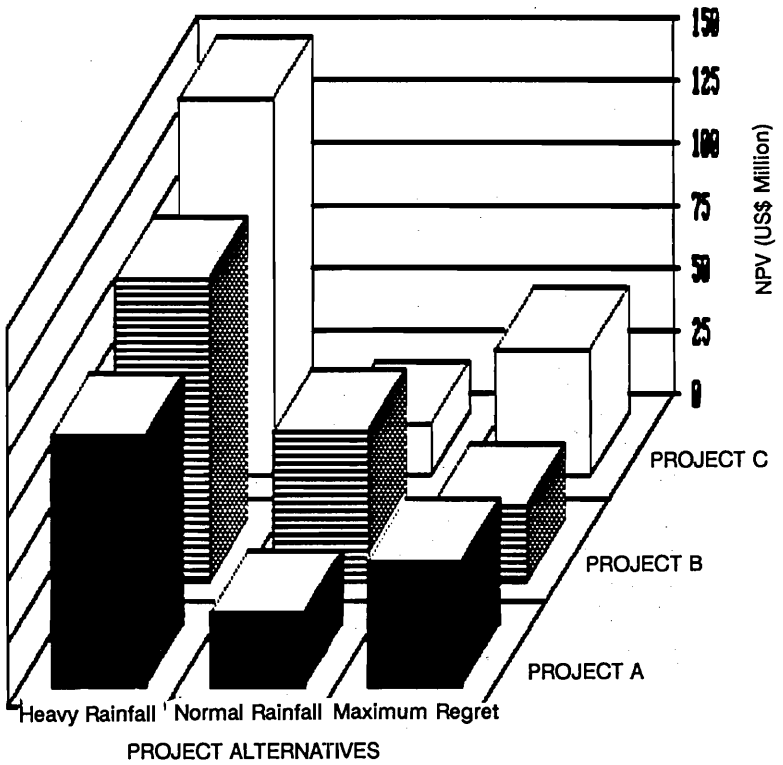
d. Sensitivity Analysis

In a sensitivity analysis, the analyst changes the value of key parameters that are subject to risk to determine the effects on the NPV of a project. Usually, the values are changed one at a time, but sometimes they are changed in combination with one another. This can be useful when the available information indicates how much each parameter should be changed (Irwin, 1978). Typically, values are changed by an arbitrary amount, say five percent.

Sensitivity analyses can help to identify project elements that need further consideration and thus can be used at the project profile stage before a more sophisticated risk analysis is completed. They can also be used to test the effect of mitigation measures. They

Figure 2-8

MINIMAX-REGRET STRATEGY



are suited to all types of hazards, even when the information available is minimal.

The types of information that are useful for this analysis are event histories, climatological and meteorological data, and previous damage reports. These data assist economists in estimating percentage variations in parameters from previous hazard information.

The example of the farming project can be used here to demonstrate this method. With the aid of a personal computer or even a hand calculator, a sensitivity analysis can be performed on each cost and benefit to determine their effects on the rest of the project. For example, a sensitivity analysis performed on crop yields may demonstrate that if production falls by 40 percent in the first year as the result of an intermediate-level flood, the overall project benefits may be greatly decreased, or it would take much longer to recover the costs.

The best way to report the results of sensitivity analysis is by means of "switching values" (Baum, 1980). These are the values of the key variables at which the NPV of the project becomes zero or the benefit-cost ratio falls below one. Switching values can be presented as shown below and in Figure 2-9.

Variable	Switching Value
Corn price	-40%
Corn yield	-20%
Construction costs	+35%
Fertilizer price	+50%
Labor cost	+60%

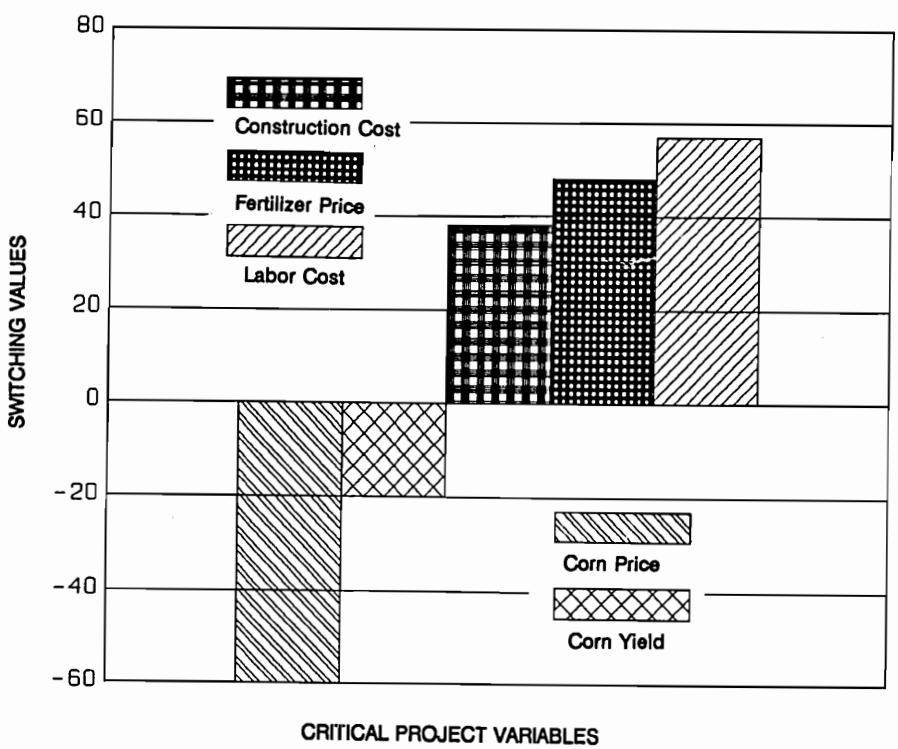
In this example, corn yields would only have to decline from their expected value by 20 percent to make the project NPV equal zero. On the other hand, labor costs could increase up to 60 percent before the NPV falls to zero.

2. DECISION CRITERIA WITH PROBABILISTIC INFORMATION

If probability distributions for key economic variables are available, a more rigorous evaluation of risk can be carried out. The probability distributions may be based on the subjective assessments of experts or on historical information such as episodic, climatologic, meteorologic, and agronomic data. For example, if adequate data are available, the probability distribution for crop yields can be estimated from historical farm or experiment station records. Where these data are not available, as is often the case,

Figure 2-9

SENSITIVITY ANALYSIS



subjective probabilities can be elicited from farmers, extension agents, or agronomists.

One relatively simple way to obtain subjective probabilities is the triangular distribution method. Analysts can estimate the most likely, the best, and the worst possible yields. The mean and variance of the probability distribution can then be estimated (Anderson et al., 1977). Subjective distributions of yields can be provided for projects with or without natural hazard mitigation measures.

Since natural hazards can affect both the benefits of a project (for example, by destroying crops) and the costs (for example, by damaging irrigation systems), in some cases it will be desirable to obtain probability distributions of natural hazard events. Probabilistic information can be obtained for any type of natural hazard with measurable magnitude and frequency, but of course the quality of the information can vary widely.

In estimating the probability distribution of economic feasibility measures, such as NPV, only a limited number of variables are considered random or subject to fluctuations; others are considered fixed for the purposes of the analysis. The variables that are allowed to fluctuate can be determined either by making a sensitivity analysis to identify those that are important or by observing those that fluctuate widely. Various probability distributions can be combined mathematically or with computer simulation methods to form a probability distribution of NPV. The distribution conveniently conveys information about the risks of a project.

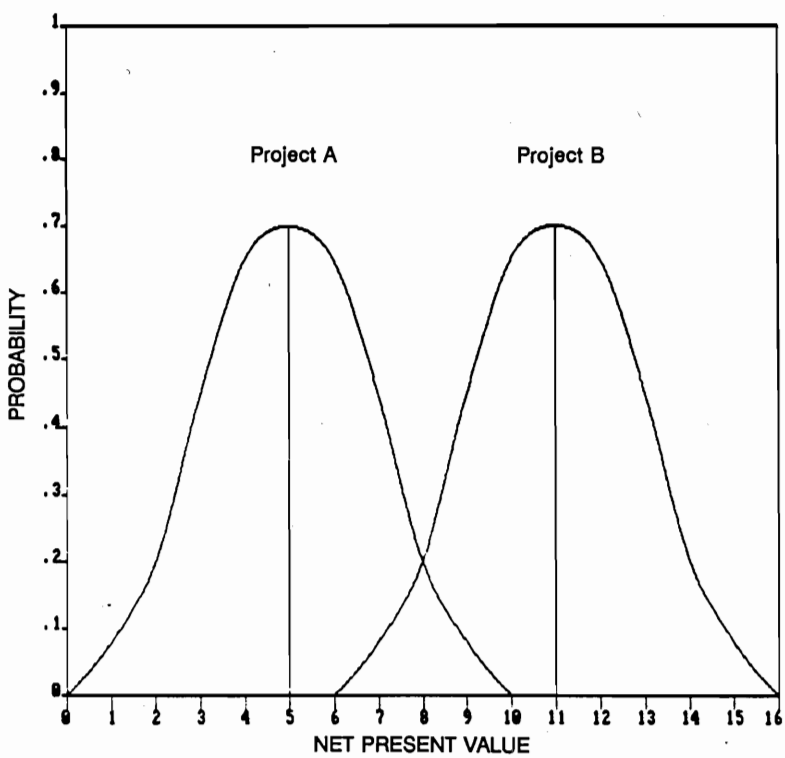
After the probability distributions have been calculated, the mean or average values of each distribution can be compared to make a selection between projects, or between alternatives within a project. But using averages alone ignores the relative risks of the projects, even though this information is available from the already prepared probability distributions. Two methods are suggested to compensate for this: mean-variance analysis and safety-first analysis.

a. Mean-Variance Analysis

With mean-variance analysis, which can be applied in the prefeasibility stage of project development, projects can be compared by graphing the NPV probability functions. In Figure 2-10, Project A and Project B have similar probability distributions--that is, they have the same risk--but the distribution for Project B is further to the right, indicating that the average NPV is greater. Project B, then, is preferable to A.

Figure 2-10

MEAN-VARIANCE ANALYSIS: PROJECTS WITH EQUAL RISK AND DIFFERENT NPVs



In Figure 2-11 Projects C and D have the same mean, but Project D has a greater dispersion around the mean, and thus is riskier. If only the mean values of the projects' NPV are considered, society will be indifferent between Projects C and D. However, if society considers this a critical project and cannot afford to have it give low yields, Project C will be preferred, since there is less chance that the NPV will fall below the mean. The comparison of Project C with Project E is less clear-cut: Project E has a much higher mean than Project C, but its variance is also greater. Clearly, there is a trade-off between a higher expected NPV and the acceptance of greater risk. The decision-maker, not the analyst, will have to decide what weights to apply to higher mean NPV versus greater risk.

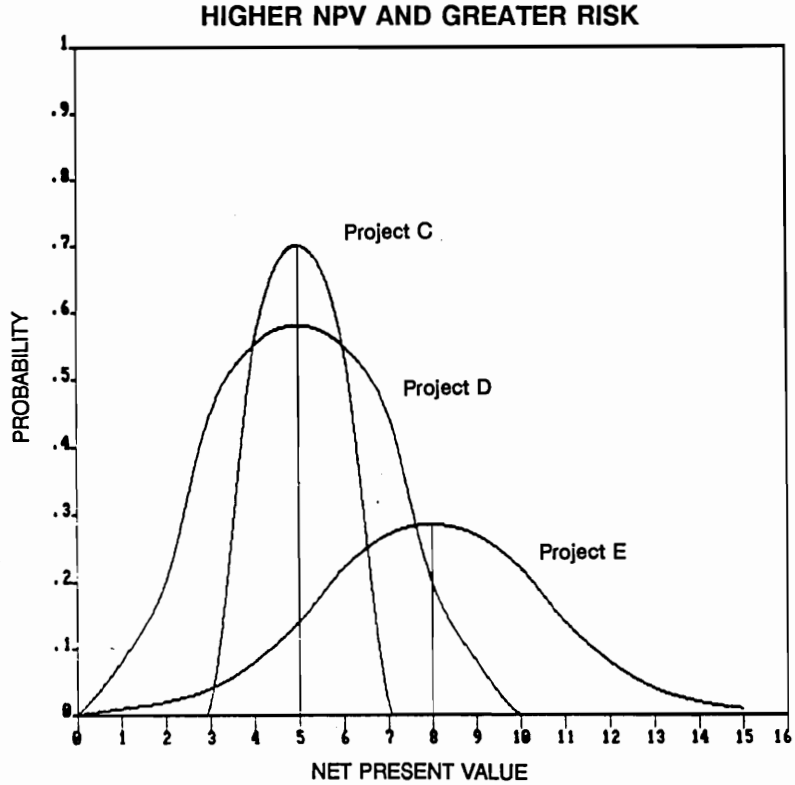
A mean-variance analysis can be easily applied to the example of the flood control projects presented earlier. The information needed includes historical data on past flood events--magnitudes and frequency of occurrence--from which statistical means and variances can be calculated to provide sufficient data for determining the probability of flooding. This information can be used by planners in making a decision. It can also be used to calculate the probability distribution of the NPV of alternative flood control projects and, in turn, the means and the variances of the projects' NPV. This analysis enables the project planner to view the variance, or the risk, of the NPV resulting from flood events.

b. Safety-First Analysis

Since risk management is concerned primarily with reducing losses, the left-hand side of a probability distribution is of more interest to an analyst than the right-hand side. If the distribution is symmetrical, as is normal, decisions based on the variance will be suitable for risk management because negative and positive fluctuations around the mean are equally likely. However, some real-world phenomena of interest to risk analysts appear to follow distributions that are skewed in one direction or the other. For example, corn yields may average 100 bushels per acre, and a drought that occurs every five years could cause yields to fall to zero, but there will probably never be yields fluctuating as far above the mean as 200 bushels. Thus, analysts may want to choose a decision criterion that focuses on the lower tail of a distribution. An additional advantage of such an approach is that it lends itself more easily to discussions of minimizing losses, which can be useful when considering hazard mitigation measures. Safety-first criteria can be applied to relatively frequent natural hazards, such as floods and severe storms, but they are not as useful for low-frequency catastrophic events such as volcanic eruptions and tsunamis.

Figure 2-11

MEAN-VARIANCE ANALYSIS: TRADE-OFF BETWEEN HIGHER NPV AND GREATER RISK



THE SAFETY-FIRST APPROACH:

Maximize NPV subject to P(NPV < C) < a

The box above shows the following values: **NPV** = net present value, **P** = probability, **C** = critical threshold value, and **a** = small probability value. The decision criterion is to maximize expected NPV subject to a constraint that there is only a small probability that it will fall below some constant value. For example, the decision-maker might choose the project with the highest expected NPV as long as the probability of its falling below zero is less than 5 percent (Pandey, 1983).

Suppose the safety-first criterion is established as follows: maximize NPV subject to no more than a 20 percent chance that NPV will fall below $20,000. The cumulative probability of the NPV for two different projects is shown in Figure 2-12. As the graph indicates, the probability is 40 percent for Project A and 15 percent for Project B. The safety-first criterion would eliminate A from further consideration. If there were other projects with less than a 20 percent chance of having an NPV smaller than $20,000, then the one with the highest NPV would be recommended for implementation.

A safety-first approach can be applied to the flood control example. The project planner can decide what level of NPV is the absolute minimum for the project to continue. If the minimum acceptable NPV is $1 million and the probability of falling below that is 40 percent, 20 percent, and 70 percent, respectively, for the different flood control projects, the one with the smallest probability might be preferred.

With the methods described in this section, projects can reflect the additional costs that natural hazards pose and the additional benefits resulting from mitigation measures. Figure 2-13 summarizes the relationships between these methods and the investment preparation process. Some of the key considerations for incorporating natural hazards into the evaluation of investment projects are listed in the following box.

Figure 2-12

SAFETY-FIRST APPROACH

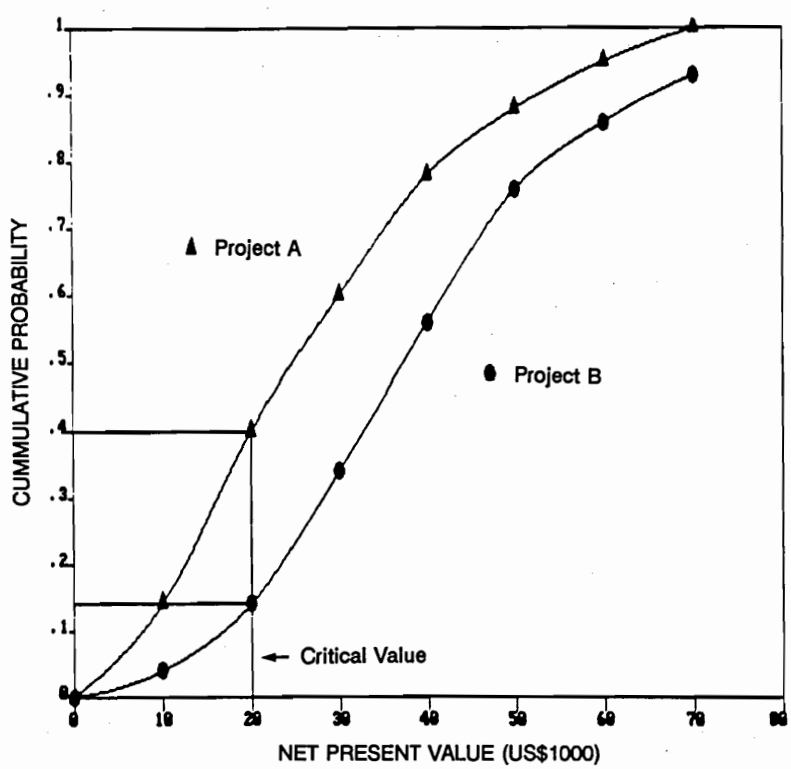


Figure 2-13

APPLICABILITY OF ECONOMIC APPRAISAL METHODS FOR INCORPORATING NATURAL HAZARD CONSIDERATIONS INTO THE EVALUATION OF INVESTMENT PROJECTS

INTEGRATED DEVELOPMENT PLANNING STUDY STAGES	INVESTMENT PROJECT PREPARATION PROCESS	ECONOMIC APPRAISAL METHODS AND THEIR PRINCIPAL USES
PRELIMINARY MISSION Determination of study areas and interest; preparation of project agreement →	Generation of investment project ideas →	* Multicriteria Analysis: - Can be used to establish societal goals and priorities with respect to investment projects and to natural hazard issues. - Makes decision process more explicit in terms of the evaluation criteria used for the selection of programs and projects.
PHASE I: DEVELOPMENT DIAGNOSIS Regional needs and resources diagnosis; identification of critical issues and of institutional settings →	PROJECT PROFILE Preparation of project profiles →	* Multicriteria Analysis (see above) * Cut-Off-Period Method: * Discount Rate Adjustments Method: * Maximin-Gain / Minimax-Regret Methods: - When no probabilistic information is available these methods use on historical data to make a preliminary appraisal of projects. - These methods mostly avoid considering uncertain data rather than directly incorporating natural hazard risk information into the appraisal process.
PHASE II: PROJECT FORMULATION & ACTION PLAN Formulation of regional development strategy including institutional, legal & fiscal support programs; formulation of investment projects →	PREFEASIBILITY Project formulation; review of technical & economic viability →	* Cut-Off-Period Method: * Discount Rate Adjustments Method: Maximin-Gain / Minimax-Regret Methods: - At the prefeasibility and feasibility stages, when more information on a project exists, these methods can be used more effectively; cost of generating more specific natural hazard information can be shared by other data research activities.
	FEASIBILITY Detailed formulation & final appraisal of selected projects →	* Sensitivity Analysis: - This method can be used to identify project components which are vulnerable to natural hazard events. This can orient research and the design of mitigation measures. * Mean-variance Analysis: * Safety First Analysis: - When probabilistic information is available or can be generated, these methods provide a good measure for the consideration of hazard risks within the economic evaluation process.
IMPLEMENTATION Implementation of the integrated development strategy: institutional, legal & fiscal programs, & investment projects →	IMPLEMENTATION Implementation of selected investment projects	

KEY CONSIDERATIONS FOR THE INCORPORATION OF NATURAL HAZARDS INTO THE EVALUATION OF INVESTMENT PROJECTS

- Natural hazards should be considered in the evaluation of public and private sector projects alike.
- Multicriteria analysis can be used to incorporate natural hazard considerations into general development and project investment planning.
- When little risk information is available, cut-off period, discount rate adjustments, maximin-gain, minimax-regret, and sensitivity analysis methods can be used to consider natural hazards in the economic evaluation of investment projects.
- When probabilistic information is available, mean-variance analysis and safety-first analysis, among other methods, can be used to consider natural hazards in the economic evaluation of investment projects.

G. Concluding Remarks

Natural hazards can have considerable human and economic impacts on the agricultural sector in developing countries. Since these and other forms of risk can make the outcome of development projects uncertain, they need to be considered early in the development process. For this to happen, a large effort will be required to modify current project formulation and evaluation practices. But the changes should not be limited to project planning. If natural disasters are to be reduced significantly and consistently, not just in isolated projects, changes will also have to come about in government agencies, development assistance agencies, banking institutions, scientific communities, and attitudes toward natural hazards. Without a doubt, the availability of timely and adequate information will be a key factor in making these groups aware of the human and economic significance of disasters and of the necessity to support hazard mitigation at different levels. As intermediaries, development assistance agencies should take advantage of their inherent capabilities and assume a leading role in this process.

Because resources are scarce and costly, hazard mitigation actions should be focused and well articulated. Natural hazard mitigation actions should reflect legitimate social, economic, and political priorities, and new investment projects in key economic sectors, such as agriculture, should be given preference over retrofitting mitigation measures into already existing projects.

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CHAPTER 3

RESOURCE EVALUATION AND THE ROLE OF ECOSYSTEMS IN MITIGATING NATURAL HAZARDS

CHAPTER 3

RESOURCE EVALUATIONS AND THE ROLE OF ECOSYSTEMS IN MITIGATING NATURAL HAZARDS

Contents

List of Figures

RESOURCE EVALUATION AND THE ROLE OF ECOSYSTEMS IN MITIGATING NATURAL HAZARDS

SUMMARY

This chapter describes methods for integrating natural hazard assessments into natural resource evaluations, with emphasis on land-use evaluations. It also explains the role of ecosystems in naturally mitigating or intensifying hazardous events and how this role is affected by development.

During the initial stages of a regional development study, a region's problems and potentials are diagnosed. An assessment of the natural resource base is fundamental to any development planning and project formulation effort. This provides baseline information that will help in formulating a strategy and identifying projects. Land-use studies, including present land use and land capability, are part of these evaluations and require mapped information on resources and natural hazards. The planning process should identify all assumptions and reveal potential conflicts between current and proposed development activities and natural hazards. For example, deforestation on unstable soils may increase landslide activity upstream of a reservoir, resulting in high siltation, and shorten the life of the reservoir. Execution of an agricultural scheme in a flood plain may result in flooding of the project or in excessive expenditures to mitigate the effects of the flood. Although hazard assessments should take place throughout the planning process--especially during land-use evaluations--the evaluation of natural hazards generally receives minimal attention.

Natural hazards influence the security and viability of projects and communities. Furthermore, because they influence land use, they should also influence land-use decisions. The first objective of this chapter is to provide guidance for integrating natural hazard assessments into land-use evaluations. Among the many natural services provided by ecosystems is the mitigation of natural hazards. For example, a coral reef causes large waves to break some distance from the shoreline, reducing the impact of tropical storms; but if harbor development breaks down the coral, the natural protection is lost. This chapter examines the mitigating effects of ecosystems and the precautions necessary to ensure that unsound development does not undermine that effect.

A second objective of the chapter is to provide a synthetic view of the natural mitigation of natural hazards. By way of introduction to the detailed material on individual hazards and their assessment in Part III, it briefly examines the implications of development for the natural mitigation of all major hazards by setting them in a realistic, albeit hypothetical, landscape. This composite system examines the implications for volcanic activity, earthquakes, landslides, hurricanes, flooding, and desertification of upland (highlands, piedmont), coastal or lowland, near-shore (reefs and estuarine) and marine (open sea) ecosystem. Thus a second objective of the chapter is to provide a synthetic view of the natural mitigation of natural hazards.

Both objectives contribute to an overriding objective of promoting the consideration of natural hazards in the context of the system in which they occur.

A. Land-Use Evaluations in Latin America

The methods of land-use evaluation used in Latin America and the Caribbean demonstrate the difficulties in understanding nature and the limitations the planner's training, experience, and interests bring to decisions concerning land use. Land-use evaluation methods are always subjective, as can be observed by comparing the results of the application of a number of methods currently in use. Several of these methods were reviewed by Posner et al. (1982) in their preparation of a land classification system for the steep lands of the northern Andes. With notable exceptions, the methods reviewed emphasized soil

analysis. Since most soils specialists are also agronomists, the results are skewed towards agriculture.

The land-use evaluation methods generally used in Venezuela, Nicaragua, and Mexico are based on the methods of the Soil Conservation Service of the U.S. Department of Agriculture (USDA, 1938). These methods are widely accepted, but they have been criticized as inappropriate for developing countries. Also included in the review cited above was an evaluation method developed in Central America in the 1960s by the UN Food and Agriculture Organization (FAO). This method was also extensively criticized, as having "a flatland bias," and was replaced by a method developed in Africa that was based on the number of growing days for several crops. These two and the "Integrated Ecological Land Capability Classification" (IELCC) method developed in Latin America are major examples of methods that are not based solely on soil analysis and slope characteristics.

The IELCC method is based on the World Life Zone System of Ecological Classification by Holdridge (1967). It has been adopted as the official land classification system in Peru and has been used to map virtually all Central and South American countries. Of all the land-use evaluation systems in use in Latin America, this one is perhaps the most "complete" (Tosi, 1988) in that it includes bio-climate, land gradient, and micro-relief observations as well as alternative levels of technology that could be used in land management. Factors that influence social and economic risk as well as soil depth and texture, stoniness, soil permeability, fertility and pH, accelerated soil erosion, salinity, and flood hazards are then analyzed to suggest land use at a local level.

Modern technology is also used in the evaluation of land-use capability. The French Overseas Scientific and Technical Research Organization has mapped a large portion of the Andean highlands in Ecuador using satellite imagery. This information is used in regional development programs. A computerized mapping system (1:1,000,000 scale) was designed by the International Center for Tropical Agriculture in Colombia to support land-use decisions in the lowland tropics of Latin America.

The purpose of these methods is to assess the characteristics of a site in order to make decisions concerning its capability and/or suitability for use. Several conceptual problems add to the deficiencies of current land-use evaluations, starting with the terms "capability" and "suitability" themselves. Although they are often used interchangeably, they do not mean the same thing (AAAS, 1983). "Land-use capability" is the more general term and makes reference to limitations such as the degree of stoniness or slope that can negatively affect use. "Suitability" on the other hand, refers to qualities that permit specific land uses such as irrigation or the production of a certain crop. The term "capability" is heavily identified with the U.S. Soil Conservation Service method and its agricultural bias. In order to avoid confusion in some contexts, the term "suitability" may be preferable (FAO, 1976). A more significant problem arises from the capacity of current technology to render almost any land area "capable" of almost any use if the necessary investment is made (Hawes and Hamilton, 1980), although specific areas are more physically "suitable" for a given use than others. Land-use decisions are based on a number of factors in addition to the physical landscape.

B. Limitations of Land-Use Evaluations

Current land-use evaluation methods and their application are extremely limited for two main reasons: they show little interest in the cultural components of the landscape, and they lack standardized procedures that would make manifest the relationship between proposed land uses and natural hazards.

1. LIMITED EMPHASIS ON CULTURAL COMPONENTS

Although land-use classification systems are still generally based on physical data (Beek, 1978), most writers and practitioners acknowledge the importance of socioeconomic data in making land-use decisions. Less emphasis is placed on cultural factors, which are often more important than physical and even economic and social characteristics in determining land-use patterns.

For example, in Saint Lucia, areas that are potentially productive according to soil and slope parameters and to the prevailing social and economic factors do not sustain the activities that a land-use evaluation would assign to them. The reason these areas are not used is the fear people have of the fer-de-lance, which was introduced to the island and has taken refuge in these areas. This fear is so great that the national agricultural development plan had to include a project to eradicate this viper so that the area could be put into agriculture production.

A typical cultural bias which intensifies hazardous phenomena in many parts of Latin America, favors livestock ownership, because of the prestige and authority it brings. People will own as many head of livestock as they can afford, preferably cattle, even if the biotic, climatic, edaphic, economic, and social

characteristics of the area are unfavorable for grazing (Clausen and Crist, 1982). Poorly managed grazing often results in the intensification of such natural phenomena as erosion and mass movement of soil in much of Latin America.

Cultural factors that affect land use include information, technology, and any number of biases and taboos. Production of a given land unit depends on the knowledge of the resource manager, local taboos, the availability of appropriate technology, and the willingness of the local culture to accept the proposed technology and land use. Because cultures can be remarkably different from one another, land-use evaluations cannot be standardized for similar physical conditions. People living and working in a given space often disregard the proposals of studies on the physical parameters of the area. Evaluations can only suggest the potential for production and loss under a specified land use; they cannot dictate a decision, which depends on the characteristics of the populations affected.

2. LACK OF STANDARD PROCEDURES TO INCORPORATE INFORMATION ABOUT RISK FROM NATURAL HAZARDS

A significant limitation of all land-use capability evaluation methods is that they do not adequately portray the risks that natural hazards pose to development activities. Yet reviews of resource evaluation methods (McRae and Burnham, 1981; AAAS, 1983) indicate that most do discuss natural hazards briefly and that it should be easy to incorporate information about them throughout the planning process. Numerous studies have been made on the assessment and display of specific hazards such as landslides (Varnes, 1985; Brabb and Harrod, 1989), earthquakes (Blair and Spangle, 1979; Jaffe et al., 1981; Brown and Kockelman, 1983; Kuroiwa, 1983), flooding (U.S. Water Resources Council, 1972; Waananer et al., 1977), tsunamis (Houston, 1980; URR, 1988), and volcanoes (Booth, 1979; Crandel et al., 1984). However, there is no standard method for assessing natural hazards in resource evaluations for development planning. Different methods are a response to specific concerns about individual hazardous phenomena.

C. Land-use Evaluations Based on a Systems View

Since approaches to the evolution of individual natural hazards are detailed elsewhere, this section looks at them from the point of view of the system in which they occur, within the context of land-use evaluations.

1. A SYSTEMS VIEW

The combination of attributes of a landscape and the linkages between them can reinforce or restrict possible uses of the landscape. Hence, landscapes should be regarded and studied as systems (Chapman, 1969; Steiner and Brooks, 1981; Rowe and Sheard, 1981; Steiner, 1983). A systems view takes in a broader array of attributes and linkages than is normally considered in current land-use evaluation methods (see Figure 3-1), including as it does the relationships between natural phenomena, development activities, and natural elements (Hawes and Hamilton, 1980; FAO, 1976; Posner et al., 1982). Merely listing the important natural elements--slope, exposure, climate, evapotranspiration rates, surface water availability, and others (see Figure 3-2)--though helpful, is an incomplete approach that fails to integrate natural hazards information into land-use evaluations.

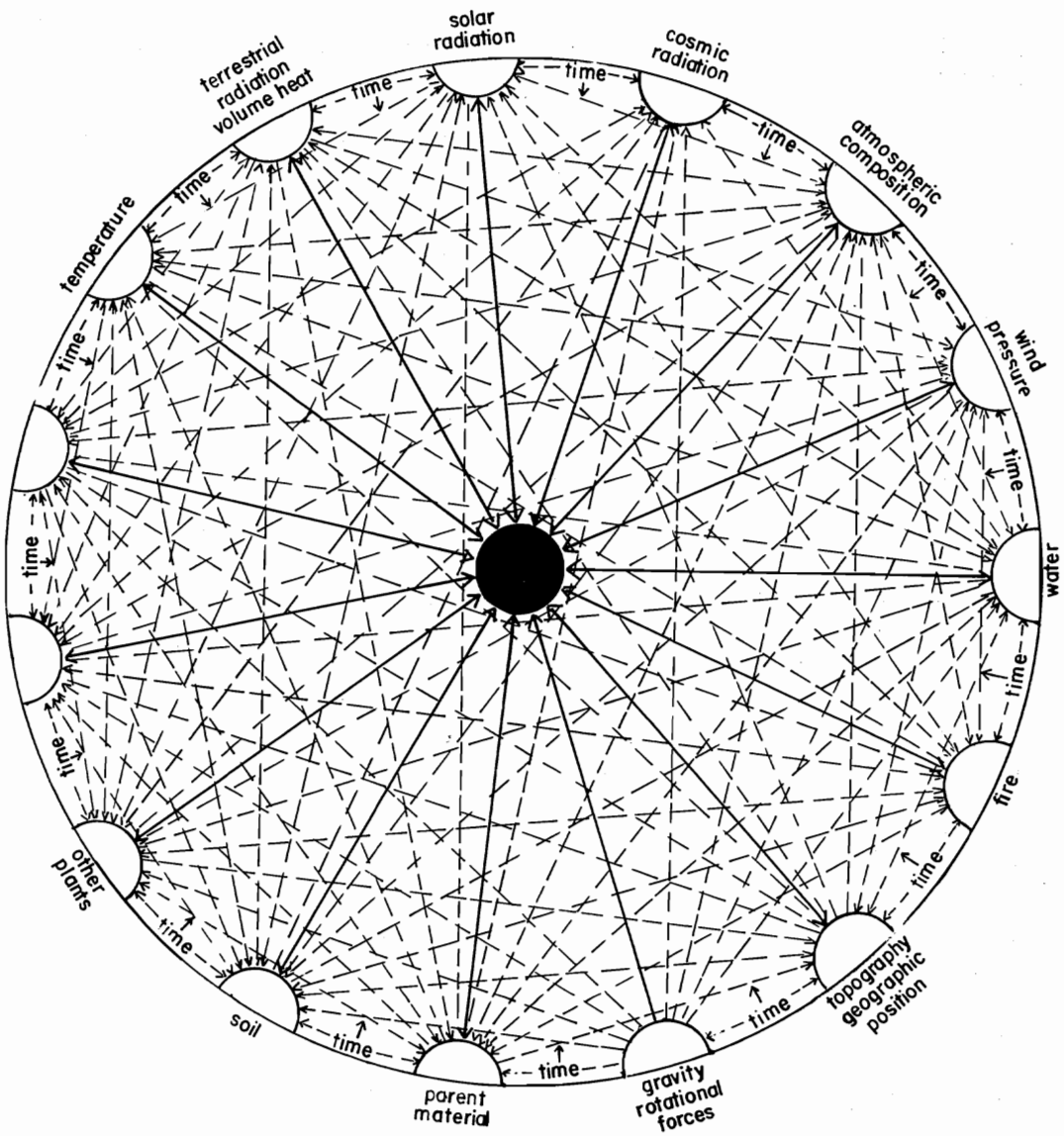
For purposes of land-use classification, all landscapes must be thought of as systems which provide goods and services for the satisfaction of human needs. Any aspect of a system structure and function that is of human interest can be classified as a system good or service (OAS, 1987). Photosynthesis, for example, produces biomass that becomes wood and then, through human activity, timber. If the system attribute is dangerous to human activity (e.g, high wind or heavy precipitation), it is considered a hazard. However, since the needs of humans vary, individuals will value system attributes and processes differently; goods and services valued by some may have no meaning for others. For some, the danger inherent in a specific system attribute makes it a service (e.g., rapids to run, mountains to climb). On the other hand, some phenomena are always hazardous (e.g., lava flows). It is these that must be considered in land-use evaluations.

The analysis of the goods, services, and hazards of a system, together with the needs of its population, permits the identification of alternatives not normally defined in land-use evaluations. This is consistent with the purpose of a systems analysis land-use evaluation, which is to formulate a strategy that includes the use, improvement, and conservation of the region's potential goods and services. Figure 3-3 is a regional model with examples of internal and external linkages.

Human needs involve nutrition, shelter, and personal or collective security. Landscapes contain structures and elements that are hazardous and that

Figure 3-1

AN ENVIRONMENTAL COMPLEX



Source: Based on Billings, W.D. "Physiological Ecology" in Annual Review Plant Physiology, vol. 8 (1957), pp. 375-392.

Figure 3-2

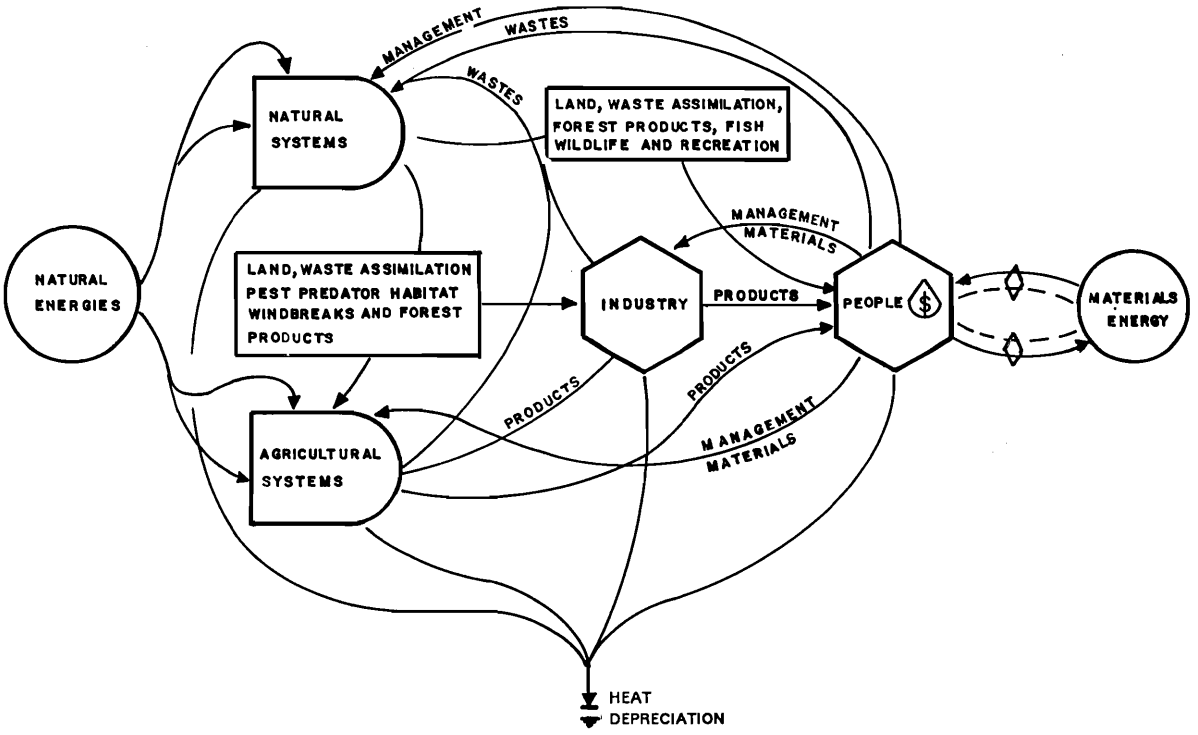
LANDSCAPE ATTRIBUTES AND ELEMENTS RELATED TO LAND USE

Characteristics	Related Land Qualities
Air temperature	Frost risk
Precipitation, including distribution and intensity	Erosion, flooding, moisture availability
Wind speed and direction	Evapotranspiration, storms, wind erosion
Net radiation	Evapotranspiration
Hail and snow	Climatic hazards
Evaporation	Evapotranspiration
Depth to water table	Drainage and aeration
Frequency of flooding	Drainage and aeration
Soil texture and stoniness	Ease of cultivation, moisture availability, drainage, aeration, water/wind erosion, permeability
Visible boulders/rock/outcrops	Ease of cultivation, moisture availability
Soil depth	Moisture availability, rootability, ease of cultivation
Soil structure, including impermeable layers, crusting, compaction	Water/wind erosion, rootability, moisture availability
Organic matter and root distribution	Moisture availability, water/wind erosion, ease of cultivation
pH (reaction)/CaCo2/gypsum	Soil fertility, soil alkalinity
Clay mineralogy	Water erosion, ease of cultivation
Soil chemistry	Fertility, nutrient availability, toxicities
Soil permeability	Drainage and aeration, moisture availability
Available water capacity	Moisture availability
Infiltration/runoff	Water erosion, flooding
Soil salinity	Drainage, toxicity, flood
Soil parent material	Fertility, nutrient availability, including deficiencies and toxicities

Source: Adapted from McRae, S.G., and Burnham, C.P. Land Evaluation (Oxford: Clarendon Press, 1981).

Figure 3-3

REGIONAL MODEL SHOWING EXAMPLES OF INTERNAL AND EXTERNAL LINKAGES



can negatively influence the secure appropriation of the goods and services indicated by a land-use evaluation. Figure 3-4 lists attributes of ecosystem structure and function that provide a wide array of goods and services that satisfy human needs; Figure 3-5 identifies other attributes that are hazardous.

2. SYSTEMS ATTRIBUTES

a. Linkages and System Function

It is not just the basic components, but the linkages between them, that make a system. They are the "tubes," "wires," and "connections" that relate one component of a system to another. The "First Law of Ecology" concerns linkages: "Everything is related to everything else" (Commoner, 1971). The sheer number of interconnections present in any given system makes methods that can identify these linkages valuable tools for planners (Steiner and Brooks, 1981).

A basic array of linkages can be identified for any ecosystem: terrestrial, marine, or urban. In all cases, these linkages have to do with the flow of material, energy, or information between components. It is important to identify and evaluate linkages between as well as within ecosystems (Karr and Schlosser, 1978). The characteristics of a lake ecosystem, for example, depend on all the human activity around that lake, including activities that take place in the rivers that feed it and the chemical characteristics of the precipitation in its watershed. Exchanges of material and energy between ecosystems also influence the nature, timing, and severity of hazardous events. Earth tremors causing landslides many miles from the epicenter, and heavy rainfall--or the thawing of snow and ice--hundreds of miles upstream causing major flooding downstream, are two examples of linkages between seemingly unrelated ecosystems.

Most severe hazards involve the flow of energy (ecosystem function) rather than its storage (ecosystem structure). Despite this fact, structure and function are often studied separately. Consequently, land use is not studied in a system context, and the hazard analysis suffers accordingly.

Of equal importance are linkages between physical and biotic attributes of an ecosystem on one hand and social, cultural, and political factors on the other. The construction of a road or the urbanization of upstream

Figure 3-4

ECOSYSTEM GOODS AND SERVICES

GOODS/PRODUCTS

1. Potable water (surface and ground)
2. Industrial water (surface and ground)
3. Irrigation water (surface and ground)
4. Timber
5. Firewood/charcoal
6. Construction material from wood (posts, beams, etc.)
7. Ornamental plants (indoor, landscaping, dry)
8. Vegetable fibers (rope, cloth)
9. Medicinal plants
10. Food for humans (fruits, nuts, sap, shoots, seeds, gum, honey, leaves)
11. Food for domestic animals
12. Food animals for human consumption
13. Aquatic plants for human consumption
14. Condiments (spices, salt)
15. Plant chemical substances (dyes, stains, waxes, latex, gums, tannins, syrups, drugs, etc.)
16. Fertilizers
17. Aquatic precious/semiprecious materials (pearl, coral, conchs, mother of pearl)
18. Materials for artisan work (rock, wood for carving, fibers for basket making)
19. Metallic minerals (bauxite, ores, nuggets)
20. Non-metallic minerals (asbestos, clays, limestone)
21. Construction materials (sands, clay, cinders, cement, gravel, rocks, marble)
22. Mineral nutrients
23. Mineral dyes and glazes
24. Hides, leather, skins
25. Other animal materials (bones, feathers, tusks, teeth, claws, butterflies)
26. Other vegetative material (seeds, pods)
27. Live fish (ornamental)
28. Live animals for pets and zoos
29. Live animals for human work
30. Live animals for research
31. Fossil fuels (crude oil, natural gas, coal)
32. Other fuels (peat, other organic matter, dung, biomass)
33. Livestock forage protection

ECOSYSTEM OPERATIONS, MAINTENANCE, ADAPTATION AND EVOLUTION

1. Nutrient cycling
2. Nutrient storage
3. Nutrient distribution (floods, dust, sediment transport)
4. Photosynthesis
5. Respiration
6. Oxidation
7. Adaptation
8. Self-regulation
9. Competition testing and design (population control, evolution)
10. Mineral cycling
11. Habitat for local land, air and aquatic animals, insects, and other life forms (feeding, breeding, nursery, shelter)
12. Habitat for migrating land, air, and other life forms (feeding, breeding, nursery, shelter)

NON-TANGIBLE GOODS AND SERVICES

1. Windbreak
2. Shade
3. Recreational use of water (swimming, boating, skating, waterskiing, sailing, surfing, snorkeling)
4. Recreational use of land (hiking, climbing, sports)
5. Recreational use of air (flying, gliding, parachuting, hang-gliding, kiting)
6. Recreational use of animals (sport hunting, sport fishing, horseback riding, insect collecting, photography, observation)
7. Recreational use of ecosystem (sightseeing, tourism)
8. Scientific tourism
9. Exploration
10. Wealth accumulation and speculation
11. Spiritual development
12. Historical values
13. Cultural values
14. Early warning system (weather, climate change, hazardous events)
15. Moisture modification
16. Temperature modification
17. Light modification
18. Ultraviolet and other radiation filtration
19. Storage of life from adaptive (genetic) information
20. Other scientific values

ECONOMIC SERVICES

1. Energy sources (wind, solar, hydro, tidal, biomass, geothermal)
2. Dilution of contaminants
3. Decomposition of contaminants (oxidation, evaporation, dissolution)
4. Transport of contaminants (wind, water, animal consumption, air and water dilution)
5. Storage of contaminants
6. Erosion control
7. Sediment control
8. Flood control
9. Other control of water regime
10. Ground water recharge
11. Space for urban, industrial, agricultural occupation, roadways, canals, airports
12. Physical sites for structures
13. Climate control and protection
14. Disease control and protection
15. Storm buffer

Source: Organization of American States (OAS). Minimum Conflict: Guidelines for Planning the Use of American Humid Environments (Washington, D.C.: OAS General Secretariat, 1987).

Figure 3-5

ECOSYSTEM ATTRIBUTES AS NATURAL HAZARDS

1. Diseases and plagues (viruses, bacteria, flukes, parasites, fungi)
2. High water
3. Avalanches (landslides, landslips, debris flows)
4. Wind (tornadoes, hurricanes, cyclones, dust storms)
5. Natural erosion and sedimentation
6. Temperature extremes
7. Extremes of humidity
8. Drought
9. Snow
10. Ice
11. Hail
12. Fog, mist
13. Frost
14. Solar radiation
15. Lightning
16. Fire
17. Toxic chemicals, gas concentrations
18. Nuclear radiation
19. Volcanoes
20. Earthquakes
21. Tsunamis
22. Seiches
23. Subsidence
24. Expansive soils
25. Noxious vegetation (poisonous plants, invader species)
26. Poisonous animals (reptiles, insects)
27. Predators

Source: Organization of American States. Minimum Conflict: Guidelines for Planning the Use of American Humid Tropic Environments. (Washington, D.C.: OAS General Secretariat, 1987).

areas will have a major influence on the flood hazard for that watershed. Ecosystem dynamics include human-induced and natural phenomena. Natural hazards, such as an excess or scarcity of water, can be intensified by human activity both inside and outside the system being studied. Unfortunately, off-site activities and events that can influence the project area are seldom considered in land-use evaluations.

Furthermore, not enough attention is paid to a number of natural impediments to development beyond stoniness, slope and occasional flooding. Structural components (soil texture, depth, and distribution; slope; vegetation density and type; base rock; and precipitation and temperature) are emphasized at the expense of the functional processes of the system (hydrological cycle, track and timing of storms, photosynthesis and respiration, shear strength of soil, rhythm, succession, and energy dissipation).

b. Limiting Factors

Natural phenomena may have positive effects on development or they may have negative effects and be limiting factors (see Figure 3-5). Removing a limiting factor--say, by reducing soil moisture through drainage or adding to it through irrigation--allows further growth and development. The action that removes a limiting factor, called a "trigger factor," creates chain reactions that can be far-reaching. For example, a landscape that can sustain a specific number of livestock under a given level of management may deteriorate or improve as a result of fire or heavy rainfall. This event, in turn, can initiate a chain of events leading to overgrazing, erosion, sedimentation, and flooding, on one hand, or to increased production of edible vegetation, fewer insects, and control of both plant and animal diseases on the other. Some natural phenomena can be limiting factors because they occur

infrequently or not at all; inadequate precipitation is a good example.

Phenomena like high water are often considered limiting factors and are classified as natural hazards, but they can have positive effects on the proposed land use. For example, the Necholandia rangelands of the Pantanal area of Brazil have very sandy soils and soil nutrients are rapidly depleted with infiltration of precipitation. However, annual flooding of these soils for lengthy periods replenishes nutrients in the soils and sustains vegetation. Figure 3-6 lists other examples of natural phenomena with positive and negative attributes.

c. Buffering

Ecosystems are continually adaptive to change. This adaptability is attributable to a number of ecosystem characteristics such as species diversity and physiological variability, storage capacity, and cycling rates of nutrients and other materials. The resistance of an ecosystem to outside perturbations is high. Swamps, reservoirs, floodplains, and soil absorb and slowly release water, reducing the extremes of high and low water. Forests buffer high winds and temperatures and reduce soil drying, erosion, and slope failure. Buffering mechanisms are important information for land use planners concerned with natural hazards. Again, the Pantanal region of Brazil provides an excellent example. This large area of swamps and lakes absorbs the Upper Paraguay River flood water and slows its arrival at the confluence with the Parana some six months later. Were it not for this buffering capacity, flood waters of the Parana and the Paraguay Rivers would reach the lower sections of the Parana River at the same time and cause catastrophic flooding.

d. Thresholds

The point at which an effect is manifested is called a threshold. Every system has limits, and despite buffering mechanisms, the components and processes of a system will eventually fail if pushed beyond the threshold. For example, soils move despite being covered by vegetation if rainfall is intense and the slope steep, or they may remain stable under increasing grazing pressure until vegetation cover is reduced below a threshold level.

D. Assessing Natural Hazards in Land-use Evaluations

As has been said, incorporating the consideration of natural hazards early in the planning process can minimize their negative effects on development projects. A systems approach identifies hazards by looking at limiting and trigger factors, thresholds, buffers, and internal and external linkages.

Information about a study area's natural hazards needs to be examined during the various planning stages (see Figure 3-7). The process of iteration focuses the planning studies on important factors.

1. PRELIMINARY MISSION

The definition of the major land units (river basins, sub-basins, watersheds, and life zones) is required at this stage. Satellite imagery is particularly useful for this activity. Time and money can be saved by using lower resolution imagery because of the possibilities it affords to identify potential off-site influences and linkages to other systems.

Conceptual modeling of the region to evaluate important internal and external linkages is also useful. Data obtained through local informants and through available literature are very important to the process. Both upstream and downstream linkages (influence on and influence from the study area) should be identified. A team working at this level defines the work plan, team makeup, and terms of reference for experts to work in the next stage.

2. PHASE I ACTIVITIES

During the Phase I analysis, major ecosystems should be defined in more detail. This will require, for example, evaluations of flood frequencies and water surface levels by a geomorphologist or fluviomorphologist to look into the system's buffering mechanisms and to locate, identify, and quantify factors that influence the water level. The nature and extent of streams and river valleys should also be evaluated in terms of flood hazard and flood control possibilities. Other specialists should identify threshold levels of system attributes that will ameliorate hazards and man-made features that influence the frequency, elevation, and duration of high water. Estimates of stream channel filling should be made, and slope stability and potential erosion under different scenarios should be examined. A scale of 1:250,000 or larger for maps will probably be required to outline floodplains and identify problem areas where floods or other hazards need to be studied in more detail (See Chapter 8.)

Similar evaluation of geological hazards may be necessary (see Chapter 11). The analysis of off-site and on-site seismic-prone systems will involve the identification of past earthquake intensities. The

Figure 3-6

EXAMPLES OF POSITIVE AND NEGATIVE EFFECTS OF SELECTED NATURAL PHENOMENA FOR DEVELOPMENT ACTIVITIES

Natural Phenomena	Positive Effects	Negative Effects
Hurricanes	Bring water, nutrients, sediments and propagules.	Remove structures.
Low temperature	By slowing down processes, allows for conservation and storage.	Freeze can be lethal.
High temperature	Accelerates processes, particularly respiration and recycling.	Can be lethal; reduces species diversity.
Heavy rains	Trigger phenological events in deserts; relieve salinity in coastal environments; redistribute nutrients.	Remove structures and can cause other stresses such as flooding, which affects gas exchange of wetlands sediments and turbidity in aquatic systems.
Fire	Makes nutrients and moisture more available; reduces competition.	Removes structures.
Salinity	Allows higher gross productivity in mangroves up to seawater concentrations.	At values higher than 35 parts per 1000, increases respiration rates and decreases transpiration net production rates.
Volcanic eruptions	Allow for better nutrient, moisture, and competitive environments.	Suffocate and kill plants and animals.
Flooding	Removes competition; triggers phenological events.	Increases energy maintenance costs; temporarily decreases the number of taxa and individuals.
Water flow	Transports nutrients and oxygen; removes toxics; redistributes larvae.	Removes structures; causes high energy maintenance costs to biota.
Tidal extremes	Redistribute nutrients, sediments, organic matter, and organisms.	Expose organisms to lethal conditions.

Source: Adapted from Lugo, A. Stress and Ecosystems (1978).

Figure 3-7

ORDERS AND TYPES OF SOIL SURVEYS, THEIR CHARACTERISTICS, DATA SOURCES AND USES

	Order of Soil Survey				
	5th order	4th order	3rd order	2nd order	1st order
Survey type	← Reconnaissance →		Semidetailed	Detailed	Intensive
Survey scale	1:300,000-1:1,000,000	1:125,000-1:300,000	1:32,000-1:125,000	1:12,000-1:32,000	1:1,000-1:12,000
Size of mapping unit	35-50 km2	500-500,000 ha	10-1000 ha	1.0-1.6 ha	0.5 ha or smaller
Kind of mapping unit	Associations of phases of subgroups/great groups, suborders, orders	Associations of families of soil series	Associations of phases of soil series	Consociations of phases of soil series	Phases of soil series
Use in development planning	← Resource inventory →				
		← Project location →			
			← Feasibility surveys →		
				← Management surveys →	
Common in potential remote sensing data sources	Landsat 1-5 MSS and TM (images) →				
		← Landsat 1-5 MSS + TM (digital) →			
				← Landsat 4 and 5 TM (digital) →	
	NOAA 6/7 →				
	← Aerial photography (high altitude) →				
			← Aerial photography (low altitude) →		
Socioeconomic and land use features	Broad land use categories	Regional land use	Sets of villages	Villages pastures, open fields	Villages fields, village residential areas

Source: Adapted from American Association for the Advancement of Science (AAAS). Resource Inventory and Baseline Study Methods for Developing Countries (Washington, D.C.: AAAS, 1983).

geologist will need to study the location and direction of active faults and identify probable fault ruptures. Micro-zonation technique will identify the most vulnerable areas. Similarly, a detailed study of volcanic hazards should incorporate information on the extent of previous ash falls, tephra falls, and lava flows. The proximity of a volcano to the project area and to large bodies of water must be considered because water intensifies the violence of the eruption and accelerates the velocity of lava or ash flows.

Planning is a dynamic process that responds to the dynamics of local systems. Land-use mapping should reflect this. Map overlay techniques are appropriate, and special hazard maps can be developed if they are not available (Giuesti, 1984; Singer, 1985; see Chapters 4-6).

3. PHASE II ACTIVITIES

The most appropriate scales for an action plan and project formulation during Phase II are between 1:20,000 and 1:60,000. In the case of floods, the geomorphologist or fluviomorphologist would further define thresholds for erosion and infiltration of precipitation, and examine changes in floodplains and peak discharge frequencies due to human intervention, both on-site and in linked ecosystems. In the case of seismic activity, development projects should be steered away from the most vulnerable areas. A typical recommendation in the development of new areas would be to restrict uses in zones that have exhibited significant ground movement to low-density functions such as agriculture or parks. Additional suggestions should be made for mitigation measures in already developed areas.

4. GENERAL RECOMMENDATIONS

1. Include specific hazard-related terms of reference for specialists working in the Preliminary Mission and in Phase I (e.g., hydrologist, soils specialist, environmental management adviser). These terms of reference should include the need to develop and analyze information at the points of interaction between sectoral activities. Include hazard-related terms of reference for technicians who will be responsible for project formulation in Phase II.

2. Add the short-term participation of a geomorphologist, hydrologist, or geologist to look into areas that have been shown to be problematic during an earlier study phase.

3. Evaluate proposed uses of floodplains, with special attention to downstream consequences that may result from a loss of flood-water storage capacity caused by development activities. Upstream activities should be evaluated for the same reasons even if they fall outside of the region being studied.

4. Look at the projects being considered under different scenarios of potential development in linked ecosystems.

5. Evaluate the influence of the projects being considered on other activities of the ecosystem, including buffering and threshold characteristics.

6. Account for changes in the hydrologic regime that will be induced by the creation of impervious surfaces (e.g., urbanization, road surfaces, soil compaction from trampling by livestock, change in vegetation cover).

7. Be explicit in all instructions concerning land-use capability or suitability, including statements on the technology requirements for development projects.

E. Natural Services in Support of Hazard Mitigation

1. ECOSYSTEM BOUNDARIES, WATERSHEDS, AND RIVER BASINS

The discussions in Chapters 8 to 12, focusing on man's relationship to each of the principal natural hazards, demonstrate that actions taken in the name of development often exacerbate hazard impact and prescribe actions that can be taken to mitigate damage. Here the focus is on the natural services of ecosystems that serve to reduce the impact of hazards. It follows logically that one strategy of hazard mitigation is to maintain the natural capacity of ecosystems to accomplish this. Secondly, in contrast to Chapters 8 to 12, this section discusses all the hazards simultaneously in the context of the natural ecosystem in which they occur. Again, it follows that the mitigation strategy is to maintain the natural functions of the ecosystems intact.

To put the hazards in the context of ecosystems, a hypothetical composite system has been imagined which includes several ecosystems: uplands (highlands, piedmont), lowlands, coastal lands, near-shore waters (estuary and reef), and marine waters (open sea) and the development activities representative of each. Such a place would approximate a small volcanic island, part at low elevation and arid, and part at sufficient elevation to catch moisture-laden winds from the sea. The island would experience, if at a high enough latitude, that given the variations in its elevation, both high and low

temperatures extreme enough to influence development activities would occur. It would be located near an extensive fault zone and would contain a variety of development possibilities and a number of natural services that would help protect these development activities from natural hazard events. It should be added that there are real places very much like this.

The hypothetical system is made up of "watershed" or "catchment" subsystems and coastal subsystems. The term "watershed" is variously defined, and is sometimes used interchangeably with "river basin." As used here, these terms refer to two entities that differ significantly in complexity. A watershed is a system of streams that discharge all their water through a single outlet. Watersheds may range in size from a few hectares up to thousands of square kilometers, but each, whether large or small, is more or less homogeneous with respect to its geology, soils, physiography, vegetation type, and climate. A river basin, on the other hand, is made up of a number of component watersheds, among which there may be great variation (see Figure 3-8), and its hydrograph responses is therefore complex.

In such systems, water and gravity are the two major natural components that integrate system structure and function (the specific combination of components and processes that define a given system). Their influence on development activities in terms of the natural events they can present (seismic forces, hurricanes, mass movements, etc.) is generally forgotten by planners. Only when valuable downstream development is threatened or damaged by landslides, drought, floods, or sedimentation is attention shifted upstream or uphill.

The hypothetical composite system also includes the coastal zone where terrestrial, marine, and atmospheric processes create a greater range of hazards than in most other well-defined geographic areas. Combined with the likely presence of population centers, productive agricultural lands, communication routes, buildings, etc., the risk in such a zone for heavy losses in lives and infrastructure when hazardous events occur is ever present.[1/]

Watersheds and coastal systems, of course, do not occur independently. By their very nature they are integrated and must be seen as a whole. Indeed, the concept of "expanded" watershed, which includes upstream, coastal, and near-shore characteristics, is relevant particularly where offshore hazards such as hurricanes, tsunamis, and storm surges are modified by near-shore bathymetry and coastal configuration and where the effects of inland hazards such as flash flooding and debris flows often reach coastal and near-shore areas due to the presence of steep and relatively short watersheds.

This concept of watershed can be used to illustrate an area's vulnerability to hazardous events caused by human intervention in the system. Such interventions may alter the landscape upstream, for example. But, because of the integrating characteristics of water and gravity, these alterations are not only important on-site, but are also important downstream, including near-shore areas where a sediment plume caused by upstream erosion may cover and suffocate a reef or sea-grass bed. Development activities of any kind (i.e., the use, improvement, or conservation of system services, including those that mitigate hazardous events) also require "integration." This kind of integration implies planning and, as a result, watersheds are often a basic unit of development planning. Even more importantly, however, it is necessary to understand the characteristics of watersheds if a concern for natural hazards is to be included in development planning.

Given the range of natural events affecting this broadly defined hypothetical watershed, the "boundary" of its coastal or lowlands portion should remain flexible. Offshore, the boundaries can be placed at a well-defined isobath located below the depth of any bottom features capable of influencing seaborne hazards. In contrast, the watershed's uplands boundaries are readily defined in physical terms (drainage areas) but are often quite porous in biotic, social, and economic terms.

2. ECOSYSTEMS AND ASSOCIATED HAZARDS

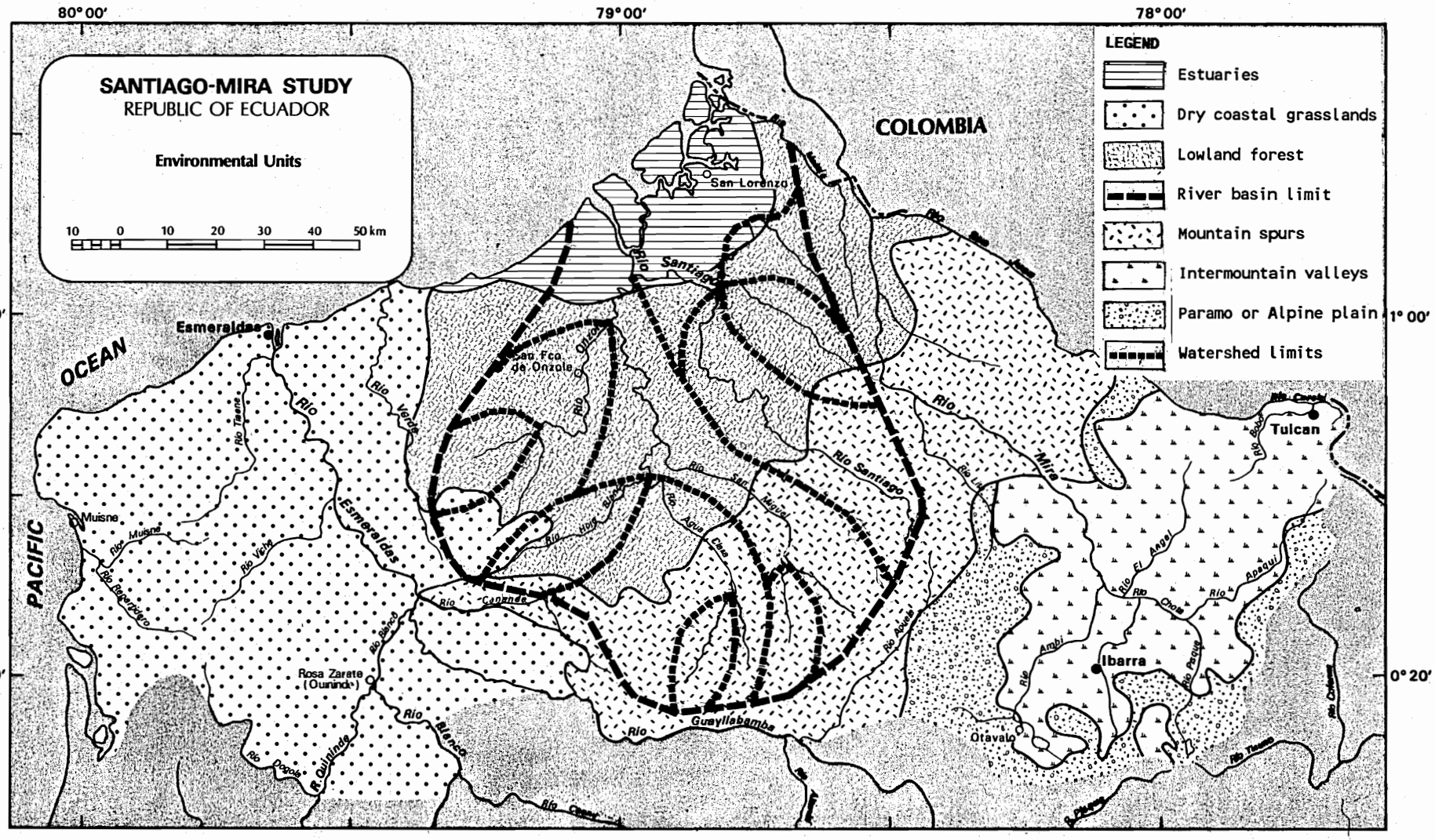
The subsystems of our imaginary expanded watershed offer a surprisingly large number of natural services which can mitigate the effects of many of these natural hazards. Equally important, however, are attributes of these subsystems which can intensify the effects of natural hazard events.

Figures 3-10 and 3-11 indicate which subsystems of the expanded watershed contain attributes that influence the hazards summarized here. The paragraphs below describe how the natural services of these systems mitigate or intensify each natural hazard risk; interestingly, they are not all intuitively obvious. In the early planning phases these and other services are looked at fairly broadly, and in later iterations their roles are further and more explicitly defined. For

[1/] Though not included in this discussion, significant development activities and infrastructure also exist at sea (sea-bearing mining, off-shore oil rigs and pipelines, shipping lanes, transoceanic communication links, fishing and whaling activities, security patrols, research and monitoring, refuse dumping, incineration at sea, recreation and tourism, etc.), and these too should be seen in terms of their vulnerability to hazardous events.

Figure 3-8

MAP SHOWING DIFFERENCES IN COMPLEXITY BETWEEN A RIVER BASIN AND ITS WATERSHEDS



Source: Adapted from OAS/INERHI/CONADE. Plan de Desarrollo Región I: Esmeraldas-Carchi-Imbabura. (Quito, Ecuador: OAS/INERHI/CONADE, 1979).

Figure 3-9

HYPOTHETICAL WATERSHED ON A SMALL VOLCANIC ISLAND

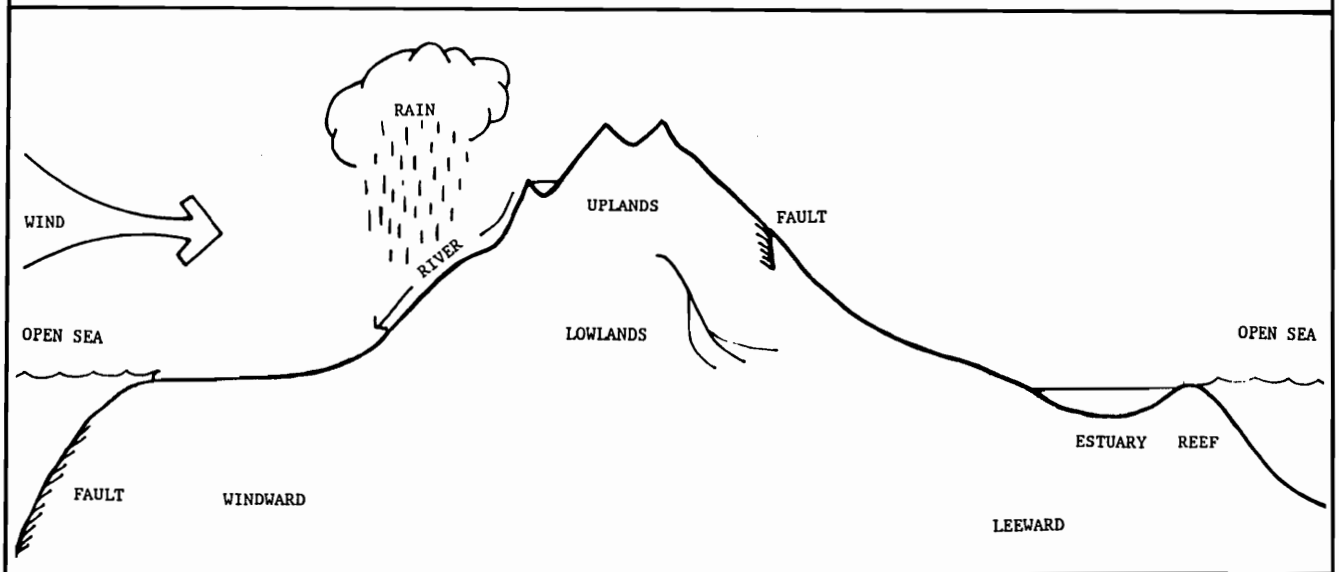


Diagram of a small island showing various ecosystems (open sea, reef, estuary, lowlands, uplands) and indicators of potential natural hazards (rain, wind, and waves indicate hurricanes and flooding; volcano indicates eruptions; faults indicate earthquakes; faults and gullies indicate mass wasting).

example, the diagnosis may say only "The natural structure and processes of the upland ecosystem in this region play a role in the control of erosion and of flooding." At later stages the specific ecosystem function responsible for a given service would be cited and discussed. These might be that the "high soil water storage capacity of 'Uplands sandy loam' soil type, the transpiration from the deeply rooted species, and the high infiltration rates due to the strongly fractured structure of the sub-watershed's parent rock decrease the flood potential in storms of short duration." This gives the planner a better idea of what should be done in an ecosystem if natural flood control services are to be used, improved, and/or conserved rather than go unused or deteriorate or be destroyed.

a. Uplands and Volcanic Activity (U1)

The structures and functions of upland ecosystems that can influence the effects of volcanic eruptions are few. However, included in what does exist are:

- Relief (including valley depth, slope direction and steepness), which may orient the flow of lava, ash, mud, etc.
- Location and extent of the rift, which may absorb volcanic material and move it away from (or toward) populated areas.

These may either intensify or mitigate the effects of a volcanic eruption depending on the location of the development activity with reference to the event. In terms of the services provided, "storage of volcanic outflow material" could be possible depending on the relief of the watershed. The "location and extent of the rift" might intensify the hazard if development activities were sited without considering the numerous hazards that accompany volcanic activities.

b. Uplands and Earthquakes (U2)

Upland ecosystems do little to mitigate the consequences of earthquakes. They may, however, intensify the consequences because of landslides caused by groundshaking. One of the more dangerous aspects of this relationship occurs in areas of current and past glacial activity and concerns the natural damming of watercourses by terminal or lateral moraines and the consequent creation of lakes. Such dams are often quite weak and are easily breached if landslide material fills the lake. An unfortunate example of this phenomenon, of course, is the 1970 earthquake in Peru that jarred loose a large piece of the Huascarán mountain, which fell into a natural lake of this type. This material together with the water from the lake covered several villages as it moved down the narrow valley, causing the loss of over 10,000 lives.

Figure 3-10

ECOSYSTEMS AND THE NATURAL HAZARDOUS EVENTS THEY CAN MITIGATE OR INTENSIFY

	NATURAL HAZARDS					
ECOSYSTEMS	VOLCANIC ACTIVITY	EARTHQUAKES	LANDSLIDES	HURRICANES FLOODS	LAND/SEA-BORNE[a]	DESERTIFICATION[b]
	(1)	(2)	(3)	(4)	(5)	(6)
UPLANDS (U)	U1	U2	U3	U4	U5	U6
LOWLANDS (L)	---	---	---	---	L5	L6
ESTUARY (E)[c]	---	---	---	E4	E5	---
REEF (R)	---	---	---	R4	R5	---
OPEN SEA (S)	---	---	---	S4	S5	---

[a] Land/sea-borne flood includes the hazards of tsunamis, storm surges, and storm water run-off.
[b] Desertification in this discussion is concerned with erosion, sedimentation, and salinization in areas of dry-land farming and livestock grazing.
[c] Estuary consists of mangrove, salt-ponds, sea-grass beds, and beaches.

Because many upland areas do not have much level space for construction, fill material is often used to create some, and the buildings put up on this unstable ground can be destroyed when the earth shakes.

c. Uplands and Landslides (U3)

The structure and function of upland ecosystems can both intensify and mitigate landslide hazards. Landslides often occur naturally in these areas owing to very steep slopes, the nature of the bedrock and overburden, the amount and regimen of precipitation, other disturbances such as natural fires which clear soil-holding vegetation, and ground shaking. Any vegetation on the slopes of the upland system is a natural part of the soil stabilizing services, although this can only ameliorate landslides and will not stop them completely on the steeper slopes. If loose mantle overlays rock (especially sedimentary rock) that has been tilted off the horizontal plane, landslides will be intensified on the slope parallel to the sediment plain. On the other hand, there are fewer and less severe landslides on the slope that runs across the sedimentary strata. Landslides occur on the parallel slopes especially if high rainfall saturates and increases the weight of the soil and lubricates the interface between mantle and base rock. In these cases even vegetation may act as extra weight and intensify a landslide.

d. Uplands and Hurricanes (U4)

Upland areas, if extensive, can serve to reduce the energy level of hurricanes, since these storms receive their energy from warm open seas. On the other hand, the heavy rainfall, in terms of both intensity and amount, can cause high runoff levels from steeply sloping landscapes. It can also saturate the soil mantle and create conditions for substantial slope failure, especially where the holding capacity of tree and shrub roots has been disturbed. A major example of this phenomenon occurred along the north coast of Honduras in 1974 when landslides caused by Hurricane Fifi killed thousands of people.

e. Uplands and Land/Sea-Borne Floods (U5)

Upland ecosystems can indeed help mitigate the effects of "land-borne flooding" through the services of storage and slow release of water. Water is stored in lakes, ponds, streams, rivers, wetlands, soil, and snow or ice, and in aquifers when the service of groundwater recharge is also present. Further, there are services (evaporation, transpiration) which reduce the total amount of water available for flooding. The infiltration rate also has an influence, and this can change according to a number of physical, chemical, and biotic characteristics of the soil. Even the physical layout and size of the watershed or river basin can make a difference. And, depending on the nature and timing of each precipitation event, these also can mitigate flooding.

Many of these same ecosystem attributes can intensify land-borne flooding. If precipitation is heavy and infiltration slow or if the soil is already saturated because of previous storms, flooding can be more frequent and its consequences more grave. Lack of

Figure 3-11

ATTRIBUTES WHICH CAN INFLUENCE THE EFFECTS OF NATURAL HAZARDS

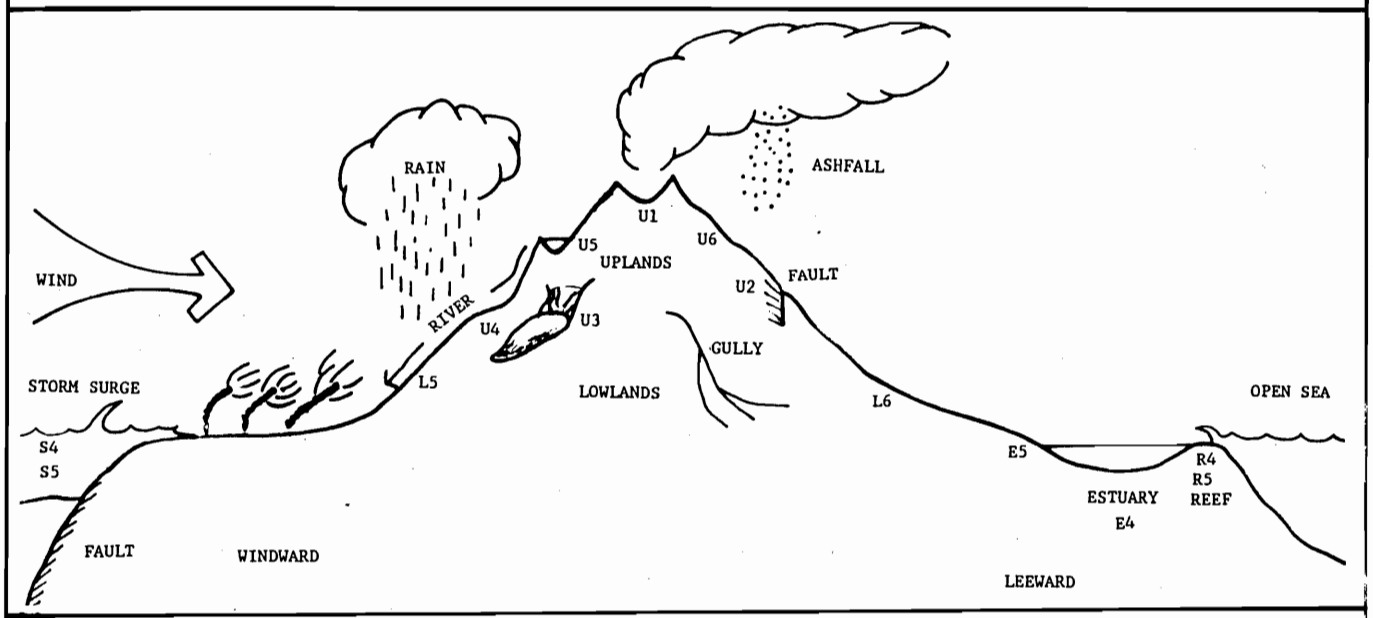


Diagram of a small island showing major ecosystems and associated natural hazards. The text explains the potential impact of natural hazards on an ecosystem and how natural services of the ecosystem can mitigate the effect of natural hazards.

LEGEND
ECOSYSTEM AND ASSOCIATED NATURAL HAZARDS

U1 Uplands and volcanic activity
U2 Uplands and earthquakes
U3 Uplands and landslides
U4 Uplands and hurricanes
U5 Uplands and land-borne flooding
U6 Uplands and desertification
L5 Lowlands and land/sea-borne flooding
L6 Lowlands and desertification
E4 Estuary and hurricanes
E5 Estuary and land/sea-borne flooding
R4 Reef and hurricanes
R5 Reef and land/sea-borne flooding
S4 Open sea and hurricanes
S5 Open sea and land/sea-borne flooding

storage capacity and the size and configuration of drainage can combine to increase the speed and amount of runoff. There are numerous combinations of characteristics that can influence flooding, each of which is further influenced by human activities.

f. Uplands and Desertification (U6)

Upland areas are related to desertification in both positive and negative ways. Indeed, over much of the earth's surface, it is the presence of uplands that create the conditions for deserts because of the rain-shadow effect. That is, if upland areas force moisture-laden winds upward, two important phenomena take place: (a) the rising air mass cools and its moisture is released on the windward side of the uplands; and (b) on the leeward side the air mass loses altitude and becomes warmer in the process, and this creates desert conditions because the moisture is tightly held and precipitation is reduced (Figure 3-11). In Latin America the prevailing winds are generally from east to west, so that the western slopes of mountains are drier. Exceptions occur, as in southern Chile, Argentina, northern Ecuador and Columbia, where the phenomenon is reversed: the western slopes of the Andes receive higher precipitation and the eastern slopes receive less, becoming drier as one moves eastward. Often, the dry areas occur fairly close to relatively wet areas, from which their populations and development activities can be supplied with water.

g. Lowlands and Land/Sea-Borne Floods (L5)

Coastal areas receive the brunt of heavy seas and high tides as well as tsunamis and storm surge. The combined effect can be that high tides act as barriers damming river and stream outlets to the sea, so that any heavier than normal flow caused by upstream runoff will overflow banks. The normal flow from uplands tends to spread out upon reaching lowlands, where slope is less pronounced and valleys are wider. Furthermore, water flow from the uplands loses some of its energy on reaching the lowlands, causing much of the sediment load of the river or stream to be dropped. This fills in the river bed with sediment and may even raise its level above the surrounding lands. If high water breaches the natural levees built up through this process, extensive areas may be flooded.

On the positive side, coastal areas, especially those having substantial estuaries, reefs, or wetlands, can absorb significant quantities of water and the wave energy accompanying sea-borne events which cause flooding (see below E4, E5, R4, and R5).

h. Lowlands and Desertification (L6)

As was noted in U6 above, lowland areas are often in a rain shadow of an upland area, which means that they can easily succumb to desertification. However, being downstream from areas that will normally have much higher precipitation rates, they potentially have a large degree of control over the distribution of water, both in space and in time, because they receive it from only a few sources of accumulation, whereas the more dispersed form in which upland areas receive water makes its control for potable, irrigation, and industrial purposes much harder. On the other hand, since water in lowland areas within a rain shadow is not generally dispersed, areas having less frequent and less sure access to a water source will generally suffer most from desertification processes (except for salinization).

i. Estuary and Hurricanes (E4)

Estuaries in their natural state are well known for their capacity to mitigate the effects of hurricanes. They can absorb the energy front of the storm with little damage, and to a large degree they can control or at least slow beach and sand erosion and distribute the effects of the accompanying storm surge over a wide area. Indeed, in some ways, such as through the flushing action of the storm, hurricanes are necessary for estuarine operations. Likewise, storm water runoff from upstream can be buffered by estuarine systems without damage if the general increase in fresh water is not too long-lasting.

j. Estuary and Land/Sea-Borne Floods (E5)

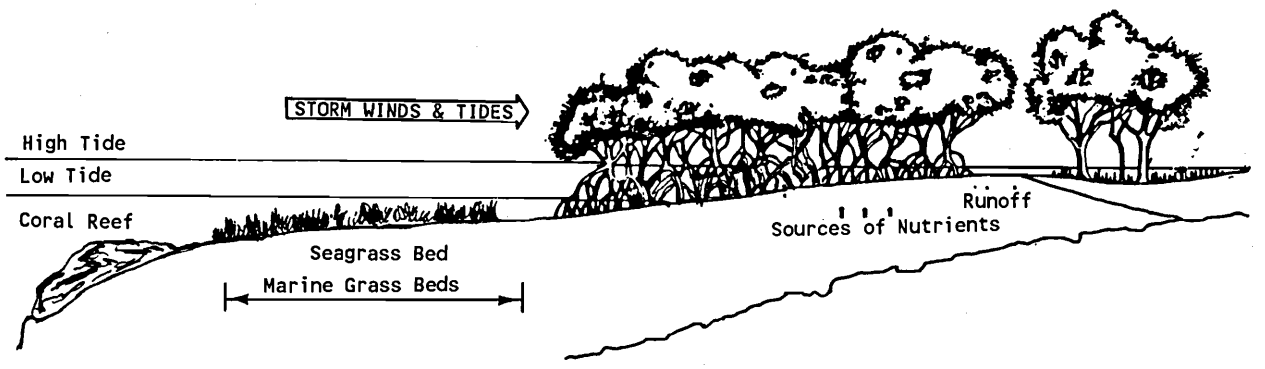
Estuaries over much of the tropics and sub-tropics are also important for buffering storm water runoff from the upland areas and the high water resulting from tsunamis and storm surges. The orientation and configuration of the estuary influence the amount and extent of flooding. The natural defenses of estuarine vegetation such as mangroves and sea grass beds (see Figure 3-12) can absorb much of the energy associated with storm surge and tsunamis. If the estuary is shallow and extensive, these characteristics can reduce wave height, and therefore can also reduce flooding.

k. Reef and Hurricanes (R4)

Many of the characteristics of estuaries that ameliorate the effects of hurricanes are shared by reefs. They can absorb much of the wave energy (see Figure 3-13), and coasts that are surrounded by barrier reefs suffer significantly less damage to beaches and shoreline infrastructure than do coastal areas that are exposed to the open sea without reefs. Again, the damage done to shore areas and infrastructure by wave energy will depend on the shape, depth, extension, width, and distance from shore of the reef system.

Figure 3-12

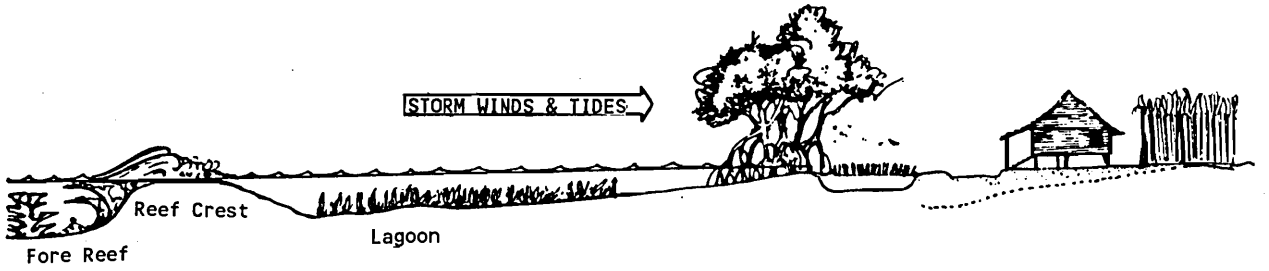
BENEFICIAL ROLES OF MANGROVE FOREST IN COASTAL ECOSYSTEM



Mangrove forests can serve as a buffer against storm waves and thus protect human lives and man-made infrastructure in coastal regions.

Figure 3-13

BENEFICIAL ROLES OF CORAL REEFS IN COASTAL ECOSYSTEM



Coral reefs can serve as a buffer against storm waves thus protecting the shoreline and coastal lands, crops, houses and human life.

Source: Both figures adapted from Snedaker, S.C., and Getter, C.D. Coasts: Coastal Resources Management Guidelines. Coastal Publication No. 2, Renewable Resources Information Series. (Washington, D.C.: U.S. Agency for International Development, 1985).

l. Reef and Land/Sea-Borne Floods (R5)

Since the major problems suffered from hurricanes result from flooding, the same characteristics of reefs that help mitigate damage from a hurricane also mitigate sea-borne flooding. Land-borne flooding, however, may be a bit different in that, if the reef acts as a dam restricting the outflow of fresh water, it may intensify lowland floods. These effects, however, will not be as severe as in the case of estuary configurations that impede river outlets to the sea.

m. Open Sea and Hurricanes (S4)

Hurricanes are spawned in the open sea, and their energy is gained by passing over open seas of relatively high temperatures. Although the configuration of the sea bottom at some distance from a coast will not necessarily influence the height of the accompanying storm surge, bottom configurations nearer the coast will significantly affect the height and energy of the surge and can direct it either away from the shore or toward the shore.

n. Open Sea and Land/Sea-Borne Floods (S5)

The influence here is generally to cause rather than to mitigate flooding. Tsunamis may be generated by large undersea mass movements of "land," underwater eruptions of volcanoes, and earthquakes in the open sea. And storms other than hurricane-force winds are born at sea. Global phenomena like "El Niño" can change weather patterns over lengthy periods from little precipitation to heavy precipitation, as in the desert areas of northern Peru, which were severely flooded in 1982-1983 as a result of the related ENSO phenomenon.

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PART II

TOOLS AND TECHNIQUES FOR NATURAL HAZARD ASSESSMENT

CHAPTER 4

REMOTE SENSING IN NATURAL HAZARD ASSESSMENTS

CHAPTER 4

REMOTE SENSING IN NATURAL HAZARD ASSESSMENTS

Contents

List of Figures

REMOTE SENSING IN NATURAL HAZARD ASSESSMENTS

SUMMARY

This chapter provides planners with an overview of remote sensing technologies and their general application in natural hazard assessments. Characteristics of both aerial and satellite remote sensing techniques and the role remote sensing can play in detecting and mitigating several natural hazards are highlighted.

One of the most important tools available to the regional planner is the remote sensing of the environment. Not only is it very useful in the planning process in general, but it is also valuable in detecting and mapping many types of natural hazards when, as is often the case, detailed descriptions of their effects do not exist. If susceptibility to natural hazards can be identified in the early stages of an integrated development planning study, measures can be introduced to reduce the social and economic impacts of potential disasters.

All natural hazards are amenable in some degree to study by remote sensing because nearly all geologic, hydrologic, and atmospheric phenomena that create hazardous situations are recurring events or processes that leave evidence of their previous occurrence. This evidence can be recorded, analyzed, and integrated into the planning process.

Most remote sensing studies concerned with natural hazards have been about an area's vulnerability to a disaster, the monitoring of events which could precipitate a disaster, and the magnitude, extent and duration of a disaster. This chapter tells planners what types of remote sensing information are suitable for identifying and assessing particular natural hazards and where to look for it.

Since the existing remote sensing information may be inadequate for a planning task or phase, this chapter also provides guidelines on selecting and acquiring the appropriate data. Only those sensor systems that are deemed capable of making a insignificant contribution to the development planning process are discussed, with their specific applications to the assessment of each of several natural hazards. It is assumed that planners and other readers are already familiar with basic remote sensing technology and vocabulary. If further details of techniques and/or applications are required, near state-of-the-art information is available in Sabins (1986), Lillesand and Kiefer (1987), and ASP (1983). An excellent overview of satellite imaging systems and disaster management can be found in Richards (1982).

While both aerial and satellite remote sensing techniques are presented, emphasis is placed on satellite-derived sensing because the data provide the synoptic view required by the broad scale of integrated development planning studies. Aerial remote sensing data are useful to natural hazard management for focusing on priority areas, verifying small-scale data interpretations, and providing information about features that are too small for detection by satellite imagery, but extensive aerial surveys commonly exceed the budget constraints of a planning study and may also provide more information than is necessary, particularly during the early stages of the study.

A. Overview of Important Remote Sensing Attributes

Effective utilization of remote sensing data depends on the ability of the user to be accurate and consistent when interpreting photographs, images, graphs, or statistics derived from remote sensing sources. While most planners have been introduced to photo and image interpretation in their formal training, the best use of the data usually requires analysis by people with experience in landform analysis, such as geologists, physical geographers, foresters, etc. A relatively small investment in the services of an experienced interpreter may avoid needless delays and inappropriate use of remote sensing data. Whether or not the planner does his own interpretation, he should have a working knowledge of remote sensing techniques and the capability to assess the validity of an interpretation, as well as the ability to use the derived information.

The factors that determine the utility of remote sensing data in natural hazard assessments are scale, resolution, and tonal or color contrast. Other factors

DEFINITIONS

Instruments which record electromagnetic radiation emitted or reflected from the earth can be mounted on aircraft or satellites. The former are called aerial or airborne remote sensors and the latter, satellite or spaceborne remote sensors. These instruments record data using optical, electro-optical, optical mechanical, or electronic devices. In this chapter, visual displays analogous to photographs, made with such processes as radar and thermal infrared scanning and produced on a medium other than film, are referred to by the general terms "image" or "imagery".

include area of coverage, frequency, and data cost and availability.

1. SCALE

The scale to which a photograph or image can be enlarged, with or without optical or computer enhancement, determines in what phase of the development planning study this information should be used. Presentations at scales of 1:500,000 or smaller are useful during the Preliminary Mission and certainly in Phase I, Development Diagnosis, when more detail is not necessary. Imagery at a scale of 1:250,000 or larger is required during the project formulation and feasibility study activities of Phase II when detail is more important and where certain, but less obvious, aspects of natural hazards must be defined. Frequently it is possible to detect natural hazard phenomena on a small scale photograph or image, but it is impossible to annotate it without enlargement to larger scales. Thus, it is necessary to use imagery at scales commensurate with the levels of detail required for the particular stage of the study, as well as the size of the study area itself. In addition, the larger the areal extent of change associated with a natural event, the more useful satellite imagery becomes.

2. RESOLUTION

Scale is meaningless in the absence of adequate spatial resolution, the capability of distinguishing closely spaced objects on an image or a photograph. Image resolution is determined by the size and number of picture elements or pixels used to form an image. The smaller the pixel size, the greater the resolution. In photography, resolution is limited primarily by the film grain size, but lenses and other technical considerations play important roles.

In both cases, imagery and photography, separability between adjacent features plays a very important part in the identification process. Enlargements of photography or imagery cannot improve resolution but only the working space for the interpretation.

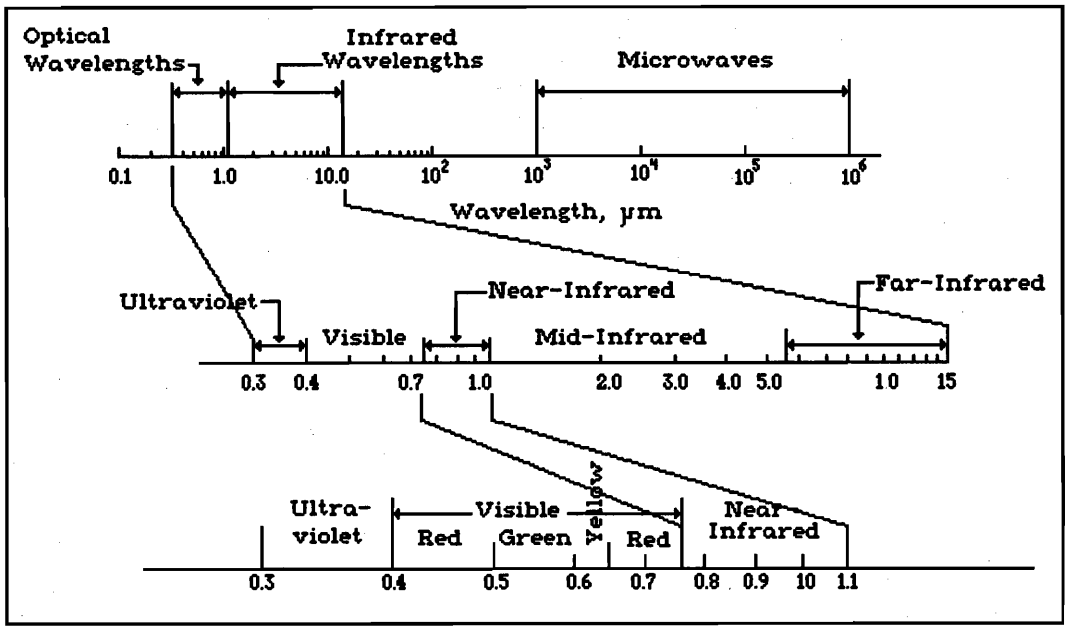
Spectral resolution also needs to be taken into consideration when selecting the type of data since different sensors are designed to cover different spectral regions. Spectral resolution refers to the band range or band width offered by the sensor. Figure 4-1 shows the spectral regions most commonly used in remote sensing. Most natural disasters involve spectral changes. Floods lead to significant spectral changes whereas earthquakes lead to little spectral variation due to less spectral contrast in relation to non-affected areas.

3. IMAGE CONTRAST

The contrast between features on an image or photograph is a function of the sensor's ability to record the tonal or spectral content of the scene. Different spectral bands of sensing systems may exhibit strong or weak contrasts depending on the regions covered on the electro-magnetic spectrum and the surface viewed. For example, a given band may show little contrast between vegetation types in a forest environment but may show strong contrasts between rock types in an arid area. Hazardous areas such as earthquake fault zones or areas susceptible to landslides may be too small for some sensors, e.g., Advanced Very High Resolution Radiometer (AVHRR) imagery, but may be readily visible on imagery produced by other sensor systems, e.g., Landsat Thematic Mapper (TM). The heavily vegetated and cloud-covered terrain of tropical Latin America and the Caribbean is among the most difficult to interpret geologically, but expert interpreters can detect many

Figure 4-1

ELECTROMAGNETIC REGIONS MOST COMMONLY USED IN REMOTE SENSING



natural hazards through physiographic analysis of radar data which can penetrate clouds.

When an image does not provide the detail, resolution, or contrast that is needed, there are several options available. Since the identification of all desired features by interpretation from one sensor is not always possible, a second, completely different type of sensor, or even a combination of sensors, may be needed. Digital data can be enhanced and/or manipulated by using techniques such as contrast stretching, false color composites, principal component analysis, filtering, and supervised and unsupervised classifications.

4. TIME FRAME

The temporal occurrences of natural events will also affect the utility of remotely sensed data. Certain sensors can detect a phenomenon quite readily although their repeat coverage is every 16 days (Landsat). A flood could easily occur and recede within this time frame. On the other hand, desertification of an area can be a long process and the utility of remotely sensed data could be great for monitoring these changes. Events which are seasonal, predictable, or highly correlated with other events are more likely to benefit from imagery than events which occur randomly such as earthquakes or tsunamis (see Chapters 8-12).

5. REMOTE SENSING IMAGES AND MAPS

To derive the most benefit from the use of available remote sensing data, the planners should use all supporting information on the study area (see Appendix A). Maps are particularly helpful in interpreting remote sensing data. Topographic maps are foremost among maps which help clarify many terrain recognition ambiguities found on remote sensing images. Geological maps bring attention to formations conducive to particular types of hazards. This knowledge can assist in localization and the systematic search for these hazards. Soils maps can serve a similar purpose, but to a lesser extent. Finally, vegetation and land-use maps can provide information on the moisture content, underlying geologic formations, and types of soils present.

In summary, remote sensing imagery should be regarded as data available to assist the planner in the assessment of natural resource and natural hazard information throughout the development of a planning study. The meaning and value of remote sensing data

is enhanced through skilled interpretation used in conjunction with conventionally mapped information and ground-collected data.

6. OUTPUT FORMATS

Output formats consist of different ways in which remote sensing data can be presented. Photographic data are usually used in a film positive format or as a photographic print. Film data and photographic prints can be scanned and converted into digital data by being recorded on a computer compatible tape (CCT). The main advantage of digital data is the fact that they can be quantified and manipulated using various image processing techniques. Satellite or other images recorded on a CCT can be presented in a film positive format or photographed directly from the display monitor.

B. Aerial Remote Sensing

Aerial remote sensing is the process of recording information, such as photographs and images, from sensors on aircraft. Available airborne systems include aerial cameras, multispectral scanners, thermal infrared (IR) scanners, passive microwave imaging radiometers, and side-looking airborne radars (SLAR). The systems offering the most practical and useful data in the context of integrated development planning and natural hazard assessments are aerial cameras, multispectral scanners, and thermal IR scanners and SLAR. This section describes the characteristics of the photography or imagery obtained from these three systems.

Availability of aerial remote sensing imagery varies for the type of data required. Aerial photography is readily available for many areas of study in most parts of the world, although in some instances it must be declassified for non-military use by the government of the country involved in the study. Radar imagery is also frequently classified.

Acquisition of infrared (IR) and radar data is more complex than aerial photography, although for a large area, radar may be less expensive than photography. Due to the specialized systems and operators required to produce IR and SLAR imagery, such data are usually available only from a limited number of organizations which either own or lease the systems. The cost to mobilize aircraft, equipment, and crews is high, but the cost of data coverage per line kilometer or per unit area can be reasonable if the area to be flown is large.

In addition to the type, availability, and cost of data, the planner should consider the conditions under which the acquisition of the appropriate data is taking place. Each sensor type has an optimum time of day, season, and/or table of appropriate conditions under which the best results are obtained. Also, to establish the current status of a hazard such as a volcano's activity, the interpretation of thermal IR imagery must be made close to the time of acquisition, and anomalies should be checked out immediately to determine the magnitude of temperatures that correlate with them. Currently obtained data, flown under similar instrument, weather, and terrain conditions, may be used to compare temporal variations of the hazard. In this way thermal pattern changes may be determined.

Thermal IR imagery information is the most transitory of any sensor data. There is a procession of changes in the thermal contrasts between the different materials on the ground, both terrain and vegetation. The transitions occur over daily and seasonal cycles and are modified considerably by the weather, soil, climate, relief, slope direction, and land-use practices. In spite of these masking variations, the thermal contrasts resulting from volcanic and geothermal activity can be interpreted by an experienced thermal IR interpreter.

The primary utility of SLAR imagery is in the interpretation of the relatively unchangeable elements of basic geologic structure and geomorphologic conditions. As a result, it is useful in studying many features related to natural hazards. Special SLAR image data acquisition is not normally feasible in a planning study budget, but previous coverage of the study area may be available. If it does exist, it should be sought and used to its fullest extent.

Both IR and SLAR imagery can be used in a stereoscopic mode but only where adjacent flight lines overlay. Since distortion due to air turbulence and/or differential altitude occurs during the raster-like development of each image as the aircraft moves forward, the stereoscopic model is imperfect. Despite these distortions the stereoscopic dimension is definitely an asset in helping to define natural hazards.

1. AERIAL PHOTOGRAPHY

Of all the sensors, aerial photography gives the closest representation to what the human eye sees in terms of wavelength response, resolution, perspective, stereoscopic viewing, and tonal or color values. The interpreter familiar with photographs can easily interpret these scenes, whereas other sensors, such as thermal IR scanners and SLAR systems, produce imagery whose appearance and physical basis is completely foreign to the inexperienced eye. Aerial photographs are probably the remote sensing data source with which the planner is most familiar (OAS, 1969).

a. Scales and Wavelengths

The most useful scales for aerial photographs range from 1:5,000 to 1:120,000. The need for reconnaissance type of information over large areas limits the use of photographs to the scales of 1:40,000 or less.

Photography is limited to the optical wavelengths which are composed of ultraviolet (UV), visible, and near-IR portions of the electromagnetic spectrum (see Figure 4-1). The first and last of these portions are recoverable on film under special film-filter conditions. The near-IR wavelengths are the reflective part of the larger infrared portion, which also includes emitted or thermal wavelengths.

b. Type of Film

Aerial photography may be obtained using black and white film, the least expensive medium, or with conventional color or color IR film. The type of film that should be used depends on its utility for a particular terrain being studied and the cost of the film. The speed of the film is also an important factor: the slower color films may not be used where the terrain is too dark, such as areas of ubiquitous heavy vegetation or predominantly dark rocks.

The two general types of black and white films used most frequently are the panchromatic and IR-sensitive films. Panchromatic films, which are negative materials having the same approximate range of light sensitivity as the human eye, are regarded as the standard film for aerial photography. It is the least expensive medium for aerial mapping and photo interpretation, but it may not be the logical choice for a given study area.

Black and white IR-sensitive film, although not commonly used, is a better choice for the penetration of strong haze and/or lush vegetation in humid tropical areas. It renders surface water, moisture, and vegetation contrasts much better than the standard film, and, as a result, can be an effective tool in regional planning and natural hazard assessments in humid tropical areas. There is, however, a diminution of detail in shadowed areas since scattered cooler light (blue end) is filtered out.

In high relief areas, it is best to shoot close to mid-day using IR films. In areas of low relief, photographs should be taken when the sun is low on the horizon (10° to 30°), causing shadows on the fine-textured surface. Low-sun-angle photography (LSAP) emphasizes textural characteristics of particular rock types, discontinuities, and the linear topographic features associated with faults and fractures. Vegetation types, both natural and cultivated, can also be defined to a large extent on a textural basis, and this may provide further information on the terrain. Almost any state-of-the-art aerial camera can capture LSAP using panchromatic or red-filtered infrared film.

The use of color films for natural hazard assessment takes various forms: negative film from which positive color prints are made, and positive transparencies, including color slides. To a limited extent, the negative films can be printed to emphasize certain colors and offer the ease of handling of prints. They do not have, however, the sharpness and dynamic color range of the positive transparencies, which are significantly better for interpretation purposes.

There are two major spectral types of color film: the natural or conventional color film, which covers the visible spectrum, and color IR film (green through near IR). The former is available as a negative (print) film and positive transparency, and the latter is available only as a positive transparency.

The IR color film response is superior to that of natural color films for a number of reasons. First, the yellow filter required for its proper use eliminates blue light that is preferentially scattered by the atmosphere. Eliminating much of the scattering greatly improves the contrast. Second, the differences in reflectance within vegetation types, soils, and rocks are commonly greater in the photographic IR component of this film. Third, the absorption of infrared and much of the red wavelengths by water enables a clearer definition of bodies of water and areas of moisture content. And fourth, the diminution of scattered light in shadowed areas enhances relief detail, thus improving the interpretation of the geomorphology. In view of these attributes, color IR film is preferred if color aerial photography is desired for humid tropical climates.

2. RADAR

Radar differs from aerial photography as an aerial remote sensor. Unlike photography, which is a passive sensor system using the natural reflection from the sun, radar is an active sensor that produces its own illumination. Radar illuminates the terrain and then receives and arranges these reflective signals into an image that can be evaluated. These images appear similar to black and white photographs. The best use of airborne radar imagery in the development planning process and natural hazard assessments is the identification of geologic and geomorphologic characteristics. Radar imagery, like photography, presents variations in tone, texture, shape, and pattern that signify variations in surface features and structures. Of these elements, tonal variations which occur in conventional aerial photographs are the same

as the eye sees. The tonal variations, which occur in radar images and appear as unfamiliar properties, are the result of the interaction of the radar signal with the terrain and vegetation. Just as it is not essential to fully understand the optical theory and processes involved with photography to be able to use aerial photographs, it is also possible to use radar images without a thorough understanding of electromagnetic radiation.

However, an interpreter needs to know something about how the image is formed in order to interpret it correctly and to appreciate fully the potential and limitations of radar. A skilled interpreter need only become familiar with the parameters that control radar return, understand their effect on the return signal, and recognize the effect of the side-looking configuration of the sensor on the geometry of the return signal.

Many useful radar images have been acquired in X-band, K-band, and Ka-band wavelengths (see Figure 4-2). However, X-band airborne radar systems are currently the most commonly offered by commercial contractors. In this band-width there are two basic types of systems: real aperture radar (RAR) and synthetic aperture radar (SAR). Real aperture or "brute force" radar uses an antenna of the maximum practical length to produce a narrow angular beam width in the azimuth (flight line) direction. The longer the antenna, the narrower the azimuth beam. A typical length is 4.5m, which approaches a maximum practical size for aircraft. For this reason the SAR was developed. The SAR is capable of achieving higher resolution without a physically large antenna through complex electronic processing of the radar signal.

The resulting resolution, coupled with the small scales at which images can be acquired, makes radar more suitable than photographic surveys for covering large areas. While RAR has a simple design and does not require sophisticated data recording and processing, its resolution in the range direction is relatively limited in comparison with the SAR of the same waveband. SAR maintains its high resolution in the range direction at long distances as well as its azimuth resolution. Resolution with SAR approaches 10m in azimuth and range.

3. THERMAL INFRARED SCANNERS

An airborne electro-optical scanner using a semiconductor detector sensitive to the thermal IR part of the spectrum is the best way to produce imagery that defines the thermal pattern of the terrain. Alternative methods using a television-like presentation have inadequate spatial resolution and thus cannot be

Figure 4-2

RADAR WAVELENGTH AND FREQUENCIES USED IN REMOTE SENSING FOR AIRCRAFT RADAR SYSTEMS

Band Designation[a]	Wavelength (cm)	Frequency (v), GHz (10^9 cycles/sec^{-1})
Ka (0.86cm)	0.8 to 1.1	40.0 to 26.5
K	1.1 to 1.7	26.5 to 18.0
Ku	1.7 to 2.4	18.0 to 12.5
X (3.0cm, 3.2cm)	2.4 to 3.8	12.5 to 8.0
C	3.8 to 7.5	8.0 to 4.0
S	7.5 to 15.0	4.0 to 2.0
L (23.5cm, 25.0cm)	15.0 to 30.0	2.0 to 1.0
P	30.0 to 100.0	1.0 to 0.3

[a] Wavelengths commonly used in imaging radars are shown in parentheses.

Source: Sabins, Floyd F., Jr. Remote Sensing: Principles and Interpretation (New York: W.H. Freeman, 1986).

used effectively from aircraft altitudes. They also lack adequate thermal resolution.

Spatial resolution in scanners decreases with altitude above the terrain. Most commercial thermal infrared systems have spatial resolutions which provide for 2m to 2.5m resolution per 1,000m altitude at the nadir point (the point in the ground vertically below the camera) of the scan. Increasing the altitude above terrain to 2,000m would produce 4m to 5m spatial resolution.

Commonly, the 3.0μm to 5.5μm band provides the best information for "hot" objects (active volcanic vents, hot springs, etc.), while the 8.0μm to 14.0μm band provides the best information for features that are at ambient or cooler temperatures (flooding streams under canopies, warm springs, etc.). Frequently in studies involving IR surveys both bands are used to provide simultaneous imagery.

Properties of the airborne IR scanner system indicate that its practical use is restricted to the lower altitudes (under 3,000m) and, consequently, to relatively smaller areas than either radar or aerial photography. In natural hazard assessments, its best use would be in areas that are known or suspected to be areas of volcanism or where abnormal moisture conditions indicate dangerous situations. The latter may include, for example, trapping of water along active faults, or in back of landslide slumps, or moisture conditions associated with karst terrain.

IR scanning systems have drawbacks, but their unique capability of thermal imaging is unsurpassed. In addition, they can provide critical information for relatively small areas once specific hazard-prone areas have been identified.

4. ADVANTAGES AND LIMITATIONS OF PHOTOGRAPHY, RADAR, AND THERMAL IR SCANNERS

a. Photography and Radar

Both aerial photography and radar have advantages and limitations. Photography cannot be used at any time in any weather as can radar. Radar can map thousands of square miles per hour at geometric accuracies conforming to national mapping standards. An area can be surveyed much more rapidly by radar than by aerial photography, and the final product provides an excellent synoptic view. Distance can be measured more accurately on radar than photography, and maps as large as 1:24,000 scale have been produced experimentally. The RADAM project of Brazil covered the country completely at a scale of 1:250,000. On the other hand, photography at the same scale shows considerably more detail, and it provides an excellent stereoscopic model for interpretation purposes in contrast to a more limited, but still useful, model obtained from radar. Aerial photography has the advantage of offering instantaneous scene exposures, superior resolution, ease of handling, and stereoscopic capability.

b. Thermal IR Scanners

Airborne electro-optical scanners, in general, can cover the electromagnetic spectrum using semiconductor electronic sensors from the UV through the visible and near IR into the thermal IR range of the spectrum. The utility of the UV spectrum in natural hazard and resource investigations has yet to be demonstrated, particularly when the image is degraded due to intense scattering of its rays. Scanners in the visible range are useful, especially when two or more wavebands are algebraically combined or manipulated.

Scanning imagery, because of its technique of recording a raster on film or tape, produces inherent distortions in the final built-up image scene. The lateral distortion from the flight line is reasonably corrected in the scanner system. Along the flight line, however, the rapid changes of altitude above the terrain during the formation of one scene from many scan lines produces many distortions. The persistent movement of the aircraft on three axes with limited stabilization presents the same problem. These distortions result in images that are difficult to interpret and whose location is difficult to identify, especially in mountainous and/or forested terrains. Despite these deficiencies, scanning from aircraft continues to be a very valuable method of obtaining thermal infrared imagery with reasonable spatial and thermal resolution.

In summary, aerial remote sensing provides information from aerial photographic cameras, side-looking radar, and thermal imaging scanners that is unsurpassed in resolution in their respective coverage within the electromagnetic spectrum. These systems produce imagery that ranges from the familiar visible spectrum to the unfamiliar infrared and microwave radar (short radio) spectra. This information can be used in conjunction with conventional maps of all kinds to enhance the data available to the planner.

C. Satellite Remote Sensing

This section describes several satellite remote sensing systems which can be used to integrate natural hazard assessments into development planning studies. These systems are: Landsat, SPOT satellite (Système Probatoire pour l'Observation de la Terre), satellite radar systems, Advanced Very High Resolution Radiometer (AVHRR) on NOAA-10 and 11 satellites,

metric camera, large format camera (LFC), and Sojuzkarta. Remote sensing from satellite vehicles has become increasingly important following the successful launch of the Landsat 1 satellite (formerly ERTS-1) in 1972. Since then many satellites with remote sensing capabilities have been developed and used successfully.

The Landsat multispectral scanner (MSS) provided the first practical imagery in four different spectral bands from space. The characteristics of this and other Landsat sensors are summarized in Figure 4-3. The accompanying return beam vidicon (RBV) sensor on this and subsequent satellites of this series were never noticed by scientists and planners like the MSS. The broad areal coverage of the Landsat sensors and the others that have followed, together with the capability to process the sensor data digitally, has made the satellite-derived data useful to regional planners and others interested in natural hazard assessments. The synoptic view of lands targeted for development can be imaged in an instant of time. Satellite imagery can provide a continuity of viewing conditions for large areas that is not possible on aerial photographic mosaics.

In addition to MSS, other satellite-borne sensors warrant discussion since they are potential tools for assessing natural hazards. Each sensor has its advantages and limitations in coverage of areas of interest and its resolution capability to define certain types of hazards. Some sensors are experimental, and provide limited areal coverage and lack temporal continuity. However, where coverage is available for a study area, the sensor data should be used in conjunction with existing data derived from Landsat or SPOT. The data derived can produce an inexpensive synergistic effect by combining data from more than one part of the spectrum, and are well worth the relatively small expense.

Ideally, it would be desirable to use a "multi-stage" approach to the natural resource and natural hazard assessments. This would involve using aerial photography and ground checks to establish more detailed knowledge of sample or representational sites. This may then be extrapolated over a larger area using Landsat or other satellite-derived data. Figure 4-3 shows the needed imagery characteristics for the assessment of various natural hazards--earthquakes, volcanic eruptions, landslides, tsunamis, desertification, floods, and hurricanes--for purposes of planning and mitigation. The characteristics of applicable satellite sensing technologies are described below.

1. LANDSAT

Since the Landsat series of satellites have been operational for a long period of time, there is a very large data base available, both in areal coverage and in repetitive coverage, through different seasons and during periods of natural disasters. Landsat MSS coverage exists from 1972 to the present in four spectral bands at 80m resolution. The thematic mapper (TM) was introduced on Landsat 4 in 1982, with seven spectral bands, six of them with 30m resolution and one in the thermal IR range with 120m resolution (see Figure 4-3).

Sensor data are digitally transmitted to ground stations in various parts of the world where they are recorded on magnetic tapes and preprocessed to improve their radiometric, atmospheric, and geometric fidelity. Ground receiving stations that cover Latin America and the Caribbean are in California, Maryland, Brazil, and Argentina. Distribution centers for Landsat sensor imagery are listed in the box below.

Although none of the existing satellites and their sensors has been designed solely for the purpose of observing natural hazards, the variety of spectral bands in visible and near IR range of the Landsat MSS, and TM and the SPOT HRV sensors provide adequate spectral coverage and allow computer enhancement of the data for this purpose. Repetitive or multitemporal coverage is justified on the basis of the need to study various dynamic phenomena whose changes can be identified over time. These include natural hazard events, changing land use-patterns, and hydrologic and geologic aspects of a study area.

The use of Landsat MSS and TM imagery in natural resource evaluations and natural hazard assessments is facilitated by the temporal aspect of available imagery. Temporal composites from two or more different image dates allow the recognition of hazard-related features that have changed, such as alteration of floodplains or stream channels and large debris slides, and to some extent, early recognition of disasters that evolve over time, such as drought or desertification. Chapter 8 has a detailed discussion of the use of Landsat sensors in flood hazard assessments. Specific manipulation and combination of the MSS or TM tape data of various bands of the same scene can increase the utility of the data.

Three-dimensional analysis, or stereoscopy, is essentially missing on the MSS and TM data. With MSS on Landsat 1, 2, and 3, there is an 18-day cycle, and sidelap is 14 percent at the equator, increasing poleward to 34 percent at latitude 40 and to 70 percent at polar latitudes. (Sidelap is the amount of overlapping of adjacent image coverage.) On Landsat 4 and 5, a lower altitude and a 16-day cycle with wider spacing results in only 7.6 percent sidelap at the equator and negligible increase toward the poles for both MSS and TM data. Unfortunately, the areas at

Figure 4-3

CHARACTERISTICS OF LANDSAT SENSORS

SENSOR[a]	LANDSAT PLATFORM	SPECTRAL BANDS AND RANGE (micrometers)		ALTITUDE (km)	RESOLUTION (m)	IMAGE SIZE (km)	COVERAGE REPEAT
RBV	1,2,3	PAN	0.505-0.750	920	79x59 [d]	185x185 [d]	every 18 days
		1 [b]	0.475-0.575		30x30 [e]	99x99 [e]	
		2 [c]	0.580-0.680				
		3 [c]	0.690-0.830				
MSS	1,2,3,4,5	4 (green)	0.5- 0.6 [f]	920 [g]	79x57 [g]	185x185 [f]	every 18 days [g]
		5 (red)	0.6- 0.7	705 [h]	60x60 [h]	185x170 [g]	every 16 days [h]
		6 (near IR)	0.7- 0.8		237x237 [i]		
		7 (near IR)	0.8- 1.1				
		8 (thermal)	10.4-12.6 [b]				
TM	4,5	1	0.45-0.52	705	28.5x28.5 [k]	85x170	every 16 days
		2	0.52-0.60		120x120 [l]		
		3	0.63-0.69				
		4	0.76-0.90				
		5	1.55-1.75				
		6	10.40-12.50 [l]				
		7	2.08-2.35				

[a] RVB, Return Beam Vidicon; MSS, Multispectral Scanner; TM, Thematic Mapper; IR, Infrared.
[b] Panchromatic and Landsat 3 only
[c] Bands 1,2,3 on Landsat 1 and 2 only
[d] Landsat 1 and 2
[e] Landsat 3
[f] Also called bands 1 to 4 on Landsat 4 and 5
[g] Landsat 1 to 3
[h] Landsat 4 and 5
[i] Band 8 on Landsat 3
[j] Thermal
[k] Bands 1 to 5 and 7
[l] Band 6 only

Source: Adapted from Budge, T. A Directory of Major Sensors and Their Parameters (Albuquerque, New Mexico: Technology Application Center, University of New Mexico, 1988).

the lower latitudes where our interests lie have the minimal stereoscopic coverage.

If the terrain is flat with little relief, the little stereoscopic sidelap present would not be effective. In areas of rugged terrain, any small stereoscopic coverage would be welcome, especially if it fell within a critical part of a project area.

The return beam vidicon (RBV) is a framing camera system that operates as an instant television camera. It has not enjoyed the same popularity as the MSS, even though it provides useful information. Landsat 1 and 2 carried three RBVs that recorded green, red, and solar IR images of the same scene as the MSS did. They were capable of producing color IR images of 80m resolution, the same as the MSS, but were decidedly inferior due to technical problems. Landsat 3 carried an RBV system that acquired single black and white images in quadrants of the MSS scene in the 0.50μm to 0.75μm waveband, a spectral response from the green through red. The ground resolution was 40m, much better than the existing MSS and the earlier RBV resolution, enabling the recognition of natural hazard evidence of smaller scale.

The broad response of the RBV, however, did not enhance any particular feature or differentiate vegetation or rocks as well as the MSS bands. Its advantage lay primarily in providing higher spatial resolution for larger scale mapping of spectrally detectable features. In this regard it complemented the lower resolution MSS data which covered the same area. The RBV system was dispensed with entirely on

SOURCES FOR LANDSAT IMAGERY

Argentina
Established: November 1980
Reception: MSS
Distribution Center:
Comisión Nacional de Investigaciones Espaciales
Centro de Procesamiento
Avenida Dorrego 4010
1425 Buenos Aires, Argentina
Telephone: 722-5108; Telex: 17511 LANBA AR

Brazil
Established: May 1974
Reception and Processing: MSS and TM
Distribution Center:
INPE-DGI
Caixa Postal 01, Cachoeira Paulista, SP
CEP 12630, Sao Paulo, Brazil
Telephone: (125) 611507; PBX: (125) 611377
Telex: 1233562 INPE BR

United States
Established: July 1972
Reception and Processing: MSS and TM
Distribution Center:
Earth Observation Satellite Company (EOSAT)
4300 Forbes Blvd., Lanham, Maryland 20706
Telephone: (301) 552-0500 or 800-344-9933
Telex: 277685 LSAAT UR

Landsat 4 and 5, leaving only the MSS and TM sensors. The former was included to continue the temporal library with that type of sensor data and their 80m spatial resolution. The TM, with a 30m resolution, negated any requirement for the ineffective and little-used RBV system. Despite its absence on Landsat 4 and 5, RBV data of certain heavily vegetated tropical areas may be the only available source of data with adequate resolution for temporal comparison with later TM data.

The thermal IR portion of the TM was originally placed in the 10.4μm to 12.5μm spectral window where the earth's radiant energy is so low that a large detector is required. This resulted in a 120m ground resolution cell which generalized thermal detail, limiting its value for detecting the subtle and finely detailed geothermal changes associated with volcanic activity. The thermal resolution is 0.5° K (degrees Kelvin), which by airborne IR scanner standards (0.1° K or smaller),is poor. The best possible application in natural hazard assessments may be in active floodplain delineation and perhaps as a crude index to regional volcanic activity. The thermal infrared band (band 8) in Landsat 3 (10.4μm - 12.5μm with 240m spatial resolution) never worked properly and is, therefore, of no consequence for the applications discussed here. The blue-green band (0.45μm - 0.52μm) in the TM system (band 1) is unique among sensors aboard natural/resource-oriented satellites. The reason that this band has not been a part of the spectrum sought from satellites is the severe scattering of the blue light, which can badly degrade the image contrast where there is high humidity and/or high aerosol content in the atmosphere. However, in water, blue light has the best penetration capability in the visible spectrum.

In clear, sediment-free waters it can define sea bottoms to depths of 30 or more meters, depending primarily on the angle of incidence of the sun's illumination and the reflectance of the bottom. This property is useful for determining offshore slope conditions relevant to potential tsunami run-up.

SATELLITE REMOTE SENSING: APPROXIMATE COSTS OF BASIC DATA ACQUISITION (CCTs, June 1989)

System	Cost per km^2
Landsat MSS	US$.02
Landsat TM	US$.11
SPOT	US$.47 - .61

Figure 4-4

CHARACTERISTICS OF SPOT SENSORS

SPOT SENSOR: MULTISPECTRAL HIGH-RESOLUTION VISIBLE (HRV)

Band	Wavelength (μm)	Resolution (m)	Image Format
XS1	0.50-0.59	20	60km swath with vertical viewing angle and up to 80km with +/- 27° viewing angle from vertical
XS2	0.61-0.68	20	
XS3	0.79-0.89	20	

SPOT SENSOR: PANCHROMATIC HIGH-RESOLUTION VISIBLE (HRV-P)

Band	Wavelength (μm)	Resolution (m)	Image Format
P	0.51-0.73	10	60km swath with vertical viewing angle and up to 80km with +/- 27° viewing angle from vertical

2. SPOT

The SPOT satellite with its High Resolution Visible (HRV) sensors is similar in many respects to the Landsat satellite with its MSS and TM sensors. The HRV multispectral sensor (XS) ranges from the green wavelength into the near IR. The HRV-XS coverage is in three spectral bands rather than the four found in the MSS, but with much higher spatial resolution (20m versus 80m), although it covers only about 1/9 of the area covered by a Landsat scene. Additionally, SPOT carries a panchromatic sensor (HRV-P) which covers the green through red portions of the visible spectrum in a single band with 10m resolution. Both HRV sensors cover a 60km swath along the orbit path. It is possible to obtain simultaneous side-by-side coverage from each sensor, producing a 117km swath width, although this capability has not been frequently used. Figure 4-4 above summarizes the characteristics of SPOT sensors and their image formats.

The SPOT sensors have the unique capability of being pointable, 27 degrees to the left or right of the orbital track. This feature allows for repeated off-nadir viewing of the same ground swath, producing image stereopairs. The base-height ratios range from 0.75 at the equator to 0.50 at the mid-latitudes. This provides a strong vertical exaggeration. This third dimension,

SOURCES OF SPOT IMAGERY

ARGENTINA:	Comisión Nacional de Investigaciones Espaciales (CNIE) Av. del Libertador 1513 Vicente López 1638 Buenos Aires, Argentina
BOLIVIA:	CIASER Casilla de Correo 2729 La Paz, Bolivia
BRAZIL:	SENSORA Rua Bertolomeu Portela, 25 S/Lojas Botafogo, Rio de Janeiro CEP 2290, Brazil
CHILE:	S.A.F. Casilla 67 Correo Los Cerillos Santiago de Chile
MEXICO:	INEGI San Antonio Abad 124 Mexico City, 8 D.F.,
PERU:	ONERN 355 calle 17, Urb. El Palomar, San Isidro Lima, Peru
UNITED STATES:	SPOT Image Corporation 1897 Preston White Drive Reston, Virginia 22091-4326, U.S.A. Telephone: (703) 620-2200
VENEZUELA:	CPDI Edo. Miranda Apartado 40200 Caracas, Venezuela 1040 A

if it is available for a particular study area, together with the higher image resolution, can make SPOT's sensors superior to those of Landsat if greater spectral resolution is not required. The sources for SPOT data are listed in the box above.

3. SATELLITE RADAR SYSTEMS

There is considerable radar coverage throughout the world, and more space-derived radar data can be expected in the future.

The family of space radars stems from the Seasat (U.S.A.) radar, which was a synthetic aperture system that was especially designed for studying the ocean surface. In this capacity it had a large (70° average) depression angle to study the relatively flat ocean surface. For this reason Seasat's usefulness for imaging land extended to those land areas of low relief. During its short life in 1978, it managed to acquire a large amount of data from Western Europe, North and Central America, and the Caribbean.

Seasat was followed by Space Shuttle imaging radars SIR-A and SIR-B. Data from these radars was obtained from Space Shuttle flights in 1981 and 1984. Their characteristics along with those of Seasat are shown in Figure 4-5. SIR-A and SIR-B provided greater worldwide coverage, including large parts of Latin America, because the image data were recorded on board the Space Shuttle rather than telemetered to a limited number of receiving stations within range of the spacecraft, as was the case with the unmanned Seasat radar satellite.

Figure 4-5

CHARACTERISTICS OF SEASAT, SIR-A, AND SIR-B SYSTEMS

Characteristics	Seasat(1978)	SIR-A(1981)	SIR-B(1984)
Repeat Coverage	irregular, northern hemisphere	little to none	little to none
Resolution	25x25m	40x40m	25x(17-58)m
Wavelength (23.5cm)	L-band	L-band	L-band
Latitude coverage	72°N-72°S	50°N-35°S	58°N-58°S
Altitude	790km	250km	225km
Image-swath width	100km	50km	40km

Source: Adapted from Budge, T. A Directory of Major Sensors and Their Parameters (Albuquerque, New Mexico: Technology Application Center, 1988).

SOURCES OF SATELLITE RADAR IMAGERY

SIR-A and SIR-B:
National Space Science Center
World Data Center A for Rockets and Satellites
Code 601
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771, U.S.A.
Telephone: (301) 286-6695

Seasat:
NOAA, National Environmental Satellite Data and Information Service
World Weather Building, Room 100
Washington, D.C. 20233, U.S.A.
Telephone: (301) 763-8111

The long wavelengths of these radar systems permit potential subsurface penetration between 2m and 3m in extremely dry sand (Schaber et al., 1986). There may be areas of hyperaridity in South America that may permit this type of penetration. This property may have some application to natural hazard assessment that is not readily apparent, as well as to integrated development planning studies. The problem seems to be that while significant amount of radar coverage is available, much has yet to be acquired where needed.

The SIR series of radar data acquisition is expected to continue with SIR-C in the future. Other radar sensors will be placed into orbit soon: Canada's Radarsat, a C-band (6.0cm) radar designed to provide worldwide stereoscopic coverage, is planned for the 1990s; the European Space Agency expects to launch a C-band synthetic aperture radar aboard the Earth Resources Satellite (ERS) in 1990; and Japan will launch an L-band imaging radar satellite in 1991. Thus, it can be expected that more radar imagery is forthcoming which will provide additional tools for natural hazard assessment.

4. AVHRR

The Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA-7 through 11 satellites would not normally be considered useful for natural hazard assessments on the basis of its low resolution (1.1km at nadir) alone. However, its large swath width of 2253km provides daily (day and night) coverage of the inhabited parts of the earth (see Figure 4-6). The near-nadir viewing repeat cycle is nine days, but the same area is still viewable from different angles within the swath from space. This results in complicated radiometric and geometric comparisons between different dates of data acquisition.

This scanning radiometer has 5 bands, which include band 1 (green to red), band 2 (red to reflected IR), band 3 (middle IR), band 4 (thermal IR), and band 5. The most useful bands are the thermal IR bands 4 and 5 particularly where moisture or ice is involved. These have been successfully used to delineate flooded areas using temporal analysis techniques within 48 hours following a major flood event (Wiesnet and Deutsch, 1986). The thermal resolution in these bands is better than the Landsat TM thermal band 6 but with a significant trade-off loss in spatial resolution (1.1km versus 120m, respectively).

5. METRIC CAMERA

The metric camera was an experiment on the STS-9/Spacelab 1 Mission in 1983 to determine whether topographic and thematic maps at medium scales (1:50,000 to 1:250,000) could be compiled from mapping camera images taken from orbital altitudes. Due to a late November launch date, illumination conditions were poor over many of the candidate target areas. As a result, slower shutter speeds had to be used than were planned, causing some image

Figure 4-6

AVHRR CHARACTERISTICS

Platform: NOAA satellites (formerly Tiros)

Spectral bands	Tiros-N	NOAA-6,8,10	NOAA-7,9,d,H,I,J
1	0.55 - 0.90	0.58-0.68	0.58 -0.68
2	0.725- 1.00	0.725-1.00	0.725-1.00
3	3.55 - 3.93	3.55-3.93	3.55 -3.93
4	10.50 -11.50	10.50-11.50	10.30-11.30
5	none	none	11.50-12.50

Altitude: 833-870km
Resolution: Large Area Coverage (LAC): 1km
Global Area Coverage (GAC): 4km
Image size: 2253 km swath
Repeat coverage: Daily, worldwide

SOURCE OF AVHRR IMAGERY

Satellite Data Services Division
NOAA/NESDIS/NCDC
World Weather Building, Room 100
Washington, D.C. 20233, U.S.A.
Telephone: (301) 763-8111

SOURCE OF METRIC CAMERA PHOTOGRAPHY

Deutsche Forschungs- und Versuchsanstalt für
Luft- und Raumfahrt e.V. (DFVLR)
Oberpfaffenhofen
D-8031 Wessling
Federal Republic of Germany

smear. Nevertheless, high quality images with a photographic ground resolution of about 20m were obtained on a 23cm x 23cm format panchromatic and color IR film. Analysis has shown that these images may be used for mapping at a scale of 1:100,000. On this mission, despite the fact that many problems were encountered, an area of more than 11 million km^2 was covered. Plans are now underway to modify the camera to compensate for forward image motion and to refly it. It is expected that a ground resolution of about 10m would be obtained, permitting maps with a scale as large as 1:50,000 (Schroeder, 1986).

Ground coverage of 190km x 190km per photograph frame was obtained using a 305mm lens from an altitude of 250km, yielding an image scale of 1:820,000. Overlap of 60 to 80 percent, obtained for topographic mapping purposes, is of great value in interpretation for natural hazards. The high resolution and stereocoverage make this photographic sensor system a potentially useful tool when sufficiently enlarged.

Five lines of metric camera photography cover parts of Latin America, and with resumption of the U.S. Space Shuttle program, additional high quality space photographs of areas of interest may become available.

6. LARGE FORMAT CAMERA

The large format camera (LFC) photography was obtained during a Space Shuttle flight in October 1984. The term "large format" refers to the 23cm by 46cm film size, which was oriented with the longer dimension in the line of flight. LFC acquired 1,520 black and white, 320 normal color, and 320 IR color photographs, covering many areas within Latin America and the Caribbean. The scale of the photographs ranges from 1:213,000 to 1:783,000 depending on the altitude of the Space Shuttle, which varied between 239km and 370km. The swath covered a range between 179km and 277km, and each frame covered between 360km and 558km in the flight direction. Forward overlap up to 80 percent was obtained, allowing vertical exaggerations of 2.0, 4.0, 6.0, and 7.8 times in the stereomodels. Most photographs were taken with 60 percent overlap, which provided 4 times vertical exaggeration and an excellent stereomodel. The spatial resolution was about 3m for the black and white film and about 10m for the color IR film.

The availability of this excellent stereophotography, which can be enlarged ten times or more with little loss of image quality, is limited to certain areas covered by the ground track of the Space Shuttle. Some of this coverage includes clouds or heavy haze, but despite the limitations of coverage and occasional poor quality, the existing photography should be examined for its possible use in any regional natural hazards assessment and planning study.

Given the range of tools available for aerial and satellite remote sensing, their applications vary based on the advantages and limitations of each. The planner can regard each of these as a potential source of information to enhance natural resource evaluation and natural hazard assessment. The next section covers some of the applications of photographs and images in natural hazard assessments.

7. SOJUZKARTA

Sojuzkarta satellite data consist of photographs taken with the KFA-1000 and KM-4 camera. Computer compatible tapes (CCTs) for digital image processing are not available, although it is possible to convert the data into digital format by using a scanner. Photographs obtained through the KFK-1000 camera have 5m resolution in the panchromatic mode and 10m resolution in the color mode; scales range from 1:220,000 to 1:280,000. KM-4 photography has a 6m resolution and is available at scales of 1:650,000 and 1:1,500,000. Applications of this sensor to natural hazard studies are likely to be in desertification monitoring, flood hazard and floodplain, and landslides studies.

SOURCES OF LFC PHOTOGRAPHY

Chicago Aerial Survey, Inc.
LFC Department
2140 Wolf Road
Des Plaines, Illinois 60018, U.S.A.

Martel Laboratories
7100 30th Avenue North
St. Petersburg, Florida 33710, U.S.A.

U.S. Geological Survey
EROS Data Center
Sioux Falls, South Dakota 57198, U.S.A.

D. Applications of Remote Sensing Technology to Natural Hazard Assessments

For purposes of assessing natural hazards in the context of integrated development planning studies, it is not necessary to have real-time or near real-time remote sensing imagery. What is required is the ability to define areas of potential exposure to natural hazards by identifying their occurrence or conditions under which they are likely to occur and to identify mechanisms to prevent or mitigate the effects of those hazards. This section considers the practical detectability by remote sensing technology of the potential for floods, hurricanes, earthquakes, volcanic eruptions and related hazards, and landslides. It will become evident that some of these hazards are interrelated, e.g., floods and hurricanes; earthquakes, volcanoes and landslides.

The ability to identify these natural hazards or their potential for occurring depends on the resolution of the image, the acquisition scale of the sensor data, the working scale, scenes free of clouds and heavy haze, and adequate textural and tonal or color contrast. The availability of stereomodels of the scene being studied can greatly enhance the interpretation. Figure 4-7 displays satellite remote sensing attributes to be taken into consideration for the assessment of various hazards.

After a hazard is identified, formulating appropriate mitigation measures and developing response plans may require different remote sensing data sets. This additional remote sensing data needed are most likely to include greater detail of the infrastructure, e.g., roads and facilities. This may have to be derived from aerial photography.

1. FLOODS

Floods are the most common of natural hazards that can affect people, infrastructure, and the natural environment. They can occur in many ways and in many environments. Riverine floods, the most prevalent, are due to heavy, prolonged rainfall, rapid snowmelt in upstream watersheds, or the regular spring thaw. Other floods are caused by extremely heavy rainfall occurring over a short period in relatively flat terrain, the backup of estuaries due to high tides coinciding with storm surges, dam failures, dam overtopping due to landslides into a reservoir, and seiche and wind tide effects in large lakes. Occasionally an eruption on a glacier or snow-covered volcanic peak can cause a flood or a mudflow in which the terrain is radically changed and any agrarian development is totally destroyed, frequently with much loss of life. See Chapter 8 for a more detailed discussion of flood hazards and Chapter 11 for a discussion of floods and mudflows associated with volcanic eruptions.

It is impossible to define the entire flood potential in a given area. However, given the best remote sensing data for the situation and a competent interpreter, the evidence for potential flood situations can be found or inferred. The most obvious evidence of a major flood potential, outside of historical evidence, is identification of floodplain or flood-prone areas which are generally recognizable on remote sensing imagery. The most valuable application of remote sensing to flood hazard assessments, then, is in the mapping of areas susceptible to flooding.

Synoptic satellite sensor coverage of a planning study area is the practical alternative to aerial photography because of cost and time factors. The application of Landsat MSS imagery to floodplain or

Figure 4-7

SATELLITE IMAGERY APPLIED TO NATURAL HAZARD ASSESSMENTS

	EARTHQUAKES	VOLCANIC ERUPTION	LANDSLIDES	TSUNAMI	DESERTIFICATION	FLOODS	HURRICANES
INFORMATION TO BE OBTAINED	Land-use maps, geological maps	Maps of areas vulnerable to lava flows, ash fall, debris fall and fires	Slope maps, slopes stability, elevation, geology, soil type, areas of standing water, land-use maps	Bathymetric/ topographic maps	Land-use maps, soil moisture content, crop condition and natural vegetation	Floodplain delineation maps, land-use classification, historical data, soil cover and soil moisture	Land-use maps
SPECTRAL BAND	Visible and near IR	Visible, near IR and thermal IR	Visible	Visible, including blue and near IR	Visible, near IR, and microwave	Near IR, thermal IR and microwave	Visible and near IR
SPATIAL RESOLUTION	20-80m	30-80m	10-30m	30m	80m-1km	20m (for cultural features); 30-80m (for land use); 1km (for snow cover and soil moisture)	20m (for cultural features); 30-80m (for land use)
AREAL COVERAGE	Large area	Large area	Large area	Large coastal area	Large regional area	Large regional area	Large area
ALL WEATHER CAPABILITY	No	No	No	No	No	No	No
SYNOPTIC VIEW	Yes	Yes	Yes	Yes	Yes	Yes	Yes
STEREO CAPABILITY	Yes	Yes	Yes	Yes	No	Yes	No
FREQUENCY OF OBSERVATIONS FOR PLANNING STUDY USE	1 to 5 years	1 to 5 years	1 to 5 years	1 to 5 years	Monthly	Seasonal (except weekly for snow cover and soil moisture)	Yearly

Source: Adapted from Richards, P.B. The Utility of Landsat-D and other Satellite Imaging Systems in Disaster Management (Washington, DC: Naval Research Laboratory, 1986).

flood-prone area delineation has already been demonstrated by comparing pre-flood scenes with scenes obtained at the height of the flood, using Landsat MSS band 7 (near IR) images in a color additive viewer (Deutsch et al., 1973). This temporal comparison can now be done pixel by pixel in a computer. Landsat TM, with its greater spatial resolution than MSS data (30m versus 80m) and its additional spectral coverage (7 bands versus 4 bands), can be used for more detailed mapping of floodplains and flood-prone areas on larger scale maps of 1:50,000 or greater. TM data have been used for discriminating land cover classification (Kerber et al., 1985) and to provide useful input to flood forecasting and flood damage models for urban and agricultural areas (Gervin et al., 1985).

This approach to floodplain delineation does have its limitations. The area of potential flooding delineated in this manner may represent a flood level that exceeds an acceptable degree of loss. Also, no floods may have occurred during the period of the sensor operation. In this case, indirect indicators of flood susceptibility are used. A more detailed discussion of flood susceptibility and the use of Landsat imagery can be found in Chapter 8. Landsat and presumably similar satellite data floodplain indicators are listed in Figure 4-8.

There are large parts of tropical humid ecosystems where adequate Landsat or other similar imagery is not available due to cloud coverage or heavy haze. In some instances the heavy tropical vegetation masks many geomorphic features so obvious in drier climates. In this case the use of available radar imagery from space or previously acquired from an aircraft survey is desirable. The radar imagery, which has a resolution comparable to Landsat TM and SPOT from both space and sub-orbital altitudes, can satisfactorily penetrate the clouded sky and define many floodplain features. Moisture on the ground noticeably affects the radar return and, together with the textural variations emphasized by the sensor, makes radar a potentially desirable tool for flood and floodplain mapping.

2. HURRICANES

To mitigate the impact of hurricanes, the planner needs to know the frequency of storms of given intensity in the study area, to what extent these storms could affect people and structures, and what sub-areas would be most affected such as low-lying coastal, estuarine, and riverine areas threatened by flooding and storm surge. See Chapter 12 for a more detailed discussion of hurricanes and coastal areas.

The determination of past hurricane paths for the region can be derived from remote sensing data from the U.S. National Oceanographic and Atmospheric Administration (NOAA) satellite sensors designed and operated for meteorological purposes. These data are already plotted by meteorological organizations in the U.S.A. and other countries where hurricanes are a threat. For plotting new data, the best sensor is the

Figure 4-8

LANDSAT FLOODPLAIN INDICATORS

- Upland physiography
- Watershed characteristics, such as shape, drainage, and density
- Degree of abandonment of natural levees
- Occurrence of stabilized sand dunes on river terraces
- Channel configuration and fluvial geomorphic characteristics
- Backswamp areas
- Soil-moisture availability (also a short term indicator of flood susceptibility)
- Variations in soil characteristics
- Variations in vegetation characteristics
- Land use boundaries
- Flood alleviation measures for agricultural development on the floodplain

Source: Adapted from Rango, A. and Anderson, A.T. "Flood Hazard Studies in the Mississippi River Basin Using Remote Sensing" in Water Resources Bulletin, vol. 10, 1974.

AVHRR which, with its 2,700km swath, makes coverage twice a day, and has appropriate resolution. The red band is useful for defining daytime clouds and vegetation, while the thermal IR band (10.50μm to 11.50μm) is useful for both daytime and nighttime cloud observations.

The AVHRR is not useful in other aspects of hurricane contingency planning due to its limited spatial resolution. These planning needs require higher resolution available from other satellite sensors. If imagery of areas inundated by floods, hurricane storms, or other storms is obtained with any sensor immediately after the event, it should be used, of course, regardless of its resolution. Any such information that is obtained in a timely fashion should be used to delineate the problem areas since their definition is more exact than can be interpreted from higher resolution data obtained during a non-flood period.

Predicting areas of potential inundation along coasts and inland can be achieved using topographic maps with scales as large as 1:12,500. When such maps are not available, remote sensing techniques can be used. In areas with a distinct wet and dry season, it is desirable to obtain information for the wet season from Landsat or comparable imagery in the near IR bands, or use a color IR composite made from Landsat MSS or TM imagery or from SPOT HRV imagery. These image products can be used to identify the moisture-saturated areas susceptible to flooding as well as the higher and drier ground for potential evacuation areas. Likewise, consideration of development plans in view of this potential natural hazard can proceed in a way similar to that for areas prone to flood hazards. For flood hazard assessments, radar imagery from space or aircraft could be used (if available) in lieu of the Landsat MSS imagery. Since there is a general lack of relief in low-lying coastal areas and estuarine areas, stereoscopy would not normally play an important role in this situation. However, stereoscopic viewing even without significant relief enhancement can still reinforce the details of the scene, although at considerably greater cost.

The development planner also needs to consider the additional feature of a hurricane--its high winds. In identifying measures to mitigate wind effects, the planner may consider the type of crops grown, if an agricultural development is being planned, and the design and construction materials used in buildings.

3. EARTHQUAKES

The planning of development in earthquake-prone areas is laden with problems. There are large human settlements already located in earthquake/prone areas. As with other geologic hazards, the frequency of occurrence can fall in cycles of decades or centuries. Earthquakes are particularly difficult to predict at this time. Thus, mitigation emphasis is on land use planning (non-intensive uses in most hazardous areas), on building strength and integrity, on response planning, and on incorporating mitigation measures into reconstruction efforts. The main problem is the identification of the earthquake damage-prone zones (see Chapter 11 for detailed discussion of earthquakes and their assessment). While in most areas of great earthquake activity some seismic information is available, it may not be sufficient for planning purposes. Remote sensing techniques and resulting data interpretation can play a role in providing additional information.

Tectonic activity is the main cause of destructive earthquakes, followed by earthquakes associated with volcanic activity. Where the history of earthquakes due to seismic activity is present in an area, the faults associated with the activity can frequently be identified on satellite imagery. Where volcanic-related earthquakes occur, the source is generally not as obvious: it may be due to movement on a fault near the surface or deep within the earth, to caldera collapse, or to magma movement within the volcanic conduit.

In order to identify earthquake hazards it is necessary to have the expertise to recognize them and then determine the correct remote sensing tools to best delimit them. Landsat imagery has been effectively and widely used for this purpose since it is less expensive and more readily available than other remote sensing data. Airborne radar mosaics have been successfully used for the delineation of fault zones. Generally, two mosaics can be made of an area: one with the far range portion of the SLAR and the other with the near range portion. The former is best used in areas of low relief where the relief needs to be enhanced, and the latter in areas of high relief where the shadow effect is not needed or may be detrimental to the image.

Radar is applicable to delineate unconsolidated deposits sitting on fault zones--upon which most of the destruction occurs--to identify areas where an earthquake can trigger landslides. This is best accomplished on stereomodels using adjoining and overlapping radar flight lines. Conventional aerial photography, in black and white or color, would also work well for this purpose.

An alternative, which is adequate but not as good as using radar and aerial photography, is to use multispectral imagery obtained from the Landsat TM and/or MSS or SPOT HRV sensors. Color IR composites or straight near-IR imagery from these

sensors at scales up to about 1:100,000 can be used to define active surface fault zones, but not as efficiently as with the radar images. The distinction between bedrock versus unconsolidated materials and the areas of potential landslide hazards can be defined but, again, only if stereocoverage is available. SPOT sensors can provide this capability.

While radar imagery is an ideal data source, available coverage is extremely limited, and contracting airborne radar is usually prohibitively expensive. Landsat TM and MSS are the most practical data source, simply because of its availability, and both provide sufficient resolution for regional planning studies.

4. VOLCANIC ERUPTIONS AND RELATED HAZARDS

Many hazards are associated with the conditions brought about by volcanic activity. Active volcanoes pose hazards which include the immediate release of expelled ash, lava, pyroclastic flows, and/or poisonous hot gases; volcanic earthquakes; and the danger of mudflows and floods resulting from the rapid melting of snow and ice surrounding the vent during eruption. Some secondary hazards may threaten during volcanic activity or during periods of dormancy. These include landslides due to unstable accumulations of tephra, which may be triggered by heavy rains or by earthquakes. A more detailed discussion of volcanic hazards and their assessment can be found in Chapter 11.

Each volcano has its own particular behavior within a framework of given magmatic and tectonic settings. Prediction of a volcano's behavior is extremely difficult, and the best evidence for the frequency of activity and its severity is the recorded history of eruptions. Imminent eruptions are now best recognized by on-site seismic monitoring. Some classifications distinguish between active, inactive, dormant, and extinct volcanoes. But since some of the most catastrophic eruptions have come from "extinct" volcanoes, many volcanologists have abandoned such a classification, settling for a simple distinction between short-term and long-term periodicity.

Gawarecki et al. (1965) first detected volcanic heat from satellite remote sensing using thermal IR imagery from the high resolution IR radiometer (HRIR). Remote sensing data interpretation can lead to the recognition of past catastrophic events associated with recently active volcanoes (recently in the geologic sense), as in the Andes and the Lesser Antilles. This information together with the available historical data can be used as the basis of assessing the risks of an area with potential volcano-related hazards.

The varied nature and sizes of volcanic hazards require the use of various types of sensors from both satellites and aircraft. The relatively small area involved with volcanoes should encourage the use of aerial photography in their analysis. Panchromatic black and white stereo aerial coverage at scales between 1:25,000 to 1:60,000 is usually adequate to recognize and map geomorphic evidence of recent activity and associated hazards. Color and color IR photography may be useful in determining the possible effects of volcanic activity on nearby vegetation, but the slower film speed, lower resolution, and high cost diminish much of any advantage they provide.

The airborne thermal IR scanner is probably the most valuable tool in surveying the geothermal state of a volcano. The heat within a volcano and underlying it and its movement are amenable to detection. Because of the rapid decrease in resolution with increasing altitude (about 2m per 1,000m) the surveys need to be made at low altitudes under 2,000m.

An IR pattern of geothermal heat in the vicinity of a volcano is an indication of thermal activity which many inactive volcanoes display. Many volcanoes thought to be extinct may have to be reclassified if aerial IR surveys discover any abnormally high IR emissions from either the summit craters or the flanks. Changes in thermal patterns can be obtained for a volcano only through periodic aerial IR surveys taken under similar conditions of data acquisition. The temperature and gas emission changes, however, can be monitored on the ground at ideal locations identified on the thermal imagery, making periodic overflights unnecessary. Continuous electronic monitoring of these stations is possible by transmission through a geostationary data relay satellite, another phase of remote sensing.

The thermal IR bands of the satellite sensors now available have inadequate spatial and thermal resolution to be of any significant value to detect the dynamic change in volcanic geothermal activity. In addition to sensing geothermal heat, however, other remote sensing techniques are useful in preparing volcanic hazard zonation maps and in mitigating volcanic hazards. Mitigation techniques requiring photo interpretation and topographic maps include predicting the path of potential mudflows or lava flows and restricting development in those areas.

5. LANDSLIDES

Landslides, or mass movements of rock and unconsolidated materials such as soil, mud, and volcanic debris, are much more common than is generally perceived by the public. Many are aware of the catastrophic landslides, but few are aware that

small slides are of continuous concern to those involved in the design and construction business. These professionals can often exacerbate the problem of landsliding through poor planning, design, or construction practices. Frequently, the engineer and builder are also forced into difficult construction or development situations as a result of ignoring the potential landslide hazard. This can be avoided if there is early recognition of the hazard and there is effective consultation between planners and the construction team prior to detailed development planning. See Chapter 10 for a more detailed discussion of landslide hazards and their assessment.

The mass movement of bedrock and unconsolidated materials results in different types of slides, magnitudes, and rates of movement. An area with a potential landslide hazard usually has some evidence of previous occurrences, if not some historical record. Unfortunately, some types of landslides, particularly those of small size, cannot be delineated on remote sensing imagery or through aerial photography. Usually the scars of the larger slides are evident and, although the smaller slide features may not be individually discerned, the overall rough appearance of a particular slope can suggest that mass movement occurred. If a fairly accurate geologic map is available at a reasonable scale (1:50,000 or larger) rock types and/or formations susceptible to landslides may be examined for evidence of movement. An example of this would be finding a shale in a steeper than usual slope environment, implying the strong possibility of a landslide history. An examination of stream traces frequently shows deflections of the bed course due to landslides. If one can separate out the tectonically controlled stream segments, those deflections due to slides or slumps often become evident.

Typical features that signify the occurrence of landslides include chaotic blocks of bedrock whose only source appears to be upslope; crescentic scarps or scars whose horns point downward on a normal-looking slope; abnormal bulges with disturbed vegetation at the base of the slope; large intact beds of competent sedimentary or other layered rock displaced down dip with no obvious tectonic relationship; and mudflow tongues stretching outward from the base of an obviously eroded scar of relatively unconsolidated material. A good understanding of the structural geology of the study area frequently places these superficial anomalies into perspective. As discussed in Chapter 10, the susceptibility to landslides is relative to the area. Landslides can occur on gentle slopes as well as on steep slopes, depending on landscape characteristics.

Most landslide discussions do not address the problem of sinkholes, which are a form of circular collapse landslides. The karstic areas in which they occur are easy to identify even on some satellite imagery (MSS, TM, SPOT, etc.) due to their pitted appearance and evidence of the essentially internal drainage. Despite the obvious occurrence of many sinkholes, many individual small sinkholes are subtle and not easily recognized. These are frequently the sites of collapse and subsequent damage to any overlying structure when ground water is removed to satisfy development needs, which results in lowering the water table and undermining the stability of the land.

The spatial resolution required for the recognition of most large landslide features is about 10m (Richards, 1982). However, the recognition depends to a great extent on the ability and experience of the interpreter and is enhanced by the availability of stereoscopic coverage, which can be expensive to acquire. Stereoscopic coverage and the resolution requirements preclude use of most satellite-borne sensor imagery, although large block landslides can be detected on Landsat MSS and TM imagery.

Given the spatial resolution requirement, SPOT HRV-P (panchromatic mode) imagery can be useful with its 10m resolution. Its broad band coverage, however, is not conducive to providing adequate contrast in scenes involving heavily vegetated tropics, where most of the potential hazards occur. Ameliorating this factor slightly is the availability of stereocoverage. It is important to understand that this is specifically programmed for the SPOT satellite and that stereocoverage is not normally acquired during sensor operation.

Detection of landslide features is more easily achieved using airborne sensors. Aerial photography with its normal stereoscopic coverage is the best sensor system with which to define landslides, both large and small. Aerial photographic scales as small as 1:60,000 can be used. Black and white panchromatic or IR films are adequate in most cases, but color IR may prove better in some instances. The IR-sensitive emulsions, as stated earlier, eliminate much of the haze found in the humid tropics. The open water or other moisture in back of recent slump features stands out as an anomaly in the aerial IR stereomodel, either in black and white or color. The color IR photography might, in some rare cases, show the stress on the vegetation caused by recent movement. If the scales are large enough, tree deformation caused by progressive tilting of the slope of the soil might also be detected.

A more sensitive detector of moisture associated with landslides is the thermal IR scanner. This sensor is particularly useful in locating seepage areas that lubricate slides. It is particularly effective during the

night, when there is a maximum temperature difference between the terrain and the effluent ground water. Despite its utility many factors rule out the widespread use of the thermal IR scanner. These factors include the low altitude required for reasonable spatial resolution, the large number of flight lines required for the large area involved, and the geometrical distortions inherent in the system. If the terrain to be interpreted has some relief and is nondescript, these distortions become an even greater problem when the data are interpreted by making the location of features very difficult.

SLAR, especially the X-band synthetic aperture radar with its nominal 10m resolution, can be marginally useful in a stereo mode because of its ability to define some larger textures related to landslides. In some cloud-prone environments radar may be the only sensor that can provide interpretable information.

6. DESERTIFICATION

Desertification occurs when an ecosystem experiences a diminution or loss of productivity. This process can have a natural and an anthropic component, which may reinforce each other, creating a synergetic effect (see Chapter 9). The degree of desertification risk is directly related to certain natural conditions such as climate, topography, natural vegetation, soil, and hydrology, as well as to the intensity and type of anthropic activity in the area. Desertification is among the most serious problems of the region. This trend indicates the increasing need to consider desertification processes in integrated development planning studies. Remote sensing, both spaceborne and airborne, provides valuable tools for evaluating areas subject to desertification. Film transparencies, photographs, and digital data can be used for the purpose of locating, assessing, and monitoring deterioration of natural conditions in a given area. Information about these conditions can be obtained from direct measurements or inferred from indicators (keys to the recognition of a desertification process).

In order to describe, evaluate, and decide about the type of action to be taken, the following issues should be addressed:

- Location: involves the identification of areas that are currently undergoing desertification and areas expected to be exposed to the forces that can lead to deterioration.

- Assessment: involves the identification and quantification of vegetative cover types, soils, land forms, and land-use change patterns. Vulnerability to change, rate of change, and direction of change in desertification patterns can be studied through this assessment.

- Monitoring: accomplished by detecting and measuring changes in landscape characteristics over a period of time. Comparisons are made between present conditions and previously observed conditions for the purpose of recording the reduction in biological productivity.

Chapter 9 presents an initial assessment technique utilizing information commonly available in the early integrated development planning stages. For a more detailed approach, four sets of data should be taken into consideration for a desertification study of a given area: a set taken at the end of the humid season, a set taken at the end of the last dry season, and the same two seasons taken five or ten years earlier (López Ocaña, 1989). Data selection for a given area will be directly related to the desired amount of detail, size of the area, required degree of precision and accuracy, and available time frame.

Large-scale aerial photography provides a great amount of detail for this type of study. Systematic reconnaissance flights can be used for environmental monitoring and resource assessment. Radar sensors and infrared scanners may be used to monitor soil moisture and other desertification indicators. However, acquisition of this type of data is costly and time consuming.

The use of satellite imagery is recommended during the first stages of a detailed desertification study since it offers an overview of the entire region. Computer enhancements, false color composites, and classifications can offer useful information. Optical enhancements can be performed, but these lack the quantitative control available through an automated approach. Statistical data obtained from a quantitative analysis through the use of a geographic information system (GIS--see Chapter 5) can be expressed as a histogram, a graph, a table, or a new image.

AVHRR imagery is commercially available and has been used for vegetation change studies. Ground resolution of 1 to 4 km represents some limitation in making large continental area studies. Other studies have used Nimbus data to delineate moisture patterns and vegetation boundaries. Geostationary Operational Environmental Satellite (GOES) data have been used effectively to locate and measure dust plumes; and Seasat SAR imagery has been applied in the delineation of large dune morphology.

Landsat MSS and TM and SPOT data have proven to be useful and cost effective for regional assessments. Landsat transparencies of bands 5 and

7 have been used to monitor superficial changes in areas undergoing desertification, and to map present water bodies and former drainage systems. Temporal tonal variations on Landsat MSS have been correlated with variations on the field. Movement of sand-dune belts has been detected using Landsat with a multitemporal approach. Albedo changes in arid terrains have been calculated using Landsat digital data: phenomena that tend to lower productivity (increased erosion, loss of vegetation density, deposition of eolic sedimentation) also tend to appear brighter on the image. On the contrary, phenomena that tend to increase productivity (increased vegetation, soil moisture), tend to darken the land. In this way, brightness variations can be detected in an area over a period of time. These data can also be calibrated with ground data collected from the areas where change has occurred.

Aerial and space remote sensing provide valuable tools for desertification studies, although, as for any other natural hazard related study, they must be combined with ground-collected data. The use of remote sensing methods should minimize the need for ground data, therefore saving time and resulting quite inexpensive per unit of data. The combination of remotely sensed and ground-collected data can then, provide the basis for the assessment.

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CHAPTER 5

GEOGRAPHIC INFORMATION SYSTEMS IN NATURAL HAZARD MANAGEMENT

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Contents

List of Figures

GEOGRAPHIC INFORMATION SYSTEMS IN NATURAL HAZARD MANAGEMENT

SUMMARY

This chapter introduces the planner to the concept and applications of geographic information systems (GIS) for natural hazard management in the context of integrated development planning. The chapter also discusses the acquisition of a GIS, the elements involved in making that decision, and the basics of how to select, establish, and use such a system.

Natural events such as earthquakes and hurricanes can be hazardous to man. The disasters that natural hazards can cause are largely the result of actions by man that increase vulnerability, or lack of action to anticipate and mitigate the potential damage of these events. Previous chapters make clear that this book does more than describe hazards; it deals with how this information can be incorporated into development planning to reduce the impact of natural hazards. Planners are familiar with the bewildering array of disparate pieces of information that have to be analyzed and evaluated in the planning process. The process is complicated, however, by entirely new data sets on assessment of various natural hazards, separately and in combination, and by the need to analyze these hazards with respect to existing and planned development, choose among means of mitigating the damage the hazards can cause, carry out an economic analysis of the alternatives of mitigation versus no mitigation, and determine the impact of these alternatives on the economic and financial feasibility of the project.

Along with these added complications come techniques for managing the information so that it does not overwhelm the planner. Among these are geographic information systems (GIS), a systematic means of geographically referencing a number of "layers" of information to facilitate the overlaying, quantification, and synthesis of data in order to orient decisions.

This chapter demonstrates the effectiveness of geographic information systems, specifically personal-computer-based systems, as a tool for natural hazard management in the context of integrated development planning. The chapter is directed towards two different audiences. To planners it shows the utility of the tool by giving a number of practical examples of applications extracted directly from planners' experiences. To the decision-makers of planning agencies it sends the message that if their agency does not now have access to a GIS, they should certainly be thinking about it. Technical subordinates should find here the wherewithal to present the appropriate arguments for GIS use to uninformed decision-makers.

There are a number of reasons why planning agencies in Latin American and Caribbean countries would benefit from a GIS:

- It can be surprisingly cheap; very expensive equipment and highly specialized technicians can be avoided by proper selection of a system and its application. The main constraint may not be lack of funds but lack of appropriate personnel and equipment;

- It can multiply the productivity of a technician; and

- It can give higher quality results than can be obtained manually, regardless of the costs involved. It can facilitate decision-making and improve coordination among agencies when efficiency is at a premium.

On the assumption that some readers are unfamiliar with GIS, the chapter first reviews some basic concepts covering the operations, functions, and elements of a system. Next come a number of examples of applications for natural hazard management at the national, subnational, and local levels, to help the reader evaluate the benefits and limitations of a GIS. A three-step process is presented for reaching the decision to acquire or upgrade GIS capability: (1) a needs assessment, determining the agency's GIS applications and objectives and those of possible joint users; (2) analysis of the costs and benefits of the acquisition; (3) brief guidelines for the selection of appropriate hardware and software combinations. The chapter ends with a short discussion of how to set up a system.

The chapter does not attempt to replace the many technical manuals on how to select and operate a GIS. Once the agency has decided to consider the acquisition of a system, it will require more specific guidance in the form of supplementary literature and/or technical assistance.

A. Basic GIS Concepts

1. WHAT IS A GIS?

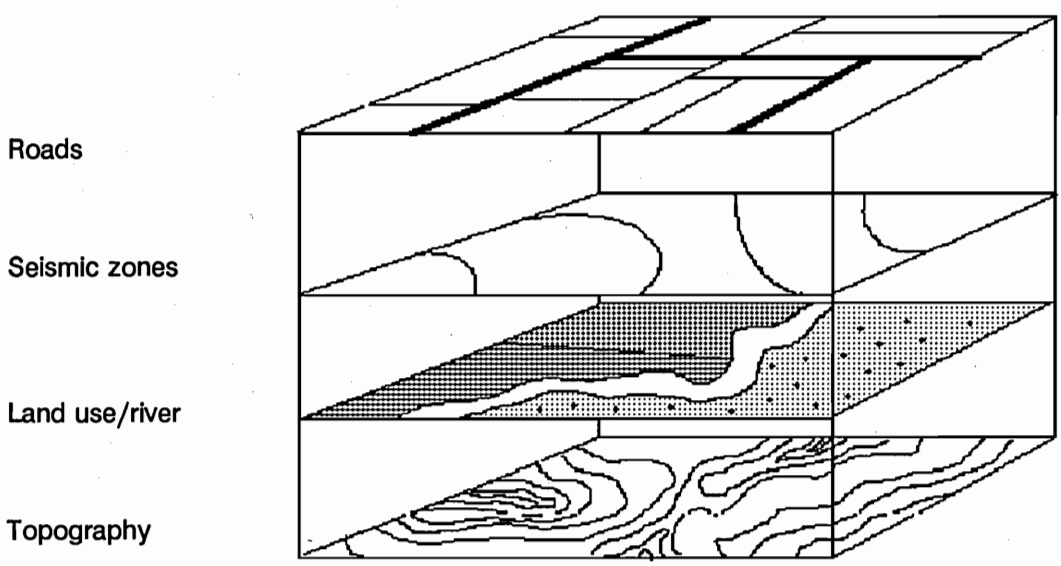
The concept of geographic information systems (GIS) is not new. It was first applied conceptually when maps on the same topic made on different dates were viewed together to identify changes. Similarly, when maps showing different kinds of information for the same area were overlaid to determine relationships, the concept of GIS was actually in use. What is new and progressing rapidly is advancing computer technology, which allows the low-cost examination of large areas frequently, and with an increasing amount of data. Digitization, manipulation of information, interpretation, and map reproduction are all steps in generating a GIS that now can be achieved rapidly, almost in real time.

The concept of a GIS is basically analogous to a very large panel made up of similarly shaped open boxes, with each box representing a specified area on the earth's surface. As each element of information about a particular attribute (soil, rainfall, population) that applies to the area is identified, it can be placed into the corresponding box. Since there is theoretically no limit to the amount of information that can be entered into each box, very large volumes of data can be compiled in an orderly manner. After assigning relatively few attributes to the box system, it becomes obvious that a collection of mapped information has been generated and can be overlaid to reveal spatial relationships between the different attributes, i.e., hazardous events, natural resources, and socio-economic phenomena (see Figure 5-1).

There are many kinds of GIS, some more suitable for integrated development planning studies and natural hazard management than others. At the most elementary level, there are simple manual overlay techniques, such as the one proposed by McHarg in *Design with Nature,* which have proven to be very valuable tools. However, the information needed for hazard management and development planning can become so overwhelming that it is almost impossible to cope with it manually. At the other extreme are

Figure 5-1

OVERLAY CHARACTERISTICS OF A GIS



highly sophisticated computerized systems that can analyze baseline scientific data such as satellite imagery and can produce, by using plotters, large-scale maps of excellent cartographic quality. Such systems are very expensive, difficult to operate, and may exceed the needs of many planning offices.

Among computerized GIS, PC-based GIS are most affordable and relatively simple to operate, capable of generating maps of varying scales and tabular information suitable for repeated analysis, project design, and decision-making. Even though PC-based GIS may not produce maps of cartographic quality or sufficient detail for engineering design, they are most viable for planning teams analyzing natural hazard issues in integrated development projects.

Data manipulated by a computer-based GIS are arranged in one of two ways: by raster or by vector. The raster model uses grid cells to reference and store information. An area for study is divided into a grid or matrix of square (sometimes rectangular) cells identical in size, and information--attributes represented as sets of numbers--is stored in each cell for each layer or attribute of the database. A cell can display either the dominant feature found in that cell or the percentage distribution of all attributes found in the same cell. Raster-based systems define spatial relationships between variables more clearly than their vector-based counterparts, but the coarser resolution caused by using a cell structure reduces spatial accuracy.

Vector data are a closer translation of the original map. These systems reference all information as points, lines or polygons, and assign a unique set of X,Y coordinates to each attribute. Usually, vector system software programs have the capability to enlarge a small portion of a map to show greater detail or to reduce an area and show it in the regional context. Vector data can offer a larger number of possible overlay inputs or layers of data with greater ease. The vector model does represent the mapped areas more accurately than a raster system, but because each layer is defined uniquely, analyzing information from different layers is considerably more difficult.

The choice of raster or vector-based GIS depends on the user's needs. Vector systems, however, demand highly skilled operators and may also require more time and more expensive equipment, particularly for output procedures. Vector-based GIS software is also much more complex than that for the raster system and should be checked for performance in all cases. It is up to the planner or decision-maker to choose what system is most appropriate.

2. GIS OPERATIONS AND FUNCTIONS

a. Data Input

Data input covers the range of operations by which spatial data from maps, remote sensors, and other sources are transformed into a digital format. Among the different devices commonly used for this operation are keyboards, digitizers, scanners, CCTS, and interactive terminals or visual display units (VDU). Given its relatively low cost, efficiency, and ease of operation, digitizing constitutes the best data input option for development planning purposes.

Two different types of data must be entered into the GIS: geographic references and attributes. Geographic reference data are the coordinates (either in terms of latitude and longitude or columns and rows) which give the location of the information being entered. Attribute data associate a numerical code to each cell or set of coordinates and for each variable, either to represent actual values (e.g., 200 mm of precipitation, 1,250 meters elevation) or to connote categorical data types (land uses, vegetation type, etc.). Data input routines, whether through manual keyboard entry, digitizing, or scanning, require a considerable amount of time.

b. Data Storage

Data storage refers to the way in which spatial data are structured and organized within the GIS according to their location, interrelationship, and attribute design. Computers permit large amounts of data to be stored, either on the computer's hard disk or in portable diskettes.

c. Data Manipulation and Processing

Data manipulation and processing are performed to obtain useful information from data previously entered into the system. Data manipulation embraces two types of operations: (1) operations needed to remove errors and update current data sets (editing); and (2) operations using analytical techniques to answer specific questions formulated by the user. The manipulation process can range from the simple overlay of two or more maps to a complex extraction of disparate pieces of information from a wide variety of sources.

d. Data Output

Data output refers to the display or presentation of data employing commonly used output formats that include maps, graphs, reports, tables, and charts, either as a hard-copy, as an image on the screen, or as a text file that can be carried into other software programs for further analysis.

3. ELEMENTS OF A GIS

a. Hardware and Software Components

Hardware components of a basic GIS work station consist of: (1) a central processing unit (CPU) where all operations are performed; (2) a digitizer, which consists of a tablet or table where analog data are converted to digital format; (3) a keyboard by which instructions and commands as well as data can be entered; (4) a printer or plotter to produce hard copies of the desired output; (5) a disk drive or tape drive used to store data and programs, for reading in data and for communicating with other systems; and (6) a visual display unit (VDU) or monitor where information is interactively displayed. Several GIS software packages are available representing a very broad range of cost and capability. The selection of the appropriate combination of hardware and GIS software components to match the user's needs is discussed in Section C.

b. Users and Users' Needs

Planners need to carefully evaluate their GIS needs and proposed applications before taking the decision to acquire an install a GIS. Once a positive conclusion has been reached, its hardware-software configuration should be designed based on those needs and applications, and within the constraints posed by the financial and human resources available to operate the system.

It is possible that the costs of establishing a GIS exceed the benefits to a single agency. Under these circumstances, it is worthwhile determining if several agencies might share the GIS. Appendix A gives a list of users of natural hazard data. The potential users must agree on the data to be compiled, the data formats, standards of accuracy, etc. As a result, the data requirements of a variety of users are made compatible, and the value of the data increases commensurately.

Sharing information has its costs as well as benefits. Negotiating with other users can be a painful task, and compromises inevitably ensure that no one user will get the equipment most precisely suited to his uses. In this regard, it is important to establish a comfortable working relationship among sharers.

c. Information and Information Sources

General reference maps and information on natural hazards and natural resources should form a "library of knowledge" for any GIS. Most areas of Latin America and the Caribbean have general background sources of such data. Virtually all countries have topographic maps, road maps, generalized soils maps, some form of climate information, and at least the locational component of natural hazards information (e.g. location of active volcanoes, fault lines, potential flood areas, areas of common occurrence of landslides, areas of past tsunami occurrence, etc.). Natural hazards locational data can be made compatible in a GIS with previously collected information about natural resources, population, and infrastructure, to provide planners with the wherewithal for a preliminary evaluation of the possible impacts of natural events.

Even though some of this information is available in almost every country and can be supplemented with satellite data, the question remains, are there enough data to justify a GIS? The principal value of the GIS is in processing and analyzing masses of data that have become overwhelming for manual handling. In determining the applicability of a GIS, an agency must decide if it is data handling or merely the lack of data that is the main obstacle to hazard management.

B. Use of Geographic Information Systems in Natural Hazard Assessments and Integrated Development Planning

GIS applications in natural hazard management and development planning are limited only by the amount of information available and by the imagination of the analyst. Readily available information on natural events (e.g., previous disaster records), scientific research (papers, articles, newsletters, etc.), and hazard mapping (seismic fault and volcano location, floodplains, erosion patterns, etc.) are usually enough to conduct a GIS preliminary evaluation of the natural hazard situation and guide development planning activities. (See Chapters 4 through 12 and Appendix A for sources of information.)

At the national level, GIS can be used to provide general familiarization with the study area, giving the planner a reference to the overall hazard situation and helping to identify areas that need further studies to assess the effect of natural hazards on natural resource management and development potential. Similarly, GIS can be used in hazard assessments at the subnational level for resource analysis and project identification. At the local level, planners can use a GIS to formulate investment projects and establish specific mitigation strategies for disaster prevention activities. The following examples of OAS applications are intended to demonstrate the versatility of the tool and suggest to planners applications that may fit their agencies' needs.

GIS APPLICATIONS AT A NATIONAL LEVEL

Sector Vulnerability Assessment

The managers of public and private sectoral agencies share a concern about the vulnerability of their sectors to hazardous events: Where are the weak links? Where might damage occur? What is the impact of losing x service in y city for z days? What mitigation investment would resolve that problem? What is the cost-benefit of that investment? As an example, in 1989 the Costa Rica Sectoral Energy Directorate (DSE) requested OAS to assist in the analysis of the vulnerability of the energy sector to natural hazards. The study was conducted using two approaches: (1) field examinations and/or interviews with energy sector personnel; and (2) use of a GIS to overlay energy subsector infrastructure information with selected hazard data.

The GIS exercise, confirmed by results obtained by field observations, clearly showed the potential disruption of important segments of main transmission lines by landslides, and pointed out critical areas where mitigation or hazard reduction activities should be undertaken (see Figure 1-5). Although GIS analyses were not done for all hazards and sub-sectors, it became obvious that the outcome would have been virtually the same as the field examination's results for coarse-grained hazards such as earthquakes, hurricanes, and droughts, but less accurate for fine-grained hazards such as flooding in narrow river valleys. It was believed that if hazard data had been available at a 1:50,000 scale, the GIS would have given the same results for all hazards (although additional time would have been required to input the data).

While not intended to supplant field observations, the GIS approach had nevertheless some striking advantages in technician time, especially for this case in which only existing information was used. In addition, the GIS also provided full color maps showing the potential impact of landslide events on the electricity sub-sector, which were very useful in explaining the results and mobilizing follow-up action.

1. GIS APPLICATIONS AT THE NATIONAL LEVEL

Use of a GIS to combine information on natural hazards, natural resources, population, and infrastructure can help planners identify less hazard-prone areas most apt for development activities, areas where further hazard evaluations are required, and areas where mitigation strategies should be prioritized. A seismic hazard map for example, even at this level, can give planners the location and extent of areas where heavy capital investments should be avoided and/or areas where activities less susceptible to earthquakes, tsunamis, or volcanoes should be considered.

Similarly, in hazard-prone areas, use of a GIS to overlay hazard information with socio-economic or infrastructure data can reveal the number of people or type of infrastructure at risk. This sort of exercise was done in 1989 by OAS/DRDE, for several OAS member states. It was shown, for example, that in Peru more than 15 million people were living in earthquake-prone areas with a seismic intensity potential of VI or greater, that close to 930,000 people were potentially at risk of a tsunami wave height of 5 meters or more, and that 650,000 people were living within a 30 km radius of active volcanoes. Overlaid with infrastructure information, this same kind of analysis identified lifelines or vital resources in high-risk areas, and with adequate sectoral information, it can be further expanded to calculate potential losses in capital investment, employment, income stream, and foreign exchange earnings.

Little time was necessary to produce the maps: two days were required to code, digitize, and edit the maps, and only minutes were necessary to do the analysis. Moreover, with the information in the system, additional requests or changes in parameters (e.g., a 40 instead of a 30 km radius around a volcano) can be processed in a few minutes, while an entirely new set of drawings and calculations would be required if manual techniques were used. Figure 5-2 gives some examples of applications of GIS at the national and subnational levels.

2. GIS APPLICATIONS AT THE SUBNATIONAL LEVEL

At a subnational level of planning, GIS technology can be used for natural hazard assessments to show where hazardous natural phenomena are likely to occur. This, combined with information on natural resources, population, and infrastructure, can enable planners to assess the risk posed by natural hazards and to identify critical elements in high-risk areas. This information can then be used to formulate less-vulnerable development activities and/or mitigation strategies to lessen vulnerability to acceptable levels.

Figure 5-2

EXAMPLES OF GIS APPLICATIONS FOR NATURAL HAZARD MANAGEMENT AT THE NATIONAL AND SUBNATIONAL LEVEL OF PLANNING

FUNCTION	POTENTIAL APPLICATIONS	EXAMPLES
Assessment	Information source, data display	Considering land form, slope, land use, vegetation cover, and wind direction, what area is likely to be affected if this volcano erupts? How many people could be affected?
	Index of information	List all available hospitals located not within 30 km radius of the volcano
	Status reporting	Periodic assessment of volcanic activity
	Monitoring change	How has the savanna desert boundary changed in the last 5 years? What changes in climate and land use could account for the on-going desertification process?
Analysis	Research support	What factors determine landslide activity in this area? According to these factors, what zones are susceptible to landslides?
	Forecasting	What population centers are likely to be affected by this hurricane? What is the most likely lava flow path in case a volcanic eruption occurs?
	Policy development	What areas in this growing urban region should be restricted to low-density development?
	Aid allocation	Where should mitigation strategies be prioritized?
	Project evaluation	If erosion trends continue, what will be the economic impact on the project? What are the costs and benefits of instituting or not instituting erosion control measures?

Source: Adapted from United Nations Environmental Program (UNEP). GRID (1985).

GIS APPLICATIONS AT A SUBNATIONAL LEVEL

Urban Expansion in an Area Prone to Landslides

Tegucigalpa, capital of Honduras, is a hilly city on geologically unstable ground, constantly suffering damaging landslides. In 1987, an OAS/DRDE study identified more than 300 landslides occupying an area of approximately 1,350 ha within the metropolitan area and determined that 20 percent of that area presented high to extreme landslide hazard susceptibility. The situation has since been aggravated by increasing rural migration, frequently occupying steep areas of questionable stability. City officials had two urgent tasks: identify landslide-hazard free urban expansion areas for new settlement and resettlement programs, and delineate priority areas where hazard mitigation should be considered.

By entering data on land use, landslide hazard susceptibility, topography, slope, and protected areas, a GIS database was created to identify areas potentially suitable for expansion. City officials could then set minimum criteria for areas of new development (i.e., no more than 5 percent of the area can be subject to landslide hazard, no access road can be located within 1000 ft. of a 20 percent slope, etc.). Using the GIS, areas meeting the criteria could be identified. The number of people living in extreme and high landslide hazard areas could also be determined, providing the basis for selecting priority areas for implementing prevention measures (relocation, construction, retrofitting, etc.).

For this exercise, the advantages of using GIS as compared to manual mapping techniques are obvious. Not only does GIS afford great time savings (for the overlay, display, assessment, and analysis of hazardous areas), but GIS also offers flexibility in selecting the minimum standards. Tentatively selected standards can be tested for feasibility and adjusted. Using a GIS, this process would take minutes, while with manual methods, it would take a week of redrafting and recalculations.

In a landslide study for example, data on slope steepness, rock composition, hydrology, and other factors can be combined with data on past landslides to determine the conditions under which landslides are likely to occur (see Chapter 10). To analyze all possible combinations with manual techniques is a virtually impossible task; thus, typically only two factors are analyzed, and the composite units are combined with the landslide inventory map. With GIS, however, it is possible to analyze an almost unlimited number of factors associated with historical events and present conditions, including present land use, presence of infrastructure, etc. OAS/DRDE has used this technology to overlay maps of geology, slope steepness, slope orientation, hydrology, and vegetation, and then overlaid the results with a landslide inventory map to identify the factors associated with past and present landslides. The resultant landslide hazard zonation map provides planners with a designation of the degree of landslide propensity for any given area.

For floods, GIS and remotely-sensed data can be used to identify flood-prone areas, map floods in progress, delineate past floods, and predict future ones (see Chapters 4 and 8). GIS can combine information on slope, precipitation regimes, and river carrying capacity to model flood levels. Synthesis information obtained from such an integrated study can help planners and decision-makers determine where to construct a dam or reservoir in order to control flooding.

Likewise, a map depicting volcano locations may be entered into the GIS; volcano attributes such as periodicity, explosivity index (VEI), past effects, and other attributes may be ascribed to each volcano record in a relational database. Combining these data with information on human settlements or population density, land use, slope, presence of natural barriers, and other natural resource or socio economic data, the GIS can generate maps and/or tabular reports depicting hazard-free areas (e.g., areas outside a certain radius or impact area of an active volcano, areas with less than 25% slope and high vegetation cover, etc.). Finally, information on other hazards can be combined to create new sub-sets of data, each one complying with different pre-established minimum standards for development.

3. GIS APPLICATIONS AT THE LOCAL LEVEL

At this level, GIS can be used in prefeasibility and feasibility sectoral project studies and natural resource management activities to help planners identify specific mitigation measures for high-risk investment projects and locate vulnerable critical facilities for the implementation of emergency preparedness and

GIS APPLICATIONS AT THE LOCAL LEVEL

Farmer Settlement and Resettlement Planning in an Erosion Vulnerable Area

Land settlement projects commonly involve multiple and complex objectives. When equitable distribution of land is defined in terms of earning capacity instead of parcel size, land capability and management practices have to be factored into the equation. If natural hazards are also considered, as they must be if the project is to be sustainable and equitable in the long term, the number of factors becomes too unwieldy for manual analysis. In 1985, an OAS study prepared GIS data files for the Mabouya Valley Project, located in east-central Saint Lucia. The project, which involved settling a large number of farmers on former plantation land subject to erosion, sought to identify current land uses in conflict with land capability and/or erosion risks in order to improve the management of some parcels, resettle remaining farmers on redesigned parcels, and improve the equity of land distribution.

Eight maps were coded into the system: Ecology, Human Settlements, Land Capability, Life Zones, Water Resources, Erosion Risk, Present Land Use and Vegetation, and a proposed development strategy. Three synthesis maps were produced by overlaying present land use with land capability, present land use with erosion risk, and the development strategy with erosion risk.

The GIS exercise showed that large commercial parcels occupied 76 percent of all the lands suitable for unrestricted or moderately restricted cultivation, while 99 percent of the land occupied by small farms was classified as severely restricted or worse. When compared with severe erosion hazard, the synthesis maps showed that 2% of the area devoted to commercial agriculture vs. 30 percent of the area of the small mixed farms was affected.

This modest GIS exercise, using readily available information, constituted a tiny fraction of the overall study, yet it demonstrated clearly that land redistribution would be required to achieve the project's objective of equitable distribution, and provided the data required to guide the redistribution and to introduce improved soil management practices.

response activities. In population centers, for example, large scale GIS databases (resolutions of 100 m^2 per cell or less) can display the location of high-rise buildings, hospitals, police stations, shelters, fire stations, and other lifeline elements. By combining these data with the hazards assessment map--previously collected or generated through GIS--planners can identify critical resources in high-risk areas and adequately formulate mitigation strategies. (See Figure 5-3).

The decision on the type of information to be used for depicting the variables included in the database--whether real-scaled or symbolic dimensions--becomes a critical decision at this level. Real-scaled data should prevail over symbolic information, especially at this level of planning, when precise information is required to assess the risk posed to specific investment projects. Floodplain elevations, for example, represented in scales smaller than 1:50,000, will show only approximate location. Any GIS calculations or operations that include cell measurements (area, perimeter, distance, etc.) need to be accurate enough to provide planners with a clear and precise illustration of the overall and project-to specific hazard situation of the study area. Floodplain hazard assessments combine thematic maps (e.g., soils, geology, topography, population, infrastructure, etc.) and need a precise cell representation of floodplain elevation in order to indicate where the probable flood areas are and what are the probable population, natural resource and infrastructure components that might be affected by a flood event. Figure 5-4 gives examples of GIS applications undertaken by the OAS/DRDE.

4. USE OF A GEO-REFERENCED DATABASE

A geo-referenced database (GRDB) is a microcomputer-based program that combines data management with map display, allowing planners and emergency managers to graphically display hazard impact areas, and relate them to people and property at risk. Although a GRDB also uses points, lines, and polygonal symbols to represent data, it differs from a GIS in that it does not have overlaying capabilities. However, GRDB's ability to manage and combine large databases with map display, text relating

Figure 5-3

EXAMPLES OF GIS APPLICATIONS FOR NATURAL HAZARDS MANAGEMENT AT THE LOCAL LEVEL OF PLANNING

FUNCTION	POTENTIAL APPLICATIONS	EXAMPLES
Data display	- Aid in the analysis of spatial distribution of socio-economic infrastructure and natural hazard phenomena - Use of thematic maps to enhance reports and/or presentations - Link with other databases for more specific information	- What lifeline elements lie in high-risk areas? - What population could be affected? - Where are the closest hospitals or relief centers in case of an event?
Land Information Storage and Retrieval	- Filing, maintaining, and updating land-related data (land ownership, previous records of natural events, permissible uses, etc.)	- Display all parcels that have had flood problems in the past - Display all non-conforming uses in this residential area
Zone and District Management	- Maintain and update district maps, such as zoning maps or floodplain maps - Determine and enforce adequate land-use regulation and building codes	- List the names of all parcel owners of areas within 30 m of a river or fault line - What parcels lie in high and extreme landslide hazard areas?
Site Selection	- Identification of potential sites for particular uses	- Where are the hazard-free vacant parcels of at least x ha lying at least y m from a major road, which have at least z bed-hospitals within 10 km radius?
Hazard Impact Assessment	- Identification of geographically determined hazard impacts	- What units of this residential area will be affected by a 20-year flood?
Development/ Land Suitability Modelling	- Analysis of the suitability of particular parcels for development	- Considering slope, soil type, altitude, drainage, and proximity to development, what areas are more likely to be prioritized for development? What potential problems could arise?

Source: Adapted from Levine J., and Landis, J. "Geographic Information Systems for Local Planning" in Journal of the American Planning Association (Spring, 1989), pp. 209-220.

Figure 5-5

ORGANIZATION OF AMERICAN STATES/DEPARTMENT OF REGIONAL DEVELOPMENT AND ENVIRONMENT EXAMPLES OF APPLICATIONS OF GIS IN HAZARD ASSESSMENT AND DEVELOPMENT PLANNING

LOCATION	SCALE	OBJECTIVES	DATA USED	RESULTS
Colombia Puerto Bogotá, Department of Cundinamarca	1:3,000 (16.81 m^2 per cell)	Identification of hazard-free urban areas suitable for the relocation of 34 families presently under high landslide risk.	- Base map - Urban perimeter map - Urban census map - Geologic map - Natural hazards map - Risk zones map - Land use information - Population density	Identification of possible relocation sites for 34 families. Sites in question had to comply with the following requirements: not in hazardous zone, 100 m. away from the river, within urban limits, and in unoccupied areas or with low population density.
Ecuador: Agricultural Sector Vulnerability Study	1:2,000,000 (1 km^2 per cell)	Determination of the vulnerability of the agricultural sector in terms of income, employment, foreign exchange earnings, and food security. Identification of possible mitigation strategies.	- Political map - Road network and storage facilities map - Flood, erosion, drought, landslide, seismic, and volcanic hazard map - Crop producing areas (26 cultivation systems) - Socio-economic data	49 possible critical events selected for further study and/or profile level mitigation strategy formulation. Follow-up institutional support delineated.
Honduras: Jesús de Otoro Valley, Department of Intibuca	1:50,000 (2.08 ha per cell)	Identification of flood- and erosion-prone areas for the selection of agricultural production projects.	- Present land use - Projected land use - Soils - Human settlements - Floodplains	66 percent of the land presently occupied or planned for irrigated agriculture investment was found to be in flood-susceptible areas.
Paraguay: Southwestern section of the Paraguayan Chaco	1:500,000 (208 ha per cell)	Identification of hazardous areas for landuse capability definition and agricultural project selection.	- Soils map - Forest tipology - Alternative forest uses - Agricultural zones - Landuse capability	Identification and quantification of areas under varying degrees of limitations or restrictions in areas previously recognized as best suited for their respective production activity.
Saint Lucia Mabouya Valley Project	1:10,000 (2.1 ha per cell)	Identification of current and proposed land uses in conflict with land capabilities and/or erosion risks; selection and distribution of farming resettlement sites.	- Human settlements - Land capability - Present land use - Erosion risk - Water resources - Life zones - Ecology - Development strategy	99 percent of the land occupied by small farms was classified as severely restricted or unsuited for cultivation. 2 percent of the land for commercial agriculture vs. 30 percent of the land for small farms was affected by severe or critical erosion hazard.

USING A GEO-REFERENCED DATABASE IN THE AFTERMATH OF A DISASTER

After a disaster, quick response in analyzing the situation and formulating a workable rehabilitation program is essential. In 1988, after Hurricane Gilbert struck Jamaica, the Government was faced with the overwhelming task of allocating a great variety of relief resources to agencies and population, and of coordinating the rehabilitation effort among all the institutions and agencies involved. At the Government's request, the OAS helped to install a geo-referenced database system to organize the compilation and analysis of damage assessment records which would then be used to help manage rehabilitation and reconstruction efforts.

Initial configuration of the system consisted of eight computer maps, ranging from 1:1 million (entire country) to 1:44,000 (enlarged Kingston area) scale maps, with main road network and individual records for each town and settlement. It took a team of three people four days to build the database and train its users. The system was put into service immediately, providing the basis for coordination among all the agencies participating in the emergency relief program.

Afterward, the system was expanded to include critical facilities location (health centers, shelters, police, fire) and lifeline networks (water and electricity) for the Kingston area. With assistance from the United Nations Development Programme (UNDP), eleven more systems were installed in key government departments directly involved in relief distribution and reconstruction. Direct phone and radio links were also installed between all systems to allow easy consultation and information interchange. Since then the base map has expanded to more than 130 maps covering the entire country at a scale of 1:50,000, with larger scales for population centers and key economic zones.

Although it will take some time to quantify the benefits of this system, it is clear that Jamaica now possesses a powerful information system which can be used not only as a decision-support system for emergency management offices, but also as a planning tool that can assist government agencies to better plan and coordinate development planning and emergency preparedness and response activities.

displayed elements (hazard impact areas, location of shelters, health centers, fire stations, police stations, etc.) to their respective descriptive information, makes it suitable for emergency planning and post-disaster rehabilitation and reconstruction work.

Through a GRDB, information can be accessed for data update and utilization by all involved agencies. In this way, emergency management offices can have almost immediate access to an updated inventory of settlements, lifelines, hazard impact areas, and special emergency needs, facilitating inventory and deployment of emergency resources; sectoral ministries and utility companies can prepare more effective plans and projects by having access to updated population and infrastructure data; and central planning agencies can use the system as a tool for reconstruction planning coordination.

This kind of system was used in Jamaica after Hurricane Gilbert as a mechanism for coordinating disaster relief (see box above), and in Costa Rica, the Ministry of Natural Resources and Mines requested the OAS to provide a GRDB to monitor the vulnerability of the country's energy infrastructure to natural events. Although there are clear benefits in using a GRDB in emergency management, its transformation as a tool in development planning will need time, cooperation, and support from all agencies involved.

C. Guidelines for Preparing a GIS

Benefits of a GIS may be so compelling that the decision to acquire a system can be made with little hesitation. In most cases, however, the decision can only be reached after a thorough analysis. The following section introduces a systematic process for reaching a decision about acquiring a GIS. Potential users must remember that a GIS is not always the right tool for a given situation, and it may not necessarily pay for itself.

1. CONDUCT A NEEDS ASSESSMENT, DEFINE PROPOSED APPLICATIONS AND OBJECTIVES

Before deciding to acquire or use a system, planners need to make a meticulous evaluation of their GIS needs. This must include a definition of how their planning activities and decisions will be assisted by using a GIS. Specific objectives and applications of the GIS should be defined. Answers to the questions outlined in the box below can help.

QUESTIONS PLANNERS NEED TO FORMULATE TO ASSESS THE NEED OF A GIS

- What planning decisions need to be made?
- Which decisions involve the use of mapped information and information susceptible to map display?
- What information cannot be managed efficiently with manual techniques?
- What information management activities will be supported by the proposed GIS?
- What are the number and types of decisions that will be supported with a GIS?
- Is the GIS principally for analysis? Is cartographic quality output needed?
- To what extent will a GIS help achieve the desired objectives?
- Who will be the users of the information generated with a GIS? How many user groups will there be?
- In terms of information, time, and training needs, what is required to obtain the desired results? Is there budget and staff suport?
- What agencies are participating in similar projects?
- To what extent would a GIS help to attract the interest of other agencies and facilitate cooperation?

QUESTIONS THAT HELP IN EVALUATING THE SUITABILITY OF AN AVAILABLE GIS

- What kind of system is it?
- What hardware and software are used?
- Are its capabilities compatible with the needs of the new users?
- Is the in-house technical expertise capable of serving the new users?
- What are the institutional arrangements that would allow the use of this GIS?
- Who are the current users? To what extent is the current user network compatible with the network envisioned?
- What data does it contain? To what extent does the data presently in the system cover identified needs?

If this preliminary investigation indicates that obtaining and using a GIS is a good option for an agency, it should seek the most cost-effective method of doing so. A frequently neglected option is to determine if an existing system is available. If the existing GIS is underutilized, the current owner might find a time-share offer attractive, particularly if the new agency brings data and analyses to the partnership. If no suitable GIS exists, another alternative is for a group of agencies to establish a GIS that meets their common needs. Obviously, the trade-off in both these options is lower cost vs. independence of action, but if the partnership also brings improved working relationships and compatible data to a group of agencies that work on common problems, these benefits may exceed the independence cost. The questions in the box above offer planners some guidance as to whether an existing system is suitable to their needs.

Another opportunity for reducing investment cost is the use of existing equipment. If a computer is

KEY ELEMENTS NEEDED WHEN PLANNING A GIS ACQUISITION

COST CALCULATIONS:

- What is the software purchase cost?
- What hardware configuration is needed to fit the software requirements?
- Is a new computer needed? What options have to be included? What is the cost of acquiring a new computer versus upgrading an existing one?
- What are the anticipated hardware repair and maintenance, and software support costs?
- What are the personnel requirements for the installation and operation of a GIS?
- Will existing personnel be used or will new personnel have to be hired? Is a computer programmer needed?
- What training costs are anticipated?
- What is the cost of allocating personnel to hardware and software maintenance?
- What is the expected cost for the data input process? How many staff need to be hired or assigned to digitize the information?
- What is the cost involved in maintaining the data generated for and by the system?
- Is a secure facility available suitably equipped for protection of computers and data files?

BENEFIT CALCULATIONS:

- What are the production or revenue losses mostly associated with lack of information? How does this compare with the information that would be available if a GIS were present?
- What are the costs savings from substituting labor-intensive drafting processes with a GIS?
- What are the benefits of integrating more timely information in the decision-making process, and of being able to perform sensitivity analysis on proposed development plan options?

available, is it compatible with the GIS envisioned? What are the economic and institutional costs of time-sharing and inconvenience?

Once an agency has reached tentative decisions to acquire GIS capability, alone or in partnership, it should undertake an economic analysis of the proposition.

2. EXECUTE AN ECONOMIC ANALYSIS FOR GIS ACQUISITION

Acquiring a GIS system is a capital investment that may represent several thousand U.S. dollars. As contended by Sullivan (1985), standard investment appraisal methods can be applicable to information technologies such as GIS. The questions in the box above will help planners to roughly estimate and compare the major cost and benefits associated with a GIS acquisition.

The cost of maintenance and repair of all components of a GIS must also be considered in the investment analysis. The more sophisticated the system, and the more remote the home base of operation, the higher its maintenance cost. Software demands maintenance too, and arrangements should be made to subscribe to effective support from the provider of the software. The hiring of expertise to modify the software according to the project should be expected. A GIS is a dynamic tool; there will always

be new data and new capabilities to be added, requiring additional efforts and expenses.

3. SELECT AMONG ALTERNATIVE SYSTEMS AND EQUIPMENT

When a new system must be established, planners must carefully select the appropriate hardware and software. The system should be simple and must, of course, fit the budget and the technical constraints of the agency. Large digitizers and plotters, which are capable of producing maps of cartographic quality, are expensive and difficult to maintain. Small equipment, which can be as effective as the larger models for map analysis, is becoming increasingly available at affordable prices. Figure 5-5 presents some of the criteria that should be considered in a GIS acquisition.

There are many GIS packages available, some more expensive and more powerful than others. Some cheaper softwares have good analytical capabilities, but lack computer graphics. Based on objectives, budget, and personnel constraints, planners should investigate the alternatives for GIS software with a simple interface, strong analytical and graphical capabilities, and an affordable price. Regardless of the selection, GIS software must be tested, and its claims must be verified against the needs of the user. As the software for GIS projects can cost more than the hardware it is designed to run on, the testing should be done on the hardware configuration to be used.

Figure 5-6 reviews most of the GIS software currently available. The systems are ranked by cost, and information is provided on type of operating system, type of output device supported (directly related to the kind of output maps produced, raster or vector), and other capabilities such as area measurement, statistical analysis, and geo-referenced overlaying.

4. ESTABLISH A DATABASE

Once the GIS has been acquired, an information system must be designed. Typically, first-time GIS users tend to put lots of seemingly appropriate data into the system, trying to develop some application immediately. Usually, systems designed on a data-supply rather than on a information-demand basis result in a disarray of data files and a chaotic and inefficient database.

A systematic approach to building an efficient and practical database includes i) a careful determination of users' needs, defining intended applications of the needs, and, if possible, iii) a design evaluation and/or testing in a pilot study (see the GIS design procedure outlined in Figure 5-7).

a. Determination of Proposed Applications of the System

Small planning agencies or specific hazard mitigation projects may need a simple analysis of what has worked elsewhere to define what the GIS will be used for and what products it is expected to produce. Large organizations or more comprehensive projects, however, need to develop a standard and systematic approach, usually requiring interviews with management, users, and existing system support staff. Answers to the questions below can orient planners in identifying potential applications.

b. Determination of Data Needs and Sources for the Applications Selected

Data on natural hazards, demographic data, and location of population, are the prime concern of natural hazards management and should be defined very early in the process. Infrastructure and settlement sites provide the logical links that make a GIS useful in identifying population locations. When this information is combined with recent data detailing

QUESTIONS THAT HELP PLANNERS IDENTIFY POTENTIAL GIS APPLICATIONS FOR HAZARDS MANAGEMENT

- What hazard management decisions will be made that could be improved by the use of a GIS?
- How will GIS help to identify the hazards that pose a significant threat and to evaluate the risk involved?
- How could GIS help determine mitigation measures for investment projects and lifeline network elements for disaster prevention activities?

Figure 5-5

CRITERIA TO BE CONSIDERED WHEN PLANNING FOR A GIS ACQUISITION

HARDWARE

a. CPU/System Unit

- Microprocessor
- Compatibility with standards
- Memory capacity (RAM)
- Disk drives
- Backup system
- Expansion capacity
- I/O channels
- Communication ports
- Warranty terms

b. Features and Peripherals

- Keyboards
- Monitors (terminals)
- Printers
- Power supply
- Networking capacity

SOFTWARE

a. System Software

- Compatibility with standards
- Capability
- Flexibility
- Expandability
- Special features
- Documentation

b. Utilities Software

- Ease of use
- Integration with total system
- Languages available
- Diagnostics
- Peripheral control

c. Applications Software

- Appropriateness to needs
- Performance (capacity, speed, flexibility)
- Interface capability
- Support
- Upgrade potential
- Documentation
- Training and other user services

COST

- Initial hardware price (CPU, monitor, printer, etc.)
- Additional components (peripherals, digitizers, adapters, etc.)
- Availability of duty-free components
- Maintenance agreement and other service
- Transportation/ delivery
- Installation
- Software price
- Updates/ upgradings
- Training

VENDOR SUPPORT

a. Maintenance

- Maintenance staff (size, experience)
- Existing customer base
- Service facilities
- Inventory of components
- Guaranteed response time
- Capacity to deal with entire system

b. Training

- Range of courses offered
- Staff experience
- Facilities
- Documentation/ aids

Source: Adapted from USAID, Information Resources Management. Guidelines for Managing Automation Assistance in AID Development Projects, Version 1 (1986).

Figure 5-6

GIS SOFTWARE REVIEW[a]

COST	OPERATING SYSTEM COMPATIBILITY: IBM (PC DOS)	UNIX SYSTEM	OTHER SYSTEMS	OUTPUT COMPATIBILITY: DOT MATRIX	PLOTTER	OTHER CAPABILITIES
LESS			IBIS(V)	IBIS	IBIS	A C G S
THAN		SAGIS		SAGIS	SAGIS	A C S
$500	OSU MAP			OSU MAP		A C S
	IDRISI			IDRISI		A G S
	Atlas Graphics				Atlas Graphics	A S
	EPPL7			EPPL7		A C G S
	GEOVISION			GEOVISION	GEOVISION	A C G
$500-	SOLIR				SOLIR	
$1,000	MapInfo				MapInfo	A
		GRASS		GRASS	GRASS	A C G S
	PMAP			PMAP	PMAP	A C G S
$1,000-	ETAK Geocoder	ETAK Geocoder			ETAK Geocoder	C
$10,000	MIPS			MIPS	MIPS	G S
	FMS/AC	FMS/AC			FMS/AC	A C G S
	Landtrak		Landtrak(V)	Landtrak	Landtrak	A C G
	GeoSight			GeoSight	GeoSight	G S
	Geopro			Geopro	Geopro	A C G S
	ILWIS			ILWIS	ILWIS	A C G S
	MOSS	MOSS	MOSS(AO, P)	MOSS	MOSS	A C G S
	MINUTP				MINUTP	C
	MAPLE	MAPLE		MAPLE	MAPLE	A C G S
			Mapgrafix(M)*		Mapgrafix	A G
	Matchmaker				Matchmaker	
MORE	TIM	TIM	TIM(X)		TIM	A G
THAN	SPANS	SPANS		SPANS	SPANS	A C G S
$10,000	TerraPak	TerraPak	TerraPak(P)		TerraPak	C G S
		System9	System9(SU)		System9	A C G S
	Geo-Graphics	Geo-Graphics	Geo-Graphics(V)		Geo-Graphics	A G S
		VIPERS		VIPERS		A C S
			Infocam(V)		Infocam	A C G S
			UltiMap(AE)	UltiMap	UltiMap	A C G S
		Accugraph			Accugraph	A C
		System600	System600(V)	System600	System600	A C S
		GeoVision GIS	GeoVision GIS(V)		GeoVision GIS	A C G
			KGIS(V)			
		DeltaMap		DeltaMap	DeltaMap	A C G S
	ERDAS	ERDAS	ERDAS(AV,P,V)	ERDAS		A G S
	ARC/INFO	ARC/INFO	ARC/INFO(AO,P,V,VC)	ARC/INFO	ARC/INFO	A C G S

— "OTHER SYSTEMS" KEY —

AE - AEGIS M - Mac OS V - VMS
AO - AOS P - PRIMOS VC - VM/CMS
AV - AOS VS SU - Sun OS X - XENIX

— "OTHER CAPABILITIES" KEY —

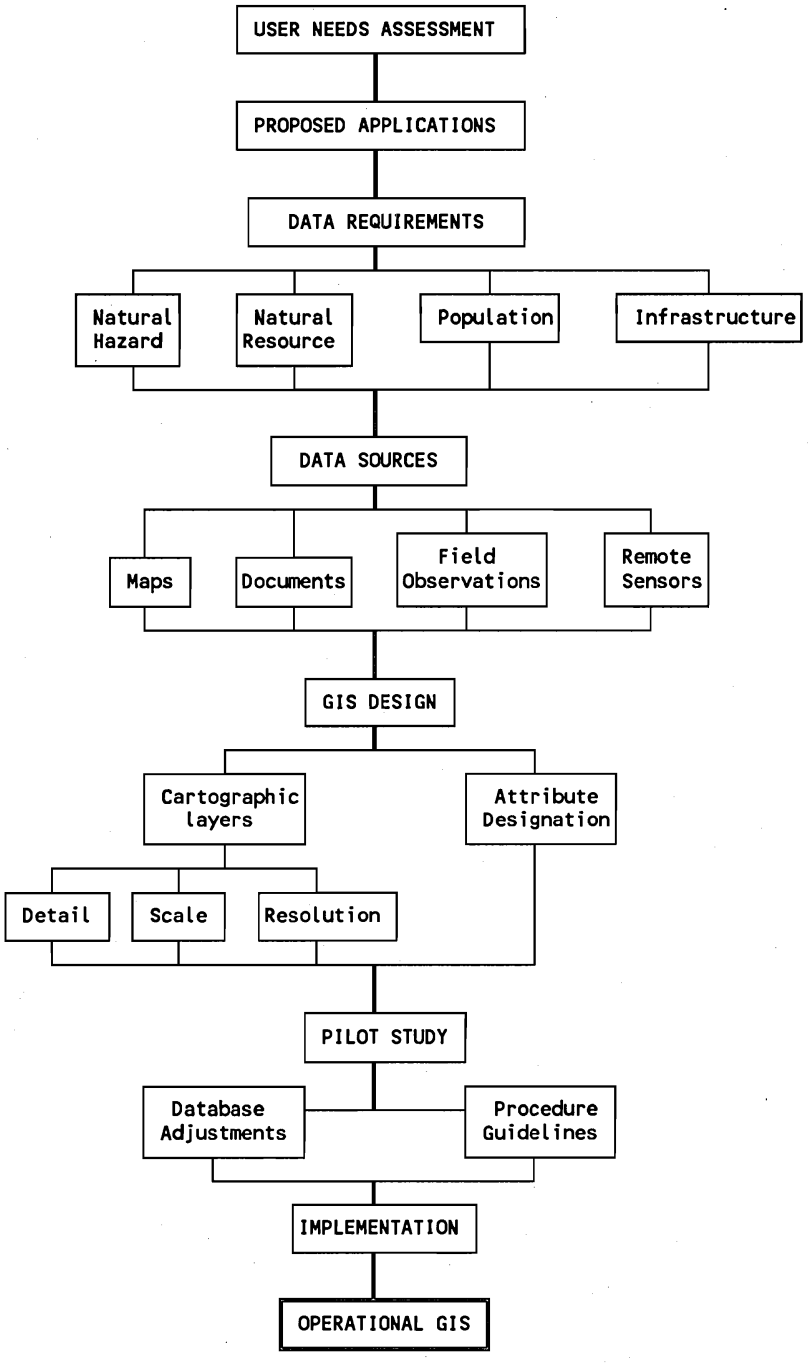
A - Area measurement
C - Command language user interface
G - Geo-referenced overlaying
S - Statistical analyses

[a] In each section software is listed in order of increasing cost.

Source: Adapted from "The 1988 GIS Software Survey" in GIS World, vol. 1, no. 1 (Fort Collins, Colorado: July, 1988).

Figure 5-7

GIS DESIGN PROCEDURE



Source: Adapted from Chambers, Don. "Overview of GIS Database Design" in GIS Trends, ARC News Spring 1989. (Redlands, California: Environmental Systems Research Institute, 1989).

changes in land use, a clear understanding of where the people are located and the kind of activities they are undertaking and how they may be affected by natural hazards can be obtained. With this information, disaster prevention and preparedness actions can be initiated.

Once the information requirements are identified, sources that will provide this information should be distinguished. Usually, a number of firsthand sources of information already exist, including maps and other documents (discussed in Appendix A), field observations, and remote sensors (discussed in Chapter 4). Figure 5-8 lists usually available natural hazard information that can be incorporated, into a GIS data file.

In concept, GIS programs should be developed to accept all kinds of data that will eventually be needed. Data may be available in the form of satellite images, weather satellite data, aerial photographs, generalized global or regional topographic or soils maps, or population distribution maps. Data such as these are sufficient to build an initial GIS. Once the framework is developed, new items can be added at any time.

c. Design of the Data Files

The next step is to design the cartographic layers to be entered into the system, and the spatial attributes to be assigned to them. In this regard, detail of the database, input scale, and resolution must be considered.

Cartographic layers are the different "maps" or "images" that will be read into the system and later overlaid and analyzed to generate synthesis information. For example, cartographic layers depicting past landslide events, geological characteristics, slope steepness, hydrology, and vegetation cover were entered and overlaid in a GIS to create a landslide hazard map, as described in Section B.

There are three basic types of layers, and many different possible combinations among them: polygons

Figure 5-8

NATURAL HAZARD INFORMATION TO BE USED IN A GIS

	BASELINE DATA	INTERMEDIATE THEMATIC INFORMATION	SYNTHESIS INFORMATION
EARTHQUAKE	Epicenters Fault lines Plate boundaries	Maximum recorded intensity, magnitude Frequency distribution and gap data	Seismic zoning (strong ground motion data, maximum expected intensity or magnitude, recurrence interval)
VOLCANO	Volcano location	Previous event impact History of eruptions	Potential affected area (ash, lava, pyroclastic flow, lahar)
HURRICANE	Landfall map Precipitation Wind Coastal infrastructure	Previous event impact Landfall frequency distribution	Design event (surge tide elevation and flood elevation
LANDSLIDE	Bedrock geology Slope Vegetation Precipitation	Previous event impact Landslide inventory	Hazard susceptibility
FLOOD	Precipitation Stream flow Floodplain boundaries	Previous event impact Maximum stream elevation	Design event (flood elevation and recurrence interval)
DESERTIFICATION	Soils Precipitation Evapotranspiration Biomass production Vegetation cover	Lifezones Aridity Erosion Population density Animal density Land use	Hazard zonation

(floodplains, landslide hazard areas), lines (fault lines, rivers, electrical networks), and points (epicenters, well locations, hydroelectric facilities). Selection of the correct layer type for a database depends on anticipated uses and on the scale and resolution of the source data. A volcano, for example, may be represented as a point at 1:250,000 scale, but it could well be a polygon at 1:20,000. Similarly, flood-prone areas may be represented as lines bordering rivers at scales smaller than 1:50,000, but as polygons on 1:10,000 scale maps. Planners must keep in mind that point and line representations may well be used for depicting variable locations, but they are seldom used for GIS operations involving cell measurement.

Spatial attributes are identifiable characteristics of the resource information assembled for the GIS. For example, attributes considered for infrastructure can include roads, bridges, dams, etc. For land use, the different land-use map units can identify the attributes. All GIS input data are filed as attributes and can be recovered as individual items or aggregated into groups.

A soils map provides a good illustration of attribute designation. One attribute in the soils "layer" of data would be sand. All occurrences of sand would be located on the map. Once the attribute has been recorded, relevant descriptive material from the accompanying text should be included in the database, not just the legend. This greatly expands the usefulness of the information available to planners.

This same procedure, when used to prepare data for more than one point in time, provides the user with the information needed to measure changes over time. The most frequent failure of time sequence data is due to the lack of details on the description of the attribute for the different time periods. Thus, it is important to include that information in text form within the GIS system.

Many attributes in some of the well known and frequently used mapped information sources can provide ample information for hazard management in the typical GIS. Six particularly useful sources are:

- land-use and soil surveys
- climatic data
- location of volcanoes, landslide areas, and major geological faults
- natural features (rivers, floodplains)
- human features (infrastructure, population), and
- topographic information (which provides elevation data, terrain complexity, and watershed information)

Natural hazard management decisions based only on the above six sources of data can serve the GIS requirements in many situations. As an example, soils information can provide saturation and runoff characteristics; topography provides watershed area and topographic relief, and combined with soils data can help to identify floodplains; climatic records are particularly useful when combined with run-off characteristics from the soils survey to provide information on flooding and erosion; and lifezone maps are useful in assessing desertification hazards. The number of people located on a floodplain, what urban support centers exist, the location of roads, airports, rail systems, etc., can all be put into the system and analyzed in map form. This information is also useful in the preparation of emergency response plans.

The correct combination of attributes for particular decisions based on a GIS may call for a surprisingly small number of data input sources. Almost all natural hazard situations will be strongly influenced by one or two combined features. Mud slides, for example, usually occur in areas having steep terrain and soils high in clay content. New volcanic eruptions are most likely to occur in areas of historically high seismic activity. Planners or GIS users must understand that the purpose of a GIS is not to procure and incorporate all possible data. That is costly, time consuming, and provides users with an over abundance of mapped data that can be counterproductive. What is important is the acquisition of an appropriate amount of data that provides the necessary information for rapid, effective decision-making for natural hazard management.

Too much detail may unnecessarily add to the cost of the GIS. If a data source is detailed beyond the point of usefulness, then generalized data should be used. If, for example, topographic data are mapped at 5m contours, but some basic decisions will be reached using 50m contours, then input and retrieval of topographic complexity can be reduced by a factor of ten. Careful study of the classification systems of the input data, combined with analysis of critical points of differentiation in the physical data sources can reduce the volume of data input without affecting the utility of the analysis.

Detail of the database must be directly correlated with the planning team's needs and it should be dynamic in nature. A planning team assigned to assess vulnerability to natural hazards could begin by looking at hazards at the national level, then shifting to more detailed studies in local areas of high risk. On the other hand, if an area is selected for regional development planning, the study of hazards can begin at the regional or local level. For example, if the development study is concerned with the transportation sector of a city and the area suffers

frequent losses to landslides, the database established should obviously reflect this issue.

Regarding scale, planners or GIS users can take advantage of the flexibility some GIS offer by entering data at various scales and later requesting the system to adjust the scale to fit the particular purpose or stage of planning: small to medium scales for resource inventory and project identification; medium scales for project profiles and pre feasibility studies; and large scales for feasibility studies, hazard zone mapping, and urban hazard mitigation studies.

Resolution or spatial accuracy of the database will be reflected in the number of cells (columns and rows or Xs and Ys) making up the database. The greater the number of cells used to cover a given area, the higher the resolution obtained. However, high resolution is not always necessary, and the tradeoff between what is gained in terms of analytical capacity and what is lost in terms of consumption of computer's memory and input time must be considered. The type of graphic adaptor, the size of computer's memory, and the user's preference as to whether a full or partitioned screen should be used, are determining factors in this respect.

Finally, the design of the database should be tested for performance. Following a pilot test, it is not uncommon to obtain a sizable set of database design rectifications. Guidelines are usually not only directed at the spatial accuracy of data and layer design, but also at the identification of possible obstacles for final system implementation, and the development of procedures or a methodology for performing tasks under normal operational conditions.

Conclusions

The wide array of GIS applications presented in this chapter illustrates the value of GIS as a tool for natural hazards management and development planning. As demonstrated, geographic information systems can improve the quality and power of analysis of natural hazard assessments, guide development activities, and assist planners in the selection of mitigation measures and in the implementation of emergency preparedness and response actions.

As enticing as GIS may look, it is not a suitable tool for all planning applications. Much of the benefit of such an automated system lie, in the ability to perform repeated spatial calculations. Therefore, before making the decision to acquire a GIS, planners need to determine what planning activities could be supported with the system and carefully assess if the amount of spatial calculations and analysis to be performed justifies automating the process. If only a few calculations are foreseen, it will probably be more cost-effective to rely on local draftsmen to draw and overlay maps and calculate the results.

PC-based GIS are the best option for a planning team. Even so, planners will have to select between scores of available hardware configurations and software capabilities, prices, and compatibilities. Given the typical financial and technical constraints that prevail in Latin America and the Caribbean, the hardware configuration must be simple and affordable. For IBM-compatible systems, for example, a standard central processing unit (CPU), a high-resolution monitor, a small digitizer, and an optional color printer are usually effective enough for a development planning agency's needs, and can be easily purchased at affordable prices in most countries of the region. Large and sophisticated equipment requires more technical skills, is difficult to maintain and repair locally, and the added capabilities may not be significant for the planning agency's needs.

Similarly, there are many GIS software packages to choose from and, accordingly, a wide variety of capabilities and prices are available. Usually the more expensive the software, the more powerful the analytical capability and sophisticated the output options. However, added capability, particularly in the area of cartographic quality output, is not always necessary, and may not pay for itself. Prices range from one hundred to more than fifty thousand U.S. dollars. Although inexpensive systems lack certain features present in more expensive ones, they have functional capabilities sufficient to meet the basic analysis needs of natural hazard management activities. It is wise to start with some of these modest systems and later expand them according to the agency's needs.

Other aspects that should be considered are data availability and institutional support. For a GIS to be effective as a planning tool, any problems and difficulties in obtaining data from institutions with different mandates and interests must be resolved. A good understanding for sharing information between the different agencies involved in collecting, generating, and using data must be established to insure the dynamic nature of a GIS.

One last issue planners will have to face is the difficulty they will encounter in implementing GIS results. When it comes to translating GIS results into planning guidelines or mandates, it is not uncommon to see them rejected for political, economical, or other reasons. This may become more complicated at the local level. When local data needs are generalized and included in a GIS for a larger area, conflicts due to people's detailed knowledge of the area may arise.

Natural hazard management requires cooperation at all levels to be successful. Convincing local staff and decision makers that the GIS can provide timely, cost effective, and correct information is a critical step that needs support and attention for every program addressing natural hazard management issues.

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CHAPTER 6

MULTIPLE HAZARD MAPPING

CHAPTER 6

MULTIPLE HAZARD MAPPING

Contents

List of Figures

MULTIPLE HAZARD MAPPING

SUMMARY

This chapter presents the concept of multiple hazard mapping, describes the benefits of using multiple hazard maps relative to individual hazard maps, and explains the preparation and use of such maps.

When an area is exposed to more than one hazard, a multiple hazard map (MHM) helps the planning team to analyze all of them for vulnerability and risk. By facilitating the interpretation of hazard information, it increases the likelihood that the information will be used in the decision-making process. In either the planning of new development projects or the incorporation of hazard reduction techniques into existing developments, the MHM can play a role of great value.

In this chapter, the MHM discussed is primarily for use in an integrated development planning study.

A. Benefits of Multiple Hazard Mapping

The main purpose of MHM is to gather together in one map the different hazard-related information for a study area to convey a composite picture of the natural hazards of varying magnitude, frequency, and area of effect. A MHM may also be referred to as a "composite," "synthesized," and "overlay" hazard map. One area may suffer the presence of a number of natural hazards. (Figure 6-1 is a tabulation of natural phenomena that can be considered for presentation on such maps). Using individual maps to convey information on each hazard can be cumbersome and confusing for planners and decision-makers because of their number and their possible differences in area covered, scales, and detail.

Many natural hazards can be caused by the same natural event. The inducing or triggering mechanism which can interconnect several hazards can more easily be seen through the use of a MHM. Characteristics of the natural phenomenon and its trigger mechanisms are synthesized from different sources and placed on a single map.

Additionally, the effects and impact of a single hazard event, as in the case of volcanoes and earthquakes, include different types of impacts, each having different severities and each affecting different locations.

The MHM is an excellent tool to create an awareness in mitigating multiple hazards. It becomes a comprehensive analytical tool for assessing vulnerability and risk, especially when combined with the mapping of critical facilities as discussed in Chapter 7.

The adoption of a multiple hazard mitigation strategy also has several implications in emergency preparedness planning. For example, it provides a more equitable basis for allocating disaster planning funds; stimulates the use of more efficient, integrated emergency preparedness response and recovery procedures; and promotes the creation of cooperative agreements to involve all relevant agencies and interested groups. It must be emphasized that the MHM will not meet the site-specific and hazard-specific needs of project engineering design activities.

The effective use of natural hazard information to avoid damage or to reduce loss requires a considerable effort on the part of both the producers and the users of the information. Unless the scientific and engineering information is translated for the layman, the effective user community is limited to other scientists and engineers. If the users do not become proficient in interpreting and applying technical information, the information is likely to be misused or even neglected in the development planning process. Studies by Kockelman (1975, 1976, 1979) on the use of earth-science information by city, county, and regional planners and decision-makers in the San Francisco Bay region of the United States show that the most effective use of hazard information is achieved when maps clearly depict the likelihood of occurrence, location, and severity. Furthermore,

Figure 6-1

EXAMPLES OF NATURAL PHENOMENA WHICH MAY BE HAZARDOUS

Atmospheric	**Hydrologic**	**Seismic**
Hailstorms	Coastal flooding	Fault ruptures
Hurricanes	Desertification	Ground shaking
Lightning	Drought	Lateral spreading
Thunderstorms	Erosion	Liquefaction
Tornadoes	River floods	Seiches
Tropical storms	Storm surges	Tsunamis
Volcanic	**Other Geologic**	**Wildfire**
Ashfalls	Debris avalanches	Brush
Gases	Expansive soils	Forest
Lava flows	Rockfalls	Savannah
Projectiles and lateral blasts	Submarine slides	Urban conflagration
Pyroclastic flows	Subsidence	
Tephra (ashes, cinders, lapilli)		

hazard reduction was more likely when agencies had scientists or engineers on their staffs. Their skills permitted a broader use of the technical information, and the agencies were able to make interpretations of the information for their own purposes.

B. Preparing Multiple Hazard Maps

A prerequisite to compiling individual hazards information onto one map is obtaining or creating a base map upon which to place this information. Characteristics and examples of such base maps are discussed in the next section, on map format. The base map is usually selected during the preliminary mission; the team needs only to select a scale appropriate to the study area. This initial map also may serve as an index to more detailed hazard maps. Several base maps at different scales may be used, depending upon the final study area or areas and the predominating scale of the individual hazard maps. The most detailed individual hazard map may be selected as the base if it provides adequate geographic orientation. The base map used for an MHM can be the same as that used for the critical facilities map described in Chapter 7.

1. TRANSLATED INFORMATION

Much hazard information will be in the form of scientific investigations into the process and prediction of a potentially hazardous event and observations of the impact of past events (Du Bois, 1985), such as volcano inventories and records of flood crest elevations. It is often in forms other than maps. This information, although a prerequisite to an MHM, is not readily understood by the layman. It must be "translated" for planners and decision-makers and placed on maps.

Successful translation must be in a format that a planning team can understand. But even more important, the information must be perceived as explaining a hazard that may adversely affect life, property, or socioeconomic activities. This can be accomplished by providing three elements--location, likelihood of occurrence (frequency or return period), and severity. A planner or decision-maker evaluating a specific land use, structure, or socioeconomic activity is not usually interested in a potential event whose (1) occurrence is not expected for a very long time, (2) location is not known, or (3) size or effect is not great. These elements vary with the phenomenon, for example:

- Coastal areas annually exposed to winds of specific velocity and storm surges of specific runups.
- Floodplains and floodways which will be impacted by specific velocities and water heights from rainfall duration and intensity having a fifty-year recurrence interval.

BENEFITS OF MULTIPLE HAZARD MAPPING

- A more concise focus on the effects and impacts of natural phenomena on a particular area is possible during early planning stages.
- Many hazards and the trigger mechanism of each can be viewed at the same time. Common reduction or mitigation techniques can be recommended for the same portion of the study area.
- Inadequate or missing hazard information (location, severity, or frequency) can be more easily identified.
- A study area or a sub-area can be expanded, reduced, or deleted.
- Study areas can be divided into sub-areas requiring more information, additional assessments, or specific reduction techniques.
- More realistic evaluation of risks to new development are possible.
- Appropriate hazard reduction techniques can be more easily built into the investment project formulation.
- Selection of appropriate land uses can become more rational.

- Fault rupture zones, liquefiable geologic materials, and landslide-susceptible areas having significant vertical or horizontal displacement by a postulated earthquake of a specific magnitude with a likelihood of occurring within the next one- or two-hundred-year period.

Figure 6-2 illustrates the types of information needed. All three elements may not be available for all hazards. In compiling an MHM it is just as important to know what is missing. More information can be sought or prepared, but at least those development and investment decisions being based on less than adequate information should be noted.

It is also important to distinguish between a hazard that can be defined as not present versus one whose presence cannot be properly evaluated because of limited information. For example, a conservative approach to development because of "inadequate" hazard information can be counterproductive over time. If the planner's or decision-maker's response to an "exaggerated" potential hazard is to avoid the area or recommend expensive resistive design, a credibility problem will occur when a "realistic" potential hazard is discovered.

2. SOURCES AND COMPILING INFORMATION

There is a vast array of sources of hazard information, including various public and private libraries, offices and reference centers at international, national, regional, and community levels. These entities may be concerned with infrastructure, community facilities, economic development, resource exploration, land use planning, emergency preparedness, geotechnical studies, disaster response, and many other activities. Sometimes these sources coordinate their compiling of hazard information, but it cannot always be expected. Many of the users of development planning information are also compilers of natural hazard information. Tinsley and Hollander (1984) have compiled a list of governmental earth-science agencies and selected major international organizations whose functions are similar to those of the U.S. Geological Survey.

Some hazard information can be extracted or inferred from photographic, topographic, geologic, hydrologic, climatologic, and soils information already prepared for settled regions. Chapter 10 of this primer, on landslide hazard mapping, suggests local authorities responsible for public works, forestry, and agricultural activities as being valuable sources of information because of their familiarity with past problems.

The Organization of American States (1969) in its casebook on physical resource investigation for environmental development cites suggestions for obtaining information on hazards. These include existing resource surveys; aerial photography; personal reconnaissance; exploratory, reconnaissance, semi-detailed, and detailed surveys; aerial photography, orthophotos, and photogrammetric mapping; geologic surveys; flood studies; and soil erosion surveys.

Hazard information may also be obtained from remote sensing data (see Chapter 4). Various sources of information on floods, desertification, earthquakes,

CHARACTERISTICS OF INFORMATION NEEDED TO ASSESS NATURAL PHENOMENA

- Location
- Likelihood of occurrence
- Severity

Figure 6-2

EXAMPLES OF THE TYPES OF INFORMATION NEEDED TO ASSESS THE HAZARD POTENTIAL OF NATURAL PHENOMENA

	EARTHQUAKE	LANDSLIDE	HURRICANES	RIVER FLOODS
LOCATION	Epicenters Geologic formations	Inventories Geologic formations Slope	Landfall Path	Channel Floodway Floodplain Elevation
SEVERITY	Intensity Magnitude Acceleration Displacement	Velocity Displacement	Wind velocity Rainfall	Volume Velocity Rate of rise
LIKELIHOOD OF OCCURRENCE	Recurrence interval Slip rates Historical seismicity	Earthquake recurrence Rainfall patterns Bank cutting rates	Historical occurrence	Historical return periods Flood of record Design event

landslides, and other natural hazards are given in Appendix A and Chapters 8 through 12.

Compiling information from these various sources includes four steps: collecting, evaluating, selecting, and combining, as described in the box below.

The overview of natural hazards by Bender (1986) for the St. Kitts and Nevis project provides an example of a preliminary evaluation of available hazard information based on readily available information. The Santiago-Mira study (OAS, 1984a) demonstrates the importance of getting a "quick picture of the region's development problems. This involved sending an 'advance man' to the study area to determine the principal issues and identify experienced local technicians. "

Chapter 10 includes recommendations which are applicable to all hazards, not only to landslides: initial consultation with technical specialists, identification of hazards early in the planning process, and an initial review of the type and content of available information. Because of the cost and time in compiling information to make an MHM, consideration should be given to collaborating with other users.

3. TIMING

The collection of general hazard information began years ago as part of development assistance agency programs. Within current OAS project procedures, the collection of specific hazard information begins when a member country makes a formal request for technical assistance and continues through the integrated development planning process (see Chapter 1). Sending a two-person team to the field for two weeks for a quick data collection effort represents a relatively low-cost method for initiating collection of specific natural hazard information (OAS, 1984a).

COMPILING INFORMATION ON MULTIPLE HAZARDS

- Collecting base maps and appropriate hazard information from the various sources identified in this book.
- Evaluating the uniformity, accuracy, and completeness of such information--areal coverage, detail, content, elements (likelihood, location, and severity), format, and symbols.
- Selecting the most appropriate base map and scale to be used, hazards to be shown, and symbols to portray those hazards.
- Combining the selected individual hazard information onto the MHM in an accurate, clear, and convenient way.

During the preliminary mission, hazard information collection can be accomplished by:

- Undertaking field travel and "overflights" of the study area.
- Contacting local officials and community leaders.
- Maintaining contact with appropriate national planning officers.
- "Brainstorming" with national counterparts.
- Using experienced staff members or consultants to get an overview.
- Determining the availability of existing data.

During subsequent study stages, the general criteria for data collection should emphasize:

- Striving for the same level of detail.
- Answering specific questions about development problems.
- Using national institutions as sources.
- Drawing on local practice experience.
- Identifying project ideas (or mitigation techniques).
- Using local research institutions and universities.
- Keeping descriptions to a minimum and emphasizing analysis.

C. Map Format

Maps are the most effective way to convey actual and relative location. Maps can be simply defined as flat geographic portrayals of information through the use of symbols. A good introduction to types and content of maps, data overlays and extractions, and land use and land cover mapping may be seen in the *Coastal Mapping Handbook* (Ellis, 1978). Such approaches help the MHM not just convey that natural hazards exist, but also to note their location, severity, and likelihood of occurrence in an accurate, clear, and convenient way.

The area covered, scale, detail, hazards shown, and format of a MHM can range widely:

- World: 1:30,000,000
- Continent: 1:5,000,000, 1:2,000,000
- Region: 1:500,000, 1:200,000, 1:96,000, 1:50,000
- Community or settlement: 1:24,000, 1:12,000
- Building sites: 1:10,000, 1:2,500

It has been said that the usefulness of a map is in its omissions. Except for its orientation information (roads, rivers, coastlines, place names) the map should be as uncluttered and stripped down as possible. Natural hazards are the information to be emphasized.

Discussion of the important aspects of MHM follows: base map, scale and coverage, hazards to be shown, and types of symbols to be used. References are made to nine examples (Figures 6-3 through 6-11) which may appear deceptively simple. Two are in color, one is computer-generated, one shows only two hazards while others show many, some stand alone while others are accompanied by extensive explanations.

1. BASE MAP

Creating a base map from scratch is a difficult and time-consuming task; therefore, it is desirable to use an existing map or controlled photograph as a base. An adequate base map must be planimetric, that is, a representation of information on a plane in true geographic relationship and with measurable horizontal distances; and must have sufficient geographic

reference information to orient the user to the location of the hazard. The top of a map is usually oriented to the north, but not always. Hence, a "north arrow" on each map sheet is mandatory.

Discussion of geographic referencing systems such as longitude and latitude, state plane coordinate systems, or Universal Transverse Mercator (UTM) grid systems is beyond the scope of this chapter. Many different projections are suitable and an indication of the map projection used as well as an insert map showing the location of the study area is very helpful.

Figures 6-3 through 6-11 are all planimetric maps, and each has sufficient reference information for the scale and area covered. For example, the map of the world (Figure 6-3) shows national boundaries and major cities; other maps show highways and rivers; some even show local street names and building site boundaries (Figure 6-11).

Sometimes a base map is available that shows hypsography, that is, elevations of land above sea level (Figure 6-9). These maps are sometimes called "topographic" or "contour line" maps. The elevation and contour information can be interpreted to help present the location and severity of flood, landslide, fault rupture, hurricane, and other potential hazards. Cadastral (property ownership boundary) maps can be excellent base maps, although they often have a scale larger than is needed for regional development planning. Controlled aerial photographs, photo maps, radar images, and satellite photography can also be used for base maps.

2. SCALE AND COVERAGE

Map scale is the measure of reduction in size from the actual environment to that portrayed on the map. The scale can be expressed as a ratio between the map distance and the actual distance. For example, the scale on Figure 6-5 is 1:500,000 which means that one centimeter on the map equals 500,000 centimeters (or 5,000 meters or 5 kilometers) on the ground. Large-scale maps show less detail for a large area.

Larger scales are more common for regional development planning (1:500,000 through 1:50,000; Figures 6-5 through 6-9), and community development plans (1:24,000 through 1:12,000; Figures 6-10 and 6-11). The scale selected will depend upon the map's purpose. There are no best scales, only more appropriate ones to coincide with planning requirements.

The scale used for an MHM is dependent upon not only the hazard information to be shown but also upon the scale of the base map. If a choice of scales is available, then the following factors become important in making the selection:

- Number of hazards to be shown.
- Hazard elements to be shown.
- Range of relative severity of hazards to be shown.
- Area to be covered.
- Use of the map in conjunction with other planning documents.
- Function of the map; for example, whether it is to be an index or detail map.

Often the individual hazard maps to be used are at different scales. This may require an enlargement or reduction to the scale of the base map selected. Use of controlled photographic or computer mapping methods makes this process easy and accurate.

3. HAZARDS TO BE SHOWN

Any number of hazards can be shown, depending upon scale, symbols, and coverage chosen. On a one-sheet topographic base map (Figure 6-9), only flood and landslide hazards are shown. On the 5-sheet map (Figure 6-10), several hazards and thirteen zones of geologic materials are shown. This dense hazard information is then supplemented by two sheets of explanations. To avoid overcrowding, hazards can be combined manually (Figure 6-8), or by computer (Figure 6-7), and into regulatory zones (see Chapter 7).

4. TYPES OF SYMBOLS

Everything shown on an MHM as well as the base map is a symbol representing reality. Symbols are selected for their legibility and clarity and/or map production characteristics; for example, artistic (Figure 6-3), numerical (Figures 6-4 and 6-10), convention (Figures 6-5 and 6-6), computer printout (Figure 6-7) innovation (Figure 6-8), resemblance to flooding (Figure 6-9), or ease of regulations (Figure 6-11).

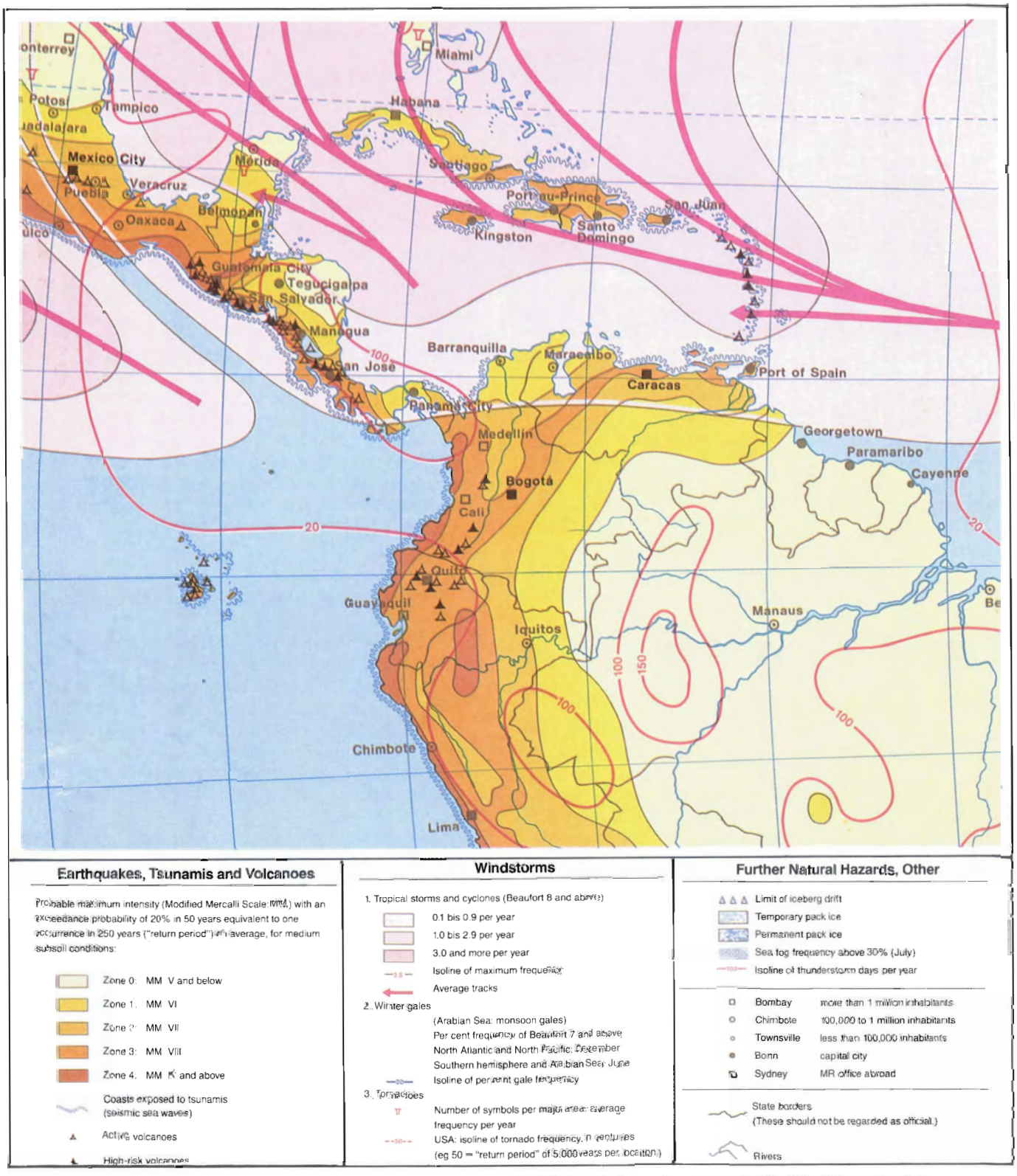
Some symbols may convey a sense of the hazard (Figure 6-5); others are totally abstract (coastal hazards in Figure 6-8). Some symbols represent derived combinations of hazards (geologic problem index in Figure 6-7) or hazards combined for ease of reading (see Chapter 7).

Likelihood of occurrence or frequency can be shown by isolines to represent the number of thunderstorm days per year (Figure 6-3) or to separate areas of landslide frequency (Figure 6-9). Areas have been used to show maximum seismic intensity in 50 years and the number of tropical storms and cyclones per year (Figure 6-3), and flooding in 100 years (Figure 6-9).

Location can be shown through the use of basic geometric symbols--a point, a line, or an area. For

Figure 6-3

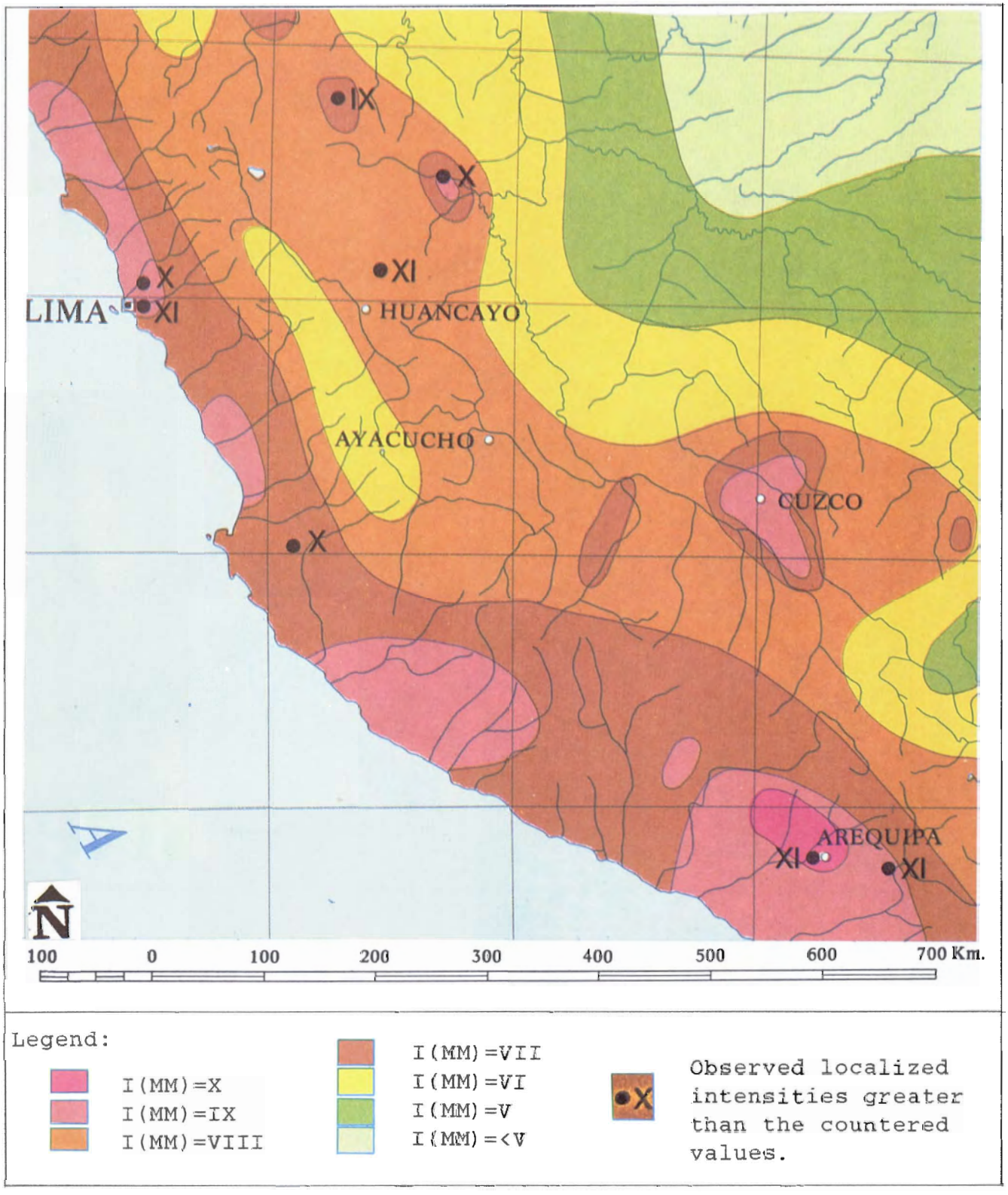
WORLD MAP OF NATURAL HAZARDS



Source: Munchener Ruckversicherungs-Gesellschaft. World Map of Natural Hazards, scale 1:30,000,000. (Munich, Federal Republic of Germany, 1978). Permission to publish.

Figure 6-4

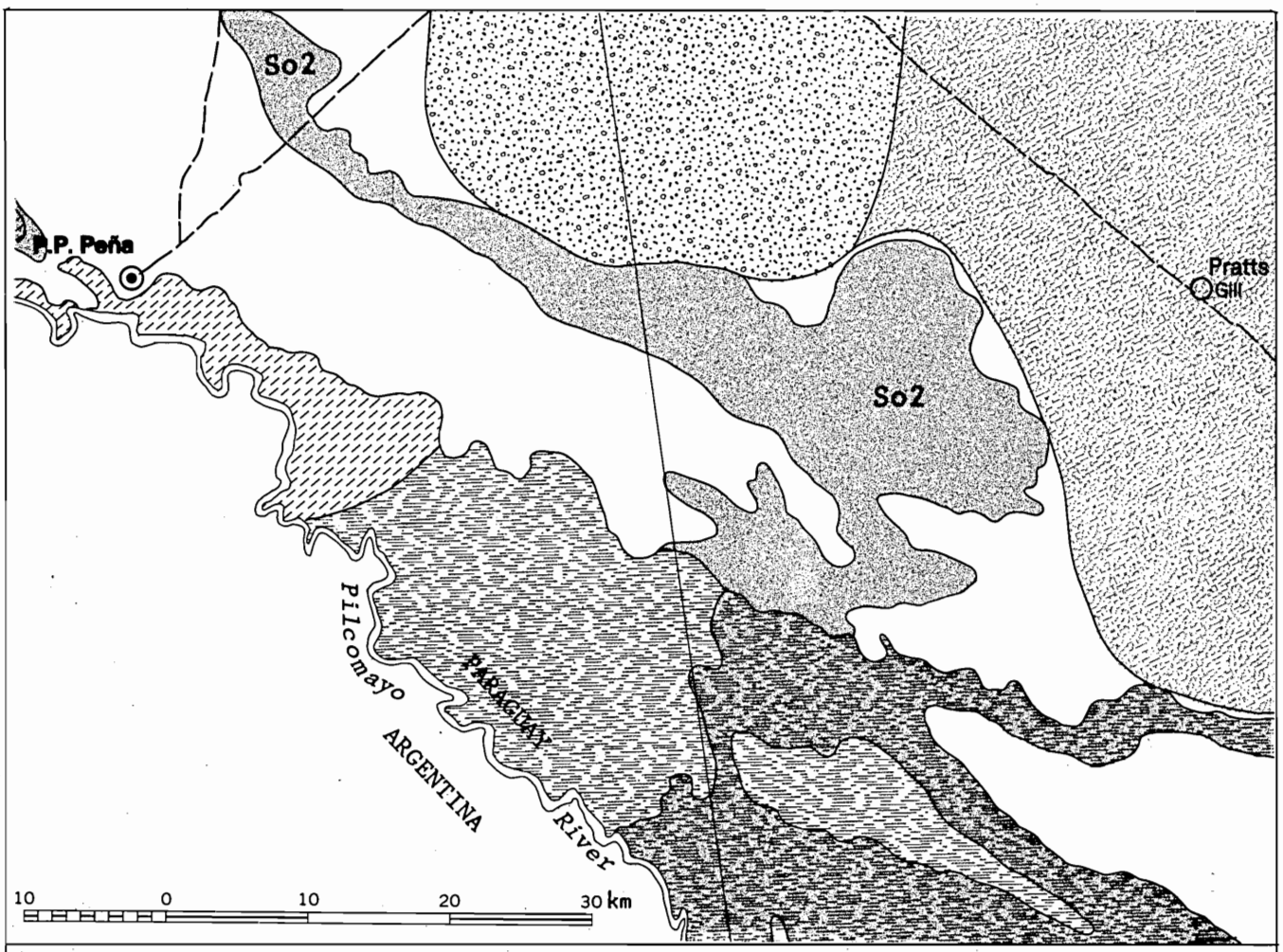
MAXIMUM EARTHQUAKE INTENSITY MAP OF SOUTH AMERICA



Source: Adapted from Regional Seismological Center for South America (CERESIS). Maximum Intensity Map of South America. (Santiago, Chile: CERESIS, 1985).

Figure 6-5

NATURAL HAZARDS MAP OF THE PARAGUAYAN CHACO



High Risk Moderate Risk	AREAS SUBJECT TO DESERTIFICATION High risk and moderate risk of desertification are identified by factor analysis of human pressure, climate, and land resources.
Very high risk High risk	AREAS SUBJECT TO FLOODING Very high risk and high risk of flooding are identified by Landsat data (MSS), aerial photography, and maps of soil, vegetation, fluviology, land use, precipitation, and desertification risk.
So2 Very high risk	HAZARDOUS SOILS AREAS Delineated areas are zones of very high risk of salinization and alkalinization. Areas with high risk of erosion were also identified.

Source: Adapted from OEA. Proyecto de Desarrollo Urbano Paraguayo, Mapa de Riesgos Naturales del Chaco Paraguayo, Area de Programa 4-C (Washington, D.C.: Organization of American States, 1985).

example, points have been used to show tornadoes and volcanoes (Figure 6-3); lines have been used to show preferred tracks of tropical storms (Figure 6-3), fault rupture (Figures 6-10 and 6-11), or tsunamis (Figure 6-3); and areas have been used to show flooding, landslides, or erosion zones (Figures 6-5 and 6-6).

Severity can be shown as points, although lines are more often used, for example, to show equal numbers of winter gales (Figure 6-3), relative severity of coastal hazards (Figure 6-11) or coastal erosion (Figure 6-10). Areas have been used to indicate severity, such as maximum seismic intensity (Figure 6-4), or a combination of hazards (Figure 6-7). In addition, areas can be used to show requirements or recommendations for further study, for example, site investigations to determine fault rupture location (Figure 6-11) or geotechnical investigations prior to development (see Chapter 7).

Innumerable variations of points, lines, and areas are available to the maker of an MHM. Lines can be solid, long-dashed, short-dashed, or composed of points and question marks as conventionally used by geologists in mapping inferred faults (see Figure 6-10 and Chapter 7). Areas can be shaded (Figures 6-4 and 6-11), patterned (Figures 6-5, 6-6, and 6-7) colored (Figure 6-3 and 6-4) or patterned and colored (see Chapter 7). Examples of the various representations of points, lines, and areas may be seen in Figure 6-11. A thorough discussion of graphic design is found in Robinson, Sale, and Morrison (1978).

D. Other Forms of Multiple Hazards Information

The foregoing discussions and examples have addressed one form of the MHM, mainly the single-sheet planimetric map combining several hazards with relatively simple explanations. This form of MHM may not always be the most suitable. Other forms of the multiple hazards information may provide increased coverage, greater detail, or more hazards. Sometimes information helpful to making a development or investment decision is already available, for example, cost estimates, graphic evidence of damage, or hazard reduction suggestions. Information in a form processed or capable of being processed by computer may be available. Examples of some of these other forms follow.

1. CROSS SECTION OF EFFECTS

One form for showing severity is by means of a cross section through an affected area. However, to be useful to planners and decision-makers, it must be accompanied by a planimetric map showing the areal extent of the hazard. For example, the geologic effects of fault rupture, ground shaking, tsunami flooding, liquefaction, and landsliding were predicted for a recurrence of a magnitude 6.5 earthquake. The hazards are shown on regional scale map sheets (1:125,000) and the severity is indicated by a cross section (Figure 6-12) at a horizontal scale of 1:150,000 in Borcherdt (1975).

2. PHOTOGRAPHS OF DAMAGE

The use of photographs of actual damage is an excellent technique for communicating a general awareness of the effects of hazards. They can also be used to illustrate the specific effects of hazardous phenomena. For example, Hays (1981) uses photographs of buildings seriously damaged by flooding, hurricanes, landslides, and subsidence that occurred throughout the United States. Ziony (1985) uses photographs of structures such as hospitals, highway overpasses, electric power stations, and dams that failed or were seriously damaged by various earthquake effects--ground shaking, fault rupture, liquefaction, landslides, and tsunamis. Steinbrugge (1982) uses numerous photographs of damaged buildings, failed structures, and disrupted building use caused by earthquakes, landslides, tsunamis, and volcanoes. Photographs of actual damage caused by a specific type of event can be keyed to an MHM to show where similar damage has occurred.

3. ATLAS OF HAZARDS

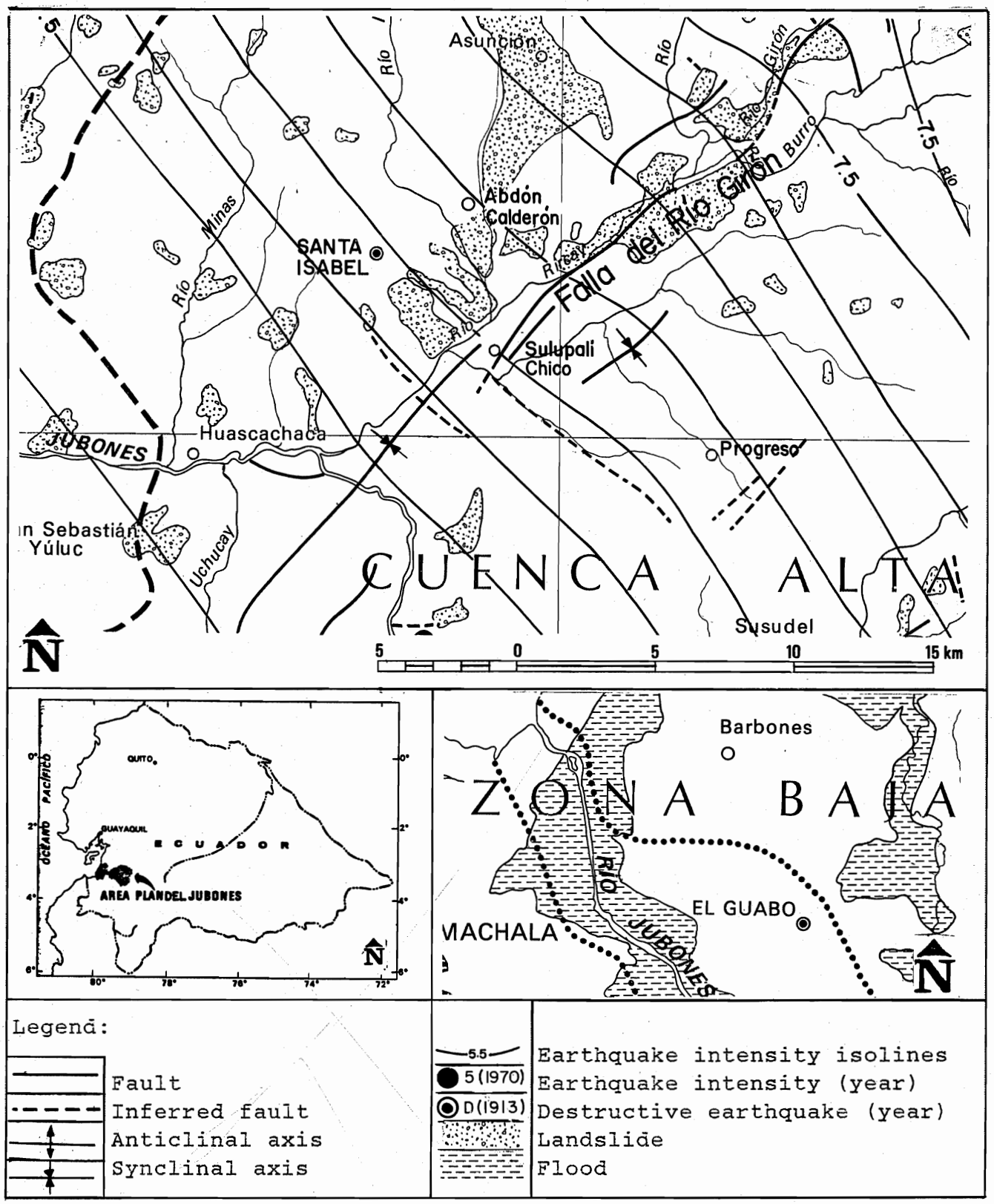
A presentation of several hazards in an atlas form provides greater opportunity for discussions, diagrams, photographs, recommendations, and references. For example, geologic and hydrologic hazards caused by seismic, atmospheric, or volcanic phenomena are mapped at scales of approximately 1:20,000,000 or larger. The maps are accompanied by diagrams of the processes, discussions of loss trends, photographs of damage, and suggested reduction techniques in the report by Hays (1981).

4. PLAN FOR REDUCING HAZARDS

Sometimes multiple hazard information is in the form of a hazard reduction plan which includes information on individual hazards. For example, the nature, magnitude, and costs of ground shaking, landslides, flooding, erosion, expansive soils, fault rupture, volcano, tsunami, and subsidence hazards are discussed in a report by Alfors and others (1973) for an entire state. Maps of each hazard at a scale of

Figure 6-6

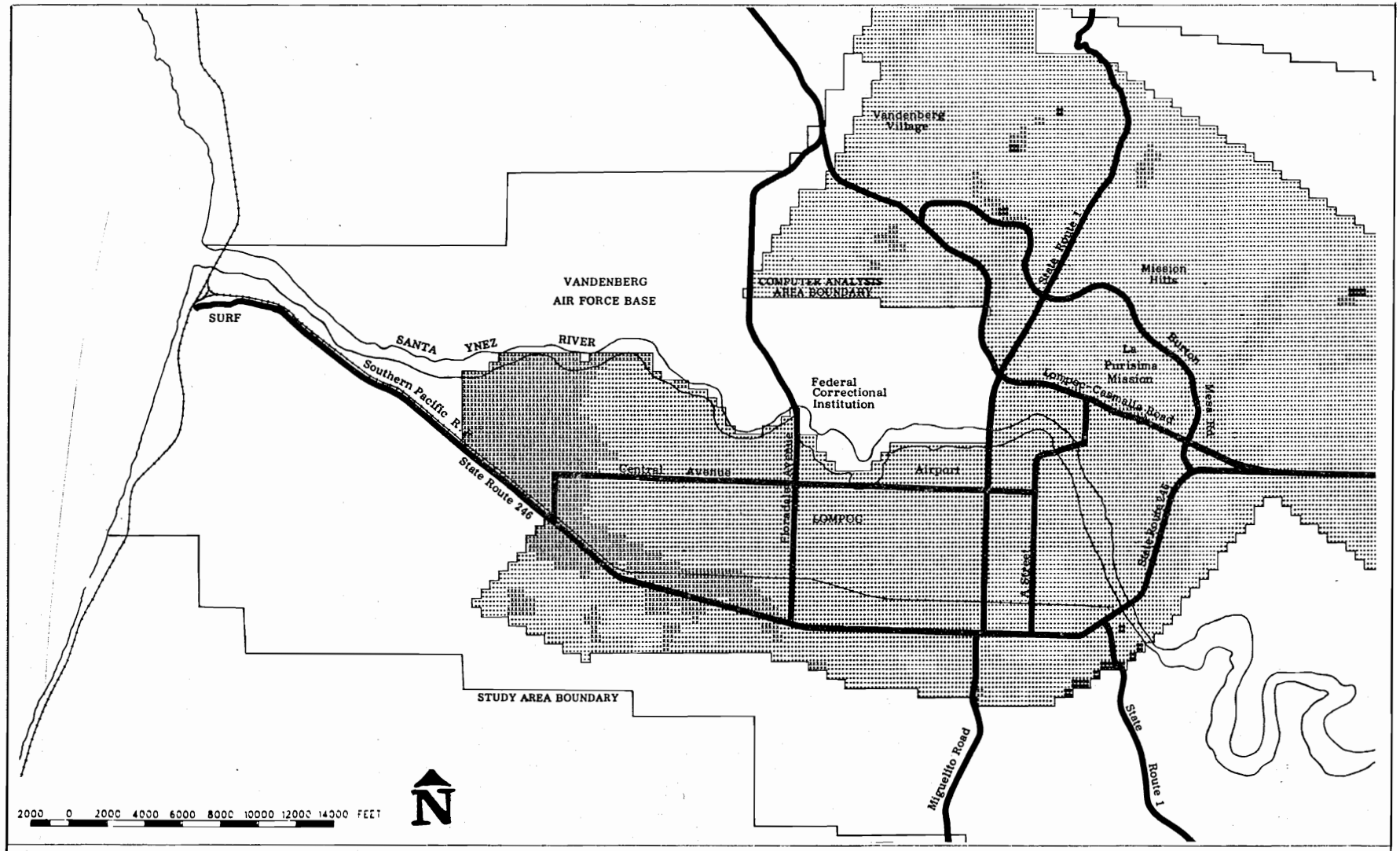
LANDSLIDE AND FLOOD HAZARD MAP FOR JUBONES, REPUBLIC OF ECUADOR



Source: Adapted from OEA. Plan Hidráulico del Jubones, República del Ecuador, Vol. III, Mapa 3-A12. (Washington, D.C.: Organization of American States, 1984).

Figure 6-7

COMPUTER-GENERATED MAP SUMMARIZING SEVERAL HYDROLOGIC, SEISMIC , AND OTHER GEOLOGICAL HAZARDS - GEOLOGIC PROBLEMS INDEX (GPI)

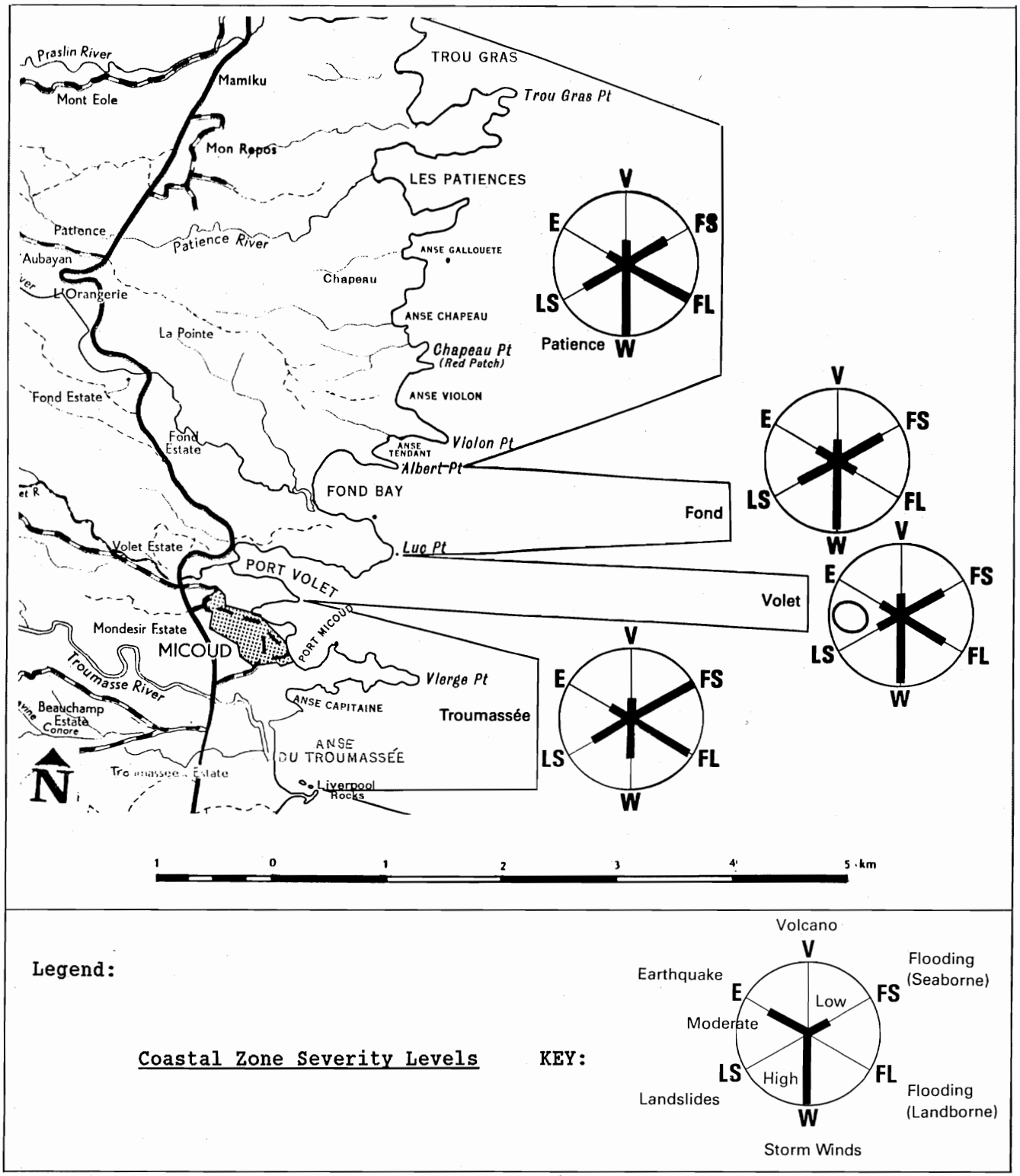


Legend: The lighter patterns indicate low to moderate hazards. The darker patterns indicate moderate to severe hazards.

Source: Adapted from Santa Barbara County Planning Department. Seismic Safety and Safety Element. (Santa Barbara, California: Santa Barbara County Planning Department, 1979).

Figure 6-8

COASTAL HAZARD MAP FOR SAINT LUCIA



Legend:

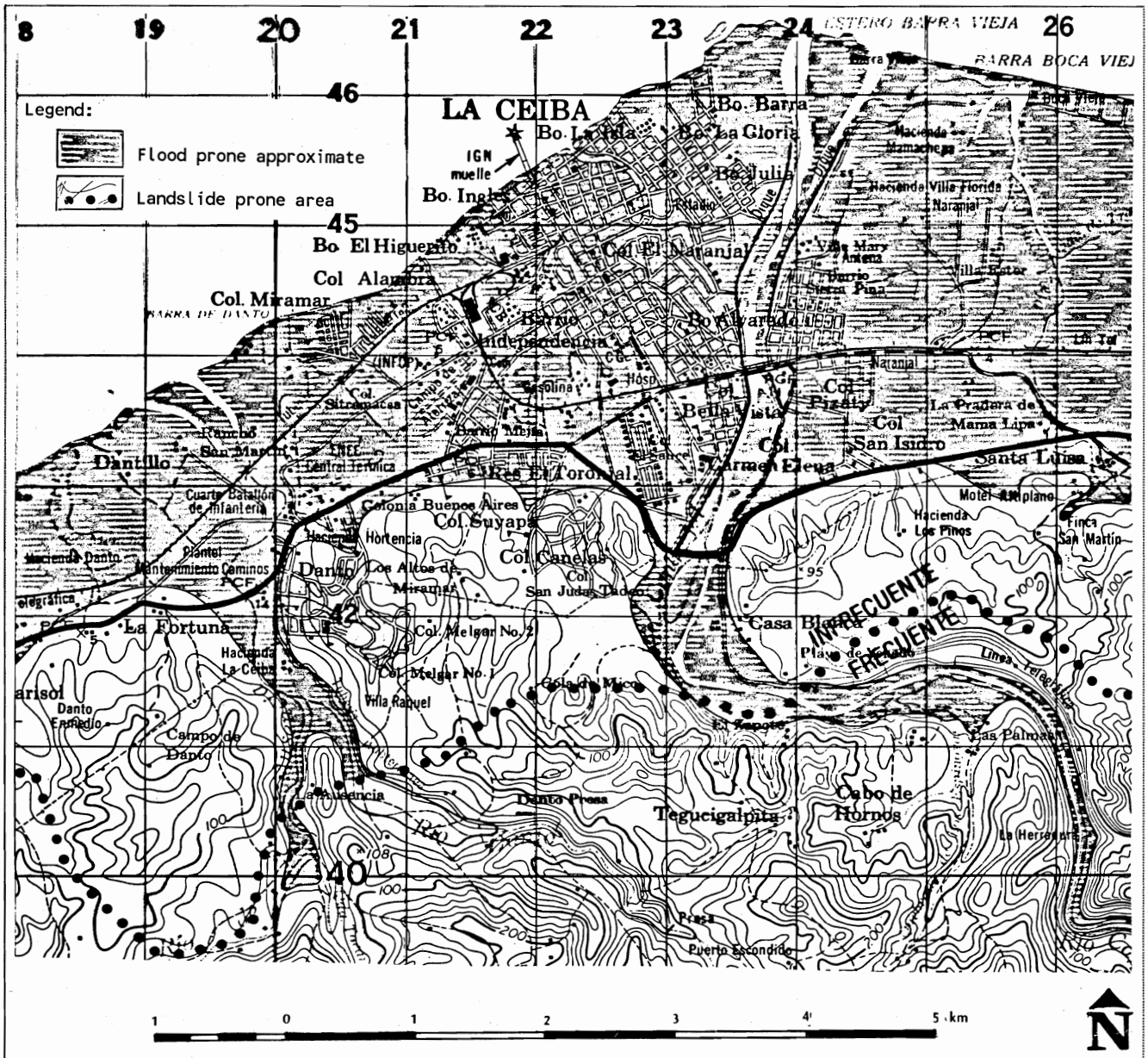
Coastal Zone Severity Levels

KEY:

Source: Adapted from OAS. Saint Lucia Coastal Hazard Map. (Washington, D.C.: Organization of American States, 1984).

Figure 6-9

NATURAL HAZARDS MAP FOR THE REPUBLIC OF HONDURAS



FLOOD RISK INFORMATION

The area prone to floods represents approximately 100-year event, that is, in a given year there is a one percent probability that this event will occur. The information was based on Landsat data (MSS), orthophotomaps (scale 1:10,000) and field observations. Certain zones within the area which are not prone to floods are not delimited because the 20m contour interval does not permit the identification of the high zones in the coastal plain.

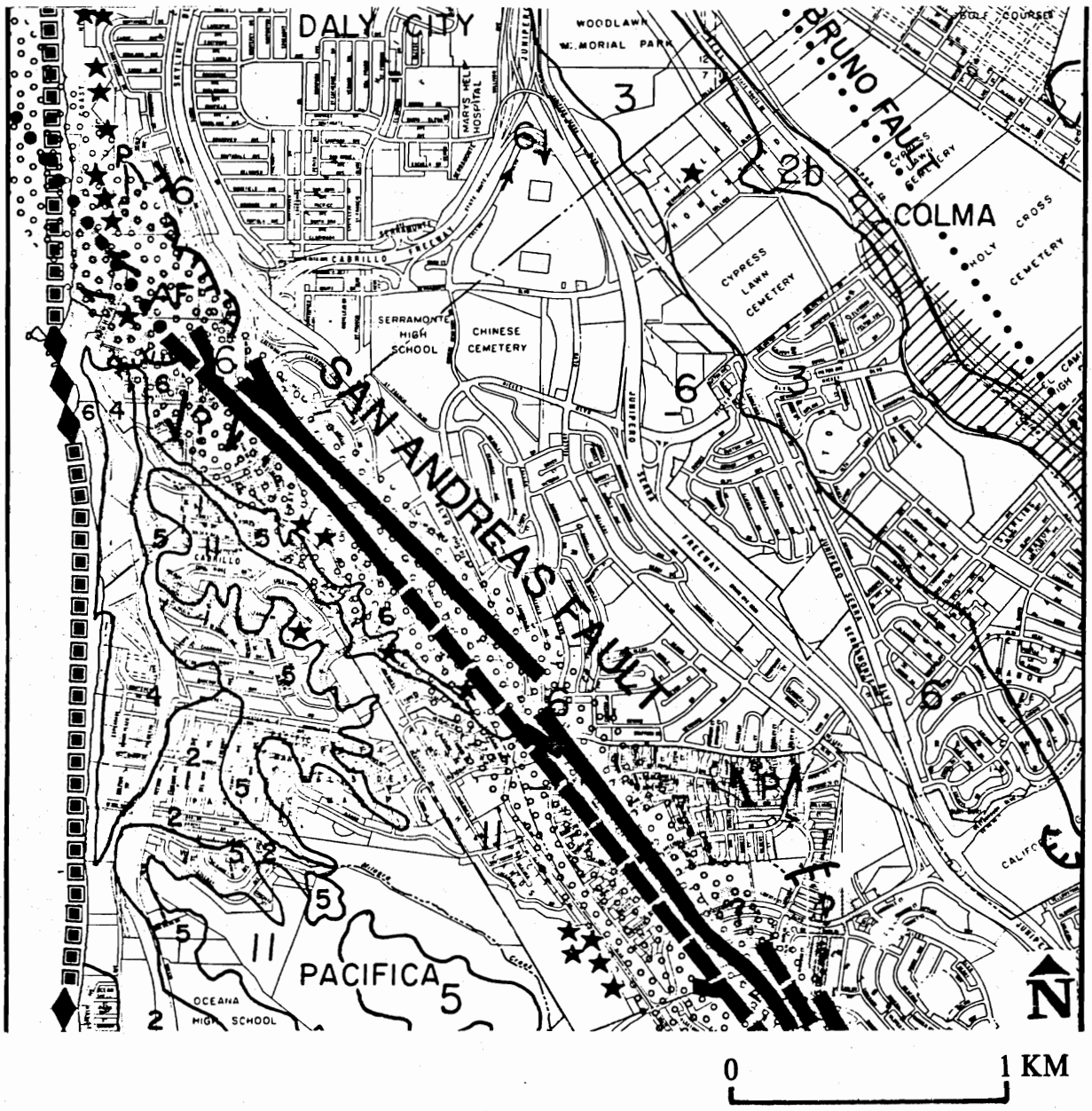
LANDSLIDE RISK INFORMATION

The areas of frequent versus infrequent landslide occurrence are delimited by isolines of points where the landslides cover one percent of the surface. Areas with less than one percent of coverage are designated "infrecuente," and areas with more than one percent of coverage are designated "frecuente."

Source: Adapted from OEA. Proyecto de Desarrollo, Islas de Bahía-Atlántida, República de Honduras, Mapa de Riesgos Naturales. (Washington, D.C.: Organization of American States, 1985).

Figure 6-10

GEOTECHNICAL HAZARD SYNTHESIS MAP



Legend: The explanation for this map is complex, combining information on geologic processes, such as faulting, landsliding, coastal erosion, and liquefaction, with information on geologic materials, shown by numbers on the map. The material units are further subdivided by both seismic and engineering characteristics. For example, areas designated "2b" are underlain by alluvial fan deposits ranging in coarseness from silt to gravel, have poor to fair slope stability, moderate liquefaction potential, good to fair stability in terms of the intensity of ground shaking during a 7.5-8.3 M earthquake, and have good foundation properties.

Source: Adapted from San Mateo County Planning Department and Leighton and Associates. Geotechnical Hazards Synthesis Map (San Mateo County, California: San Mateo Planning Department and Leighton and Associates, 1974).

NATURAL HAZARD INFORMATION AND DISPLAY SYMBOLS

SYMBOL	Earthquake	Hurricane	Flood	Landslide	Volcano
POINT	Epicenter site	Landfall measure	Flow site	Landslide site	Volcano
LINE	Fault	Path	Flood elevation	Direction of slide	Direction of lava flow, ash, or gas
AREA	Seismic intensity	Storm surge	Flood-prone area	Landslide-prone area	Coverage of ash, gas or lava flow

1:5,000,000 are accompanied by loss-reduction recommendations which include mapping of the hazards and research into their processes.

5. ANALYSES OF LAND CAPABILITY

The additional costs required to reduce a hazard (and thus overcome a constraint to development) can be crucial information for a lender or donor. For example, a method of evaluating land-use proposals by estimating the "social" costs that are attributed to hydrologic, seismic, and other geologic characteristics is described by Laird et al. (1979) and is accompanied by composite maps for a demonstration area (1:125,000). Costs are computed from a consideration of reduction techniques, probability of future damage, or lost opportunities. Cost is expressed in current dollars, and therefore provides a common basis for evaluating and comparing different land uses and different constraints and resources. Constraints to development include ground shaking, fault rupture, tsunamis, seiches, landslides, fault creep, avalanches, stream flooding, subsidence, liquefaction, expansive soils, erosion, and volcanic activity. Resources include minerals, construction materials, energy, water, soil, and scientific and educational sites.

6. SINGLE EVENT WITH MULTIPLE HAZARDS

It should be remembered that the effects of a single event, as in the case of volcanoes and earthquakes, can include various hazards, each having different severities and each affecting different locations. The consideration of one event, then, should result in the assessment and mapping of several hazards. Hazard zones for lava flows, ash clouds, lateral blasts, and mudflows are mapped at 1:62,5000 for a potential volcanic eruption by Miller (1980).

7. SERIES OF STRIP MAPS

Sometimes a physiographic province--uplands, lowlands, or coastlands--is used as the basis for mapping, and various hazards within that province are assessed. For example, eleven hundred miles of Pacific Ocean coastline are mapped (1:50,000 to 1:100,000) and divided into three hazard zones reflecting various combinations of coastal erosion--cliff retreats, slumps, bluff collapses, landslides, rockfalls, seawall breaches, wave-thrown debris, earth flows, tsunamis, and storm surges -- by Griggs and Savoy (1985). (See Chapter 7.)

8. PHOTO MAPS

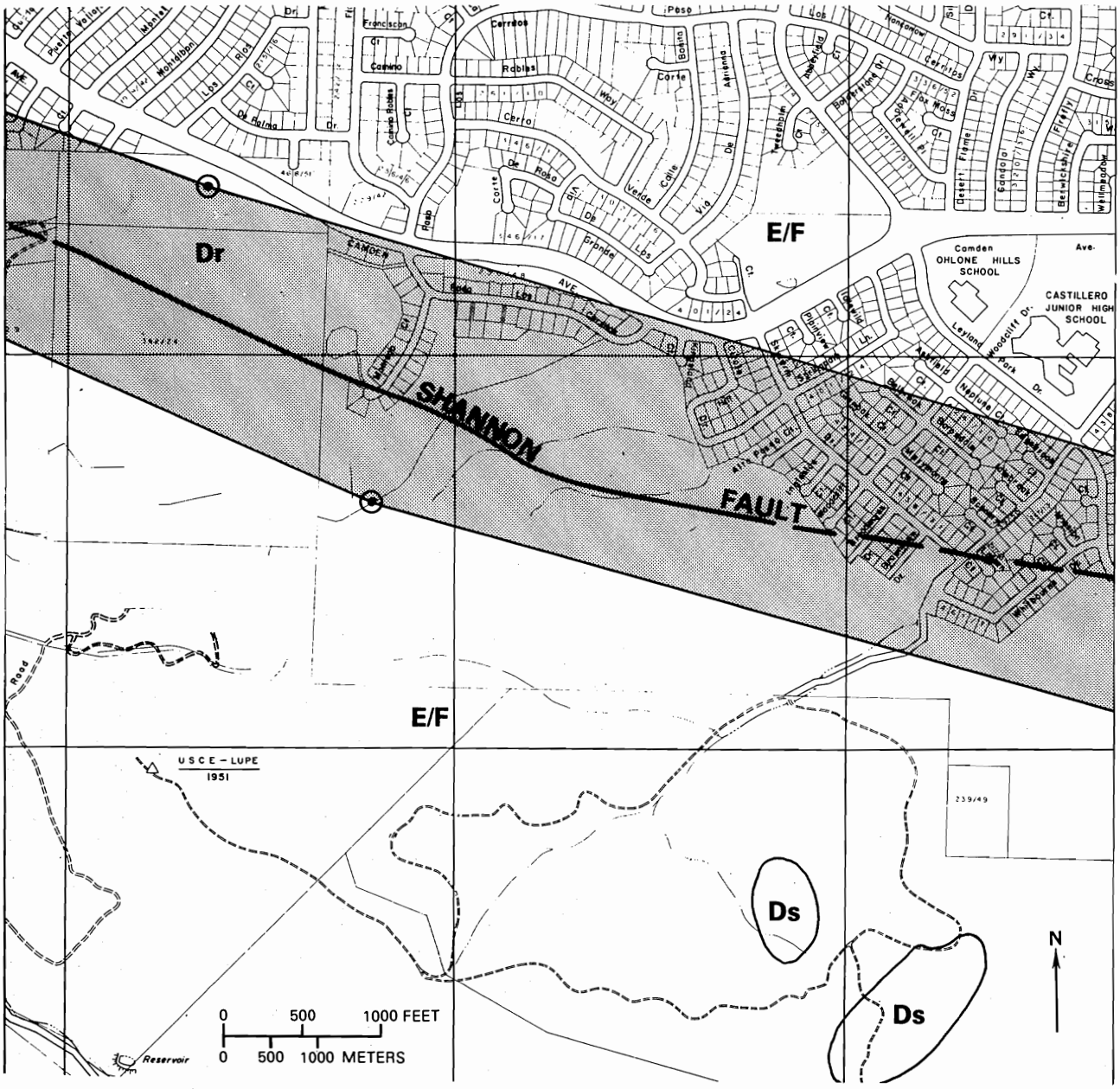
Orthophotos, stereoscopic photographs, and photographs with some topographic information are invaluable to an experienced interpreter. These maps can be used not only as base maps but to accurately locate potential hazards. For example, floodplain boundaries during high water, recent storm damage paths, fault rupture zones, or past landslides can be seen on photographs. This information sometimes can be interpreted to obtain location and severity.

9. GEOGRAPHIC INFORMATION SYSTEMS

The nature and capability of geographic information systems (GIS) provides an excellent basis for processing and presenting information in a map form (Bender et al., 1989). Natural hazards can be the information that is processed and presented. For

Figure 6-11

CADASTRAL MAP SHOWING GEOLOGIC AND SEISMIC HAZARDS

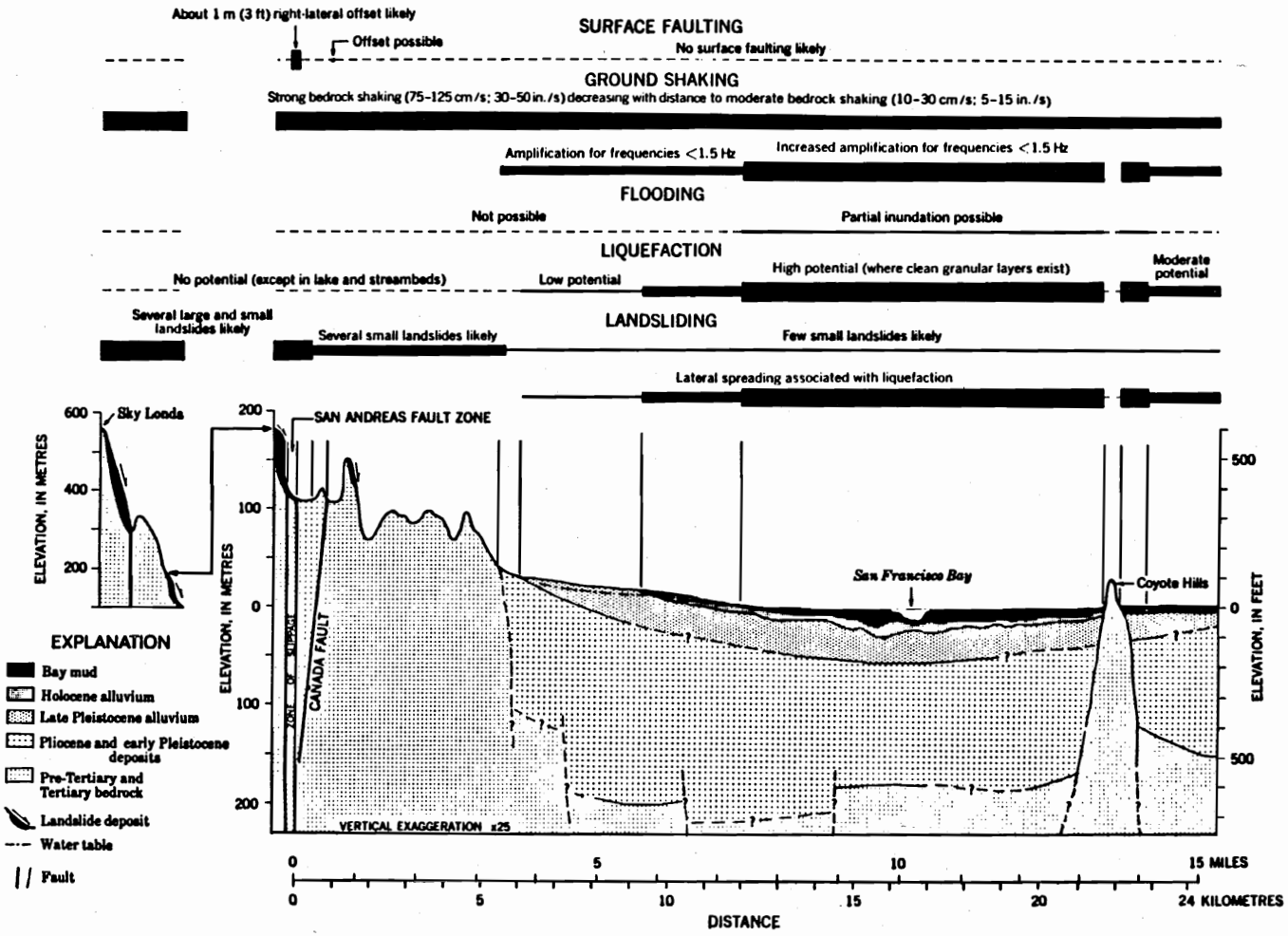


Legend: Shaded area indicates a zone where site investigations are required because of an active or potentially active fault. Letters indicate specific hazards that need to be investigated and evaluated: Dr, area of high potential for ground displacement; Ds, area of high potential for earthquake-induced landslide; E/F, areas of low to moderate potential for any geologic hazard.

Source: Adapted from Santa Clara County Department of Land Development Engineering and Surveying. (San Jose, California: Santa Clara County Department of Land Development Engineering and Surveying, 1977).

Figure 6-12

CROSS-SECTION SHOWING PREDICTED GEOLOGIC EFFECTS OF A POSTULATED EARTHQUAKE MAGNITUDE 6.5 ON THE SAN ANDRES FAULT

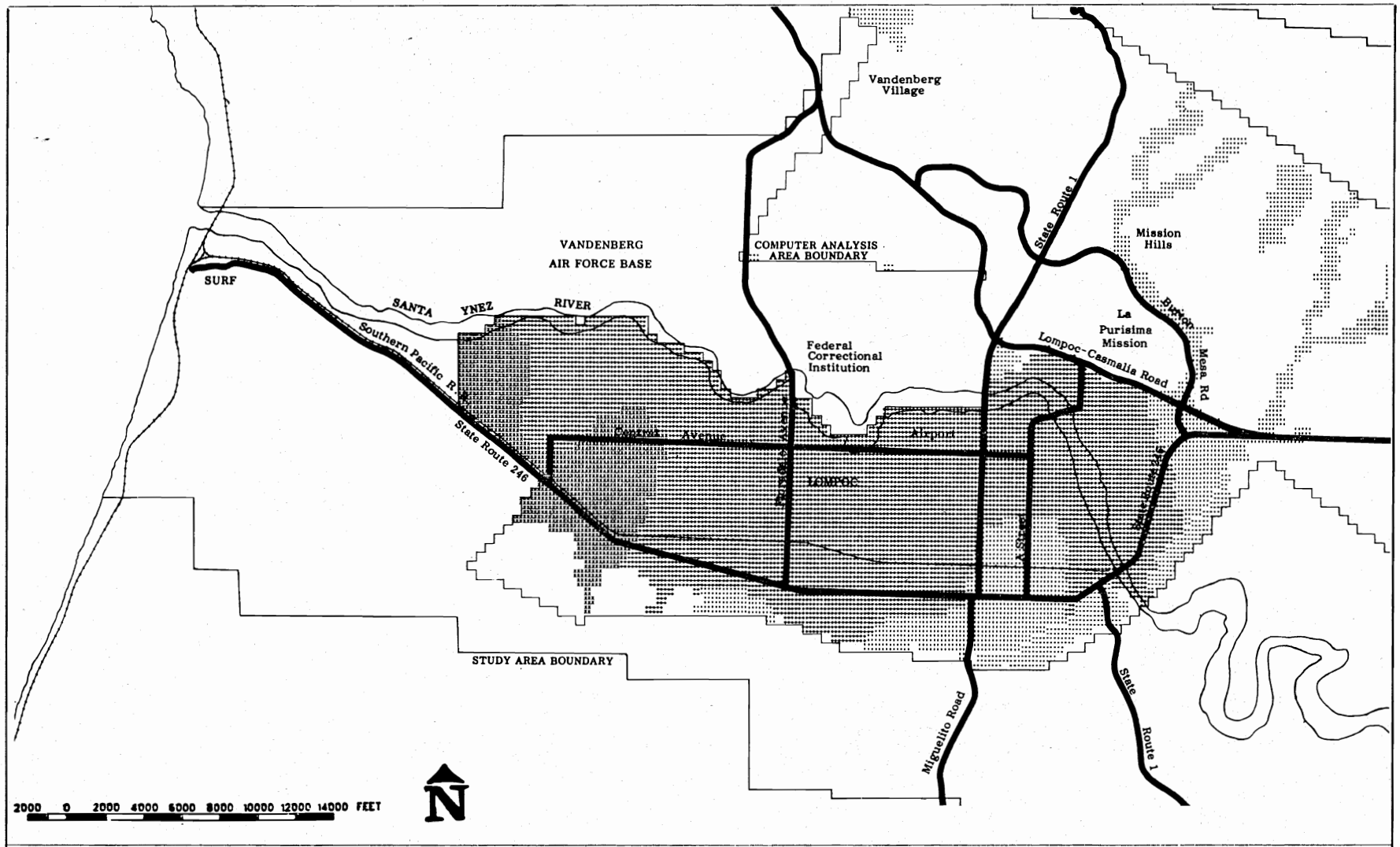


Legend: The severity of each earthquake effect is indicated qualitatively by thickness of underlining and quantified to the extent permitted by the current state of the art for seismic zonation on a regional scale (not shown). The severity of the predicted earthquake effects generally depend on the type of underlying geologic material.

Source: Borcherdt, R.D. (ed.). Studies for Seismic Zonation of the San Francisco Bay Region, U.S. Geological Survey, Professional Paper 941-A. (Reston, Virginia: U.S. Geological Survey, 1975).

Figure 6-13

COMPUTER-GENERATED MAP SHOWING SUSCEPTIBILITY TO LIQUEFACTION HAZARD



Legend: The white areas and lighter patterns within the computer-analysis area boundary indicate low problem ratings. The darker areas indicate moderate problem ratings. No high problem areas are included in the area shown.

Source: Adapted from Santa Barbara County Planning Department. Seismic Safety and Safety Elements. (Santa Barbara, California: Santa Barbara County Planning Department, 1979).

example, liquefaction potential, relative land surface stability during earthquakes, 100-and 500-year flood zones, and potential surface rupture were entered into a GIS from original data at a scale of 1:24,000 by Alexander et al. (1987) to demonstrate the use of digital mapping technology for reducing natural hazards. (See Chapter 7)

10. INFORMATION PROCESSED BY COMPUTER

Computer mapping techniques are discussed in Chapter 5. If accurate information on hazards (location, severity, and likelihood of occurrence) at an appropriate scale is available, its processing by computers can be another invaluable tool. For example, ten hydrologic, seismic, and other geologic hazards were evaluated and rated according to their relative severity. The areal extent and severity of the hazards were transferred to two-hectare (five-acre) grid base maps, and the ratings for individual hazards were encoded to produce computerized maps (1:96,000). Each hazard evaluated was given one of three ratings--high, moderate, or none to low (Figure 6-13). The Santa Barbara County (California) Planning Department (1979) devised a system for rating the hazards for a given area on both an individual and a collective basis--information that then could be processed by computer.

The resulting geologic problem index (GPI) values were obtained by multiplying each hazard by a weighting factor that took into account the seriousness of the hazard, the difficulty of alleviating it, and the frequency of its occurrence. The GPI was calculated for each two-hectare cell in the computer-analysis areas and then assigned to the appropriate severity category and displayed on a computer-produced map (Figure 6-7). These computer GPI maps thus reflect a summation of the ratings delineated on the individual hazard maps.

E. Limitations

This chapter extends only to examples of MHM; it does not address the limitations of the individual hazard maps or other hazard information transferred onto the MHM. The following discussions are directed not only to MHM users but to MHM makers for three reasons: (1) makers are users of the individual hazard maps or other information and must be just as aware of their limitations, (2) makers must be aware of the numerous opportunities for misinterpretation or misuse that users will make of their product, and (3) makers must attempt to provide caveats on the face of the MHM.

It must be emphasized that all the hazard information shown on the MHM, and also the base map information, are merely symbols--some conventional, others abstract, and some innovative. Users must carefully read the explanations (sometimes called legends), all caveats, and any supplemental text accompanying a map. The MHM maker is a key person and should leave a track (or record) for the MHM user, for example, sources of information used, scales enlarged or reduced, and limitations of the individual hazard information.

1. CREDIBILITY

It must be emphasized that the information shown on an MHM is only one factor that the planner or decision-maker will be considering. The information must be clear, convenient, and not just accurate but perceived as accurate. For example, Chapter 10 includes a note that "reliability may be questioned" when a landslide hazard map at a scale of 1:50,000 was based on a slope steepness map at a scale of 1:250,000. The location, severity, and likelihood of occurrence of each hazard must be given or, if unknown, clearly stated as such.

It should be remembered that the location, design, and operation of future critical facilities and the strengthening, abandonment, and operation of existing critical facilities will be affected by a consideration of the information shown on the MHM.

2. LIKELIHOOD, LOCATION, AND SEVERITY

Because of the geographic nature of maps, the location requirement is met, but this is not necessarily so with regard to severity and likelihood of occurrence. The user must not assume that because severity and likelihood are given (in Figure 6-3) for seismic and windstorm events they are also given for tsunamis and volcanoes; they are not.

The likelihood, location, and severity elements of certain natural hazards can be easily affected by human activities. For example, DeGraff (1985) notes that it "is entirely possible to . . . cause a major failure to occur in a moderate hazard zone. Likewise, it is possible to significantly disturb a site within a high or extreme zone without causing a landslide."

Zones with different levels of hazard severity--low, moderate, or high--represent relative, not absolute, hazards. In addition, such levels are not predictive, but rather indicate a relative susceptibility to the hazard occurring. Chapter 10 notes that landslide "susceptibility" only identifies hazardous areas, not "when" the landslide might occur.

3. ACCURACY VERSUS PRECISION

A prerequisite for the locational accuracy of hazard information is the accuracy of the base map selected. The hazard information available and transferred to an MHM may be accurate, but the level of precision varies greatly. This is not necessarily because of scale or resolution, but because of the number of the field investigations, lack of information, type of experiments, and knowledge of the processes involved. For example, the three coastal zone severity levels shown in Figure 6-8 for earthquakes, volcanoes, floods, strong winds, and landslides vary considerably when the historical basis is examined.

Another example is the location of the seismic intensity zone boundaries shown on Figure 6-4. According to Steinbrugge (1982), some observers assign the intensity as the maximum at the location, while others assign an average. Obviously, this leads to variations in location of the boundaries.

A third example is the use of an isoline or an isopleth to indicate likelihood or frequency. Chapter 10 points out that such a map is not a substitute for indicating potential hazard. Sometimes a high frequency of past landslides indicates a greater probability of future landslides; at other times it may indicate a lower probability of future landslides because an area has stabilized.

4. SCALE

Obviously, the scale selected controls the size of the area and the amount of information that can be shown. However, resolution (or accuracy of location) is also affected. For example, if a small scale map (1:1,000,000) using a 1/millimeter-wide line symbol (for fault rupture, storm path, or boundary between hazard zones) is enlarged ten times (1:100,000), the line symbol becomes one centimeter wide. Similarly, reduction of point and line symbols may result in their de-emphasis or even disappearance.

The MHM maker should assume that at some time the map will be enlarged or reduced. Map titles and explanations are usually unaffected by enlargements or reductions, but not the literal and numerical scales. Literal scales (one millimeter equals one hundred thousand meters) and numerical scales (1:100,000) remain accurate only for the original map. Therefore, a graphic scale must be placed on each map.

Spherical surfaces when portrayed on a planimetric map are only accurate at the contact of the plane with the actual sphere surface; various cartographic projection techniques are used to reduce the distortion. The projection technique used can be given or variable graphic scales can be used to alert users (Figure 6-3). Depending upon the scale and accuracy of the hazard information, this distortion may not be crucial, particularly if the base map has sufficient geographic information to locate the hazards.

5. ABUSE

Reality is usually difficult to perceive; this difficulty is increased when maps are used. If a map is treated as reality, it becomes easy to view the hazards in impersonal terms. The magnitude of the hazards is dwarfed, people are invisible, critical facilities and other information may look like a board game.

When planners and decision-makers treat a map as mere symbols and disregard the physical reality it represents, the results can be disastrous. Development planners or investors, for example, may be tempted to locate infrastructures needed for economic development along a line that looks the straightest and most convenient on the map. Such a route may lie within a fault-rupture zone. A dot symbol representing a town or a specific number of people conveys nothing about the town's economic base or the peoples' characteristics--age, schooling, skills, gender, or income sources. The map way is not always the best way; its limitations must be appreciated.

Examples of the misuse of maps by vertical and horizontal distortion, density of symbols, contrasting colors, scales, or the use of symbols and colors which have suggestive, connotative powers beyond their denotative role are discussed by Muehrcke (1978).

6. SYNTHESIS VERSUS DETAIL

Filling an MHM with the symbols from several individual hazard maps may give the impression of a more thorough study, but, of course, this is not true. Simplified multiple hazard maps only create an awareness of what information exists, and (even more important) what information is missing. An MHM cannot substitute for detailed studies and site-specific investigations. For example, the landslide and flood hazards map (1:200,000) for the Jubones River Basin in Ecuador draws attention to the hazards that will affect the irrigation system. It cannot be considered sufficient detail for project planning, but rather it indicates where large-scale (1:25,000 to 1:2,500) technical studies are needed.

7. USE OF CAVEATS

Caveats concerning the limitations of MHM should

preferably be placed on the map but also can be included in the text accompanying the map. Methods used, assumptions made, or other factors concerning the individual hazard maps used to prepare the MHM can also be shown. Examples of caveats that might be found on a map follow:

- The relative swelling-pressure potential of geologic materials is intended for use as a guide; it cannot and should not supplant detailed field study and laboratory investigations of swelling pressures at specific sites.

- The relevance of the hazard information varies according to date, quality, and scale of the aerial photographs used for photo interpretation and the type and amount of field investigations.

- Landslide deposits smaller than 500 feet (150 m) in the longest dimension are not shown because they are too small to be clearly identified on the photographs or clearly portrayed on the topographic base map.

- The age of a relatively well known volcanic event is based on a range of radiocarbon dates, stratigraphic position, soil-profile development, ring counts on trees, or other methods of approximation. Relatively poorly known events can be approximated by comparing their stratigraphic position with the stratigraphic position of well dated events.

- Some landslide hazard zones are suitable only for regional planning purposes. They serve as a guide to whether landslides will pose a problem for a development project and identify locations needing remedial measures. The zones depicted are not intended, nor suitable, for evaluating landslide hazard for a specific site.

- Inundation boundaries drawn on the maps by interpolating between the mudflow lateral limits at adjacent cross-sections using the topographic contours report are not a prediction that the debris dam will fail or that a mudflow flood will result if the blockage fails.

- The scale of the map may prohibit the illustration of sufficient detail to allow use of the map for individual site studies. Evaluation of the potential for subsidence of geologic materials at individual sites should be performed by an engineering specialist.

- General studies of liquefaction potential are not a substitute for site-specific evaluations. The maps are small scale and indicate general areas where susceptible materials are likely to be present. These maps are approximations; they do, however, provide a regional guide to those areas where liquefaction should be considered a potential hazard and where special investigations may be needed.

- The earthquake magnitude used is considered to be the maximum event that can be generated in an area, yet no speculation is made concerning the likelihood of the consequences should the evaluated event occur.

- Not all active faults can be identified; those faults active at depth because of known seismic activity may be so poorly defined at the surface that including them in a surface-rupture hazard zone is impractical.

Conclusion

Multiple hazard maps are an important tool in the integrated development planning process. When combined with the critical facilities map discussed in Chapter 7, they become a key determinant in locating and funding new development. Failure to consider all of the natural hazards in the development planning process and to provide for their reduction will result eventually in the loss of lives, bodily injuries, property damage, critical facility failures, and disruption of important economic activities. Depending upon the size of the event, its location, and its effects, the actual impact of the hazard can be catastrophic and disastrous.

A recent guidebook by the OAS Department of Regional Development and Environment (1987b) clearly restates the issue:

> Conflicts between natural hazards and development activities . . . result from a confrontation between hazardous natural events and human activity. So-called "natural disasters" occur because we have not paid sufficient attention to natural hazardous phenomena. Indeed, the term "natural disaster" is misleading for this reason: it places the blame on nature when, in fact, the blame belongs to those who decided that projects be implemented under circumstances that jeopardize the very objectives that the development activities were designed to meet.

The emphasis of the integrated development planning process is on the development of natural resources, energy, infrastructure, agriculture, industry, human settlements, and social services (OAS, 1984a). It emphasizes the collection and assessment of

information on natural hazards to reduce their adverse impact on that development. It is believed that if the hazards are assessed and appropriate reduction techniques are incorporated into each stage of the integrated development planning process, social and economic disasters caused by natural hazards can be avoided or substantially reduced.

Equally important is the attitude of those national, regional, and community scientists, planners, engineers, and decision-makers involved in the collection and assessment of hazard information for new development. Many of them are key people with responsibilities for existing development. Their use of hazard information for new development will be enhanced by their interest in using the information to meet their responsibilities in sustaining existing development.

One final reiteration: the credibility, accuracy, and content of an MHM is no greater than the individual hazard information from which the MHM was compiled. Any limitations are merely transferred from the individual hazard information to the MHM.

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* Key reference.
** Key reference specifically for multiple hazard mapping.

CHAPTER 7

CRITICAL FACILITIES MAPPING

CHAPTER 7

CRITICAL FACILITIES MAPPING

Contents

List of Figures

CRITICAL FACILITIES MAPPING

SUMMARY

This chapter presents guidelines for the preparation of critical facilities maps, giving examples of such maps, and explaining how they can be analyzed together with multiple hazard maps to assess vulnerability and to select appropriate hazard reduction techniques.

The general goal of any national, regional, or community development program should be to promote the health, safety, and prosperity of the people. Certain public and private facilities are crucial to this goal, which cannot be achieved if they are destroyed, damaged, or their services interrupted. A more specific goal, then, should be that of protecting these facilities from hazardous natural phenomena.

The importance of giving attention in development planning studies to critical facilities and the risks to them from natural hazards is described in Chapter 1. The vulnerability of new critical facilities needed to support development can be reduced by avoiding hazardous areas, designing for resistance, or operating with minimal exposure. Strategies for existing critical facilities include relocation, strengthening, retrofitting, adding redundancy, revising operations, and adopting emergency preparedness, response, and recovery programs.

Mapping critical facilities, comparing or combining that information with a multiple hazard map (MHM: see Chapter 6), and integrating both into project preparation improve decisions during the different stages of the development planning process. The use of the maps ranges from location decisions to criteria for developing construction standards.

A. Critical Facilities Characteristics and Performance

Throughout this primer a natural event causing loss of life and destruction of social and economic environments beyond the control of the affected population is considered a disaster. Large numbers of victims and economic losses are experienced every year as a consequence of natural events. For example, the Mexican earthquake of September 1985, which affected Mexico City and seven states, killed over 10,000 people and caused damage estimated at over US$4 billion. These figures, without precedent in the earthquake history of Mexico, represent a single instance of how natural events affect areas having numerous production facilities and infrastructure.

This section defines man-made structures that can be considered critical in an emergency due to natural events, and describes a technique to estimate the expected behavior of critical facilities in case of such events.

1. DEFINITIONS

The term "critical facilities" in this chapter is used to include all man-made structures or other improvements which because of their function, size, service area, or uniqueness have the potential to cause serious bodily harm, extensive property damage, or disruption of vital socioeconomic activities if they are destroyed, damaged, or if their services are repeatedly interrupted.

The definition used is an expanded version of that proposed by the U.S. Office of Science and Technology Policy (1978). In terms of the development planning process it is important to ensure that the key elements described in the box below are included when considering critical facilities within project planning.

Terms such as "lifelines," "urban lifelines," and "emergency infrastructure" are used in post-disaster damage studies, emergency preparedness planning, and socioeconomic impact evaluations. They usually refer to two particular categories: transportation and utilities. These two categories are of particular importance to (1) locating and serving new economic activities, (2) supporting existing economic activities, (3) providing the connections to, and support of, emergency facilities, (4) contributing to any disaster preparedness, response, recovery, and reconstruction activity, and (5) receiving a high priority for strengthening before a disaster, for emergency operations, and for rerouting or rapid repair after damage or interruption. The term "lifelines" has been variously defined as:

KEY CONSIDERATIONS WHEN IDENTIFYING CRITICAL FACILITIES WITHIN A DEVELOPMENT PLANNING PROCESS

- Unique or large structures whose failure might be catastrophic.
- Emergency facilities whose operation is crucial immediately before, during, or after a disaster.
- High-density occupancy structures whose failure would result in numerous deaths and injuries.
- Facilities required for public safety and security.

- Systems vital to the support of any community (Earthquake Engineering Research Institute, 1977).

- Facilities which are required to transport people, things, energy, and information, necessary "for a community in a modern industrial society to survive and prosper," and "indispensable . . . to other facilities and services that are critical in a disaster setting such as hospitals, fire fighting, and emergency operation centers" (Schiff, 1984).

- (1) Those water, sewage, transportation, and communications facilities necessary for the survival of a community, (2) those systems that provide essential services to a community, (3) those services that are important in our daily lives and that, if interrupted, could cause widespread social and economic inconvenience or loss, and (4) geographically spread networks on which society is dependent (Taylor et al., 1982).

- Critical segments or components (for production facilities, infrastructure networks, and support systems to settlements) which should be recognized as priority elements for rehabilitation following a disaster (Bender, 1987).

According to Taylor et al. (1982), "fire, medical, food, banking, education, and industrial services might be included as lifelines," and what is important "is not a precise definition of lifeline systems so much as a coverage of those safety issues that are likely to be of great concern." For example, the term "vital community facilities" has been used by the U.S. Office of Science and Technology Policy (1978) to include hospitals, fire and police departments, communication and administration centers, and major repair and storage facilities.

In this chapter all vital structures necessary for community health, safety and prosperity are considered critical facilities. Figure 7-1 provides an expanded listing of critical facilities beyond the traditional definition of lifeline systems.

2. CHARACTERISTICS OF CRITICAL FACILITIES

When a natural or man-made event affects a critical facility, the impacts are dramatically multiplied when compared to the effects that a similar event may have on non-critical systems. Chapter 1 discusses the effects of an event on the built environment as dependent on the characteristics of the structures (location, design, materials used, and maintenance) and characteristics of the occupants (density, freedom of movement, and health during the event). The effects of hazardous events on critical facilities depend not only on such characteristics, but also on a number of other characteristics unique to a critical facility.

The secondary hazards created from critical facilities (collapse or failure of dams, toxic-chemical storage facilities, etc.), the disruption of certain services (medical, fire, police, etc.), and infrastructure disruption (electricity, damage to roads and highways, etc.) can all bring increased negative impact to the community above the importance of the critical facility itself.

The critical facilities discussed in this chapter can be destroyed, damaged, or interrupted by technological hazards which are beyond the scope of this chapter. Nevertheless, it is important to emphasize that the facilities discussed are "critical" regardless of their exposure to hazardous events because of their special function, size, service area, or uniqueness. These characteristics can be summarized in the box below.

Other vital national or regional economic activities or facilities besides those defined above vary with each governmental jurisdiction, its resources, and its needs, and should be included in the preparation of a CFM.

Different scenarios have been used to anticipate the behavior of critical facilities when a hazardous event occurs. The property losses to structures and their contents and the number of deaths and injuries of its occupants are estimated. Examples of the use of damage scenarios are given below.

Figure 7-1

EXAMPLES OF CRITICAL FACILITIES THAT CAN BE ADVERSELY AFFECTED BY NATURAL HAZARDS

PUBLIC SAFETY AND SECURITY

Civil defense installations
Communications centers
Emergency management centers
Fire stations
Hospitals and other medical facilities
Mass emergency shelters
Police stations and other installations for public security

HIGH-DENSITY OCCUPANCY

Auditoriums, theatres, stadiums
Churches
Educational facilities
Hotels
Office buildings
Penal institutions

TRANSPORTATION

Airways--airports, heliports
Highways--bridges, tunnels, roadbeds, overpasses, transfer centers
Railways--trackage, tunnels, bridges, yards, depots
Waterways--canals, locks, seaports, ferries, harbors, drydocks, piers

UTILITIES

Communications--lines, stations, printing presses, relay points, antenna complexes
Electric power--water impoundments, fuel storage, generators, transmission lines, substations, switchyards
Petrochemical installations--production, transmission, storage, terminals
Potable water--collection, transmission, siphons, flumes, treatment, storage
Waste water--collection, treatment, discharge

INDUSTRIAL

Corrosives--manufacture, transfer, storage, disposal
Explosives--manufacture, transfer, storage, disposal
Flammable materials--manufacture, transfer, storage, disposal
Radioactive materials--manufacture, transfer, storage, disposal
Toxins--manufacture, transfer, storage, disposal

AGRICULTURAL

Food--storage, processing, transfer
Irrigation systems
Water containment--dams, reservoirs, levees, dikes, other impoundments

CHARACTERISTICS OF CRITICAL FACILITIES

- Extensive exposure in terms of their lineal character (e.g, railways and pipelines).
- Capacity or service areas affecting large numbers of people and vital national or regional socioeconomic activities (e.g., energy systems, irrigation systems, public offices, potable water installations).
- Large numbers of people exposed, requiring immediate and intensive use of skilled persons and limited resources during search and rescue operations (e.g., medical facilities).
- Size and continuous-use character, whose failure can cause secondary hazards over very large areas and an increase in the number of people affected (e.g., flooding because of dam failure, lost food production because of irrigation system damage, conflagrations because of chemical explosions).
- Sole supply to emergency facilities (e.g., electricity) or sole access for repairs to other critical facilities (e.g., highways).
- Interconnections between other critical facilities, thereby aggravating damage and outages (e.g., pipelines and transmission lines).
- Remoteness which causes delays in repairs and increases in outage time (e.g., transmission lines, repeater stations).
- Vital for everyday emergencies, easily overloaded during a disaster, and no substitutes available if damaged (e.g., hospitals and emergency management centers).
- Operation necessary for effective response and recovery activities during and after an emergency (e.g., airports, power generators).

3. DAMAGE SCENARIOS

A scenario is usually thought of as a synopsis or outline of what might happen; thus, a "damage scenario" can be considered a synopsis or outline of a hazardous event and its impacts on a region or community. The following scenarios and techniques have been designed to reflect a particular disaster setting in terms of earthquake hazard.

The designing of a scenario may assume a natural phenomenon that is hazardous and then estimate casualties, property damage, and failure of critical facilities (Figure 7-1). For example, property losses to buildings and their contents, deaths, injuries requiring hospitalization, and failure of critical facilities were estimated for seven postulated earthquakes by the (U.S.) Federal Emergency Management Agency (1980). In addition, the National Oceanic and Atmospheric Administration (Algermissen et al., 1973) researched earthquake losses, the U.S. Geological Survey (1981) presented detailed scenarios for the seven postulated earthquakes affecting major population centers in the State of California (U.S.), and Blume et al. (1978) predicted damage to structures.

Davis et al. (1982) show how a scenario can be used to assess the effects of a future earthquake on several critical facilities. Using an intensity map provided by the U.S. Geological Survey, the State of California Division of Mines and Geology prepared a planning scenario based on a repeat occurrence of the great Fort Tejon earthquake of January 9, 1857. The mapped information was based on the method described by Evernden et al. (1981) and was modified according to additional geologic information. The scenario assumed a magnitude 8.3 earthquake on the southern San Andreas fault.

Zones roughly paralleling the postulated surface rupture along the San Andreas fault were displayed as isoseismal areas (that is, areas within which the anticipated seismic intensities are comparable). Each zone was assigned an intensity rating based on the Rossi-Forel scale. Davis et al. (1982) then showed the distribution of seismic intensity values based on the following hypothetical chain of events: the specified earthquake occurs, various localities in the planning area experience a specific type of shaking or ground failure, and certain critical facilities undergo damage while others do not. An analysis of readiness was then used to provide planning insights, recommend

Figure 7-2

CHARACTERISTICS OF INFORMATION SHOWN ON FIGURES 7-3 THROUGH 7-12

FIGURE NUMBER	SCALE (thousands)	COVERAGE a/	LOCATION AND INDEX OF QUANTITATIVE CHARACTERISTICS	LOCATION	CRITICAL FACILITY TYPE	CAPACITY	SERVICE AREA	NATURAL HAZARDS	COMPUTER-GENERATED MAPS
7-3	1,000	N	X		X				
7-4	400	R	X		X	X			
7-5	250	R		X	X		X	X	
7-6	200	R	X	X	X		X		
7-7	125	R	X		X			X	X
7-8	100	R	X	X	X	X		X	X
7-9	66	R		X	X			X	
7-10	50	R		X	X		X		
7-11	33	U		X	X			X	
7-12	24	U		X	X			X	

a/ N = national, R = regional, U = urban settlement.

further work, and serve as a basis for making or improving emergency preparedness, response, recovery, and reconstruction plans.

The University of California at Los Angeles (UCLA) Ad Hoc Joint Senate-Administration Earthquake Safety Committee (1985) report begins:

> A major earthquake on the San Andreas Fault or on one of the earthquake faults in the vicinity of UCLA could cause from 1,500 to 2,000 deaths on campus, if it were to occur during normal classroom/working hours. The number of serious injuries could be at least twice that number. The likelihood of occurrence of an earthquake of these dimensions within the next 20 years is considered to be high. These estimates take into account expert evaluations of the quality of construction and furnishings of classroom, dormitory, and office buildings as well as the libraries and auditoriums. This report proposes that a campus-wide program be initiated aimed at mitigation of a threat that poses a significant hazard to life as well as to property.

The report addresses vulnerability of the campus and includes performance ratings, priority, and structural evaluation of 27 buildings; nonstructural elements; overpasses and bridges; chemical, biological, and radiation spills; utilities and energy facilities; UCLA Medical Center; and Stone Canyon Dam.

Perkins (1987) used expected damage to selected building types as generalized from past earthquake experience. The building types included tilt-up concrete, concrete and steel frame, and wood frame buildings. This information was then used to create a damage potential map that combines several intensity maps. The cumulative damage factors ranged from "very low" to "extremely high" potential and were defined as the cost of repairing a building divided by the cost of replacing that building. Although these maps show damage for a particular type of structure, several critical facilities can be seen, namely, major highways, railways, bridges, harbors, and airports (Figure 7-7). The identified expected damage factors may or may not apply to the critical facilities.

Additional attention can be brought to expected damage by preparing a comprehensive inventory of past hazardous events and the resulting damage; see Singer et al. (1983) for geologic hazards in Venezuela. For each state, a glossary of past events was prepared which included codes for administrative unit (state), a map-locator code, the location of the event, and its date of occurrence. For each event, the nature of the event, its physical evidence, its relationship to seismic activity, type of material damage that occurred, and the number of victims were noted.

B. Preparation and Use of Critical Facilities Maps

Critical facilities maps (CFM) are a graphical reference which includes information on the location and characteristics of these vital systems. The impact of a natural event on critical facilities is sufficiently important that the mapping of such vital systems should be part of any development planning study. A CFM can be used to assess and reduce vulnerability especially when combined with a multiple hazard map. Such a process is extensively described in Section C.

The CFM discussed here is primarily for use in an integrated development planning study by the various working groups that execute the study prepared under this process. Reference is made in this section to ten examples (Figures 7-3 through 7-12). A summary of the characteristics of the information displayed on Figures 7-3 through 7-12 is shown in Figure 7-2.

Much of the information in Chapter 6, on multiple hazard maps, is applicable to critical facilities and is repeated or adapted in this section for the reader's convenience. Discussions on the benefits of critical facilities mapping, selection of base map, convenient scales and coverage, types of symbols to be used, facilities to be shown, accuracy, key elements, compilation, and sources of critical facility information follows.

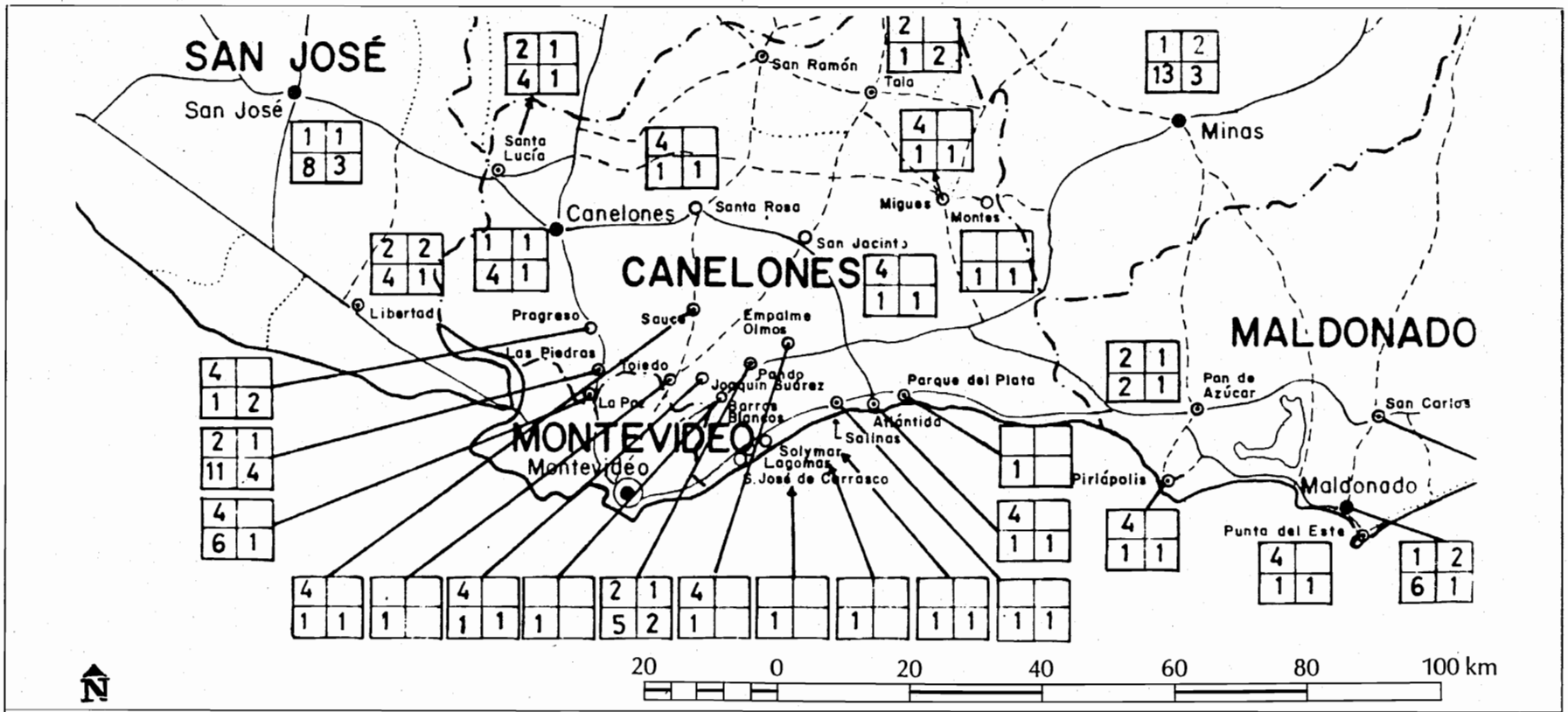
1. BENEFITS OF CRITICAL FACILITIES MAPPING

Maps are the most effective way to convey actual and relative location of critical facilities. A CFM is a prerequisite to addressing and reducing natural hazards that may affect new or existing critical facilities.

The primary purpose of a CFM is not just to convey to planners and decision-makers the location of a facility, but to show its capacity and service area in an accurate, clear, and convenient way. When using a CFM, an extensive number of critical facilities can be included and reviewed at the same time. Also, when combined with multiple hazard maps, they can provide information on which areas require more information, which ones require different reduction techniques, and which locations need immediate attention when a hazardous event occurs. The benefits of using a CFM are summarized in the box below.

Figure 7-3

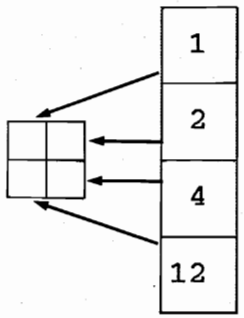
INFRASTRUCTURE AND EQUIPMENT MAP



Legend:

TYPE OF HEALTH FACILITY

1. Departamental center
2. Aid center
3. First-aid post
4. Polyclinic
5. Health center



HEALTH: Type of facility

TECHNICAL UNIVERSITY OF URUGUAY: Number of establishments

SECONDARY: Number of schools

PRIMARY: Number of schools

Source: Adpated from OEA. Proyecto de Asistencia Técnica al Departamento de Planeamiento Regional de SEPLACODI -- República Oriental del Uruguay, Mapa de Infraestructura/Equipamiento. (Washington, D.C.: Organization of American States, 1980).

BENEFITS IN USING CRITICAL FACILITIES MAPS

- A clear and convenient representation of critical facilities in the project area is provided.
- The land-use plans can be assessed prior to implementation.
- The impact of existing infrastructure on potential development can be assessed before project implementation.
- A more concise focus on different types, configuration, structural design, and use of critical facilities in the project area can be made.
- More realistic benefit-cost ratios for new development are possible.
- Lack of information (location, number, size or capacity, and service area) on critical facilities can be identified.
- Identification of a need for more (or better) investigations into the process or susceptibility of hazards is created.
- Facilities requiring emergency preparedness and immediate recovery or repair are identified.

2. PREPARING CRITICAL FACILITIES MAPS

Maps are a planimetric reference which can be prepared to include critical facilities information in hazardous areas. These maps can be used to assess and reduce vulnerability, since they can postulate information on natural phenomena that is hazardous (location, likelihood, and severity) and estimate its effect on numerous critical facilities.

Identifying the various characteristics of critical facilities and understanding how natural events may impact these man-made structures can become a complex and time-consuming task. Weighing and accumulating the impacts may seem almost impossible. Various techniques for assessing critical facilities vulnerability are shown in Section C. However, simple guidance is required when planners and decision-makers prepare a CFM.

The following subsections describe the basic elements that should be considered when preparing a CFM.

a. Base Maps

A prerequisite to compiling critical facilities information onto a map is the selection or creation of a base map upon which to place this information. Such maps are usually identified during the preliminary mission; the team needs only to select a scale appropriate to the study area. Also, the base map used for an MHM (see Chapter 6) can be the same as that used for the CFM.

An adequate base map must (1) be planimetric, that is, a representation of information on a plane in true geographic relationship and with measurable horizontal distances; and (2) have sufficient geographic reference information to orient the user to the location of the facility to be shown. Figures 7-3 through 7-12 are all planimetric and each has sufficient reference information for its scale and areal coverage. For example, the map of Uruguay from which Figure 7-3 is taken shows each city; other maps show highways and rivers; some even show the size and shape of large buildings (Figures 7-11 and 7-12).

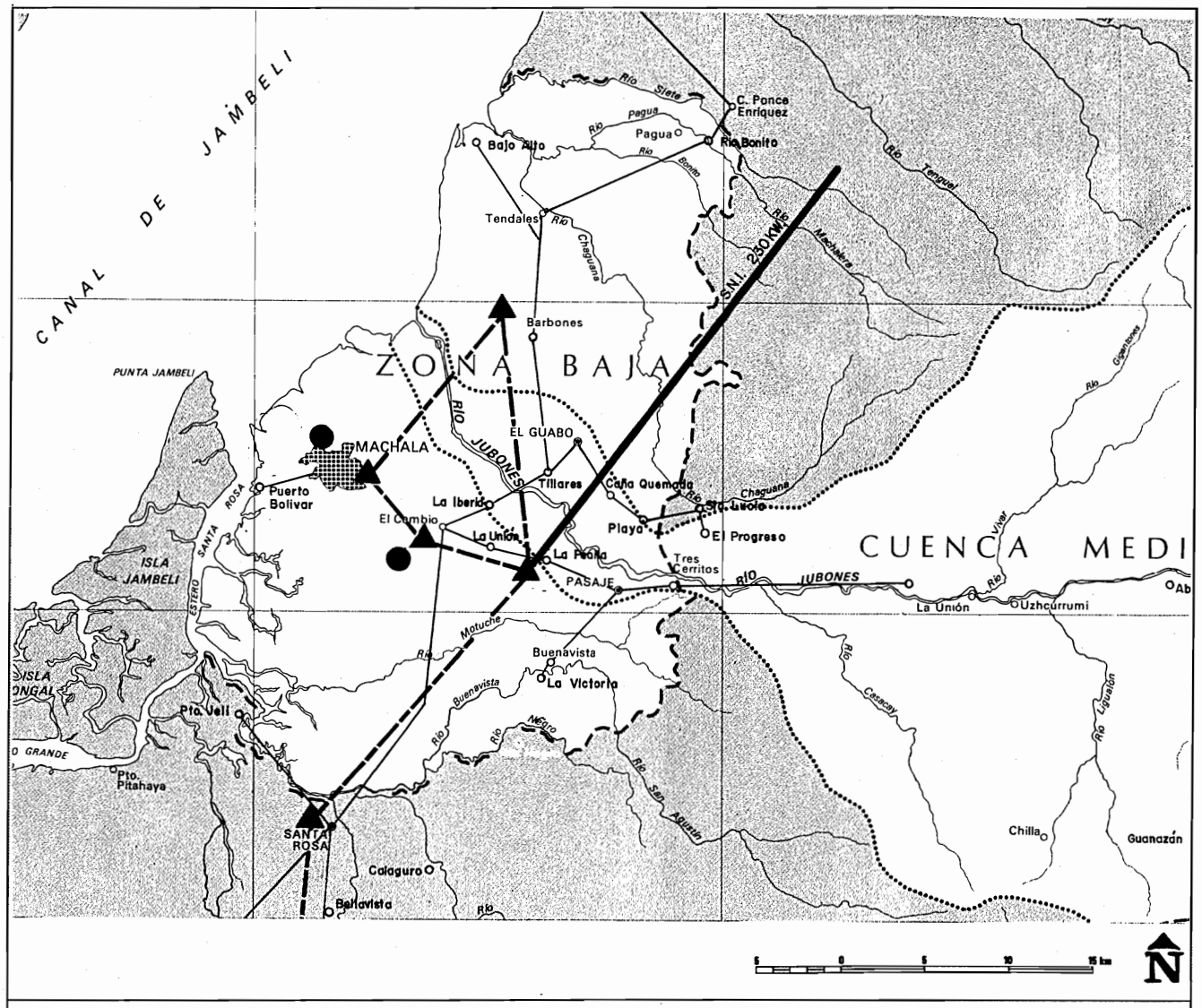
If existing maps cannot be adopted for use as a base map, then one must be constructed. This process can be expensive, since an adequate planimetric representation containing different kinds of information can require trained staff and the use of special equipment and techniques.

Whenever possible, the planning team should adopt as a base map one of the many maps widely available. Chapter 6 provides many examples of the variety of maps that can be used as a base map. Several base maps at different scales may be considered, depending upon the final study area or areas and the predominating scale of the individual facilities maps. The most detailed facilities map may be selected as the base, if it provides adequate geographic orientation. Many maps are created with north at their top, but not all. Therefore, a north arrow must always be included.

Sometimes local agencies prepare a base map that displays information on various man-made improvements (Figures 7-11 and 7-12). For example, base maps at a scale of 1:2,500 to 1:10,000 can be obtained for many urban areas. The OAS Department of Regional Development and Environment and other development assistance agencies have prepared various inventory maps (Figures 7-3, 7-4, and 7-10).

Figure 7-4

CONFIGURATION OF ELECTRICAL ENERGY NETWORK



Legend:

Central thermal station	●	69kv line	
Sub-station	▲	22kv line	
230kv line		13.8kv line	

Source: Adapted from OEA. Plan Hidráulico del Jubones, República del Ecuador, Vol I, Mapa 4-1. (Washington, D.C.: Organization of American States, 1984).

These types of base maps, sometimes called "topographic" or "contour line" maps, are invaluable because many of the critical facilities are shown. Figures 7-11 and 7-12 are good examples of topographic maps which show critical facilities.

Cadastral maps are excellent base maps for CFM because of their scale and orientation information (see Chapter 6). Their characteristics, coverage, scale, accuracy, and cost are discussed in *Physical Resource Investigations for Economic Development* (Organization of American States, 1969).

b. Information Display Techniques

It must be emphasized that the information shown on the CFM is an important factor that the planner or decision-maker should consider when assessing vulnerability or the location of new development. Thus information included in the CFM must be clear, convenient, and not just accurate but perceived as accurate. The selection of an adequate scale and symbols and avoiding large amounts of information which can be difficult to analyze are important display techniques necessary to consider when preparing a CFM. Information on these aspects follows.

Scale and Coverage

Map scale is the measure of reduction in size from the actual environment to that portrayed on the map. Maps are smaller than the area mapped and therefore have a ratio between map distance and actual distance, for example, 1:200,000. This ratio means that one meter on the map represents 200,000 meters on the ground, or one millimeter represents 200 meters. Larger-scale maps usually provide information showing more detail and greater resolution; however, less areal coverage can be shown.

Many different scales are appropriate for the CFM. For example, the map from which Figure 7-3 is taken shows a nation at a scale of 1:1,000,000. However, larger scales (greater detail) are more common for regional development planning (1:500,000 through 1:50,000, Figures 7-4 through 7-10), and community development plans (1:50,000 through 1:24,000, Figures 7-11 and 7-12). Maps at a scale of 1:125,000 can represent a division between presenting facility information in a symbolic way and fixing its location and areal size (compare Figures 7-6 and 7-7).

The scale selected will depend upon the map's purpose; there are no best scales, only more convenient ones (Figure 7-2). The box below lists what scales generally provide useful information for covering certain areas.

The scale used for a CFM is selected on the basis of the information on the facilities to be shown, but also may be dependent upon the scale of the base map. The area covered, scale, detail, facilities shown, and format of a CFM range widely, as shown in Figures 7-3 through 7-12. Sometimes the coverage is limited by the purpose of the map, jurisdiction of the map-maker, or enabling legislation. For example, an awareness of coastal hazards, disclosure of flood and fault rupture hazards, and regulation of fault rupture zones are illustrated by Figures 7-9, 7-11, and 7-12.

If a choice of scales is available, then the factors listed in the box on page 7-15 become important in making the selection.

Maps may be enlarged or reduced. In the case of a CFM, often various types of facilities are mapped at different scales. Also, when combining mapped information about different facilities, an enlargement or reduction to the scale of the base map may be required. Use of controlled photographic methods, or digital registration by computer, makes this process easier and more accurate.

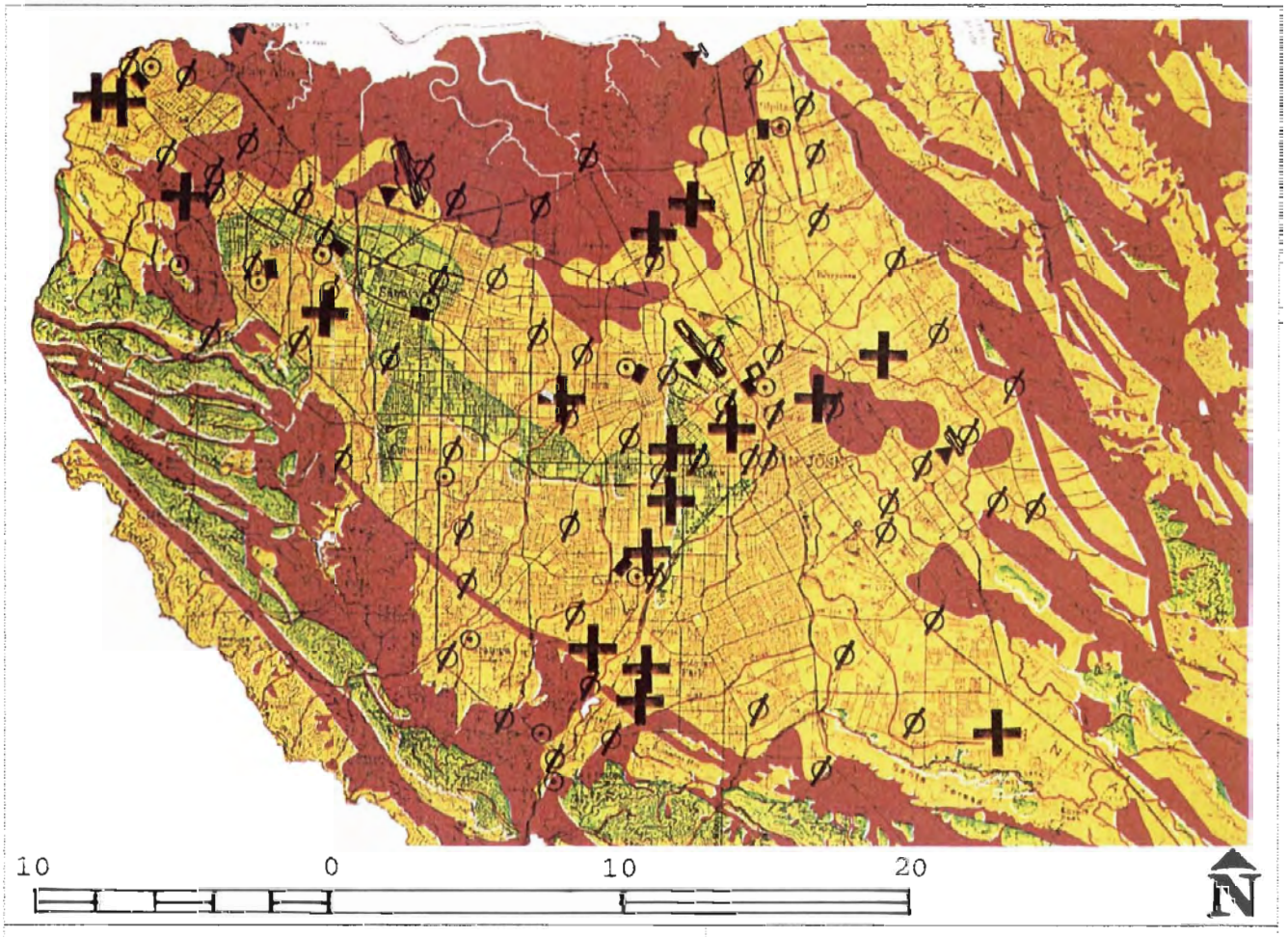
Map titles and explanations are usually unaffected by enlargements or reductions, but not the verbal and

USEFUL MAP SCALES

Area Covered	Map Scales
Nation	1:1,000,000-1:250,000
Region (or island countries)	1:500,000-1:50,000
Urban areas	1:50,000-1:2,500

Figure 7-5

MULTIPLE HAZARD MAP COMBINED WITH EMERGENCY FACILITIES



Legend:

- Where geologic investigation is normally required
- Where geologic investigation is not normally required
- Where geologic investigation may be required
- Hospital
- Airport
- Police station
- Fire station
- City hall
- County administrative center

Source: Adapted from Santa Clara County Planning Department. Seismic Safety Plan. (San Jose, California: Santa Clara County Planning Department, 1975).

FACTORS TO CONSIDER WHEN CHOOSING APPROPRIATE MAP SCALES

- Number and type of facilities to be shown.
- Size or capacity of the facilities.
- Area to be covered.
- Size of final flat or folded sheets of the map.
- Function of the map (for example, whether it's to be an index or detail map).

numerical scales. Written scales (one millimeter equals one hundred meters) and numerical scales (1:100,000) remain accurate only for the original map. When adapting, using, or preparing a map, a graphic scale should always be included.

The map scale selected affects not only the size of the area and the amount of detail that can be shown, but also the location of the facility. For example, if a small scale map (1:1,000,000) using a 1/millimeter-wide line symbol is enlarged ten times (1:100,000), the line symbol becomes one centimeter wide. Similarly, reduction of point and line symbols may result in their de-emphasis or even disappearance.

Symbols

Everything shown on a CFM as well as the base map is a symbol representing reality. Innumerable variations of points, lines, and areas are available to the maker of a CFM. Point symbols can be shaded, patterned, colored, numbered, or lettered. Lines can be solid, long-dashed, short-dashed, or paired, as conventionally used by cartographers in preparing topographic maps. Areas can be shaded, patterned, or colored (Figure 7-7).

Symbols are selected for easy reference and reproduction--examples include numbers (Figure 7-3), letters, conventions (Figures 7-10 and 7-11), computer printout (Figures 7-7 and 7-8), nonconventional symbols (Figure 7-10), and resemblance to real physical form (Figure 7-11). Conventional symbols used on topographic maps may show critical facilities; others indicate jurisdictional boundaries or provide orientation. Some symbols may convey a sense of the facilities; others are totally abstract (electric stations and lines in Figure 7-4). There are no best symbols, only more convenient ones.

The variety of symbols in a CFM is limited only by visual variables--location, shape, size, color, volume, pattern, and direction. The location, type, capacity, and service area of each facility should be given or, if unknown, clearly stated as such. The information provided in the box below presents an explanation of the use of symbols in a CFM.

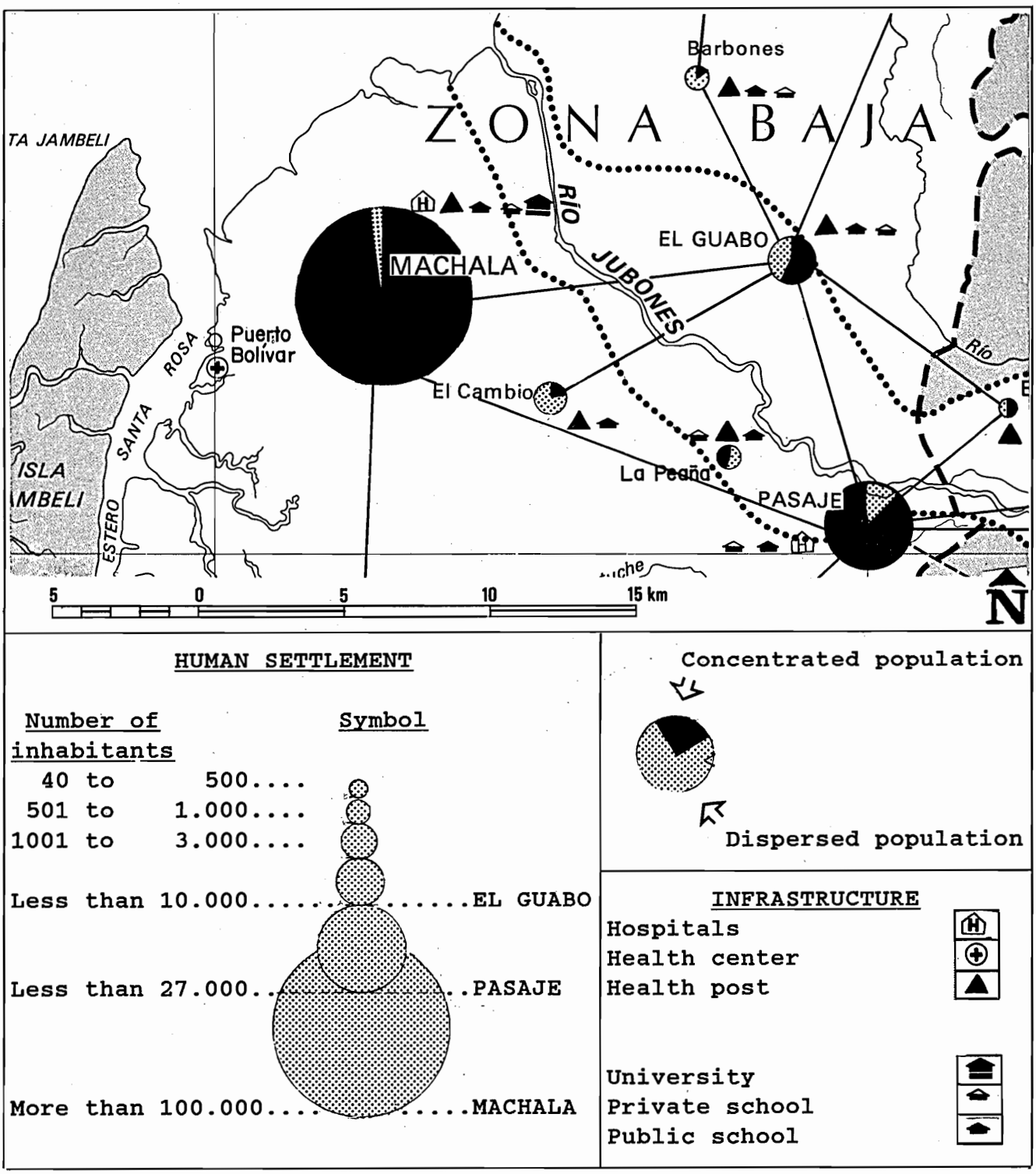
It must be emphasized that all the facilities information shown on the CFM, as well as on the base map information, are symbols--some conventional, others abstract, and many innovative. Planners and decision-makers should be aware that the use and interpretation of symbols may be limited, since often they can be misleading. For example, filling up a CFM with the symbols from several individual facility maps may give the impression of a more thorough study, when, of course, this may be untrue. Simplified critical facilities maps only create an awareness of what information exists and, even more importantly, what information is missing. In this sense, the planning team should understand that a CFM cannot substitute for detailed studies and site-specific investigations.

Also, development planners or decision-makers may be tempted to misinterpret the symbols with the reality they represent. This erroneous practice can be very costly. For example, development planners or investors may want to locate critical facilities needed for economic development along a line that looks the straightest and most convenient on the map. Such a route may lie in a hazardous area. Examples of the misuse of maps by vertical and horizontal distortion, density of symbols, contrasting colors, scales, or the use of symbols and colors which have suggestive, connotative powers beyond their denotative role are discussed by Muehrcke (1978). Map limitation must be appreciated and, when necessary, further investigations should be undertaken.

A thorough discussion of graphic design is beyond the scope of both this chapter and the previous chapter on multiple hazard mapping (Chapter 6). However, the reader and map-maker will find an excellent discussion by Robinson et al. (1978) on a design process, relation to the arts, objectives, components, content, audiences, limitations, and graphic elements of maps.

Figure 7-6

HUMAN SETTLEMENT AND INFRASTRUCTURE MAP



Source: Adapted from OEA. Plan Hidráulico del Jubones, República del Ecuador, Vols. I and III, Mapa 5-A2. (Washington, D.C.: Organization of American States, 1984).

CRITICAL FACILITY INFORMATION DISPLAY

- **Location** can be shown through the use of basic geometric symbols, such as a point, a line, or an area. For example, points have been used to show cities where facilities are located (Figures 7-3 and 7-4); lines have been used to show general routes of electric power lines and water supply pipes (Figure 7-10); and areas have been used to show location of schools and runways (Figure 7-11).

- **Type** can be shown by point symbols, for example, educational and medical facilities (Figure 7-3), communications (Figure 7-10), and emergency facilities (Figure 7-5); lines have been used to show various types of highways (Figures 7-11 and 7-12).

- **Capacity** can be shown by lines, for example, electric transmission line kilowatts (Figure 7-4), and areas have been used to show population size of urban settlements. Combinations of varying line widths have been used to show both direction and volume of energy flow in pipelines or surface transportation. The size of the lettering for the name of a facility has been used to show reservoir capacity.

- **Service Area** can be shown by areas. If service areas have not been defined, interpretations or estimates can be made. For example, where there are only one or two medical facilities serving an isolated urban settlement (Figure 7-3), or a single power line or road serving several urban settlements (Figures 7-4 and 7-10), or specific fire stations in a metropolitan area having a uniform pattern of streets or density of development (Figure 7-5), or where the facility is unique, such as an international airport (Figure 7-11), the service areas should be obvious.

- **Impact** can be shown through various symbols. Computer printout lines have been used to show the intersection of a linear hazard and major water and gas mains (Figure 7-8). Lettered zones can show the percent of telephone system effectiveness (Davis et al., 1982). Computer printout colored patterns can be descriptive in terms of showing the percent of damage affecting specific building types (Figure 7-7).

Critical Facilities To Be Shown

A varying number of different facilities can be shown on a map depending upon scale, symbols, and coverage chosen (Figure 7-7). On a one-sheet national base map only educational and medical facilities are shown (Figure 7-3), or on the one-sheet map of an island numerous facilities are shown or indexed (Figure 7-10). Usually when an area or the number of critical facilities shown is very large, the base maps will be presented on more than one sheet. In some cases certain facilities (Figure 7-5) are shown on one sheet in a series, while other critical facilities--gas and electric transmission lines, or freeways, railways, and bridges--are shown on other sheets in the series. In other cases, three types of facilities and the capacity of one of those types are shown for only one critical facility--electricity (Figure 7-4).

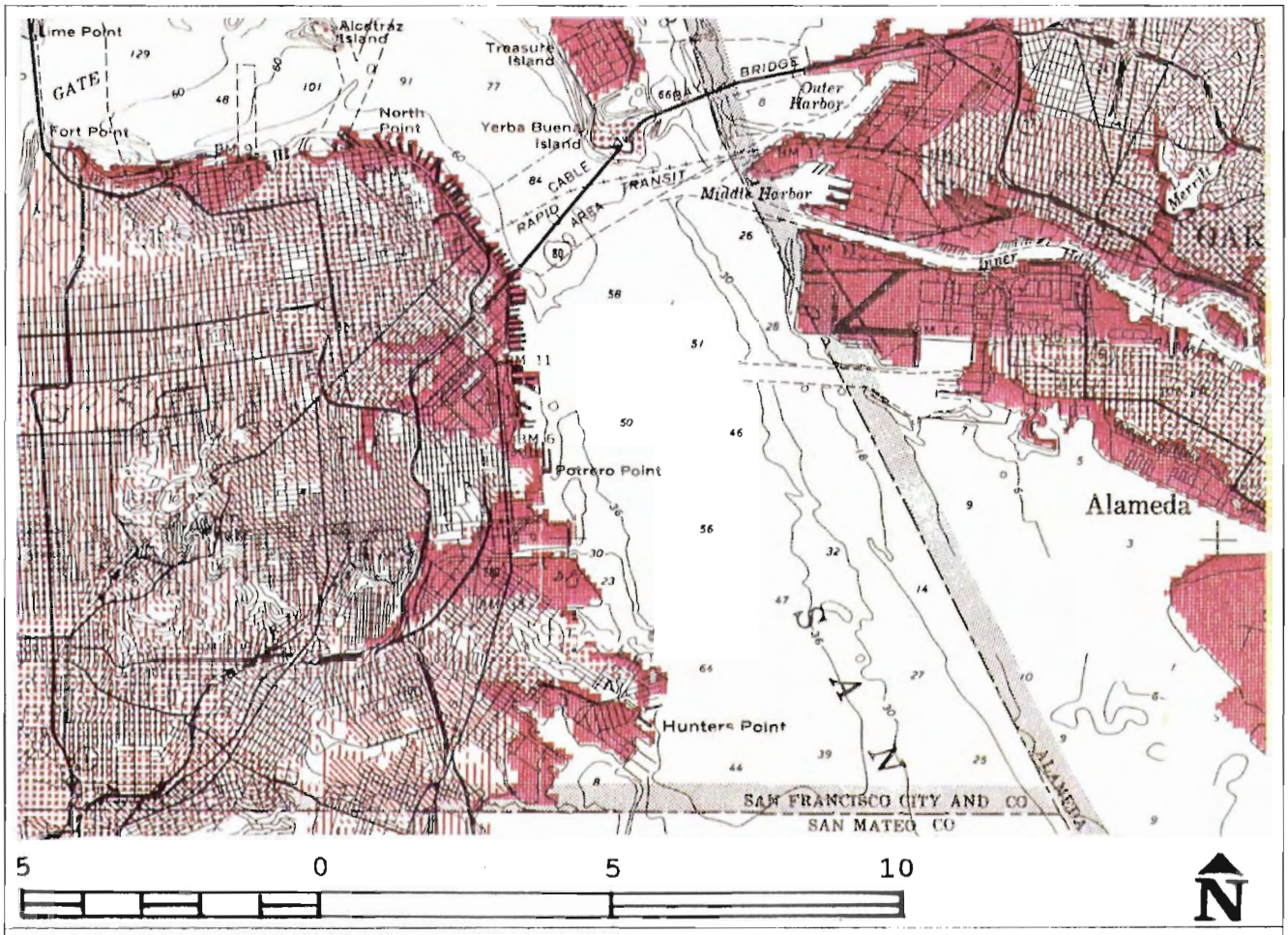
To avoid overcrowding, facilities can be shown by color, by index (Figure 7-3), or by symbol (Figures 7-4 and 7-5). If room is available on the map sheet, or if a written report accompanies the map, photographs of typical and familiar critical facilities can be added.

Accuracy

The locational information on facilities available for the CFM may be accurate, but precision and uniformity may vary when it is transferred. When spherical surfaces are portrayed on a planimetric map, they are only accurate at the contact of the plane with the

Figure 7-7

RISK OF GROUND SHAKING DAMAGE FOR TILT-UP CONCRETE BUILDING MAP



Legend: Cumulative damage potential expressed as expected damage discounted to present value.

- Extremely high cumulative damage potential (6.1+%)
- Very high (5.1-6.0%)
- High (4.1-5.0%)
- Moderately high (3.1-4.0%)
- Moderate (2.1-3.0%)
- Moderately low (1.1-2.0%)
- Low (.3-1.0%)
- Very low (0-.2%)

Source: Adapted from Perkins. The San Francisco Bay Area on Shakey Ground. (Oakland, California: Association of Bay Area Governments, 1987).

actual sphere surface. This can affect location in terms of a CFM. Thus, the locational accuracy of the CFM is dependent upon the accuracy of the base map selected.

Various cartographic projection techniques are used to reduce distortion. The projection technique used can be given to alert users. Depending upon the scale and accuracy of the hazard information, this distortion may not be crucial, particularly if the base map has sufficient geographic information to locate the facilities.

Another form of inaccuracy occurs when the information available does not have an acceptable degree of accuracy because of the limited number of field investigations, lack of available records, and incompatible purpose of the original compilation. The planning team should make sure that decisions for project formulation are based on adequate information. Thus, in a case where information is inaccurate an effort should be made to collect additional and more reliable information. When this is not possible, the planning team should express that any decision at this point is based on less than complete information.

c. Key Elements of Critical Facility Information

The user must perceive the destruction or interruption of the critical facility as adversely affecting human lives, property, or socioeconomic activities. Information translated into a CFM must contain at least four elements and be in a format that a nontechnical user can understand.

The key elements that should be shown when preparing a CFM are (a) location, (b) type, (c) size or capacity, and (d) service areas. These elements are needed by planners and decision-makers to assess the impact on (and protect) critical facilities from hazards. For example, if the facilities are not located in a hazardous area, have limited capacity, or serve a small area, they become of less concern in the planning process.

Usually location is provided because of the geographic nature of maps, although sometimes location can be schematic and not actual, as is the case shown in Figure 7-4.

However, other elements--facility type, capacity, and service area--are not always provided. The user must not assume that because the number of health facilities and schools is given, it is also available for other facilities, as in the case shown in Figure 7-3. Neither must they assume that because capacity is given for electric power lines, it is available for other facilities, as is shown in Figure 7-4.

Information on the type of facility is usually provided. Different categories of road and highway systems are often clearly shown on maps. Nevertheless, other details in terms of type, condition, configuration, and age of the structures are usually reserved for more detailed studies applicable to engineering design stages of investment project preparation.

Information on size or capacity may include diameter of a pipeline, number of highway travel lanes, cubic feet per minute of flow, number of beds or operating rooms, and type of fire fighting equipment. Examples of location may be seen in Figures 7-11 and 7-12, of numbers in Figure 7-3, and of sizes in Figures 7-4 and 7-8.

Service areas are usually not shown, but can be estimated. For example, from Figure 7-10 urban electricity and water supply on Saint Lucia can be easily inferred. Rural service areas may be estimated (Figure 7-5) for a certain area, or easily developed for an area (Figure 7-10), or are obvious in the case of the only aqueduct (Figure 7-12). Population served may be given on the map (Figure 7-6), but many other CFM may lack such information (Figure 7-8). When the number of medical facilities, schools, and fire stations is given for urban areas (Figures 7-3 and 7-5), additional information concerning their capacity or type of equipment should be obtained to ascertain their importance to the lifeline network.

3. COMPILING CRITICAL FACILITIES INFORMATION

Compiling information on critical facilities to make a CFM is similar to making a MHM. It consists of the same four steps--collecting, evaluating, selecting, and combining information.

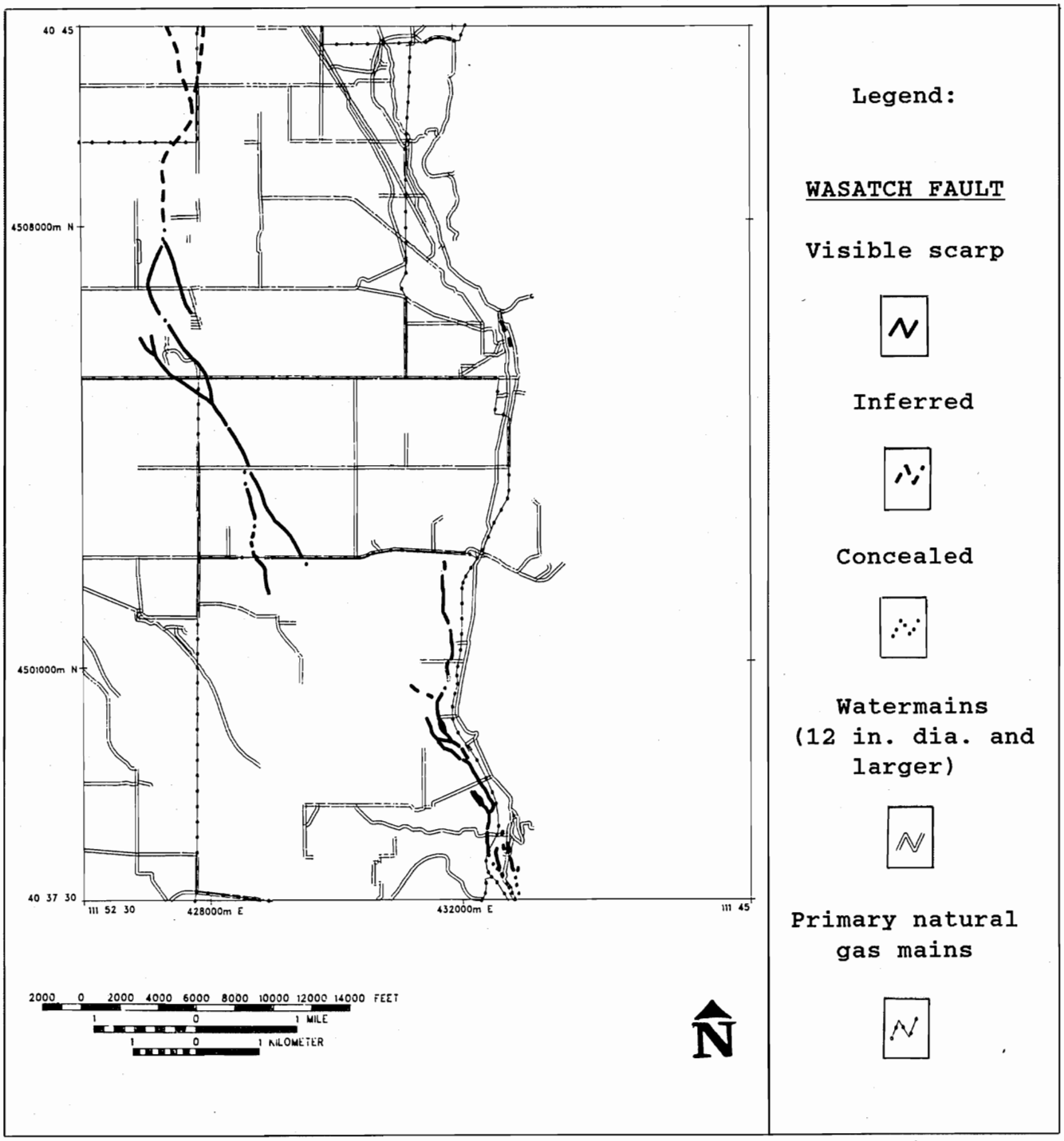
The map compilation process and procedures are discussed in various textbooks on preparing maps (for example, "Elements of Cartography" by Robinson et al., 1978). Chapters 1, 2, and 8 through 11 include recommendations applicable to facilities as well as hazards. Early consultation with technical specialists, identification of facilities early in the planning process, and an initial review of the type and content of available information is recommended.

There are various combinations of base, facilities, and hazard maps already prepared that may only require combining information to prepare a CFM. For example:

- A few critical facilities on a general base map to which hazards and other facilities may be added.
- Numerous critical facilities on a general base

Figure 7-8

SELECTED LIFELINES MAP FOR AN URBAN AREA NEAR SALT LAKE CITY (UTAH)



Source: Adapted from Alexander, et al. "Applying Digital Cartographic and Geographic Information Systems Technology and Products to the National Earthquake Hazards Reduction Program" in Proceedings of a Workshop on Earthquake Hazards along the Wasatch Front, Utah. (Reston, Virginia: U.S. Geological Survey, Open-File Report 87-154, 1987).

GENERAL CRITERIA FOR DATA COLLECTION WHEN COMPILING CFM

- Collecting base maps and appropriate facilities information from the sources identified in Appendix A.
- Evaluating the uniformity and completeness of such information--areal coverage, detail, content, information needed (location, number, type, size or capacity, and service area), format, and symbols.
- Selecting the most appropriate base map (and scale) to be used, facilities to be shown, and symbols to portray those facilities.
- Combining or integrating the selected facilities information into the CFM in an accurate, clear, and convenient way.

(Figure 7-10) to which the coastal hazard information (see Chapter 6) can be overlaid and compared.

- Three critical facilities and one hazard (Figure 7-8) which can be transferred to a topographic base map showing other critical facilities. Other hazards can be added.
- Topographic base maps showing numerous critical facilities (Figures 7-11 and 7-12) and one or two hazards to which additional hazards can be added.

Use of controlled photographic methods and digital registration by computer are excellent ways to reduce the distortion when different types of facilities are compiled or superposed at different scales or maps must be enlarged or reduced to be compatible with the base map. Utria (1988) concluded that, "given the typical financial constraints that prevail . . . deployment of GIS and computer mapping systems should be first attempted by utilizing already available and reliable information (maps, statistical records, and remote-sensing data)."

4. SOURCES OF CRITICAL FACILITIES INFORMATION

There are many examples of critical facility information that can be used when preparing maps within the integrated development planning process. There is a vast array of sources of facility information including various agencies, offices, or institutions at international, national, regional, and community levels--government and corporate. These agencies, offices, or institutions may be concerned with economic development, resource exploration and extraction, land-use planning, emergency preparedness, disaster response, geotechnical studies, utility service, transportation systems, public works, traffic control, public health and education, national security, and community safety.

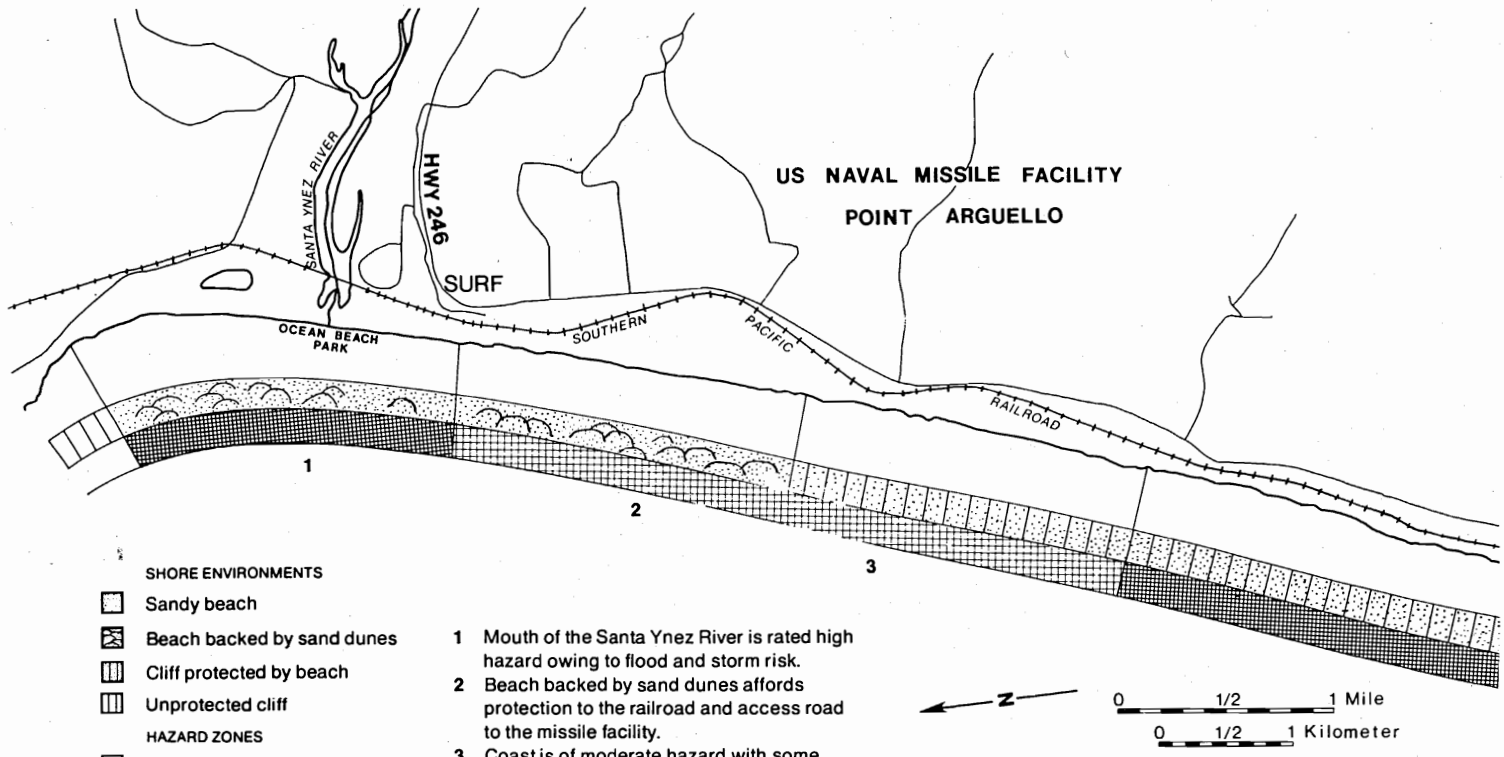
Sometimes critical information can be found in the form of engineering studies, "as built" plans, disaster reports, impacts of past events, facility inventories, etc. Usually this information is not readily understood by nontechnical users. It must be translated for planners and decision-makers and transferred onto maps. At other times, the source information is on maps and can be then transferred from land-use, photographic, topographic, demographic, and tourist maps already prepared for settled regions (see Appendix A).

Finally, conventional sources should not be overlooked when collecting critical facilities information. Chapters 8 through 11 suggest authorities responsible for public works, forestry, and agricultural activities as valuable sources of information. Also, Muehrcke (1978), in his appendix on "Sources of Maps," says:

> When searching for a map of your own region, a wise first step is to consult local sources. City, county, and regional agencies and businesses can probably provide up-to-date information on the status of regional map coverage. If you live near the state capitol, your search will be simplified, because many state agencies use maps in their daily operations. Some states even employ a state cartographer to coordinate the preparation and dissemination of map resources.
>
> If the bookstores do not stock the maps you need, it is possible that the local library will have them. Many universities and public libraries have been designated as map depositories, which means that they receive a copy of each map published by the larger federal agencies. State and local agencies also are prone to deposit copies of maps they no longer need for special projects with these libraries.

Figure 7-9

COASTAL HAZARDS STRIP MAP



SHORE ENVIRONMENTS
- Sandy beach
- Beach backed by sand dunes
- Cliff protected by beach
- Unprotected cliff

HAZARD ZONES
- Safe—low risk
- Caution—moderate risk
- Hazard—high risk

1 Mouth of the Santa Ynez River is rated high hazard owing to flood and storm risk.
2 Beach backed by sand dunes affords protection to the railroad and access road to the missile facility.
3 Coast is of moderate hazard with some areas of high hazard where the railroad approaches the cliff top.

Source: Adapted from Griggs and Savoy (eds.) Living with the California Coast. (Durham, North Carolina: Duke University Press, 1985).

KEY CONSIDERATIONS FOR REDUCING VULNERABILITY IN CRITICAL FACILITIES

- Updating of hazard information and maps by scientists and engineers.
- Continuous updating of facilities information and maps by facilities managers and designers.
- Accurate site investigations by qualified geologists or geotechnical engineers.
- Careful evaluations of facilities by architects, engineers, and safety specialists.
- Prompt adherence to facility emergency procedures by operators and managers.
- Conscientious administration of regulations by building and zoning inspectors and consistent enforcement by government officials.
- Sustained support of inspection and enforcement officials by political leaders.
- Skillful advocacy by public officials and informed interpretation by the courts, if the techniques are challenged.
- Concern for individual, family, and community health, safety, and welfare by developers, investors, donors, and insurers.

5. ASSESSING THE VULNERABILITY OF CRITICAL FACILITIES

The impact of natural events is increasing as the built environment expands. Failure to consider critical facilities in the development planning process and to protect them from natural hazards will result eventually in the loss of lives, bodily injuries, property damage, delayed recovery, impaired restoration of utilities and other services, and disruption of vital economic activities. Depending upon the location, capacity, and service area of a critical facility, its destruction or disruption can be catastrophic.

The emphasis of an integrated regional development planning study on the development of natural resources, energy, infrastructure, agriculture, industry, human settlements, and social services should include the assessment and protection of those critical facilities necessary for development. This effort promotes the activities oriented to reduce the vulnerability of new facilities by avoiding hazardous areas, designing for resistance, or operating with minimal exposure; and in terms of existing critical facilities, it promotes activities related to strengthening and retrofitting vital systems and implementing emergency preparedness, response, and recovery programs. The considerations identified in the box above should be addressed by planners and decision-makers in their activities to assess and reduce the vulnerability of critical facilities.

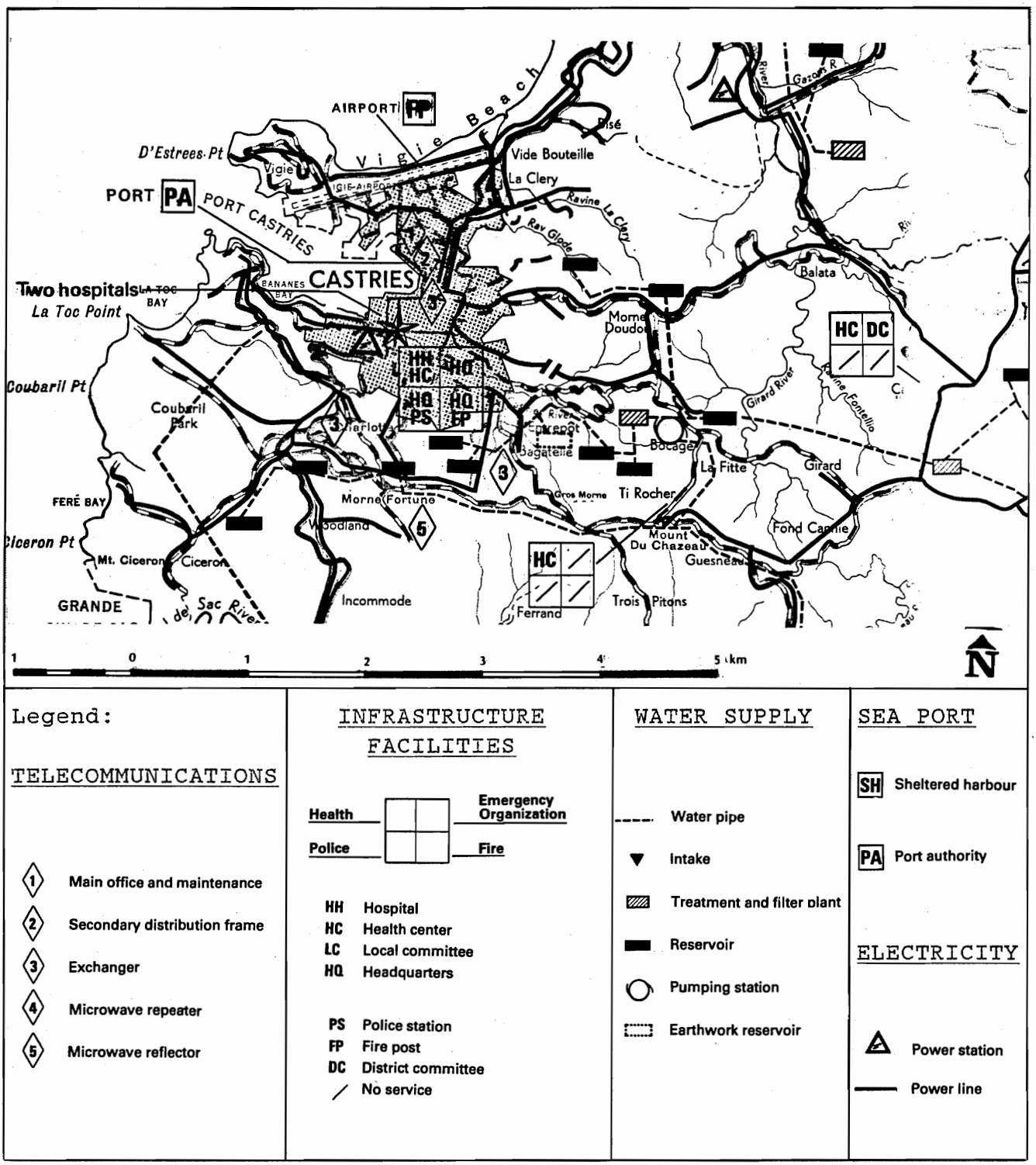
According to the Office of the United Nations Disaster Relief Coordinator (1980), information on vulnerability of critical facilities is "less plentiful, less reliable, and less clearly defined than the information usually available on natural hazards. . . . Various categories of data are required, relating not only to the details of possible material damage, but also to the degree of social and economic disorganization that may take place."

Manuals for identifying and reducing the effects of natural hazards can be prepared for towns, villages, their public officials, and the general population (e.g. St. Helene, 1987). These manuals identify critical facilities at risk, responsible agencies and their role, and actions to reduce hazards, casualties, damages, and outages. They may include matrixes for assessing vulnerability or impact for each hazard and each facility.

It is important to emphasize that the vulnerability of a critical facility does not depend solely on its exposure to hazards. Specific vulnerability depends upon the structure's characteristics, such as uniqueness, type of construction, quality, modification, age, maintenance, height, and first-floor elevation. For example: the expected damage to tilt-up concrete buildings shown in Figure 7-7 is not related to a specific building or site, but rather it is a statistical potential for a selected building type to be damaged given a certain event.

Figure 7-10

LIFELINES NETWORK MAP FOR SAINT LUCIA



Legend:

TELECOMMUNICATIONS

- (1) Main office and maintenance
- (2) Secondary distribution frame
- (3) Exchanger
- (4) Microwave repeater
- (5) Microwave reflector

INFRASTRUCTURE FACILITIES

Health | Emergency Organization
Police | Fire

- HH Hospital
- HC Health center
- LC Local committee
- HQ Headquarters
- PS Police station
- FP Fire post
- DC District committee
- / No service

WATER SUPPLY

- Water pipe
- Intake
- Treatment and filter plant
- Reservoir
- Pumping station
- Earthwork reservoir

SEA PORT

- SH Sheltered harbour
- PA Port authority

ELECTRICITY

- Power station
- Power line

Source: Adapted from OAS. Saint Lucia Lifeline Network Map, prepared with the collaboration of the Ministry of Agriculture, Lands, Fisheries, Co-operatives and Labour of the Government of Saint Lucia. (Washington, D.C.: Organization of American States, 1984b).

LIMITATIONS OF CRITICAL FACILITIES ASSESSMENTS WHEN USING A CFM

- The conclusions regarding the performance of facilities are hypothetical and not to be construed as site-specific engineering evaluations.
- The damage assessments may be based upon a specific scenario. An event of a different type, size, or location will result in a markedly different pattern of damage.
- The facilities shown on small-scale index maps may have been transferred by eye from maps of various scales and the user must view larger-scale (more detailed) maps of individual facilities for more precise locations.
- Service area boundaries may have been estimated based on settlement patterns. Facility managers must be consulted for actual boundaries.
- The scale of the map may prohibit sufficient detail to allow use of the maps for individual facility studies. Analyzing the vulnerability of specific facilities or individual sites should be performed by a specialist.

Identifying the various characteristics of critical facilities and assessing their vulnerabilities is a complex and time-consuming task. In particular, weighing and accumulating the impacts may seem almost impossible, but the method indicated in Figure 7-7 for evaluating specific building types and assessing their vulnerability to a specific hazard is usually suitable.

When assessing critical facilities the planning team should also be aware of the limitations included in the box above, in terms of a CFM.

The following Section C describes different methods of combining a CFM with an MHM. The combination of these two sets of maps becomes a useful tool for assessing critical facilities in term of natural hazard impact.

C. Combining Critical Facilities Maps and Multiple Hazard Maps

There are numerous examples of infrastructure or lifeline information describing critical facilities in the integrated development planning process. This information can be combined with an MHM and used not only for site selection but also for hazard reduction.

There are many benefits in making a CFM, comparing or combining it with an MHM, and integrating both into the development planning process. For example, the location of a critical facility in a hazardous area alerts planners and decision-makers to the fact that in the future a certain facility may confront serious problems. An evaluation of vulnerability dependent upon a careful analysis of equipment and the type, use, and condition of the facility would then be carried out. If the vulnerability of critical facilities is assessed and appropriate reduction techniques are incorporated into each stage of the planning process, social and economic disasters due to natural and other hazards can be avoided or substantially reduced.

The following box includes a listing of the benefits obtained by combining a CFM and an MHM.

1. USES OF COMBINED CRITICAL FACILITIES MAPS AND MULTIPLE HAZARD MAPS

A number of planning and development activities take place at national, regional, and international levels. At these levels, the combination of CFM and MHM can be used by agencies concerned with land-use planning, preparedness and disaster response, utility services including energy, transportation, and communication, and national security and community safety. Moreover, the use of superimposed critical facility information and natural hazard information is important when preparing economic investment projects for national and international bank lending.

A discussion of the planning and development activities which can combine CFM and MHM follows.

Figure 7-11

MID-PENINSULA CITIES STREETS INDEX MAP

Legend: Hazard zones: lightly shaded areas denote flood-prone areas; darker shaded areas denote fault-rupture zones. Numerous critical facilities are shown on this type of base map.

Source: Adapted from San-Mateo Burlingame Board of Realtors. Mid-peninsula cities street index map. (San Jose, California: San Metro-Burlingame Board of Realtors, 1979).

BENEFITS IN COMBINING CFM AND MHM

- Clear and convenient representation of critical facilities in hazardous areas is provided.
- wareness of hazards to critical facilities occurs among project planners and decision-makers prior to project implementation.
- A more concise focus on the effect and impact of natural phenomena on critical facilities is possible during the early stages of the planning study.
- Identification of the extent to which new development can be affected by the failure or disruption of existing critical facilities as a consequence of a natural event can be made.
- Hazards affecting new critical facilities may be reduced.
- More realistic benefit-cost ratios for new development are possible.
- Identification of the need for more (or better) investigations into process or prediction of hazards is created.
- Study areas can be identified and subdivided into sub-areas requiring different assessments, emergency preparedness, immediate recovery, or specific reduction techniques.

a. Examples of Combinations of MHM and CFM

The combination of CFM and MHM has been very effective for land-use planning, preparing for emergencies, increasing public awareness, and planning development.

Land-Use Planning

Land-use planning is one of the most efficient ways of avoiding development or reducing the density of development in hazardous areas. The Santa Clara County, California, Planning Department (1975) prepared an extensive land-use plan in compliance with a state law requiring all cities and counties to prepare and adopt a seismic safety plan. All the potential earthquake hazards--liquefaction, lurching, lateral spreading, differential settlement, ground displacement, landslides, and flooding due to dike failure--were combined on a seismic-stability map. Three zones were then used to indicate three different degrees of need for detailed site investigations, as determined by the level of hazards (Figure 7-5).

Urban settlements, transportation, utilities, and emergency facilities were then superimposed on the seismic-stability map. Citizens, as well as planners and decision-makers, were made aware of potential damage when presented with mapped information depicting homes, freeways, railroads, bridges, pipelines, power lines, hospitals, and fire stations located in the varying hazard zones on the map. In addition, large-scale maps are available to show potential hazards in relation to property boundaries (see Chapter 6).

Another county in California (Santa Barbara County Planning Department, 1979), in preparing its seismic safety plan, provided the location of several critical facilities for orientation, namely, highways, airports, railroads, air force base, and a federal correctional institution. (See the section in Chapter 6 on "Information Processed by Computer.")

Development Regulations

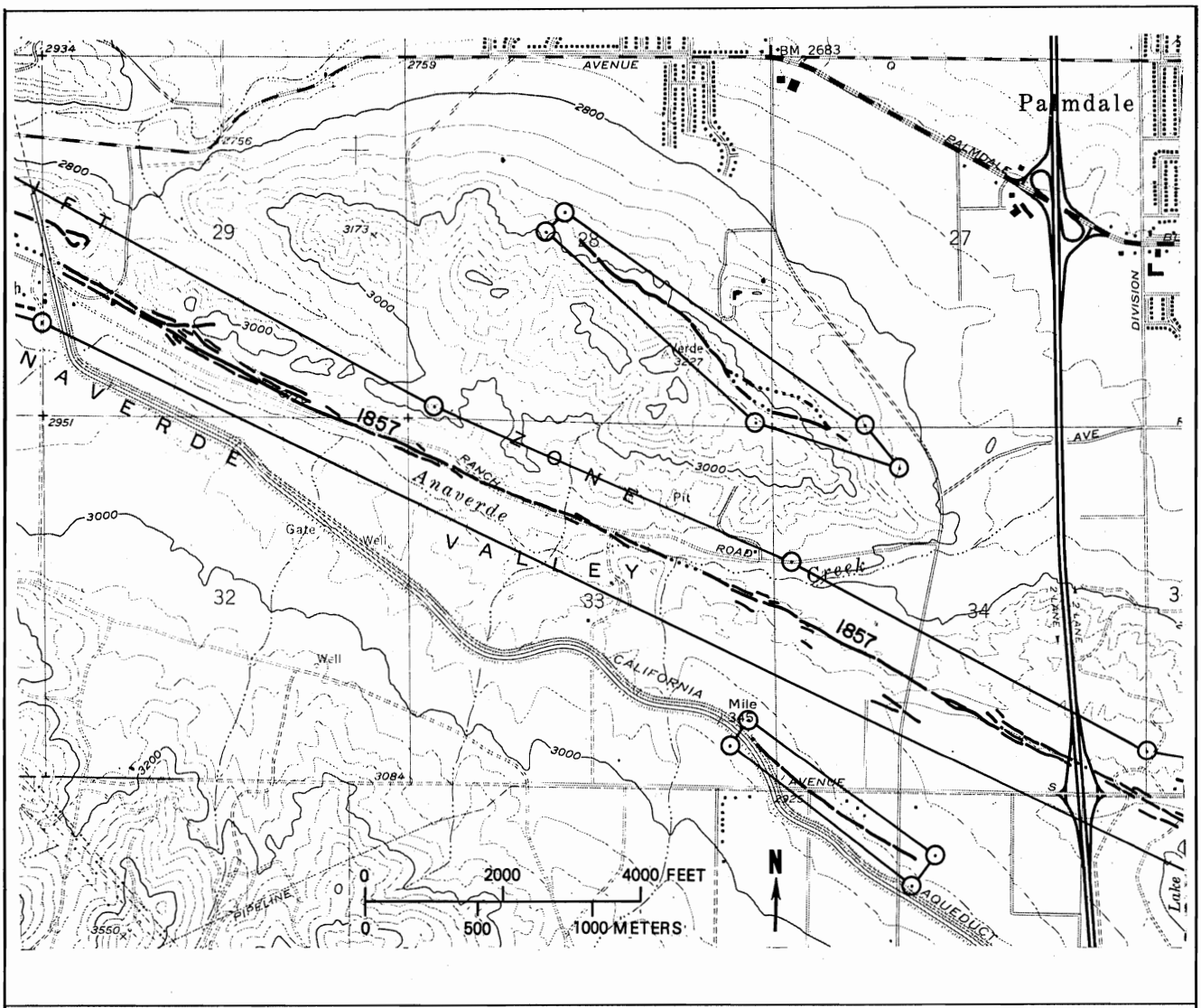
Sometimes critical facilities and hazards information are shown on a map selected for regulatory purposes. For example, the California Legislature (1972) provides for public safety by restricting development in surface fault rupture zones. These regulatory zones encompass 34 counties and 75 cities in California; reproducible copies of pertinent maps (Figure 7-12) have been provided to each affected county and city. Numerous critical facilities are shown on this type of map (e.g., major highways, overpasses, aqueducts, pipelines, and electrical transmission lines).

Disclosure in Land Title Transfers

Often the combination of critical facilities together with natural hazard information is used on maps selected for awareness and orientation of purchasers of land. For example, the U.S. Congress (1974), the California Legislature (1972), and the Santa Clara County Board of Supervisors (1978) require lenders or sellers of real property to inform the prospective borrower or buyer as to whether the property is located in a flood, fault rupture, or landslide prone area.

Figure 7-12

U.S. GEOLOGICAL SURVEY RITTER RIDGE QUADRANGLE



Legend: Part of the U.S. Geological Survey Ritter Ridge Quadrangle (topographic series), which has been used by the California Division of Mines and Geology (1979) as a base map for regulating fault-rupture hazards in the Special Studies Zones (lighter lines) along part of the San Andreas fault. Traces of potentially active faults (heavier lines) are indicated by solid lines where accurately located, by a long dash where approximately located, by a short dash where inferred, and by dots where concealed. Numerous critical facilities are shown on this type of base map.

Source: Adapted from California Division of Mines and Geology, Ritter Ridge Quandrangle-Special Studies Zones Map. (Sacramento, California: California Division of Mines and Geology, 1979).

To assist lenders and sellers in complying with these laws, local boards of real estate agents have prepared street-index maps showing the hazard zones. Figure 7-11 shows two of these hazard zones. The publisher of these street/index maps used topographic maps for the base map. Numerous critical facilities are shown on this type of base map (for example, major highways, airports, overpasses, schools, railways, electric transmission lines, and sewage disposal facilities).

Public Awareness

Often a prerequisite to obtaining support for integrated development planning and hazard reduction is public awareness of not only the hazards but those critical facilities that will be affected. As an example, Griggs and Savoy (1985) mapped more than 1,100 miles of Pacific Ocean coastline in California into three hazard zones reflecting a combination of coastal erosion, wave-cut cliffs, slumping, bluff retraction, landslides, creep, rockfalls, and storm waves. The authors intended to help their readers "make more educated decisions about building, buying, and living on the shorelines." Various critical facilities are shown (for example, a major highway, railway, and military base; see Figure 7-9).

Emergency Preparedness Planning

Alexander et al. (1987) used a digital cartography and geographic information system technology to depict natural hazards--landslides, liquefaction, floods, and fault ruptures. These hazards were then combined with various critical facilities (for example, fault rupture with schools, fire stations, medical facilities, and police stations; and with major gas and water mains; see Figure 7-8). The nature and capability of a geographic information system provides an excellent basis for displaying such information for emergency preparedness planning (see Chapter 5).

Davis et al. (1982), mapped the critical facilities that would require a major emergency response from a damaging earthquake. Facilities included highways, airports, railroads, marine facilities, communication lines, water-supply and waste-disposal facilities, and electrical power, natural gas, and petroleum lines. The communications map, for example, assesses telephone-system performance following a postulated earthquake. Maps for water-supply and waste-disposal facilities show the location and estimates of damage to facilities. Most of the lifelines are susceptible to significant damage that could require a major emergency response effort.

This last study covers a large spectrum of issues. Each CFM is accompanied by a discussion of the general patterns of the effects of an earthquake; for example:

> Not all of the [telephone] systems in the greater Los Angeles [California] region are set up to process emergency calls automatically on previously established priority bases. Thus overloading of equipment still in service could be very significant.

Also, each anticipated mapped event is accompanied by specific examples of expected damage; for example:

> The several hydroelectric-power plants located on the California and Los Angeles aqueducts in northwestern Los Angeles County and the Devil Canyon Power Plant near San Bernardino will be out of service for an extended period of time due to major damage to both of the aqueduct systems.

In addition, each map is also accompanied by emergency planning needs; for example:

> Emergency planners need to identify major emergency routes that can be most readily opened immediately following the earthquake . . . alternative emergency routes should be selected which are at grade, wide, not flanked by buildings which are likely to be damaged, and not likely to be obstructed by fallen powerlines or other obstructions.

Site Selection

Often the likelihood, location, and severity of natural hazards are used as criteria in selecting a site for a critical facility. For example, Perkins (1978) identified potential Class I sites as part of a regional solid-waste-management plan. Class I sites are defined as disposal areas for such hazardous wastes as toxic chemicals, soluble industrial wastes, saline brines, and unquenched incineration ashes.

The Perkins study identifies areas that warrant further study for use as disposal sites for hazardous wastes, and recommends that these disposal sites and facilities be located so as not to adversely affect human health and safety, air and water quality, wildlife, critical environmental resources, and urbanized areas. Sites that may be subject to inundation, washout, faulting, liquefaction, landsliding, or accelerated erosion were deemed unacceptable.

The location and assessment of natural hazards have been a key determination in the evaluation and selection of sites for other critical facilities--offshore

structures, nuclear generating stations, hydraulic fill dams, water pipes, liquefied natural gas terminals, educational facilities, and electrical substations.

b. Regional Planning: The Integrated Development Planning Process

The OAS Department of Regional Development and Environment has used mapping techniques for combining natural hazards and critical facilities information in its planning studies. Multiple hazard maps for national and regional areas were prepared for Ecuador, Honduras, St. Kitts and Nevis, and Saint Lucia and combined with facilities information, which included lifelines, energy supplies, health installations, high-rise structures, water supply, and transportation. A brief discussion of these studies follows.

Ecuador

After listing all development activities for the Santiago and Mira River basins, the planning team evaluated transportation and other infrastructure development proposals. Their workplan included not only a study of the region's human settlement system but the presentation of a chapter on infrastructure development strategy. The largest investment recommended (40 percent of the total) was allocated to critical facilities, namely, developing port facilities, a road system, telecommunication services, energy and rural electrification projects, and other infrastructure (OAS, 1984a).

In another development project (Plan Hidráulico del Jubones), the OAS Department of Regional Development and Environment (1984c) mapped many of the critical facilities--electrical (Figure 7-4) and health and educational (Figure 7-6).

Honduras

The diagnostic stage of the Proyecto de Desarrollo Islas de la Bahía y Atlántida included a flood hazard map (see Chapter 6) which identified several critical facilities--electric transmission lines, highways, railways, hospitals, bridges, schools, and fuel storage. This type of infrastructure information is often available on maps at scales of 1:50,000 or larger prepared by national geodesic institutions.

St. Kitts and Nevis

As part of a development planning study, a critical infrastructure assessment can be addressed (Bender, 1986). Settlements were evaluated in terms of the potential effect of hazardous events. The study included the identification of major critical facilities, such as police, fire, and medical facilities. Their vulnerability was discussed and summarized as follows:

- Medical facilities may be susceptible to wind damage and flooding.
- Electric power lines are susceptible to wind damage and, to a lesser extent, to flooding, erosion, and debris flows.
- The domestic water supply is susceptible to flooding; pipelines from intakes in the higher reaches of the mountains are often damaged at locations where they cross guts.
- The road network and the electric power distribution system are vulnerable to service interruption.
- Damage to schools, medical facilities, and designated first aid stations and shelters can be expected.

Specific recommendations were then made to reduce damage to the road system, water supply, emergency shelters, first aid stations, medical facilities, and school buildings.

Saint Lucia

Extensive work on hazard awareness and mitigation has been carried out by the government in Saint Lucia. Of particular interest is a study (St. Helene, 1986) which identified the risks associated with known natural hazards for ten coastal settlements and their surrounding areas. Critical facilities were described using the generic titles of communications, emergency services, health, education, and energy (Figure 7-10), and facilities subject to hazards were examined (airports, roads, hotels, dynamite storage, a school for the deaf, churches, bridges, post office, electric power poles, navigational lighthouse, electric transformers, sea defense walls, petrol depots, and sewage treatment plants).

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PART III

ASSESSMENT OF SPECIFIC NATURAL HAZARDS

CHAPTER 8

FLOODPLAIN DEFINITION AND FLOOD HAZARD ASSESSMENT

CHAPTER 8

FLOODPLAIN DEFINITION AND FLOOD HAZARD ASSESSMENT

Contents

List of Figures

FLOODPLAIN DEFINITION AND FLOOD HAZARD ASSESSMENT

SUMMARY

In this chapter planners are presented with (1) terms and concepts related to flooding and the nature of areas subject to recurring floods; (2) critical issues to be addressed when considering flood hazards in the development planning process; (3) a technique for using remote sensing data for flood hazard assessments; and (4) two case studies describing the use of remote sensing data to define floodplain areas.

Floodplains are land areas adjacent to rivers and streams that are subject to recurring inundation. Owing to their continually changing nature, floodplains and other flood-prone areas need to be examined in the light of how they might affect or be affected by development. This chapter presents an overview of the important concepts related to flood hazard assessments and explores the use of remote sensing data from satellites to supplement traditional assessment techniques.

The primary objective of remote sensing methods for mapping flood-prone areas in developing countries is to provide planners and disaster management institutions with a practical and cost-effective way to identify floodplains and other susceptible areas and to assess the extent of disaster impact. The method presented in this chapter can be used in sectoral planning activities and integrated planning studies, and for damage assessment.

The satellite remote sensing method presented in this chapter is one of many flood hazard assessment techniques that are available. This method has the following characteristics:

- It uses remote sensing data covering single or multiple dates or events.
- It permits digital (by computer) or photo-optical (film positive or negative) analysis.
- It is best used as a complement to other available hydrologic and climatic data.
- It is useful in preliminary assessments during the early stages of a development planning study because of the small-to-intermediate scale of the information produced and the ability to meet cost and time constraints. The data may also be applicable to other aspects of the study.

A. Floodplains and Their Relationship to Integrated Regional Development

This section is designed to provide the planner with background information on the nature of floods and the terms and concepts associated with assessing the risks from this natural hazard.

1. FLOODS, FLOODPLAINS, AND FLOOD-PRONE AREAS

Flooding is a natural and recurring event for a river or stream. Statistically, streams will equal or exceed the mean annual flood once every 2.33 years (Leopold et al., 1964). Flooding is a result of heavy or continuous rainfall exceeding the absorptive capacity of soil and the flow capacity of rivers, streams, and coastal areas. This causes a watercourse to overflow its banks onto adjacent lands. Floodplains are, in general, those lands most subject to recurring floods, situated adjacent to rivers and streams. Floodplains are therefore "flood-prone" and are hazardous to development activities if the vulnerability of those activities exceeds an acceptable level.

Floodplains can be looked at from several different perspectives: "To define a floodplain depends somewhat on the goals in mind. As a topographic category it is quite flat and lies adjacent to a stream; geomorphologically, it is a landform composed primarily of unconsolidated depositional material derived from sediments being transported by the related stream; hydrologically, it is best defined as a landform subject to periodic flooding by a parent stream. A combination of these [characteristics] perhaps comprises the essential criteria for defining the floodplain" (Schmudde, 1968). Most

simply, a flood-plain is defined as "a strip of relatively smooth land bordering a stream and overflowed [sic] at a time of high water" (Leopold et al., 1964).

Floods are usually described in terms of their statistical frequency. A "100-year flood" or "100-year floodplain" describes an event or an area subject to a 1% probability of a certain size flood occurring in any given year. For example, Figure 8-1 shows this frequency in terms of flood levels and floodplains. This concept does not mean such a flood will occur only once in one hundred years. Whether or not it occurs in a given year has no bearing on the fact that there is still a 1% chance of a similar occurrence in the following year. Since floodplains can be mapped, the boundary of the 100-year flood is commonly used in floodplain mitigation programs to identify areas where the risk of flooding is significant. Any other statistical frequency of a flood event may be chosen depending on the degree of risk that is selected for evaluation, e.g., 5-year, 20-year, 50-year, 500-year floodplain.

Frequency of inundation depends on the climate, the material that makes up the banks of the stream, and the channel slope. Where substantial rainfall occurs in a particular season each year, or where the annual flood is derived principally from snowmelt, the floodplain may be inundated nearly every year, even along large streams with very small channel slopes. In regions without extended periods of below-freezing temperatures, floods usually occur in the season of highest precipitation. Where most floods are the result of snowmelt, often accompanied by rainfall, the flood season is spring or early summer.

2. FLOOD HAZARD ASSESSMENT

Gathering hydrologic data directly from rivers and streams is a valuable but time-consuming effort. If such dynamic data have been collected for many years through stream gauging, models can be used to determine the statistical frequency of given flood events, thus determining their probability. However, without a record of at least twenty years, such assessments are difficult.

In many countries, stream-gauging records are insufficient or absent. As a result, flood hazard assessments based on direct measurements may not be possible, because there is no basis to determine the specific flood levels and recurrence intervals for given events. Hazard assessments based on remote sensing data, damage reports, and field observations can substitute when quantitative data are scarce. They present mapped information defining flood-prone areas which will probably be inundated by a flood of a specified interval (Riggs, 1985). The approximation of a flood-prone area on a map is shown in Figure 8-2. Traditional as well as more recent approaches to gathering and analyzing the necessary information are discussed in Section C., Flood Hazard Mapping Techniques and Application of Satellite Data.

3. LAND SURFACE CHARACTERISTICS RELATED TO FLOODS

Regional development planning should be concerned with the following land-surface characteristics related to floods:

- Topography or slope of the land, especially its flatness;
- Geomorphology, type and quality of soils, especially unconsolidated fluvial deposit base material; and
- Hydrology and the extent of recurring flooding.

These characteristics are commonly considered in natural resource evaluation activities (OAS, 1984). The questions the planning study needs answered are: "How hazardous is the study area for recurring flooding?" and "What is the vulnerability of existing and proposed development activities?" One of the first steps of a planning study is to gather all available information concerning these characteristics and recommend the installation of stream gauges and hydrometeorological stations in regions proposed for development, if they are not already present.

a. Changing Nature of Floodplains

Floodplains are neither static nor stable. Composed of unconsolidated sediments, they are rapidly eroded during floods and high flows of water, or they may be the site on which new layers of mud, sand, and silt are deposited. As such, the river may change its course and shift from one side of the floodplain to the other. Figure 8-3 portrays this dynamic pattern whereby the river channel may change within the broader floodplain and the floodplain may be periodically modified by floods as the channel migrates back and forth across the it.

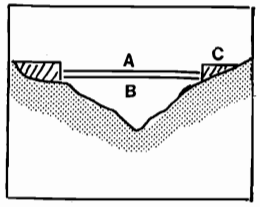
Floodplain width is a function of the size of the stream, the rates of downcutting, the channel slope, and the hardness of the channel wall. Floodplains are uncommon in headwater channels because the stream is small, the slopes and rate of downcutting are high, and the valley walls are often exposed bedrock.

In moderately small streams the floodplain is commonly found only on the inside of a bend (meander), but the location of the floodplain alternates from side to side as the stream meanders from one side of the valley to the other.

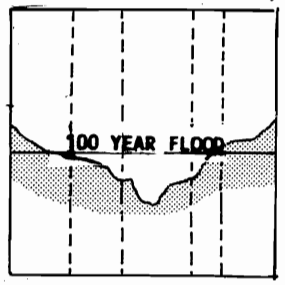
Figure 8-1

DIAGRAMMATIC CROSS SECTION OF A RIVER VALLEY SHOWING THE RELATION OF FLOOD LEVELS AND FLOODPLAINS

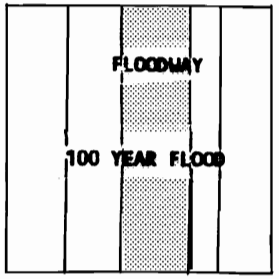
Schematic cross section of a floodplain showing the additions of fill and the creation of a floodway:
A - with floodway
B - without floodway
C - fill

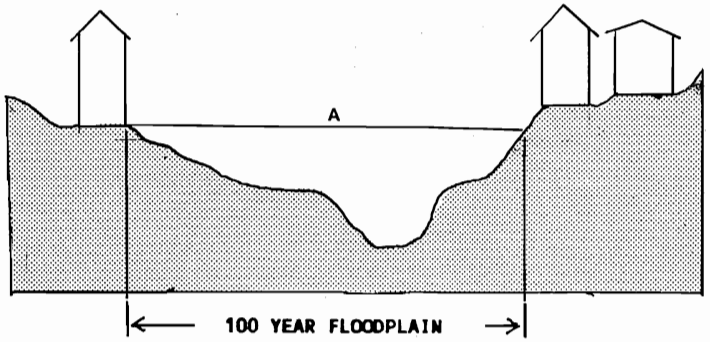


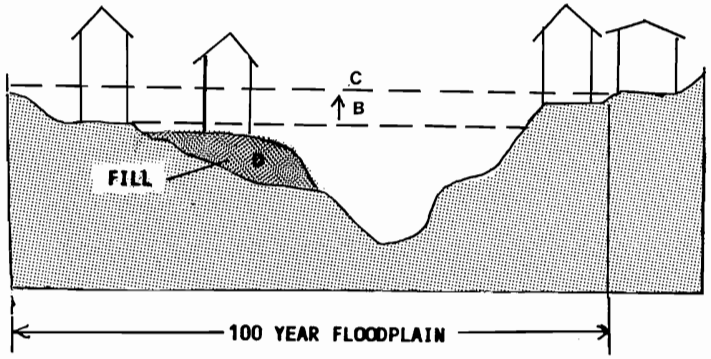
Cross section river valley



Terms







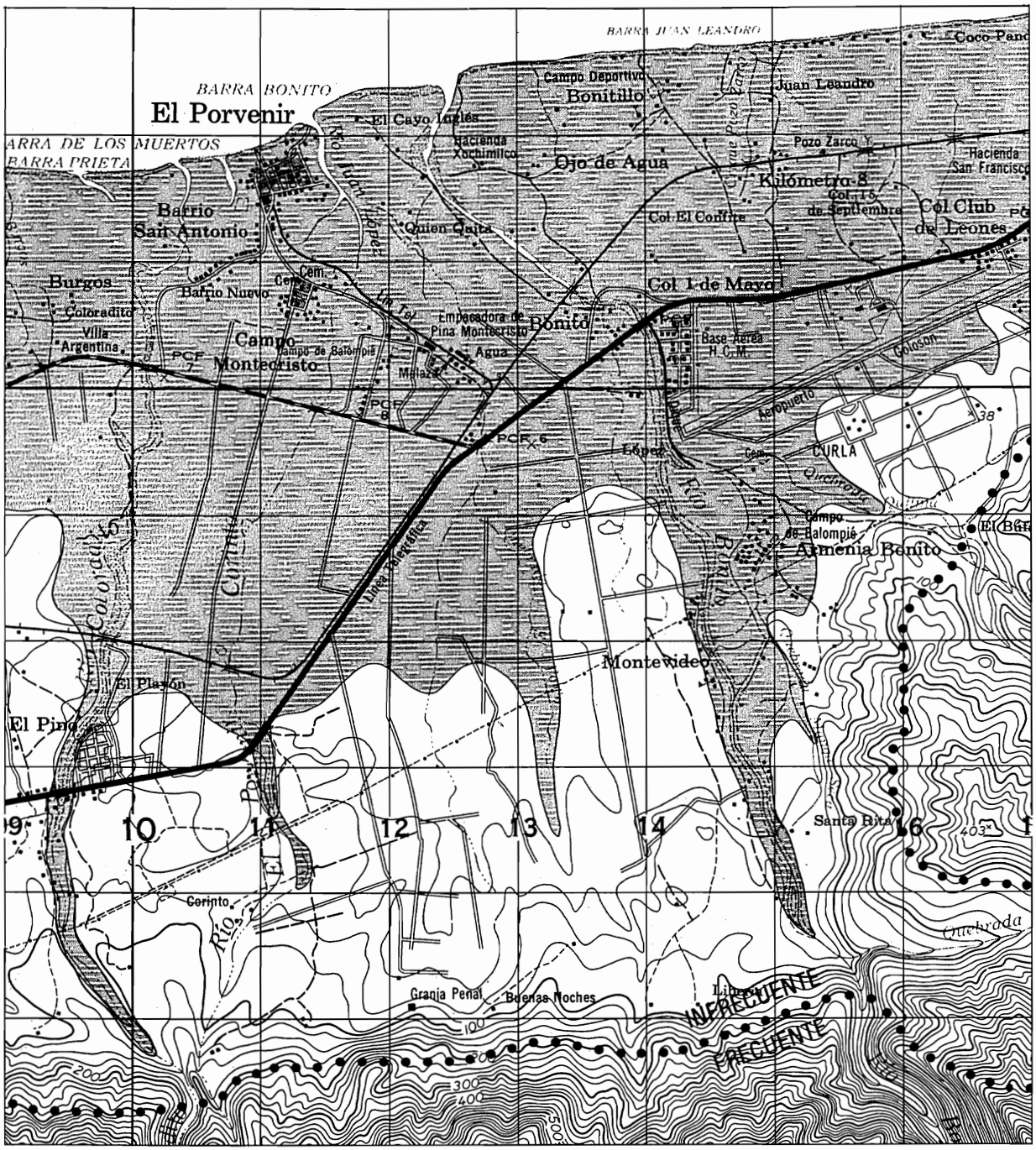
Generalized cross section of a hypothetical river floodplain showing how development on the floodplain increases the flood height:

A - before development
B - increase in flood height
C - after development
D - fill

Building, landfill and other encroachments on floodplain take up space needed for the passage of flood flows. This can result in damage to the development as well as more extensive flooding upstream of and adjacent to the development.

Figure 8-2

FLOOD HAZARD AREA, NORTH COAST OF HONDURAS

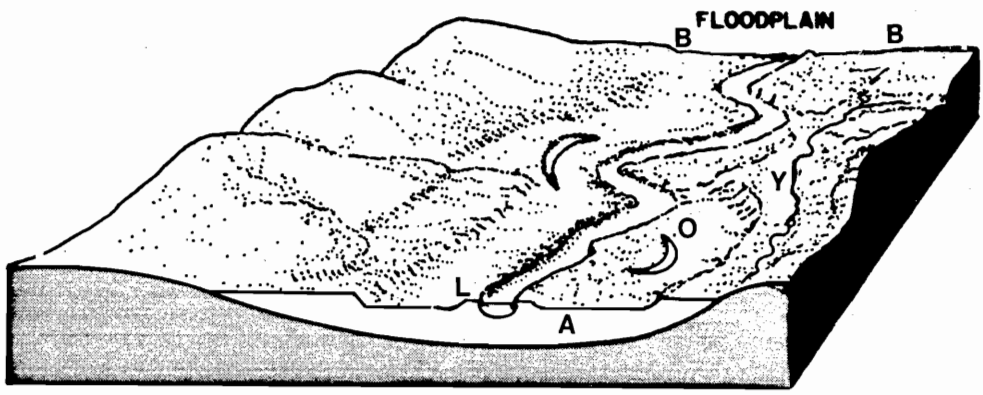


Scale: 1:50,000

Approximate 100-year Floodplain

Figure 8-3

CHARACTERISTICS OF THE DYNAMIC PATTERN OF FLOODPLAINS



Landforms of an alluvial river floodplain with freely developed meanders:

A - Alluvium
B - Bluffs
L - Levees
O - Oxbow Lake
Y - Yazoo stream

Source: Adapted from Strahler, A.N. and Strahler, A.H. Environmental Geoscience: Interaction between Natural Systems and Man. (Santa Barbara, California: Hamilton Publishing Co., 1973).

IN ORDER TO EVALUATE FLOOD HAZARD, A PLANNER NEEDS TO KNOW:

- Where the floodplain and flood-prone areas are.
- How often the floodplain will be covered by water.
- How long the floodplain will be covered by water.
- At what time of year flooding can be expected.

THUS, THE PLANNER NEEDS TO HAVE AN UNDERSTANDING OF THE DYNAMIC NATURE OF FLOODPLAINS.

Larger streams, particularly those with low channel slopes, develop broad floodplains. As these plains develop, the sideward migration of the river channel produces oxbow lakes, sloughs, natural levees, and backswamp deposits that are disconnected from the present channel. If a river carries fairly coarse sediment during a flood, it tends to be deposited along the channel bank as a natural levee. This may result in the formation of a perched channel where the channel bottom is continually raised to a point where it may actually be higher than the surrounding topography. This condition can result in surface water elevations contained within the channel being considerably higher than the land surface elevations immediately outside these levees, which results in a flooding potential that is much worse than that in the typical situation where the channel is at the bottom of a U-shaped cross section of the floodplain.

These features change with time. Widening of a river channel and destruction of part of the floodplain by major floods is common and has been observed in semiarid regions. As is the case with these regions having a high erosion potential, the phenomenon of channel migration during flooding events will often cause a large portion of flood waters to be carried in a channel that did not exist prior to the onset of the flooding event. This phenomenon occurs all too frequently in arid regions, where high velocity flood waters make drastic changes in the channel configuration during the flooding event. This can cause the area of inundation to be considerably different than in its original state.

Channel mobility can be an important characteristic when trying to delineate the potential floodplain. While mobility is not much of a problem in areas with dense vegetation and consolidated soil types, in areas where the vegetation is sparse and soil types are coarse and erodible, mapping of the floodplain must include anticipation of the possibility of channel migration in addition to the existing channel configuration.

A major flood in a humid region is less likely to cause channel widening and floodplain destruction, because vegetation inhibits erosion. However, the flood may cut secondary channels through a floodplain and deposit sand and gravel over large areas, particularly those dedicated to agricultural production.

Terraces along a channel may be mistaken for a floodplain. In fact, some terraces may have been floodplain boundaries prior to renewed downcutting or tectonic activity. A terrace can usually be distinguished from an active floodplain by the type of vegetation and the surface material present.

Natural events such as landslides (see Chapter 10), volcanic-ash drop, lahars, and debris slides (see Chapter 11) can increase the amount of sediment available for transport by a stream. Sediments from these events may be deposited both in the channel and on the floodplain. This can result in the channel filling with debris and reducing the capacity of the channel to hold water. The reduction in channel capacity, although it may be temporary, can result in more frequent inundation of the floodplain and contribute to its modification.

b. Frequency of Flooding

Generally, only annual floods are used in a probability analysis, and the recurrence interval--the reciprocal of probability--is substituted for probability. The annual flood is usually considered the single greatest event each year. The 10-year flood, for example, is the discharge that will exceed a certain volume which has a 10% probability of occurring each year.

The floodplains of some streams, however, are inundated infrequently, at intervals of 10 years or more. Several reasons have been proposed to explain this. In some climates, several years of intense flood activity are followed by many years in which few floods occur. The floodplain may be developed and occupied during

the years with the least flood activity. As a result, this development is subject to the risk of flooding as the cycle of flooding returns. Development activity, particularly deforestation and intensive crop production, may drastically change runoff conditions, thereby increasing stream flow during normal rainfall cycles and thus increasing the risk of flooding. More intensive use of the floodplain, even under strict management, almost always results in increased runoff rates. Effects of development practices on the risk of flooding are discussed below.

c. Length of Inundation

The length of time that a floodplain is inundated depends on the size of the stream, the channel slope, and the climatic characteristics. On small streams, floods induced by rainfall usually last from only a few hours to a few days, but on large rivers flood runoff may exceed channel capacity for a month or more. In 1982-83, the Parana River Basin in Brazil, Paraguay, and Argentina was subject to extensive flooding from late November 1982 through mid-1983. The duration of a flood from tropical storms or snowmelts may inundate a floodplain several times during a single month.

Water on the floodplain usually drains back to the channel as the channel flow recedes. On the wide floodplains of large rivers bordered by natural levees, the water may drain back slowly, causing local inundation or ponding which may last for months. It is eventually disposed of by downstream drainage, water infiltration into the soil, and evapotranspiration. Where channels are perched due to repeated deposition of sediment, flood waters may never drain back to the channel since that channel bottom is higher than the adjacent floodplain.

d. Effects of Development Practices on Flooding and Floodplains, and the Role of Mitigation

People have been lured to floodplains since ancient times, first by the rich alluvial soil, later by the need for access to water supplies, water transportation, and power development, and later still as a relegated locus for urbanization, particularly for low income families. How the land is used and developed can change the risks resulting from floods. While some activities can be designed to mitigate the effects of flooding, many current practices and structures have unwittingly increased the flood risk.

In a humid climate during a major flood, a considerable part of the flow of a stream with a wide floodplain is carried by that floodplain. Clearing the floodplain for agriculture permits a progressively higher percentage of a large flood discharge to be carried by the floodplain. Some parts of the floodplain are eroded and other parts are built up by deposition of coarse sediment, while the channel capacity of the river channel is gradually reduced.

Drainage and irrigation ditches, as well as water diversions, can alter the discharge into floodplains and the channel's capacity to carry the discharge. The effects of agricultural and crop practices vary and depend upon the local soils, geology, climate, vegetation, and water management practices. In many countries agriculture dominates the use of land on floodplains. Where floods are seasonal, crops may be selected that can withstand floods of short duration and low volume during the flood season. Less resistant crops may be grown in the nonflood season.

Forest vegetation in general increases rainfall and evaporation while it absorbs moisture and lessens runoff. Deforestation or logging practices will reduce the vegetation and a forest's absorption capacity, thus increasing runoff. Overgrazing in grassland or rangeland areas decreases the vegetation cover and exposes soil to erosion as well as increased runoff. Cropland development may or may not increase runoff, depending on the land's prior use and the type of cropping patterns utilized.

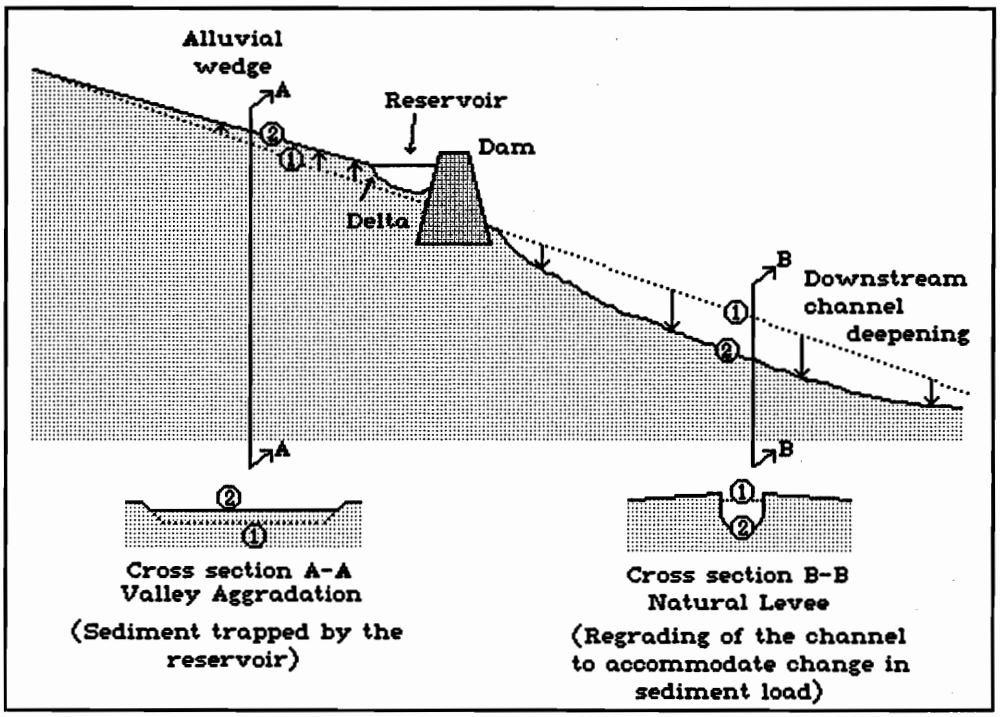
Large dams affect the river channel both upstream and downstream from the dam and reservoir. Evaporation increases as a result of the expanded surface area of the reservoir, and this process tends to degrade the water quality. The reservoir acts as a sediment trap and the channel below the dam will regrade itself to accommodate the change in sediment load, as shown in Figure 8-4. The water, now with little sediment, scours the downstream channel.

Dams may also increase ground-water recharge. They may raise the water table and even induce ground-water discharge into adjacent channels, thereby modifying stream discharge rates. Catastrophic dam failure produces a rapid loss of water from the reservoir and an instantaneously severe and dramatic change downstream.

Urbanization of a floodplain or adjacent areas and its attendant construction increases runoff and the rate of runoff because it reduces the amount of surface land area available to absorb rainfall and channels its flow into sewers and drainage ways much more quickly. Changes in the runoff are shown symbolically in Figure 8-5, where the runoff time is shortened and the discharge rate increases. Artificial fill in the floodplain reduces the flood channel capacity and can increase the flood height. Thus, the risk of flooding is increased, as shown in Figure 8-1.

Figure 8-4

SCHEMATIC PROFILE AND CROSS SECTION OF A RIVER SHOWING BOTH UPSTREAM AND DOWNSTREAM EFFECTS OF A DAM AND RESERVOIR



Note: (1) Original slope with no development.
(2) Accumulation of sediment (cross section A-A) or deepening of channel (cross section B-B) after dam.

Source: Adapted from Strahler, A.N. Planet Earth: Its Physical System Through Geological Time (New York: Harper & Row, 1972).

In summary, floodplain dynamics are basic considerations to be incorporated in an integrated development planning study. It is essential that the study recognize that changes brought on by development can and will affect the floodplain in a multitude of ways. Early review of available flood hazard information and the programming of complementary flood hazard assessments are prudent and allow the planner to foresee and evaluate potential problems related to river hydraulics and floodplain dynamics. Then, mitigation measures can be identified to avoid or minimize these hazards and can be incorporated into the formulation of specific sectoral investment projects.

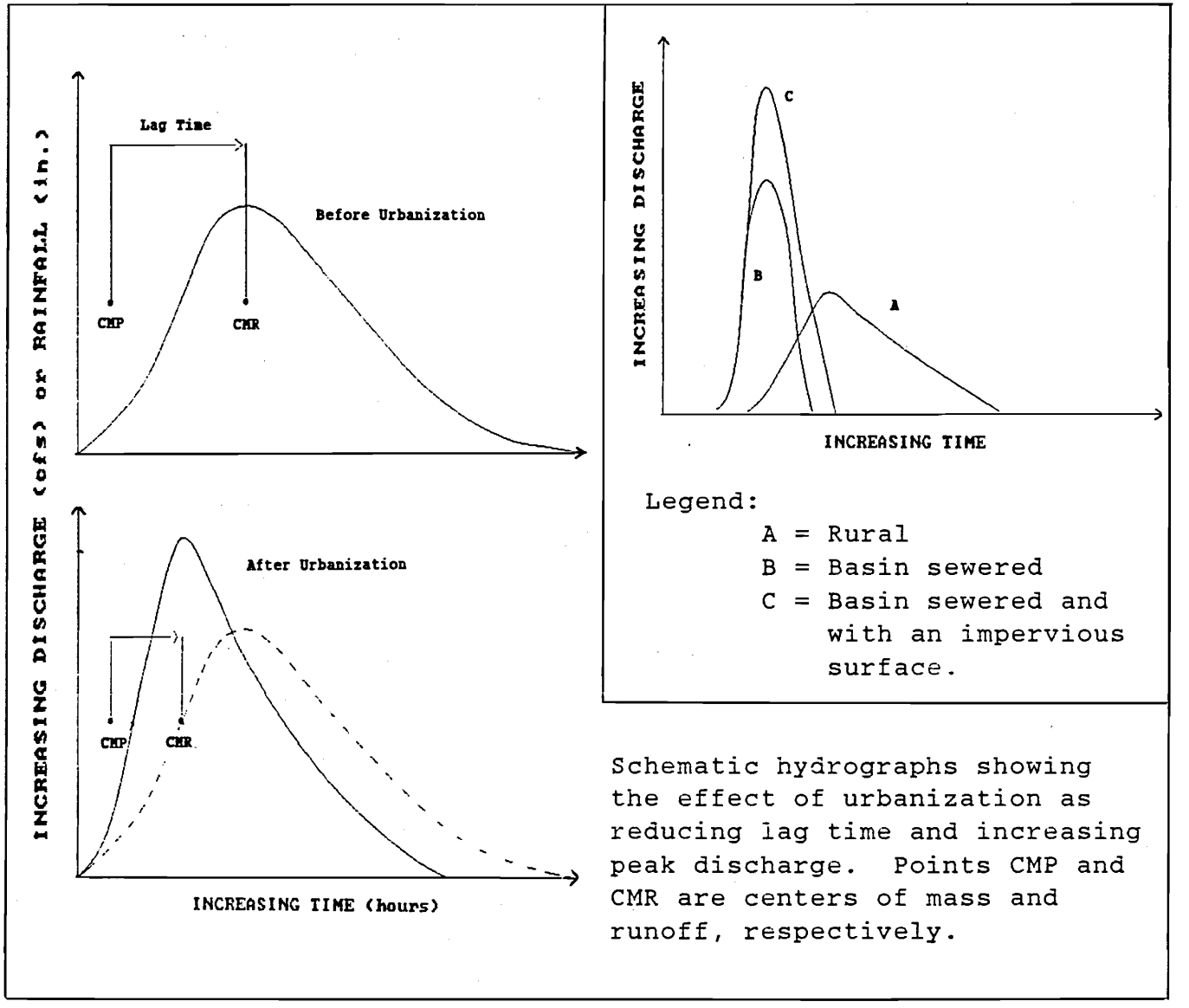
B. Overview of Satellite Remote Sensing Technology Related to Floods and the Development Planning Process

Remote sensing technology can be especially useful and desirable when applied during the planning process. With remote sensing methods, the extent of floodplains and flood-prone areas can be approximated at small to intermediate map scales (up to 1:50,000) over entire river basins. Flood hazard maps can be prepared early in a development planning study to aid in defining and selecting mitigation measures for proposed sectoral development projects. In addition to discerning the risks of flooding, the same satellite data can be used to assess other hydrologic and atmospheric hazards as well as geologic and technological hazards. Furthermore, this satellite information can provide natural resource and land-use information at a small incremental cost once the basic data (computer compatible tapes [CCTs] or film image positives or negatives) are acquired.

It must be emphasized, however, that remote sensing technology is a tool, one of many that are employed by planners today. Application of this technology does not solve problems, but it can provide a planning study with recent, historical, and repetitive information. A detailed discussion of the application of various remote sensing technologies to natural hazard assessments can be found in Chapter 4.

Figure 8-5

FLOOD HYDROGRAPHS SHOWING THE EFFECTS OF URBANIZATION



Source: Adapted from Strahler, A.N., and Strahler, A.H. Environmental Geoscience: Interaction Between Natural Systems and Man (Santa Barbara, California, U.S.A.: Hamilton Publishing Co., 1973); and Riggs, H.C. Streamflow Characteristics (New York, U.S.A.: Elsevier, 1985).

1. DETERMINING ACCEPTABLE RISK

Delineating floodplains and other areas subject to flooding is valuable input for proposing compatible development activities. Failure to understand the nature of flood hazards and to comprehend that they are not necessarily random in time and space, but are in fact roughly predictable conforming to statistical probability, can bring about increased flood risk. The planner should seek the contribution of a variety of disciplines to assess the risk of proposed activities. These concepts are more fully discussed later in this chapter.

Development planners need to know how often, on the average, the floodplain will be covered by water, for how long, and at what time of year. Natural changes as well as changes brought on by development activities affect the floodplain and must be understood to identify appropriate development and natural resource management practices. Changes in floodplain utilization--such as urbanization and more intensive agricultural production--can increase runoff and subsequent flood levels. It is critical for the planner to appreciate these and other effects of land-use change. Early consultation with water resource and management specialists during the planning study is prudent, for it enables the planner to foresee and evaluate potential conflicts between present and proposed land use and their relationship to flood events and the hazards they may pose. See chapter 3 for a discussion of these conflicts.

Acceptable risk criteria can help in distinguishing between different degrees of risk for different development activities and in evaluating constraints associated with potential investment projects. The chosen acceptable frequency of a particular flood event should be appropriate for the type of development activity. For example, it may well be worth the risk of occasional flooding to plant crops in the floodplain where soils are enriched by cyclical flooding and the deposition of sediments. Resulting sand and gravel deposits may lead to commercial exploitation. On the other hand, it is more appropriate to site a large agroindustrial or housing project in an area with a very small probability of a large flood occurring each year (see Chapter 2).

What is the probability that the floodplain will be the site for the next flood event? Will topsoil and bank erosion proceed slowly or at an accelerated rate? Where will erosion be the greatest? Will deposition occur and enlarge the floodplain? What criteria will be used for determining the level of acceptable flood risks based on the expected project life, affected population, available insurance programs, building codes, zoning laws, and other legislation? The planner, while not a technical expert in all these fields, must know to ask the pertinent questions which will be answered by those who are.

2. SATELLITE REMOTE SENSING METHODS APPLIED TO FLOOD HAZARDS

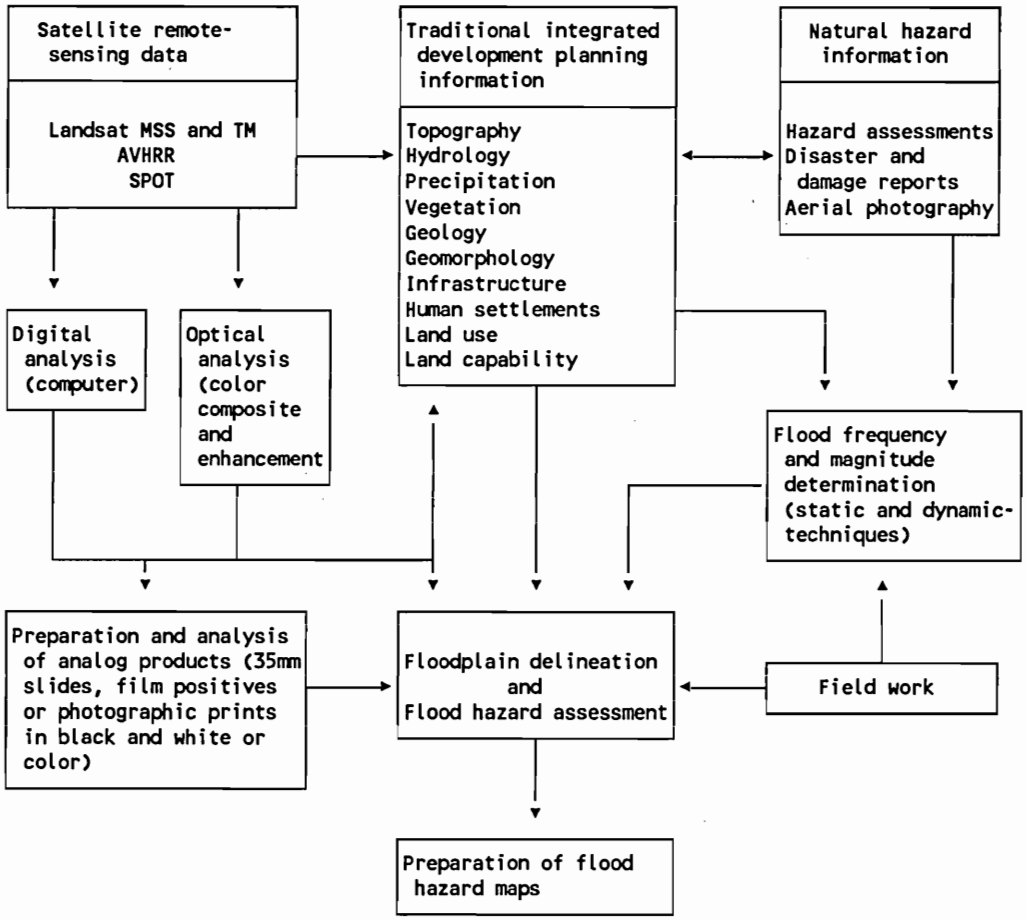
Floodplain mapping techniques are either dynamic or static methods. Many traditional techniques are dynamic: they monitor the continuous change in river or stream flow and require considerable field work and maintenance of long-term records. Some traditional dynamic techniques utilize regression analysis and rainfall estimates derived from models in which long-term records are transferred from similar basins or reaches in a given region. Though these methods do require the application of some records, they may be used where long-term records do not exist for the particular stream or river under study. In any event, the principal objectives of using dynamic techniques are to calculate the return period or frequency of particular flood events and to determine stream flow and flood-level characteristics. These are important for the planner to know in order to adequately weigh the risk of development in a floodplain.

Flood inundation and floodplain maps have been prepared from satellite data for more than a decade by hydrologists all over the world. These are considered static techniques since they characterize the area at a particular point in time. While a dynamic long-term flood history is desirable, such static techniques are capable of yielding useful information for flood hazard assessment, especially in the diagnostic and preliminary stages of an integrated development planning study. In the absence of information from dynamic techniques, it is possible to estimate the probability of a flood event occurrence when information from static techniques is combined with historical flood observations, disaster reports, and basic natural resource information, particularly hydrologic data. Flood event frequency estimates, particularly for an extreme event, is valuable information to the planning study. Figure 8-6 shows the relationship of satellite remote sensing data and other flood hazard information to the information used in the integrated development planning process.

While inexpensive photo-optical processing techniques of satellite data are still valid, the increasing price and decreasing availability of film imagery, and innovative use of digital-to-analog data processing, make computer-assisted analysis a viable option. The commonly used Landsat Multispectral Scanner (MSS) data and the high-resolution Landsat Thematic Mapper (TM) and SPOT High Resolution Visible Range (HRV) data with the potential for larger scale mapping are examples. Also, the small-scale resolution but synoptic

Figure 8-6

RELATIONSHIP OF REMOTE SENSING DATA FOR HAZARD ASSESSMENT AND TRADITIONAL INTEGRATED DEVELOPMENT PLANNING STUDY INFORMATION



regional coverage provided by the NOAA satellite series carrying the Advanced Very High Resolution Radiometer (AVHRR) provides a highly informative aid to planners in determining the extent of flood events.

3. INTEGRATING REMOTE SENSING FLOOD INFORMATION INTO A DEVELOPMENT PLANNING STUDY

One of the requirements of an integrated development planning study is to develop a clear definition of the study area and a sense of the region's general development situation (see Chapter 1). The relationship of the region's natural goods, services, and its hazards and current natural resource management practices should be put in the context of affected ecosystems (OAS, 1984).

In order to integrate floodplain information into a planning study, the definition of floodplains and flood-prone areas and the probability of a given event occurring during the lifetime of a development project should be determined. This information will assist in making decisions about whether or not a certain level of risk is acceptable. It is important to bear in mind that floodplain and flood hazard maps are not intended to be substitutes for, but rather precursors to, engineering design studies.

A variety of mitigation measures can be identified and selected which will reduce or minimize the impact of flooding. Such mitigation measures include adopting land-use classification and zoning systems, building codes, taxation, and insurance programs, in addition to the prevalent "user beware" approaches.

a. Preliminary Mission

All available flood-related information should be gathered during the preliminary mission of the planning study. It is expected that the initial information collected would be general and based on existing hydrologic and precipitation data, satellite imagery, aerial photography, damage assessments, and scientific and engineering studies. Figure 8-7 outlines the relationship of flood information and a flood hazard assessment to general development activities. Selected critical study sub-areas should be identified, and the preparation of additional flood hazard information should be designed into subsequent study activities.

Remote sensing technology can and should play an important role in the design of the planning study. Figure 8-8 provides an overview of the source, scales, and application of remote sensing data for each stage of the study. Map scales of collected information will no doubt vary. Small scale satellite image maps complement traditional thematic maps with synoptic spatial information that can be used as a basis for a regional assessment of the hydrologic regimen, including floodplain definition for major river valleys. Indeed, state-of-the-art technology now permits preparation of thematic image map within U.S. national map accuracy standards for scales as large as 1:50,000.

PRELIMINARY MISSION (STUDY DESIGN)

QUESTIONS PLANNERS NEED TO ASK:

- What type and content of flood hazard information is available for the study area (historical event accounts; disaster and damage reports; hazard, risk, vulnerability analysis)?
- Will additional information be needed? If so, what type? When?
- Will remote sensing data be used? If so, what system and what type of product?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- What complementary information or studies and data analysis equipment will be needed to fully utilize the remote sensing data?
- At what stage will the flood hazard assessment be done? At what cost and during what time period?
- What expertise will be needed to do the assessment? For which areas?
- How will the assessment information be used?
- To what other activities can the remote sensing data be applied?

Figure 8-7

FLOOD HAZARD ASSESSMENT IN AN INTEGRATED DEVELOPMENT PLANNING STUDY

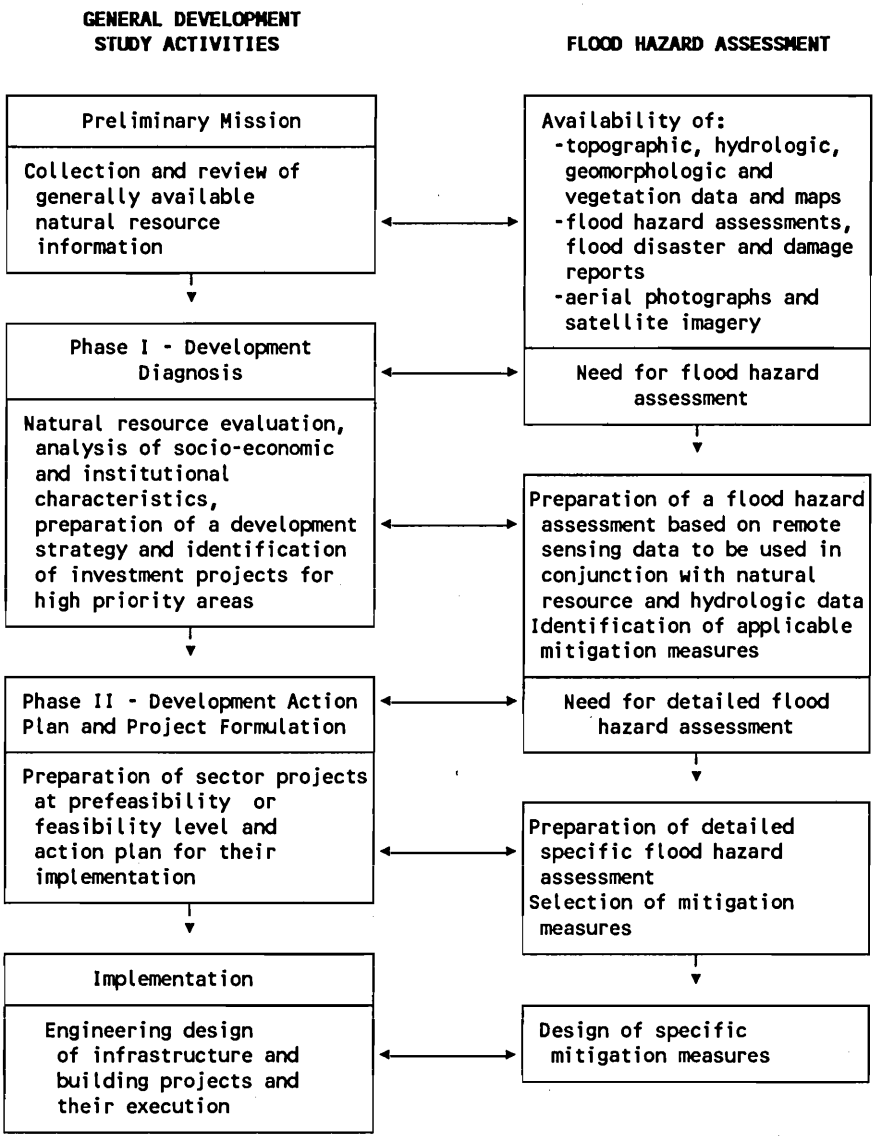


Figure 8-8

REMOTE SENSING DATA: CHARACTERISTICS FOR USE IN AN INTEGRATED DEVELOPMENT PLANNING STUDY

Application of Remote Sensing Data to Study Stages	Satellite Data Source	Nominal Pixel Resolution	Mapping Scale
PRELIMINARY MISSION - Synoptic overview of entire region - Complement small-scale regional maps with color-coded feature depiction - Spatial resolution of study area and resource management issues to broader ecosystem context	NOAA AVHRR Landsat MSS	1.1km 80m	1:1,000,000- 1:3,000,000
PHASE I - DEVELOPMENT DIAGNOSIS - Diagnoses: Natural resource evaluation Ecosystem framework Identification of priority areas	Landsat MSS Landsat TM	80m 30m	1:250,000- 1:1,000,000
Floodplain mapping Flood hazard delineation	Landsat MSS Landsat TM	80m 30m	1:50,000[a]- 1:250,000
PHASE II - ACTION PLAN AND PROJECT FORMULATION - Spatial information for: Floodplain management Flood mitigation measure selection	SPOT HVR SPOT PAN	20m 10m	1:25,000 1:50,000
IMPLEMENTATION - Aid to communications with and among activities in: Investment project execution Funding Project management and operation Emergency preparedness Disaster relief - Reports - Technical and administrative briefings - Seminars	All available sources including experimental systems, e.g., Seasat, Space Shuttle, Nimbus	20m - 1.1km	1:25,000- 1:3,000,000

[a] Mapping at scales as large as 1:50,000 can be accomplished when Landsat MSS and TM data film transparency products are used in conjunction with topographic base maps and field verification.

PHASE I: DEVELOPMENT DIAGNOSIS
(STRATEGY FORMULATION AND PROJECT IDENTIFICATION)

QUESTIONS PLANNERS NEED TO ASK:

- Do flood events and the hazards they pose present a significant variable in determining a development strategy and identifying projects? For which sectors?
- Can non-structural mitigation measures be included as part of the development strategy? Which ones?
- Do flood events pose specific risks to existing or proposed development projects? Is it likely that structural mitigation measures will have to be considered?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Are modifications needed in the original design of the additional flood hazard assessment? Who will make them? How will they be made and implemented?
- What mechanisms will be used to incorporate the assessment information into the overall study activities?
- How and by whom will flood hazard assessment information be summarized for the study documents?
- Will additional flood hazard assessment studies be needed for investment project formulation?

b. Phase I

Phase I of a planning study mandates the diagnosis of a region, which specifically includes spatial and natural resource analyses. SPOT sensors and Landsat MSS and TM sensors are designed to provide data directly relevant to these requirements. Landsat and SPOT data provide up-to-date natural resource and land-use information in spatial, map-compatible forms. Landsat MSS data, which have been collected over most land areas of the world intermittently since 1972, provide the best and most readily obtainable record of floodplains and land-use changes caused by floods, sediment deposition, and human activity.

Landsat TM and SPOT HRV imagery can be effectively used to map floodplains accurately at scales as large as 1:50,000 and to convey the idea that the river meanders across the floodplain. Satellite imagery is especially useful to update existing floodplain and flood hazard maps, particularly for those areas which are highly dynamic in nature. Satellite image maps provide clear, visible evidence to managers that floodplains are dynamic areas and should be studied in conjunction with other thematic maps to identify applicable mitigation measures.

Information from floodplain maps can be used in the preparation of land-use and land-capability maps at this stage (see Chapter 3). The areas inside the floodplains are subject to both floods and river channel meandering. Proposed crop production and construction of irrigation infrastructure, culverts, bridges, roads, and other permanent structures must be studied to evaluate their flood risk. Similarly, the flood hazard information is critically important in planning urban, industrial, recreational, tourism, and parkland development.

c. Phase II

Phase II in the execution of a planning study calls for the formulation of projects and preparation of an action plan. Natural resource management planning should include a precise delineation of floodplains and related hydrologic hazards at map scales suitable for the formulation of projects. Floodplain management, flood prevention, and flood mitigation measures (both structural and non-structural) should be included if they are not already part of the project formulation activities. Several alternative mitigation measures are listed in the box below.

FLOOD MITIGATION MEASURES:

Modify Hazard: dams, catchment areas, retention ponds, high flow diversions, cropping patterns, reforestation.
Modify Water Courses: dikes, levees, channeling, stream rectification, erosion control, drainage systems.
Modify Structures: building elevation or strengthening, flood proofing.
Modify Land Use: use zones, subdivision regulations, sanitary and water-well regulations, development restrictions, easements and setbacks, floodplain management, taxation.
Insurance: flood insurance programs.
Forecast, Warning and Emergency Systems: flood monitoring, alert systems, evacuation and rescue plans, shelter and emergency relief.

PHASE II: PROJECT FORMULATION AND ACTION PLAN DEFINITION

QUESTIONS PLANNERS NEED TO ASK:

- Is the available flood hazard assessment information sufficient to adequately formulate investment projects? If not, will additional assessment activities take place within or outside of the planning study?
- What remote sensing systems will be used, and will the data provide additional information for other study activities?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- How and by whom will flood hazard mitigation information be prepared for planning study documents?
- What complementary activities will the study team carry out to maximize the use of the flood hazard assessment and mitigation information with emergency planning and disaster relief institutions?

The planner and/or remote sensing specialist should confer with the sectoral project specialists concerning flood hazard issues related to both the overall study area and the specific site in order to determine the nature and scope of the problem and the information obtained from the analysis of remote sensing data. Since engineering studies for infrastructure and large structure design invariably require a high degree of detail, high-resolution data--both spatial and spectral--may be required. The SPOT HRV and Landsat 4 and 5 TM sensors are currently the best available sources of high-resolution data and should be considered for use as the basic data in preparing large-scale maps for flood risk assessments.

d. Project Implementation

Data products such as photographs, film positives, and slides derived from satellite imagery are also used in the implementation stage of floodplain-related projects. They are widely used and quite effective as documents for presentations and mass media communication, and as a common reference for the various affected agencies. They can be used to explain to the public, the media, and funding organizations the need for mitigation measures, the nature and locations of the project to be implemented, and the benefits to be derived. Further, they can be valuable in preparing updated maps in the future and by serving as a time-sensitive source of information to

PROJECT IMPLEMENTATION

QUESTIONS PLANNERS NEED TO ASK:

- How will flood hazard assessment and mitigation information be used in project funding approval and execution activities?
- Are there provisions for dissemination of remote-sensing data, control of their use, and periodic updating?
- How will existing or proposed geographic information systems (GIS) use remote sensing data, and how will it be entered, used, stored, and updated on an ongoing basis?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Who will be responsible for incorporating flood hazard assessment and mitigation information into the project funding and execution activities?
- Which institution will be responsible for entering, storing, and retrieving the data and information?

monitor the project. Finally, they provide excellent background material for technical and administrative briefings and seminars with national and local government officials involved in project decision making. In the project-implementation stage, where effective communications are required at all levels--planning, funding, management, and field operations--all types of satellite data collected and assembled at all scales will become increasingly valuable as users become familiar with the characteristics, information content, applicability, and use of the data.

It should also be emphasized that once the implementation stage is reached, information generated from field studies and engineering design activities should include a flood frequency analysis, if it is not already available by this time. Such information is a critical component of a risk analysis, and without it the usefulness of floodplain delineation information is greatly diminished.

C. Flood Hazard Mapping Techniques and Application of Satellite Data

Traditionally, gathering and analyzing hydrologic data related to floodplains and flood-prone areas has been a time-consuming effort requiring extensive field observations and calculations. This traditional approach uses historical data of flood events to delineate the extent and recurrence interval of flooding. With the development of remote sensing and computer analysis techniques, now traditional sources can be supplemented with these new methods of acquiring quantitative and qualitative flood hazard information. This static approach uses indicators of flood susceptibility to assess an area's flood proneness (Sollers et al., 1978). Both of these approaches are discussed below.

1. TRADITIONAL TECHNIQUES OF FLOODPLAIN MAPPING

Conventional dynamic flood frequency analysis techniques have been developed to quantitatively assess flood hazards over the past half century. These traditional techniques yield dynamic historical flood data which, when available, is used to accurately map floodplains. In addition to a record of peak flows over a period of years (frequency analysis), a detailed survey (cross sections, slopes and contour maps) along with hydraulic roughness estimates is required before the extent of flooding for an expected recurrence interval can be determined. In traditional floodplain mapping, the requisite data and maps include the following:

- The selected base (topographic) map with the surface water system
- Hydrologic data:
  * Frequency analysis (including river discharge and historical flood data)
  * Flood inundation maps
  * Flood frequency and damage reports, etc.

* Stage-area curves
* Slope maps
* Cross sections
* Hydraulic roughness

- Related maps such as soils, physiography, geology, hydrology, land use, vegetation, population density, infrastructure, and settlements.

This dynamic approach requires extensive long term field surveys, with a network of gauging stations that can develop the data needed for precise risk assessments. Such extensive long term information is seldom available for river systems in less developed countries. To obtain hydrologic data, one must contact the appropriate hydrometeorological agencies of government to secure available data and maps (see Appendix A). Soils maps and geological maps often delineate floodplains. Topographic maps at suitable scales for the project should be available within the country. What is more readily available is information derived from static techniques which are capable of yielding information on flood hazard assessment.

2. REMOTE SENSING TECHNIQUES FOR FLOODPLAIN MAPPING

For large areas, such as major river valleys, time and funds available are often limited. Therefore, it is usually not possible to conduct expensive detailed hydrologic data gathering, analysis, and mapping activities during a planning study (OAS, 1969 and 1984). Remote sensing technology, especially space technology, now provides an economically feasible alternative means of supplementing traditional hydrologic data sources. These static techniques provide pictures of an area that can be analyzed for certain flood-related characteristics and can be compared to images from an earlier or later date to determine changes in the study area.

Remote sensing methods require a platform such as a satellite (e.g., Landsat) or an aircraft, plus a sensor such as an MSS on the platform. Satellite imagery can be acquired in digital (CCT) or analog (film) formats. Digital data may not be an alternative because of the expense and requirement for sophisticated computer hardware and software. Therefore, the focus of the method presented here is to provide a technique which uses original or raw film data for floodplain mapping and floodplain hazard assessments. The concept of preprocessing CCTs is also discussed below since it is feasible to acquire digitally enhanced film products for these applications.

Flood-inundation and flood hazard maps have been prepared by many hydrologists all over the world from aircraft and satellite data, mostly from the visible and infrared bands (Deutsch, 1974). A few hydrologists have used thermal infrared data to map flooded areas (Wiesnet et al., 1974, and Berg et al., 1981).

Satellite data can be used to find indicators of floodplains, and may be easier to use than aircraft images in delineating floodplains (Sollers et al., 1978). Computer-enhanced information from aerial photography or a combination of this with satellite imagery has been used. Digitized color-infrared aerial

REFERENCES FOR FLOOD FREQUENCY AND WATER ELEVATION ESTIMATION TECHNIQUES

The history of the development of conventional flood frequency techniques and illustrations of the technique are well documented in "Bulletin No. 17B, Guidelines for Determining Flood Flow Frequency" by the United States Water Resources Council, Hydrology Committee (Washington, D.C.: Revised September, 1981).

For guidance in the estimation of flood water surface elevation, the "Flood Water Surface Elevation Determination Manual," prepared by the Oregon Department of Land Conservation and Development (Salem, Oregon: December, 1984), should be consulted. It presents a simplified method for flood profile generation. While the method does require some form of historical data, it demonstrates that there are methods that can be used by non-engineering staff to estimate floodplains without the use of computer models.

LANDSAT FLOODPLAIN INDICATORS:

- Upland physiography;
- Watershed characteristics such as shape, drainage density, etc.;
- Degree of abandonment of natural levees;
- Occurrence of stabilized sand dunes on river terraces;
- Channel configuration and fluvial geomorphic characteristics;
- Backswamp areas;
- Soil-moisture availability (also a short-term indicator of flood susceptibility);
- Soil differences;
- Vegetation differences;
- Land-use boundaries;
- Agricultural development; and
- Flood alleviation measures on the floodplain.

From Rango and Anderson, 1974.

photographs to classify vegetation that correlates with floodplains have also been used (Harker and Rouse, 1977). Landsat digital data have also been combined with digital elevation data to develop stage-area relationships of flood-prone areas (Struve, 1979). A comprehensive reference for satellite remote sensing techniques relating to water resources is *Satellite Hydrology* (Deutsch, 1981), which has more than 100 papers on the subject.

a. Floodplain and Flood-Related Changes Detected by Remote Sensing

Floods, hydraulic forces, engineering structures, and development on the floodplain can and do result in physical changes in the river channel, sedimentation patterns, and flood boundaries, as discussed earlier in this chapter. It is very costly to continually update maps to accurately depict these changing conditions. Satellite imagery can provide a record of changes to complement maps and conventional point source data. Hence, up-to-date satellite imagery of the study area can be compared with previously collected data to determine changes during specific time periods. Similarly, in mapping a flood using satellite imagery, the inundated area can be compared with a map of the area under preflood conditions.

The flood often leaves its imprint or "signature" on the surface in the form of soil moisture anomalies, ponded areas, soil scours, stressed vegetation, debris lines, and other indicators of the flooded area for days, or even weeks, after the flood waters have receded. Figure 8-9 lists the suggested bands and spectral composites of the various satellite systems for analysis of floodplains and related hydrologic features.

It should be noted that delineation of floodplains using remote sensing data cannot, by itself, be directly related to any return period. However, when it is used in conjunction with other information, the delineated floodplain can be related to an estimated or calculated event. This static method can reveal an area's flood proneness and yield information useful for a flood hazard assessment.

b. Selection of Satellite Data

A critical but generally underestimated requirement for effective use of satellite imagery in flood hazard assessments is the selection of data. A number of sensors on board Earth observation satellites have provided data suitable for mapping floodplains and areas inundated by floods. The sensing systems and observation satellites which have been in operation for the longest period of time are the MSS on all five of the Landsat series and the AVHRR on the current NOAA satellite series. More recent sensing systems and satellites include the TM on Landsat 4 and 5 and the SPOT satellite with HRV sensors (see Chapter 4 for more information and characteristics of each system). Each system has its spatial, spectral, and temporal advantages and limitations (see the box below for a summary of these).

Other remote sensing systems such as those found on the U.S. Nimbus and Seasat satellites and the Space Shuttle have been used experimentally, but their coverage is sporadic. (See Chapter 4 for a discussion of the application of these and other remote sensing systems).

Landsat, NOAA, and SPOT satellites collect data in a digital mode. The data products can be

ADVANTAGES AND LIMITATIONS OF SATELLITE DATA FOR FLOOD HAZARD ASSESSMENTS

- LANDSAT MSS: provides data for relatively small-scale mapping (1:1,000,000 - 1:100,000), with coverage only once every 16 days in 4 spectral bands.
- LANDSAT TM: data are collected with the same frequency as MSS data in six of seven solar reflective spectral bands (1, 2, 3, 4, 5, and 7) and is suitable for larger scale mapping (up to 1:50,000).
- NOAA AVHRR: provides multispectral coverage four times each day (two daytime and two nighttime) but produces data adequate for only small-scale mapping (1:3,000,000 - 1:500,000); most useful in delineating maximum flood coverage of surface areas.
- SPOT HRV: the SPOT satellite HRV sensors provide data for relatively large-scale mapping (up to 1:25,000) from three spectral bands (Multiband [XS] or single band Panchromatic [P]) once every 26 days. It has a pointable sensor mode that can provide data on a more frequent basis.

NOTE: Because the repeat cycle of the Landsat and SPOT systems is greater than 15 days, it is not always possible to collect imagery during peak flooding stages. However, data collected within a period of as much as a month following the flood commonly reveal the extent of the flooded area, due to reflectance differences between the inundated and non-inundated areas.

purchased as CCTs or in analog form as photographic prints or film transparencies. SPOT and Landsat program film product costs are such that the cost of producing thematically enhanced photo-optical data products for specific applications such as floodplain delineation and flood mapping now approaches the cost of digital image processing.

One limitation found in all of the above sensors is that none provide cloud penetration, which may limit the amount of data available in humid, cloud-covered areas. Since most satellite coverage for a single full scene extends over a large area (usually more than 33,000km^2, except for a SPOT scene, which covers approximately 3,600km^2), advantages and requirements of each system are important to keep in mind. In deciding on the scale of the base map for the study, which is dependent on the scale of available topographic maps, it is of primary importance to consider the potential use of satellite data.

3. PHOTO-OPTICAL METHOD FOR INITIAL FLOODPLAIN DELINEATION AND FLOOD HAZARD ASSESSMENT

Integrated regional development planning studies do not traditionally include original flood hazard assessments but rather depend on existing, available information. As emphasized earlier in this chapter, if such information is needed but is not available, an assessment should be undertaken as part of the study. If time and budget constraints do not permit a detailed, large-scale assessment to be carried out, a floodplain map and a flood hazard assessment can be prepared using the photo-optical method, using Landsat data and the planning study information which is usually available (see Figure 8-6). The advantages of using Landsat data, in addition to those already mentioned, are listed in the box below.

Figure 8-10 presents a diagram of the steps involved in the preparation of Landsat data for use in a flood hazard assessment. In the next section, two case studies demonstrate how Landsat data was actually used for flood hazard assessment.

In mapping floodplains, black-and-white positive film transparencies of Landsat imagery in 70mm format are especially useful for floodplain delineation. Applicable map scales range from 1:1,000,000 to 1:100,000 or larger, depending on the availability of complementary flood hazard assessment and hydrologic information. Their usefulness is achieved through their analysis with a color-additive viewer, which provides the greatest capability and flexibility for optical multispectral (more than one band),

Figure 8-9

FEATURES RELATED TO FLOODS AND FLOODPLAINS ON LANDSAT IMAGERY

Landsat Multispectral Scanner (MSS)		
Single MSS Bands		Principal Features
Landsat 1, 2 & 3	Landsat 4 & 5	
4	1	Land use, plant vigor and arid physiography
5	2	Vegetation distribution and density Civil engineering works and buildings
6	3	Good land-water contrast Terrain detail
7	4	Land-water contrast Minimum surface-water distribution Physiographic and terrain detail Soil moisture anomalies
MSS Spectral Composites* (more than one band)		
Landsat 1, 2 & 3	Landsat 4 & 5	
4B, 5G, 7R	1B, 2G, 4R	Standard false-color composite Vegetation appears as red Surface water appears blue to black
4B, 5R, 7G	1B, 2B, 3G, 4R	Scene brightness increased Vegetation is degraded, but visible in yellow to brown tones Surface-water distribution enhanced; excellent for floodplain and wetland mapping** Soil moisture appears as high-density anomaly
4B, 5B, 6G, 7W	1B, 2B, 3G, 4W	Maximum scene brightness Vegetative response in visible bands eliminated Optimum depiction of physiography Maximum separation of land and surface water

Figure 8-9 (cont.)

Landsat Thematic Mapper (TM)***	
Single Bands	Application
1	Soil/vegetation discrimination Water detail
2	Green reflectance by healthy vegetation
3	Plant species differentiation
4	Water-body delineation
5	Vegetation moisture measurements Snow/cloud differentiation
6	Thermal mapping Floodplain/soil moisture anomalies
7	Terrain and structure detail

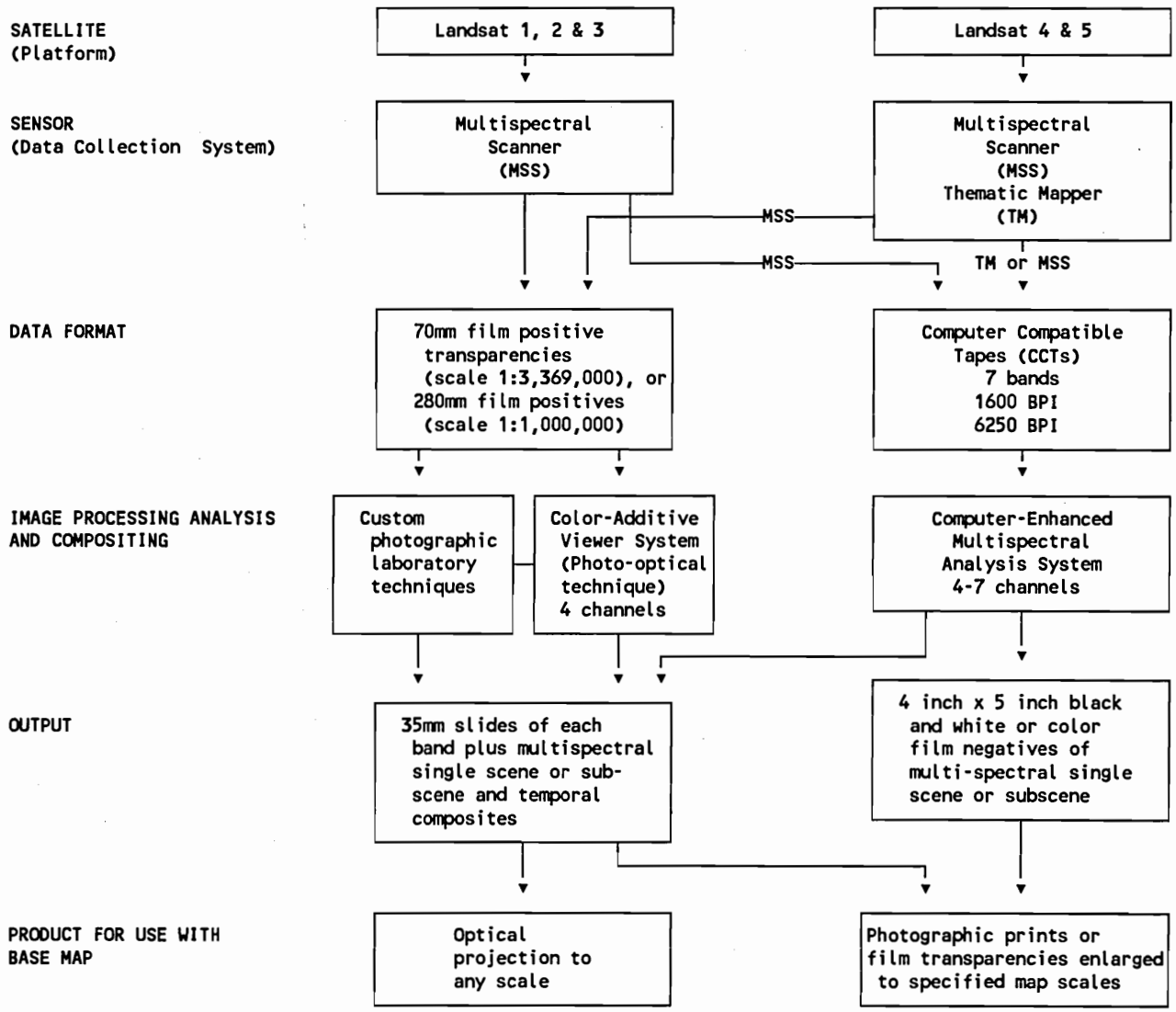
* B = blue-filtered light
G = green-filtered light
R = red-filtered light
W = unfiltered (white) light

** This enhancement was developed for use in floodplain delineation and wetlands assessment of the Paraná River (see Williams, R.S., Jr. "Geological Applications" in Manual of Remote Sensing (2nd ed.), vol. 2, chapter 31 (1983).

*** Adapted from Freden, S.C. and Gordon, F., Jr. "Landsat Satellites" in Manual of Remote Sensing (2nd ed.), vol. 1 (Falls Church, Virginia: American Society of Photogrammetry and Remote Sensing, 1983).

Figure 8-10

APPLICATION OF LANDSAT REMOTE SENSING DATA TO FLOOD HAZARD ASSESSMENT



ADDITIONAL ADVANTAGES OF USING LANDSAT DATA

- Flexibility in using either film-positive transparencies or CCTs purchased directly from the satellite data distributor.
- Flexibility in using either a color-additive viewer, photographic laboratory, or computer for image processing, analysis, and compositing.
- Ability to concurrently use scenes from two dates for comparing pre-event, event, and post-event situations.
- Flexibility in producing 35mm slides, photographic prints, or film-positive transparencies for use at selected base-map scales.

multitemporal (scenes from two dates), and multiscale (images with different scales) analysis. If 70mm film products are not available, film positives at 1:1,000,000 can be cut or reduced to 70mm size and used in the color-additive viewer. This technique permits the imagery to be used as a base for producing enlargements of subscenes.

The photo-optical data-processing method described above has been developed as a low-cost alternative to digital image processing. Digital image processing requires expensive multispectral image analyzers, computers, film writers and appurtenant equipment in addition to a custom photographic laboratory. The advantages, however, in having such a sophisticated capability are listed in the box below.

While data prices vary from source to source and country to country, experience has shown that the per square kilometer cost of data acquisition, analysis, and preparation of analog products may range from U.S. 4 cents using film-positive transparency data format to U.S. 20 cents for CCT data format (1989). A remote sensing specialist familiar with photo-optical or computer-enhanced multispectral analysis systems, in collaboration with other planning studies and with regional complementary information and logistical support, would be able to carry out a flood hazard assessment and prepare a floodplain map for a 30,000-90,000 km^2/ area at a scale of up to 1:250,000 in approximately a one month time period. Exact time allocation obviously depends on the scale of the final map product to be produced, the density of the surface water system, the topography, and the availability of relevant natural resource and infrastructure maps at appropriate scales.

Many countries do have a color-additive viewer available for photo-optical analysis. Most planning, water, and natural resource agencies, however, do not have adequate funds or the need for a full-time dedicated digital image processing facility for computer-assisted map analysis. If use of such technology is desired, international state-of-the-art digital data processing facilities are recommended. Access to either analysis system can be facilitated by specialists who are familiar with satellite data sources; the selection of available imagery, its purchase and processing; and the analysis of analog products.

A facility equipped with only photo-optical equipment and access to a photographic laboratory can utilize digital image processing by arranging for preprocessing CCTs at a qualified facility. Raw data and enhanced film products can be produced on a custom basis for specific applications and be made in formats compatible with the photo-optical equipment available to the user. Such processing should be performed, if at all possible, by a photograph developing and printing specialist in collaboration with a computer programmer and professionals knowledgeable about the study area.

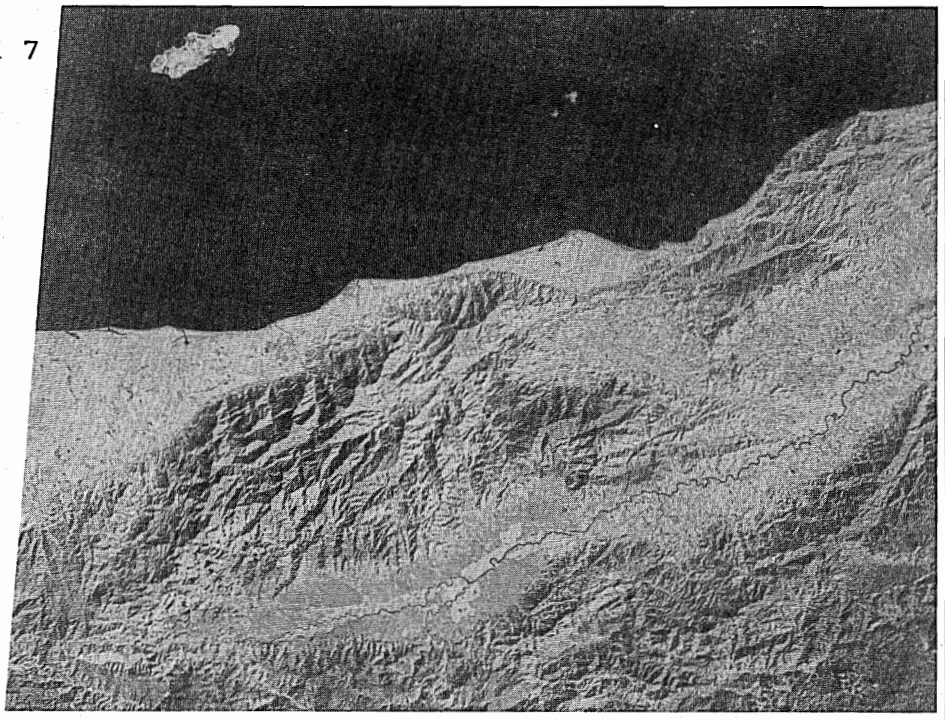
Conversion from a digital to analog or film mode at an early stage of a project will eliminate the need for a dedicated computer capability at many institutions and at the same time can increase the efficiency of the selected digital image processing facility. The film products produced from the digital analysis can then be effectively and efficiently used in the photo-optical data systems of the user without the need for such photographic reprocessing as contrast enhancements, film-density balancing, and extensive black-and-white and color film development and printing. The value and effectiveness of equipment such as a color-additive viewer is actually increased, since digitally enhanced and corrected imagery will be used instead of raw data.

The repetitive coverage of any area by operational Earth observation satellites makes it possible to monitor dynamic features of flooding that can cause changes, e.g, changes in the channel of the river itself or floodplain boundaries. Further, the spatial

Figure 8-11

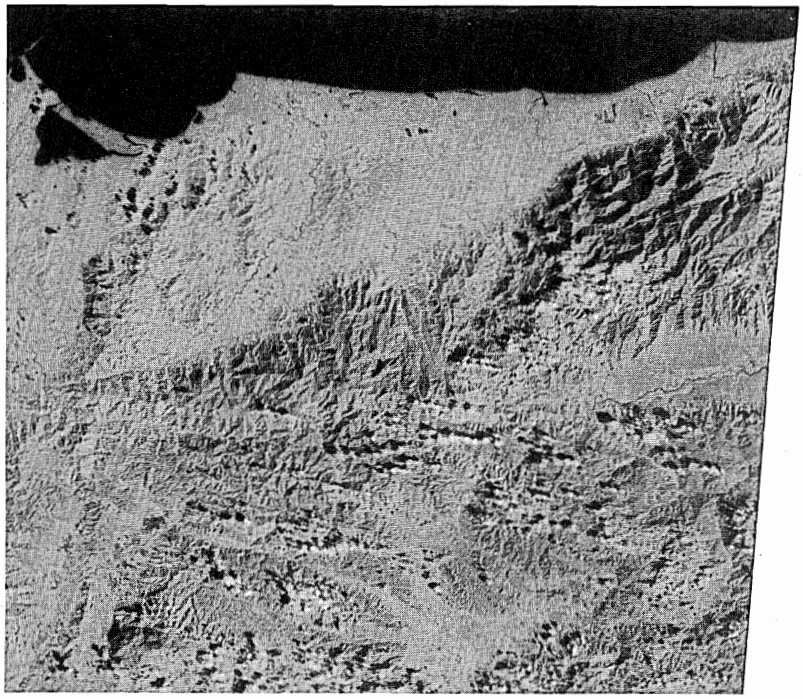
LANDSAT MSS DATA SETS FOR FLOOD HAZARD ASSESSMENT OF THE COASTAL PLAIN OF HONDURAS

Landsat-1 MSS band 7
(path 18/row 49)
December 19, 1973



53km overlap

for temporal analysis



Landsat-2 MSS band 7
(path 19/row 49)
December 3, 1978

ADVANTAGES OF DIGITAL IMAGE PROCESSING

- Automatic spatial measurements.
- Thematic enhancements, such as linear contrast stretches, band ratioing, geometric and atmospheric corrections, edge enhancements, etc.
- Maximum scene processing versatility.
- Potential utilization in geographic information systems.

distribution of the features that have changed can be readily mapped by techniques of temporal analysis developed since the launch of Landsat 1 in 1972 (Deutsch, 1976; Deutsch, 1974; and Kruus et al., 1981). Slides of full scenes and subscenes can be projected at any scale for analysis. The slides can be projected onto a base map, thematic maps, and enlarged satellite single-band prints to produce thematic image maps.

This section has outlined techniques available for the use of remote sensing data and aerial photography to assist in delineating floodplains and flood prone areas. The practical application of using Landsat MSS data to delineate flood-prone areas is described in the next section.

D. Application of Remote Sensing Data to Flood-Prone Areas: Two Case Studies

In 1985, the OAS/DRDE completed two projects employing Landsat MSS data for delineation of flood-prone areas. One study was undertaken for the coastal plain on Honduras. The second study covered the Pilcomayo River valley in Paraguay. Both utilized inexpensive, practical, yet different photo-optical processing techniques that were designed for the specific situation. The methods used are best illustrated by the following case studies.

1. CASE STUDY 1: HONDURAS COASTAL PLAIN

In September 1974 the coastal plain of Honduras was devastated by flooding from Hurricane Fifi. Subsequently, the Government of Honduras requested assistance from the OAS/DRDE to delineate the flood-prone areas of the coastal plain on 1:50,000 scale maps, employing remote sensing technology as appropriate, to be used in an integrated development planning study to formulate investment projects for restructuring the region's economy.

a. Photo-Optical Technique Employed for Spectral Analysis

A data search was made, and two relatively cloud-free Landsat MSS data sets were available covering the study area. Pre-flood and post-flood imagery was obtained. A 53-kilometer-wide overlap between the two scenes provided the basis for an analysis of temporal changes that could be attributed to the hurricane and to changing land patterns between the two dates (see Figure 8-11).

Positive black-and-white film transparencies at a scale of 1:1,000,000 of all four bands of the data were purchased for the satellite imagery base. Standard false-color composite images in the form of positive color film transparencies were produced in a custom photographic laboratory by consecutive projection of band 4 through a blue filter, band 5 through a green filter, and band 7 through a red filter. Color prints were then produced from the transparencies. See Figure 8-9 for a description of flood-related features on Landsat MSS imagery.

In addition, slides were prepared from the imagery by photographing the film transparencies mounted on a light table with a 35mm camera using Kodak EPY 50 film for tungsten light. Do not use fluorescent lamps in the light table. Each entire scene was copied onto a single slide, and close-up slides were also prepared of selected subscenes of particular interest. Several originals of each scene were photographed in the slide format not only to save time but also to avoid the alteration of color and loss of detail that commonly occur when duplicate slides are made.

The topographic base maps were mounted on a wall, and the images were projected onto, and registered with, the maps. Although the maps were at a scale of 1:50,000 and the original satellite imagery was at a scale of 1:1,000,000, the identification of the

Figure 8-12

LANDSAT MSS TEMPORAL COMPOSITE FOR FLOOD HAZARD ASSESSMENT OF THE COASTAL PLAIN OF HONDURAS

Legend:

Interpretation guide to temporal composite composed of Landsat images taken in 1973 and 1978:

Yellow: no significant change between the two dates.
Red: pre-existing conditions in 1973.
Green: new conditions in 1978.

coastal lowlands, which in general constitute the flood-hazard area, could be made by pattern recognition.

The maps had a topographic contour interval of 20 meters, which was too large to use for floodplain delineation. On the other hand, the MSS imagery, with its nominal spatial resolution of 80 meters, is normally used for mapping at scales of 1:250,000 or smaller. There is a synergistic effect when the topographic map is combined with any remote sensor imagery. Conjunctive use of the maps and the MSS imagery made it possible to delineate the floodplain boundaries with a high degree of confidence, and to approximate the limits of a 100-year design event.

It must be emphasized, however, that although the floodplain delineation was made through the interpretation of static data, it was made by an experienced hydrologist thoroughly familiar with satellite data characteristics. The specially processed imagery is a tool for the mapping process and does not replace the applications scientist, nor does it automatically produce maps.

b. Temporal Analysis of Land Surface Changes

One of the most useful applications of repetitive satellite imagery is the ability to prepare temporal composites that show changes in land-surface features that have occurred during the time between the dates of collection. To see what changes occurred in Atlántida Province, Honduras, between December 1973 and December 1978, which includes the Hurricane Fifi event, duplicate 1:1,000,000 scale film-positive transparencies of the Landsat images, band 5, were made.

The same land area from both scenes was then carefully cut out of the transparencies and mounted in a color-additive viewer. This device permits simultaneous viewing of both images on a ground-glass screen and can be photographed. The images must be precisely focused and the scale carefully adjusted. The images were then accurately registered and red and green color filters were introduced to color-code specific surface features, such as surface water, sediment deposits, and vegetation (see Figure 8-12).

By combining red and green, yellow is produced. Hence, for areas where there is no significant change in surface reflection, the area is color-coded in yellow to brown tones, depending upon the film density. If a change in spectral reflectance occurs due to flooding, the area affected by the change is color-coded as either red, showing the pre-existing condition, or green, showing the new condition. These changes could be an alteration of vegetation or land-use distribution, or changes in forestry, construction, or pollution, for example. This information could then be used to define areas susceptible to flood events.

As an aid to interpretation, the location and distribution of clouds can be noted. Where there were clouds on one date, but not on another, the area is coded red or green depending upon the date and filter combination. The very small areas that were cloud-covered on both dates appeared yellow.

2. CASE STUDY 2: PILCOMAYO RIVER FLOODPLAIN

Due to the recurring flooding along the Pilcomayo River in southwestern Paraguay, the Government of Paraguay requested assistance from OAS/DRDE to delineate the floodplain boundaries and hazards along the river. In this case the desired map scale was 1:500,000, but topographic maps at this scale were not available. The information was combined with desertification hazard and other natural resource information using a soils classification map as the base map.

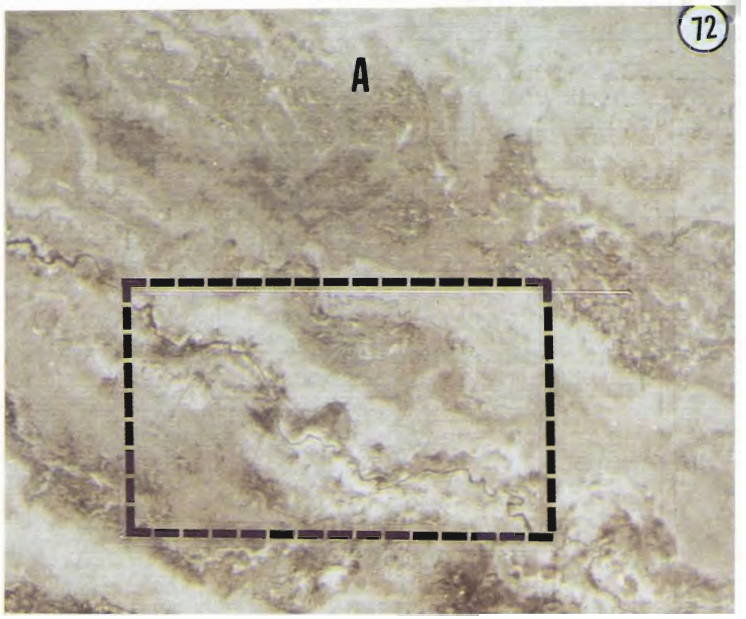
a. Photo-Optical Techniques Employed for Spectral Analysis

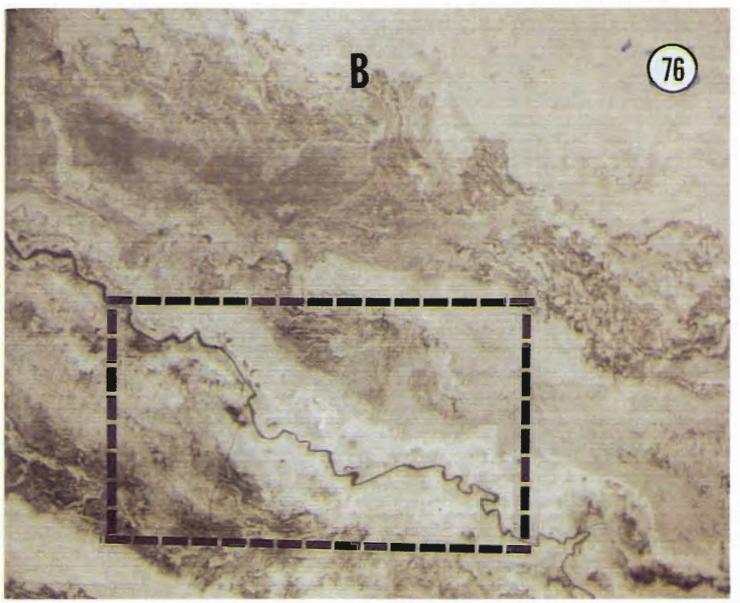
Landsat MSS data were used as the mapping and interpretation base for delineations of the floodplain and the various hazard areas. A detailed geographic search of available data revealed that Landsat 2 MSS data collected on consecutive days in 1976 were the best available for coverage of the study area. Positive black-and-white transparencies in the 70mm format at a scale of 1:3,369,000 were purchased. For temporal analysis, a transparency of Landsat 1 MSS data from 1972 was provided. In addition, a set of Landsat 4 data from 1982 covering the southwestern portion of the study area was also purchased.

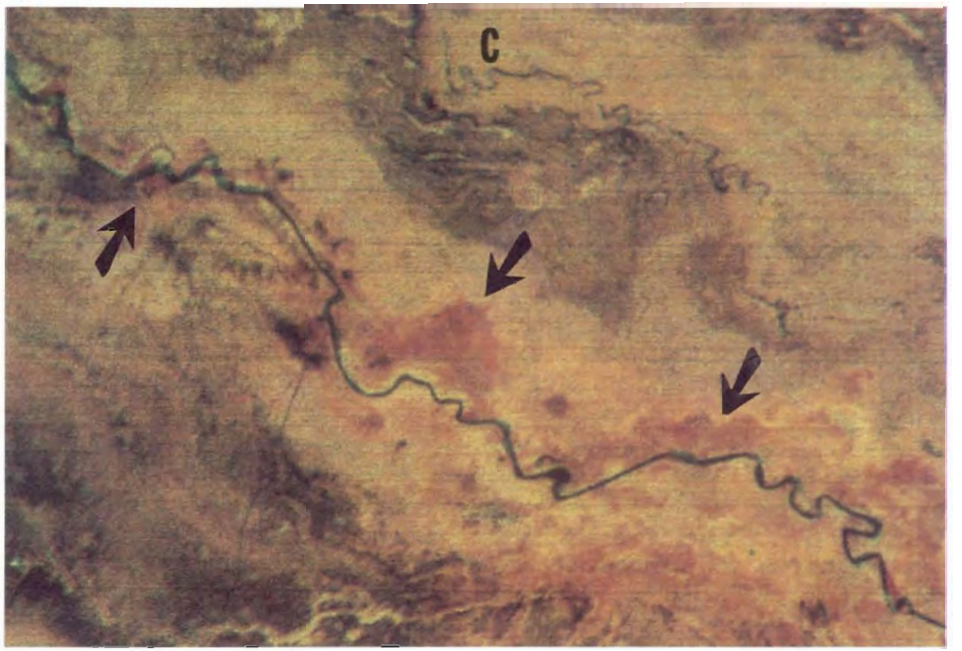
Before the actual preparation of the floodplain delineation and hazard assessment map, a spectral analysis was made of the four Landsat 2 scenes collected employing photo-optical data processing techniques. The 70mm positive transparencies or "chips" were mounted in a color-additive viewer. This viewer enabled the specialist to examine each of the single-band black-and-white images individually or in any 2, 3, or 4 band combination of transparencies. Each band was projected through a blue, green, or red filter, or by unfiltered white light, under controlled illumination intensities for each. A wide variety of band, filter, and illumination intensities is possible, but for this study, preselected band-filter combinations or spectral composites were generated.

Figure 8-13

USE OF SATELLITE IMAGERY TO DETECT SEDIMENT DEPOSITION







Legend:

A. LANDSAT-1 MSS band-5 negative.
Subscene (path 245/row 76) covering a portion of the Pilcomayo River basin.
Collected September 1, 1972.

B. LANDSAT-2 MSS band-5 negative.
Subscene (path 245/row 76) covering the same portion of the Pilcomayo River basin as in "A" above.
Collected March 29, 1976.

C. Temporal composite of subscenes A and B.
The arrows show the areas of sediment deposition in the interval between 1972 and 1976.

Source: OAS/DRDE

The transparencies were projected onto a ground-glass screen at a scale of approximately 1:800,000, and the individual chips were registered to form a multispectral composite. A set of three scenes and subscenes were photographed from the ground-glass screen on 35mm slides to provide a permanent record of the spectrally enhanced data products as well as an opportunity for discussion and interactive analysis. Kodak EPY 135 film for tungsten light, ASA 50, was used.

To prepare the 1:500,000 scale floodplain and flood hazard map of the Pilcomayo River valley in the Paraguayan case, high-contrast negative transparencies at a scale of 1:1,000,000 were prepared from the band 5 (band 2 for Landsat 4 and 5, 1:3,369,000 scale) positive transparencies in a custom photographic laboratory. From these, 1:500,000 scale positive black-and-white prints were made, and a four scene mosaic was assembled that included the entire study area. Selected slides depicting enhancements listed in Figure 8-9 and a composite map (created from a base map, soil classifications map, and forest cover map) were projected and registered to aid in the interpretation. The floodplain boundaries and hazard-level zones were then drafted on a mylar overlay of the image mosaic and composite map. The outer boundary of the floodplain was rapidly and confidently plotted on the band 5 mosaic after the imagery was studied on projections of 35mm slides showing the spectrally enhanced 3-band color composites previously prepared for the same scene.

b. Temporal Analysis of Changes in the Floodplain and River Channel

Two temporal or time-change composites along selected reaches of the Pilcomayo River were made to serve as indicators of change in the floodplain and river channel. To observe changes in the floodplain between 1972 and 1976, a high-contrast negative at a scale of 1:1,000,000 was prepared from the low contrast band 5 positive image of the same scale. A high-contrast band 5 negative at a scale of 1:1,000,000 was also prepared from the 70mm positive transparency. The color-additive viewer is designed to hold 70mm format film, so 70mm wide strips of the selected subscene were cut from the larger film and mounted in the viewer.

Figure 8-13A is a monochrome copy of a high-contrast negative of a Landsat 1 MSS band 5 black-and-white negative covering the subscene from 1972. Figure 8-13B is a Landsat 2 MSS band 5 negative of that same portion of the valley from 1976. Figure 8-13C is a temporal composite of the scenes in Figure 8-13A projected through a green filter and Figure 8-13B projected through a red filter. Areas of new sediment deposition between 1972 and 1976 appear as red on the temporal composite. Examples of these areas are identified in Figure 8-13C.

In most cases, the changing course of a river can be illustrated by use of one of the MSS solar infrared bands. Figure 8-14A is a print of the black-and-white transparency of a portion of a Landsat 2 MSS band 7 image collected in 1976, which was later projected through a green filter. Figure 8-14B covering the same area is an MSS band 7 image collected by Landsat 4 in 1982, which was later projected through a red filter. Figure 8-14C, which covers the northwestern segment of the temporal composite of the scenes in Figures 8-14A and 8-14B, vividly demonstrates the extensive changes in the river's course between 1976 and 1982. The river's course in 1976 is shown in red, and the course in 1982 is shown in green.

Although the temporal analyses do not cover the whole reach of the Pilcomayo River valley bordering the study area, they clearly demonstrate the highly dynamic nature of the floodplain and areas of sediment deposit. This indicates that there is a need for continuous monitoring of the floodplain as well as monitoring during the period of flooding for assessing the flood hazard and delineation of the flood-prone areas. The floodplain delineation and temporal analysis information was used to further assess flood hazards as part of overall project identification criteria.

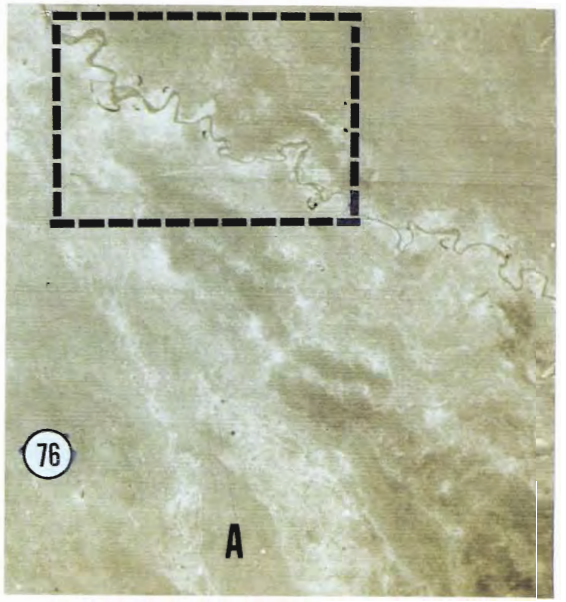
Conclusions

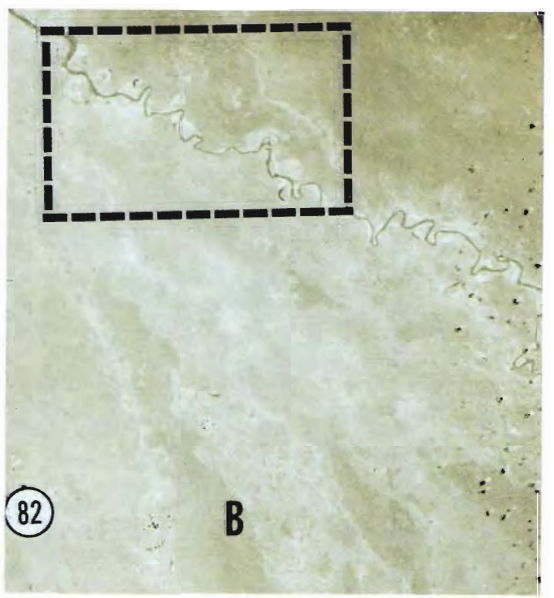
Floodplains and flood-prone areas are dynamic land areas that need to be assessed in terms of the risks they pose to existing and proposed development activities. This chapter has discussed at length some of the key concepts related to floods, floodplains, and flood-prone areas: their changing nature, frequency of occurrence, length of inundation, relationship to development practices, and ways to mitigate the effects of floods. The essential point has been to demonstrate the importance of considering floods early in the planning process, and the application of remote sensing imagery in the delineation of flood-prone areas.

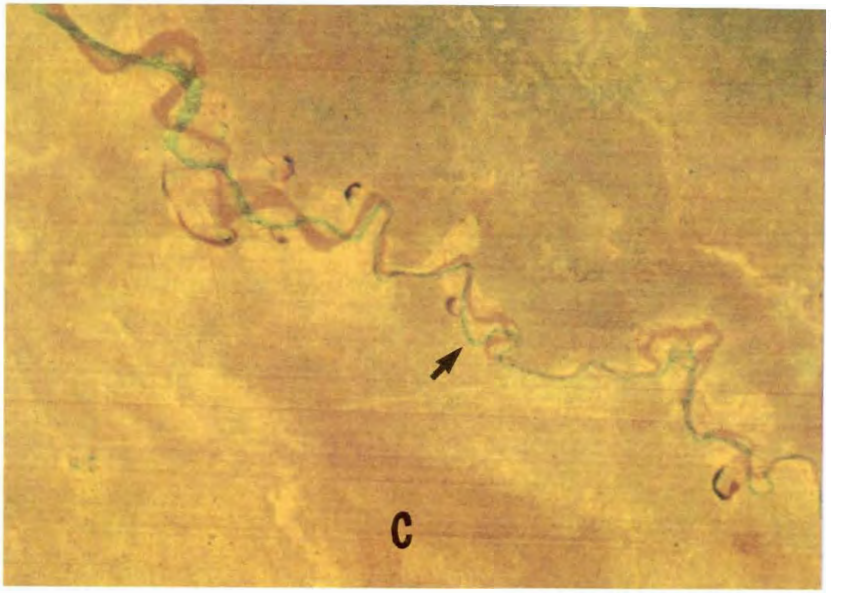
The different questions that need to be asked at the different planning stages were highlighted. Many answers can be generated from the use of remote sensing and photo-optical techniques to supplement other kinds of hydrologic data. Finally, Landsat MSS data in two different photo-optical data processing techniques to delineate flood-prone areas in the Honduras coastal plain and the Pilcomayo River floodplain provide evidence of the value and importance of satellite information. The material in this chapter should enable the planner to have a working

Figure 8-14

USE OF SATELLITE IMAGERY TO DETECT RIVER COURSE CHANGE







Legend:

A. LANDSAT-2 MSS band-7 sub-scene showing a reach of the Pilcomayo River. Collected March 30, 1976.

B. LANDSAT-4 MSS band-7 subscene showing the same reach of the Pilcomayo River as in "A" above. Collected October 12, 1982.

C. Diagram showing the change in the course of the Pilcomayo River from 1976 to 1982.

Source: OAS/DRDE

vocabulary of terms, concepts, and knowledge of the important considerations related to the use of remote sensing techniques for floodplain delineation and in flood hazard assessments.

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CHAPTER 9

DESERTIFICATION HAZARD ASSESSMENT

CHAPTER 9

DESERTIFICATION HAZARD ASSESSMENT

Contents

List of Figures

DESERTIFICATION HAZARD ASSESSMENT

SUMMARY

Planners are presented with (1) terms, concepts, and important considerations related to an analysis of desertification potential in the region being studied; (2) the critical issues that need to be addressed in integrating analysis of desertification potential into the development planning process; (3) a decision tree to help the planner decide whether or not technical assistance will be needed for further work in this analysis; (4) guidelines for adapting the available decision tree data to map relative susceptibility to desertification; and (5) integrated terms of reference for the various sectors that will play a role in the analysis.

This chapter provides planners with a method that will help them to identify areas where desertification has already started or where there is potential danger if suitable land-use practices are not followed, and thus to avoid making recommendations which may initiate or worsen the phenomenon.

Desertification became a media event before it had a definition, and supposed methods for its control were described well before it was understood as a process susceptible to practical human response. As a consequence, the popular literature is filled with misinformation, myth, and exaggeration, and the suggested "cures" often intensify rather than mitigate the phenomenon. Still, as a process, it can be as much man-caused as natural and therefore is one of the natural hazards best suited for mitigation by those who plan, implement, and manage regional development efforts.

Defining desertification has been a continuing problem. According to the United Nations Conference on Desertification (UNCOD, 1977), it is "the reduction or destruction of the biological potential of the earth which can create the conditions analogous to a natural desert." In different areas and among different peoples, it may mean (1) degradation of grazing lands, (2) destruction of vegetative cover, (3) wind erosion and moving sand dunes, (4) turning productive land into a "wasteland," and (5) degradation of vegetation and soil (Dregne, 1983). Mabbutt (1977) refers to the spread of desert conditions beyond desert margins and the intensification of desert conditions within desert boundaries. The definition used by Dregne himself (1983) comprises the impoverishment of terrestrial ecosystems under the impact of man, ecosystem deterioration measured by reduced size of crops, undesirable alterations in the biomass and the diversity of fauna and flora, and increased hazards for human occupancy. Thus, it is felt that desertification is a process of "resource degradation," though its perceived causes can cover a wide variety of activities including road building, industrial construction, geological surveys, ore mining, settlement construction, irrigation, motor transport, overgrazing, deforestation, expansion of intensive cash cropping, poor management of well water bore holes, and land settlement by previously nomadic people.

The above meanings tend to describe desertification on the basis of cause or secondary effects (generally loss of biomass production). Here, however, desertification will be looked at through the phenomena of waterlogging, salinization, increased soil temperature and aridity, increased dune formation, decreased soil organic matter, and increased albedo. Obviously, not all of these occur at one time on the same site; there are many different kinds of deserts. Nevertheless, common to all is the eventual decrease in total biomass production and an increase in noxious or unwanted flora and fauna. Obviously, without remedial measures, many development objectives will be difficult to reach.

Desertification in South America affects 56 percent of the arid lands to a moderate degree and 22 percent to a severe degree (Dregne, 1983). Several million people live in these areas of degraded soils which, if not properly managed, could worsen. Of the 28.5 million inhabitants of dry lands in South America and Mexico, 4 million live on range lands, 22 million in areas where dry-land agriculture is performed, and 2.5 million in areas under irrigation. Thus, different geographic regions suffer to a greater or lesser degree from loss of productive soil to salinization; water and wind erosion; creation and movement of dunes; waterlogging; loss of surface and subsurface water in quality and quantity; and rapid depletion of vegetation cover. Population growth pressure may increase the degree of desertification if land-use practices are not

modified. But much of it is the result of climatic conditions (high rates of evapotranspiration, scarce and erratic rainfall, and recurring drought) and inherent physical characteristics of the area (extremely permeable or impermeable soils and high water tables).

A. Terms and Concepts Used in Desertification Hazard Analysis

The idiom of desertification specialists draws from subjects like agriculture, forestry, geomorphology, hydrology, economics, physics, chemistry, sociology, and anthropology. Few people are experts in all these fields, but the planner working in arid and semi-arid areas should be acquainted with the more common "specialized" terms. This section introduces some terms and concepts used in discussions of desertification.

- **Albedo**: The ratio of light reflected from an unpolished surface to the total light falling on it. Albedo is important in calculating **potential evapotranspiration** (see below) using the heat budget method of determining evaporation. Different types of vegetation and different soils absorb different amounts of solar radiation, and their potential evapotranspiration will also be different. More solar radiation is reflected and less remains for heating and evaporation as surface albedo increases.

- **Alkali Soils**: Soils with few free salts but with enough sodium (Na) or potassium (K) to be injurious to most plants. The colloids of these soils deflocculate so that drainage and aeration are poor. The clay washes downward and accumulates as a hard pan below the surface. High Na can raise the pH above 8.5. Hydrolysis to NaOH is highly corrosive to humus, roots, and other living tissue.

- **Animal Unit**: A measure used to convert numbers of the various kinds of livestock to a common standard in relation to forage resources on the equivalent of a mature cow (live weight of about 450 kilograms). One animal unit equals about one head of cattle, one horse, one mule, five sheep, five swine, or five goats.

- **Arid Zone**: An area having a low ratio of precipitation to potential evapotranspiration (P/PET=0.03 to 0.20). As a result, arid zones are regions of low biotic productivity. Arid zones are areas of dry land with both annual and perennial species. In their natural form they generally can sustain extensive livestock grazing but no dry-land agriculture.

- **Carrying Capacity**: (a) the number of individuals of a given species that can be sustained by a given ecosystem; (b) the density of people at a given standard of living that can be supported by a system; and, (c) the maximum number of a wildlife species which a certain territory will support through the most critical period of the year in terms of forage. People use information and technology to raise the natural carrying capacity of their environment by supplementing local ecosystems through the importation of energy and resources. This allows more people to occupy the land with a higher standard of living than would be achieved with the local natural environment alone.

- **Desert**: The term "desert" has never been precisely defined. In popular thinking, it generally means a region where vegetation is scarce or absent because of deficient precipitation or edaphic aridity but may also mean "wasteland" and areas of low production of vegetation regardless of the reason.

- **Desertification Indicator**: A physical phenomenon, an organism, a biotic community, a social criterion, or a combination of these, that is generally associated with one or more conditions that demonstrate the existence of the desertification process (Reining, 1978; Dregne, 1983).

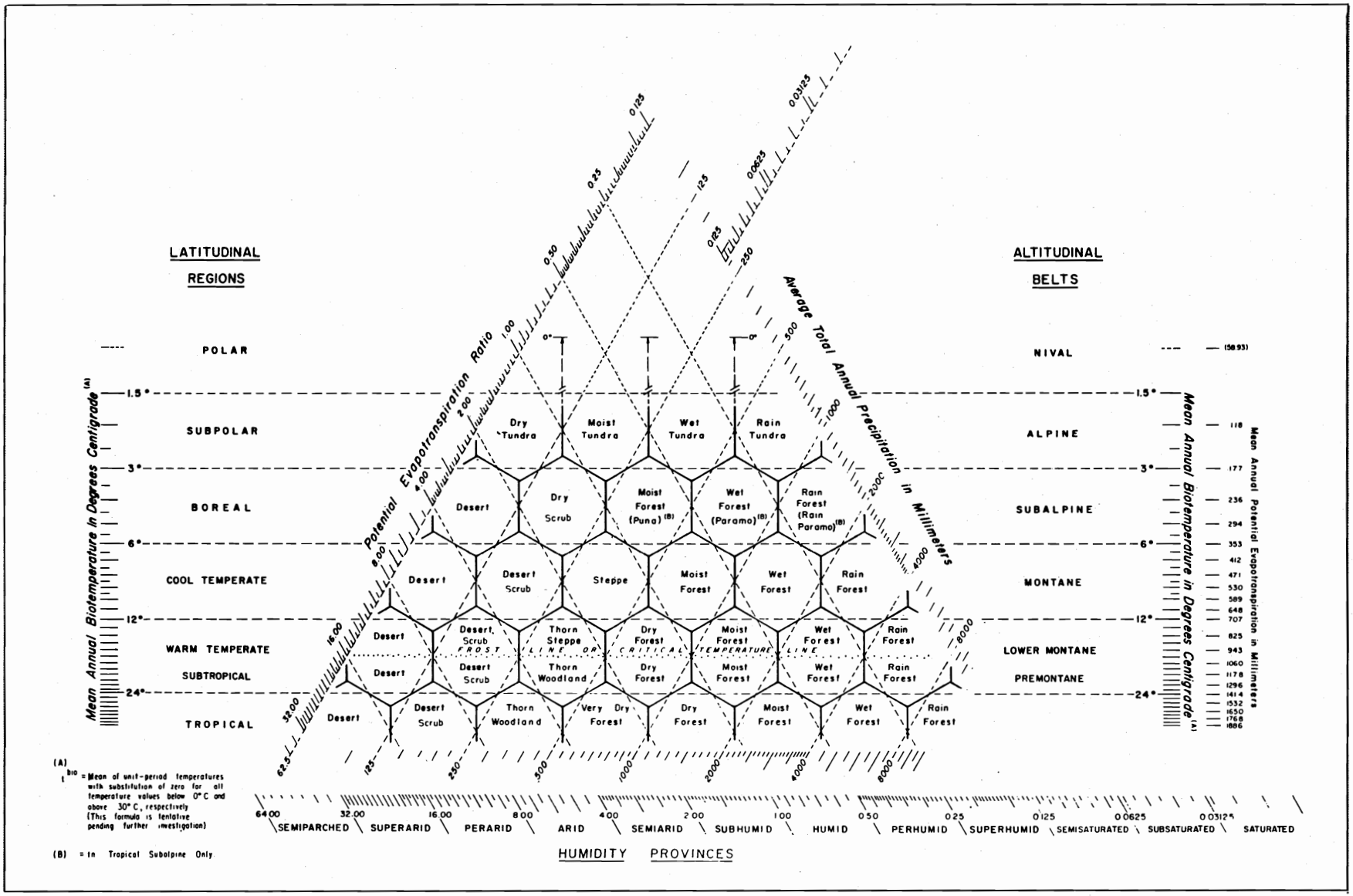
- **Desert Pavement**: In desert areas, a layer of small stones, pebbles, or gravel covering on the surface of the soil which remains after wind erosion has removed the finer material.

- **Drought**: An extended period of dryness; usually any period of moisture deficiency that is below normal for a specific area. Sharing this commonality, there are several definitions which tend to be conceptual or operational and vary by discipline (meteorological drought, agricultural drought, hydrological drought, socio-economic drought) and by country (Whilhite and Glantz, 1987).

- **Ecosystem**: Any area having living organisms and inanimate substances acting as a unit and where material is interchanged among the living and inanimate elements and a flow of energy is developed within and through the system. Though ecosystems can be extremely small, the word is used in this chapter to mean an area the size of a small farm (1-5 hectares) to a region (several thousands of square kilometers). Ecosystem

Figure 9-1

HOLDRIDGE LIFE ZONE CLASSIFICATION



Source: Holdridge, L.R. Life Zone Ecology (San José, Costa Rica: Tropical Science Center, 1967).

boundaries are set arbitrarily and are determined by the study objectives.

- **Ephemeral**: Indicates short-lived existence, in this case plants which have genetic adaptations that allow them to germinate, grow, and reproduce in a few weeks and can thus "take advantage" of certain short-lived environmental factors (soil moisture, temperature, access to nutrients) required for completing their life cycle.

- **Evapotranspiration (ET)**: Total water lost from the land and water bodies by evaporation and plant transpiration. Evaporation from soils, plant surfaces, and water bodies, and transpiration through plant stomata collectively constitute evapotranspiration. The evaporation process is simply the net loss of water from a surface by means of a change in state of water from liquid to vapor. The requirements for evaporation or transpiration are: a) a flow of energy to the evaporating or transpiring surface; b) a flow of vapor away from these surfaces; and c) a flow of liquid water to these surfaces.

- **Halophyte**: A plant growing in saline soils; a salt-tolerant plant. Some species such as alfalfa are classified as halophytes although the term generally means plants that are native to saline habitats. Different species of halophytes tolerate different degrees of salinity.

- **Humid Zone**: An area having a precipitation to potential evapotranspiration ratio of greater than 0.75 ($P/PET>0.75$). That is, it is an area having excess water where drought conditions rarely occur. Forests occur and crops may be grown without irrigation in this zone (temperature permitting), although at the lower end of the precipitation range, production may be reduced.

- **Hyper-Arid Zone**: An area of extreme aridity having a precipitation to potential evapotranspiration ratio of less than 0.03 ($P/PET<0.03$) and where periods (even years) may go by with no precipitation. Except for phreatophytes, no permanent vegetation is present, although ephemeral plants occur with precipitation. Except in rare periods of precipitation when ephemerals may be grazed, no agriculture, forestry, or grazing is possible without some kind of irrigation.

- **Life Zone**: An altitudinal or latitudinal bioregion with distinctive faunal and floral characteristics. These are areas of natural landscape that are homogeneous in terms of climate. In Latin America and to some degree in the Caribbean, life zone maps have been developed based on the Holdridge system. These are areas having equivalently weighted divisions of heat, precipitation, and moisture. Heat is expressed as biotemperature, which is a measurement of the heat effective in plant growth (0-30 degrees Celsius); precipitation is total annual precipitation; and effective moisture is a combination of biotemperature and precipitation. All major life zones can be given a graphical representation (See Figure 9-1).

- **Phreatophyte**: A plant that absorbs its water from a permanent supply in the ground. These can be found growing along the edges of watercourses where there is a permanent flow of surface or ground water and in areas where the water table is generally near the surface.

- **Population Pressure**: Human, wildlife, and livestock population densities related to the various carrying capacities of an ecosystem. Also included are the relative pressures of cropping and irrigation on lands subject to salinization. Without irrigation, maximum limits in arid zones are thought to be seven inhabitants per square kilometer and one animal unit per five hectares and in the semi-arid zones 20 inhabitants per square kilometer and one animal unit per hectare.

- **Potential Evapotranspiration (PET)**: Generally defined as the rate of evaporation and transpiration which would take place from a completely vegetated area in which soil water was not limiting. Maximum evaporation rates from large water bodies in arid areas approach 2500mm per year.

- **Precipitation (P)**: All types of moisture discharged from the atmosphere (rain, snow, hail, sleet, and measurable mist or fog).

- **Range Condition**: The status of rangeland vegetation in relation to its potential in terms of the amount and kind of biomass production. Evaluation of range condition involves an analysis of density and composition of plant species of "quality" (those that are palatable and which are preferred by livestock or wildlife) as opposed to those that are less palatable and which increase in density and composition under excessive grazing pressure, and those that are unpalatable and perhaps noxious and which invade the range under extremely heavy use by livestock.

- **Range Trend**: Evidence of change in the vegetation. For example, the species and vigor of any seedlings which, in the terminology of range management, can be called decreasers, increasers, or invaders, depending on their

behavioral characteristics under grazing pressure, are important indicators of trend. Likewise, evidence of new or increasing erosion of eroded areas, as opposed to healing, and of trampling is also important. Since range trend is of interest primarily to the livestock manager, an increase in woody vegetation usually indicates a downward trend. In terms of desertification, however, an increase of woody vegetation could indicate a favorable trend.

- **Saline-Alkaline Soils**: Soils that combine the problems of both saline soils and alkaline soils in that they have a great deal of sodium (Na), are deflocculated, and usually have a pH above 8.5.

- **Semi-arid Zone**: An area having a ratio of precipitation to potential evapotranspiration of from 0.20 to 0.50 (P/PET=0.20-0.50) and a natural discontinuous herbaceous vegetative cover with a greater frequency of perennial species than arid zones. This zone normally can sustain dry-land agriculture and livestock raising activities with little additional input if stocking rates are held at adequate levels to sustain production.

- **Soil Texture**: The relative proportions of the various sizes of mineral particles (gravel, sand, silt, clay) in the soil. Fine and coarse particles have very different properties in terms of water infiltration and holding capacity, compactability, erosivity, and nutrient availability. Textural classes range from clay consisting of particles smaller than 0.002mm in diameter (the material passes a sieve of 0.002mm), to silt (which passes a sieve between 0.002mm and 0.050mm), to fine sand (which passes a sieve between 0.050mm and 0.020mm), to coarse sand (which passes a sieve between 0.020mm and 0.200mm), to fine gravel (which passes through a mesh between 0.200mm and 2.00mm) and coarse gravel (which passes through a mesh between 2.00mm and 5.0mm). In general, the terms "fine texture" and "heavy texture" refer to soils containing large quantities of clay or clay loams while "coarse texture" and "light texture" refer to soils with relatively more sand than clay.

- **Sub-humid zone**: An area having a ratio of precipitation to potential evapotranspiration of 0.5 to 0.75 (P/PET=0.5-0.75) covered with stands of natural vegetation that are more dense but which may include tropical savannas. Dry-land agriculture is common in this zone for crops adapted to occasional drought.

- **Succession**: A process of change in ecosystems from "immature" to "mature" stages. The earlier stages are characterized by greater net primary production and less species diversity. Maintenance of the earlier stages can be difficult and costly but any excess production can be harvested as food and fiber.

- **Xerophytic Vegetation**: Vegetation, especially woody vegetation, in dry climates. These plants tend to grow in stands having low densities. They grow slowly and have leaf structure and biochemical characteristics that permit great efficiency in water use.

B. Principal Factors Which Influence Desertification Hazards

This section describes several of the factors affecting the processes of desertification. These, of course, depend on the great variety of physical (including climatic) and land-use characteristics of an area. Only those physical characteristics that can be easily measured or calculated, and which do not vary greatly with different land-use practices are considered to be principal factors; they are precipitation, potential evapotranspiration, soil texture, land form, and wind. These will be utilized to describe the methods for evaluating desertification in the early stages of development planning discussed later in the chapter. Because man can cause, intensify, or ameliorate the processes of desertification through the activities of the yearly agricultural cycle, it is important to know how these activities respond to the principal physical factors. Land use and land management are described in this section, as well as other factors such as ground and surface water levels. The occurrence of soluble salts and saline conditions in the substrate, soil structure, soil nutrients, and existence and movement of herbivores, including insect fauna, are also very influential in desertification. These, however, can rapidly change under conditions of use. As a consequence, they are not used here as primary determining factors when working at desertification potential.

1. PRECIPITATION AND THE OCCURRENCE OF DROUGHT

Data on annual precipitation levels are generally available although monthly figures are often scarce. In cases where data are missing, annual and seasonal amounts may be estimated from the observation of the types and densities of the native undisturbed vegetation. Precipitation levels may be estimated, for example, from life zone maps developed with the Holdridge life zone system (See Figure 9-2). Information concerning historical annual variation of precipitation will be needed in order to gain an insight

Figure 9-2

RELATIONSHIP BETWEEN PRECIPITATION AND DOMINANT VEGETATION

Precipitation	Dominant Vegetation
0-25.4 cm/yr.	Desert
25.4 cm-76.2 cm/yr.	Grassland, Savanna, Open Woodland
76.2 cm-127.0 cm/yr.	Dry Forest
> 127.0 cm/yr.	Wet Forest

Source: Adapted from Odum, E.P. Ecology (New York: Holt, Rinehart and Winston, 1963).

into drought occurrence. If climatic station data are not available, secondary information may be obtained from written and spoken historical records, geomorphological studies, as well as analysis of growth rings in woody vegetation.

In this primer precipitation levels greater than 1500mm/year are considered to be too humid for most forms of desertification. Thus, if the study area's precipitation level is below 1500mm/year, the methods discussed here may help in the planning process.

Several different types of storms are important in the analysis of desertification hazard. **Cyclonic or frontal** storms are long-lived and move almost continuously in definite routes across a continent. In areas where most of this type of precipitation exists, long periods of drought can occur. **Orographic precipitation** is caused by rising air currents that travel over land mass at high enough altitude that expansion and cooling of the air mass causes moisture condensation. As the air mass descends after crossing a higher elevation, it is warmed and the available moisture is tightly held. This creates arid conditions on the lee side of the elevated areas. Such is the case in much of Central America, where air movement from the Caribbean Sea contributes to the formation of cloud forests on mountain peaks but extremely arid conditions at lower elevations on the western side of the range (Figure 9-3). **Convective precipitation** occurs in hot months when the land surface becomes heated under strong insolation which then heats the lower strata of the atmosphere causing them to rise to strata of cooler temperature. Condensation causes rains, which tend to be heavy, of short duration, local in distribution, and accompanied by lightning. These storms are often accompanied by strong winds, and, at times, only the winds occur with little or no precipitation, causing intense dust storms. Because of both orographic and convective precipitation, rainfall maps made at stations a few miles distant in mountainous country may be subject to considerable error.

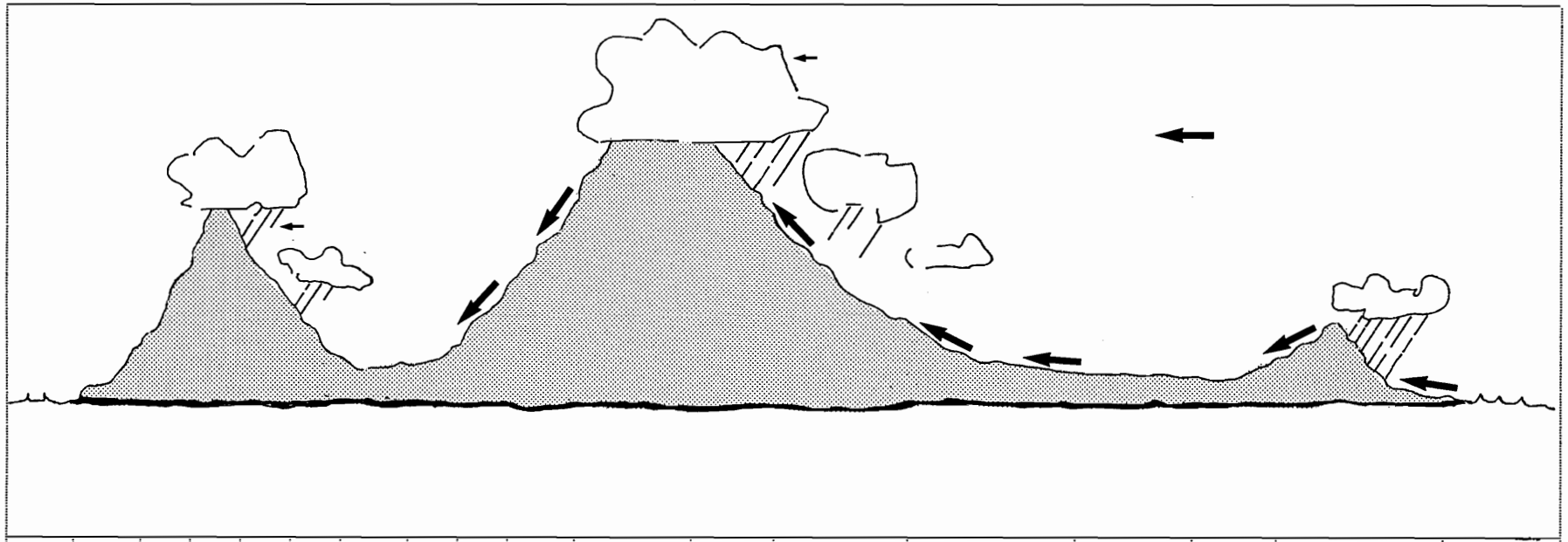
2. POTENTIAL EVAPOTRANSPIRATION (PET)

The concept of potential evapotranspiration is defined as an estimation of evaporation and transpiration rates if soil water is not limited. It compensates quite easily for the lack of information on transpiration and allows a clear synthesis of the numerous measurements of soil moisture, infiltration, runoff, etc., that are needed to understand climatic parameters. Evapotranspiration rates are related to several climatic factors, the most important one being temperature. For example, adjusting temperature figures for variations in day length (hours of daylight) using a formula developed by Penman (Chow, 1964) demonstrates that there is a close relationship between mean temperature and potential evapotranspiration. Consequently, this formula may be used to compute potential evapotranspiration for any place whose latitude is known and where temperature records are available or can be estimated. Data on water surplus and deficit can be inferred by comparing monthly precipitation and monthly potential evapotranspiration figures.

Evaporation rates can be obtained from readings on controlled bodies of open water (evaporation pans). Although transpiration is a product of evaporation from leaf surfaces, its rates depend on the availability of soil water as well as the structural and functional features of the plant (location of stomata and the internal processes governing loss and gain of

Figure 9-3

REPRESENTATION OF CENTRAL AMERICAN TOPOGRAPHY WHICH IS RESPONSIBLE FOR THE OROGRAPHIC PHENOMENON THAT CAUSES CLOUD FORESTS IN CLOSE PROXIMITY TO ARID AREAS



	2	3	6	3	2	1	2	3	4	7	4-5	3	2	1	2	8	
Pacific Ocean			Isolated Volcanoes							Monti Cristi Massive			Lowlands		Coast Range		Caribbean

Legend:

1. Subtropical desert scrab
2. Subtropical thorn woodland
3. Subtropical dry forest
4. Pre montane moist forest
5. Pre montane moist forest
6. Montane wet forest
7. Montane rain forest (cloud forest)
8. Tropical moist forest

water in the guard cells) as these are influenced by light. For example, light increases transpiration rates more than it does evaporation rates. On the other hand, wind increases evaporation rates more than it increases transpiration rates. Thus, evaporation rates do not always indicate transpiration rates.

3. WIND

Wind is a climatic factor that can intensify desertification in many ways. Its force can erode, transport, and deposit soil particles. Damage to plants can occur either through the impact of its physical force when velocities are high or through the impact of transported abrasive soil and salt particles (sand blasting). In dry areas where soil is not held in place by vegetation, wind is a major factor in the formation of dunes. In the formation process of these dunes the wind, due to its velocity, leaves coarser material behind and continues transporting the finer soil particles. Although dunes can exist in non-desertification environments like coastlines or close to loosely cemented sandstones, their movement towards the outside limits of deserts is a clear indicator that desertification is taking place.

Wind increases water evaporation rates from land and plant surfaces. This evaporative power of moving air increases with higher temperatures and decreased relative humidity. As a result, hot dry winds during a plant's growth period can increase the amount of water it uses.

Although wind is a part of the climate and is much more regional in scope, wind patterns can change drastically under the influence of man's activities through the removal or addition of vegetation--especially woody vegetation--which acts as a barrier, provides shade, and decreases albedo.

4. SOIL TEXTURE

Soil texture can influence many other soil characteristics, especially those concerned with soil moisture (Figure 9-4) and soil fertility. Sandy soils that are irrigated require relatively more water than finer textured soils but an excess of water may leach away any available colloids and nutrients. On the other hand, because precipitation penetrates almost immediately on coarse-textured soils, runoff is reduced to almost nothing. Fine-textured soils may hold more water than coarse-textured soils but in general: (a) they hold it in the upper soil layers where drying is greater; (b) there is greater water loss due to lower rates of infiltration and higher rates of overland flow or runoff; (c) they restrict root growth and seedlings, which may sprout on such soils and die before reaching the moisture held at deeper soil levels; (d) they are responsible for shallow root growth, which makes the plant susceptible to drought; and (e) they are less susceptible to gully and sheet erosion.

5. LAND FORM

Two land form characteristics are of interest to this discussion of desertification: (a) degree or steepness of slope and (b) depth from soil surface to the water table.

Steepness of slope is important because it influences the velocity and the amount of surface water flow. Runoff, of course, is greater if the hillside slope is steeper. Slope steepness also influences amount and intensity of sunlight that a particular site receives. Desiccation, or drying, is greater if the slope faces the sun for longer periods of time and increases further if the slope angle is perpendicular to the sun's rays. Due to the erosional agent running water, particles are carried to flatter areas or areas of depression. Thus, soils tend to be shallower and of coarser texture near the top of a hill and are relatively deeper and finer textured at the foot of a slope. Desiccation is less severe in areas that face the sun less often and are therefore largely in shadow, again depending on the steepness of the slope. Desiccation is also lower in areas with leeward positions that are protected by intervening lands of higher elevations. If such elevations are high enough and abrupt enough, a rain-shadow effect could be established that would cause a decrease in overall precipitation (Figure 9-3).

Depth to ground water is important because if the water table lies too deep, the plant roots will not be able to obtain the available moisture. On the other hand, if the water table is too close to the surface, waterlogging will become a problem. And, in these areas, saline and alkaline conditions can kill vegetation or decrease their growth rates.

6. LAND USE

How a landscape is used can initiate the process of desertification. Certain kinds of agricultural practices, overgrazing by livestock and wildlife, extractive forestry, construction activities, and the use of fire are often considered the important contributors to the process.

Dry-land agricultural practices can contribute to the process because they expose soil to wind and water erosion during periods of early planting and after harvest. The finer soil particles are blown or washed away with the essential organic matter that will be missed in the following agricultural cycle. Thus, a gradual reduction of nutrients occurs through the years.

Figure 9-4

RELATIONSHIPS BETWEEN SOIL TYPE AND SOIL MOISTURE CONSTANTS (PERCENTAGES)

Moisture Constant	Clay	Loam	Silt	Sandy loam	Fine sand
Moisture equivalent	28.4	21.7	16.1	9.5	3.2
Permanent wilting point	13.4	10.3	7.5	2.9	1.0
Ground-water storage capacity	15.0	11.4	8.6	6.6	2.2

Source: Daubenmire, R.F. Plants and Environment, 2nd ed. (New York: John Wiley and Sons, 1964).

Irrigated agriculture also may contribute to desertification if it is responsible for waterlogging and salinization. Waterlogging reduces soil aeration and the plant roots are unable to survive in this soil. This condition worsens the closer the water table is to the surface. Salinization or alkalization of lowland areas occurs when excess irrigation induces accumulation of soluble salts, which also impairs plant growth.

Grazing by domestic livestock, feral or exotic animals, and both large and small game animals, if poorly managed, contributes to loss of vegetative cover for the soil. In some ecosystems overgrazing promotes invasion by woody plant species that the grazing animals find unpalatable. Thus, the biomass level increases with a less desirable mixture of plant species. Competition for available soil water between the plants combined with the continuing overuse of the palatable species by the grazing animals can cause the rangeland to deteriorate further in terms of its production of fodder and animals.

Cutting of firewood for both domestic and industrial purposes likewise can contribute to desertification. Firewood collection, and charcoal production, normally become significant in areas near population centers where this is the cheapest or only source of energy. In other areas the collection of firewood on recently logged or burned sites is of secondary importance. Collection for industrial purposes can rapidly and significantly reduce vegetative cover since the demand is high and the gatherer obtains income from collecting wood.

Like agriculture, construction of buildings, reservoirs, roads, etc., and indiscriminate use of fire also remove the vegetative cover and leaves the soil unprotected and susceptible to erosion. Activities such as these, which change the normal drainage patterns, can be responsible for the erosion of extremely large amounts of soil. Almost any disturbance of stable soil surfaces such as desert pavement can initiate a new cycle of wind and water erosion.

7. LAND MANAGEMENT

The consequences of land management practices can be positive or negative. It is estimated that 23 million metric tons of wheat production a year are lost throughout the world to desertification (Dregne, 1983). Through proper agricultural, forestry, and rangeland management techniques many of these losses can be minimized. Enriching soils whose nutrients have been lost is costly and can be prevented.

Management of land, however, involves much more than land itself, and must consider other physical, biotic, social, economic, and cultural attributes. In many parts of the world these attributes lead to an annual cycle of events that represent what can be called, in a rural context at least, the agricultural year. In such areas, a year can be divided into distinct periods that depend on the number of crop cycles that can be grown in one year's time. This number is related to the length of the growing season, which may be dictated by temperature and day length--photoperiod--and by how precipitation is distributed over the year. All of these factors, of course, influence plant growth, flowering, and seeding and thus dictate the kinds and timing of activities that a farmer, forester, or livestock producer will undertake during the year.

In temperate climates there are generally four distinct periods which dictate the agricultural year. Given adequate and evenly distributed precipitation, the agricultural year follows this cycle: spring for land preparation and planting; summer for growth of the

crop and the activities of cultivation (weeding, fertilizing, etc.); fall for the activities of harvest; and winter for fallow. These will vary greatly as one moves toward more tropical climates, where more than one crop cycle may be possible, sometimes with almost no fallow period. It also varies as one moves toward more arid climates, where irrigation may be necessary to replace natural supplies of moisture or where the fallow period may be quite lengthy because of the lack of precipitation.

Over time, a cycle of activities evolves that fits the climatic pattern for a given site. Problems arise when drought throws the cycle out of phase and wind or heavy rain occurs when the vegetative ground cover has been removed or disturbed. Problems also occur in areas that have been recently opened to cultivation, and where a proper crop/climate fit has not been developed; or where new crops have been introduced that do not quite match the peculiarities of a local climate. The problem of soil erosion arises when land lies in a state of preparation or uncovered fallow during periods of wind and heavy rain or if droughts follow land preparation and seeding.

Management of livestock, especially ruminants, must also fit the local climatic and biotic cycles. Heavy grazing in spring, for example, when grass is young and the ground is wet, can cause problems of trampling and soil compaction, while excessive grazing pressure during periods of drought can uproot plants and place even more stress on vegetation that is struggling to survive and reproduce.

Many other variations and combinations occur in the myriad climates that exist in arid and semi-arid zones regardless of whether they are tropical or temperate. The activities of agriculture and livestock management should be matched against the agricultural year to evaluate if moisture deficits, wind, and bare surfaces occur and if they occur together.

C. Evaluation of Desertification Hazard in Regional Planning Studies

Integrated regional development planning studies can be prepared for physically defined river basins as well as for areas that are best defined geopolitically. In such regions, the moisture available to support life and human activities varies (OAS, 1984). As discussed in Chapter 1, a planning process that leads to integrated development of a region can be divided into four stages, each requiring more detail on more specific topics of concern and interest. Each stage requires distinct kinds and levels of information to help understand and consider the degree of desertification hazard (Figure 9-5). The methods proposed here are designed to fit these stages. And, as in planning in general, more detailed information will be required on fewer subjects in each succeeding stage.

1. THE STAGES OF PLANNING

Evaluation of desertification hazards is undertaken during all planning stages: Preliminary Mission; diagnosis of the region and project identification (Phase I); action plan and project formulation (Phase II); and program implementation. Planning should include projects to reduce desertification hazards as well as to monitor effects that projects may have on the desertification process. To carry out such evaluations, basic information on natural resources and socio-economic characteristics will be necessary. This information will help in making decisions on the work required to evaluate and manage desertification hazards later on. A major task of the Preliminary Mission and Phase I (see Chapter 1) is to identify the sources and availability of such information.

a. Preliminary Mission

The Preliminary Mission is the first response to an invitation of a government to undertake a planning study on its behalf. Typically a preliminary mission includes three professional disciplines: economics, natural resources development, and regional planning. Although each of these should look at the status of, or the potential for, the desertification process in the region, the professional in natural resources management takes primary responsibility for the subject.

An assessment as to whether any of the region under study has the potential for suffering the process of desertification can be made using any one of a number of world or regional maps available in moderately sized libraries holding information on natural resources. The "World Map of Desertification" (1:25,000,000) which was developed for the United Nations Conference on Desertification (FAO, 1977) is an example. Another useful map is the one prepared by Dregne in 1983 (Figure 9-6). Figure 9-7 has been adapted from this map and identifies the potential areas for desertification in the countries of South America.

Holdridge life zone maps, which are available for virtually all Central and South American countries, may also be used. In the Holdridge (1967) system, the dry tundra, dry scrub, steppe, dry forest, desert scrub, thorn steppe, thorn woodland, very dry forest, or desert life zones indicate areas of potential desertification. If any part of the area under study is

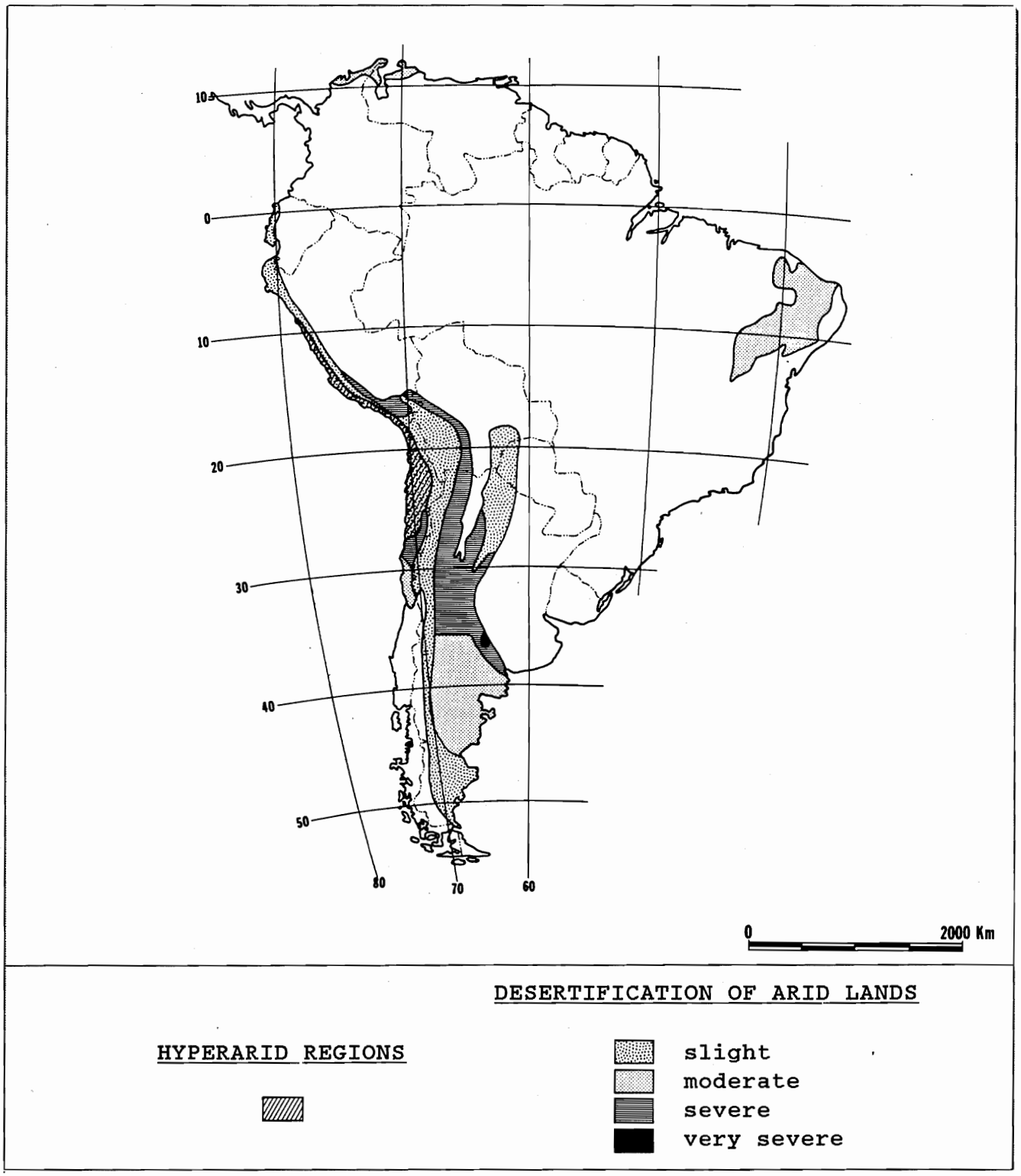
Figure 9-5

FLOW CHART RELATING INFORMATION NEEDS ON DESERTIFICATION HAZARD EVALUATION TO THE STAGES OF THE INTEGRATED DEVELOPMENT PLANNING PROCESS

DEVELOPMENT PLANNING STUDY ACTIVITIES	DESERTIFICATION HAZARD ASSESSMENT NEEDS/ACTIVITIES
Preliminary Mission Collection and review of generally available information on natural resources and socio-economic characteristics	Availability of: Life zone maps Vegetation maps Topographic and soils maps Land-use maps Climatic maps Remote sensing images, photos Precipitation and temperature data Agriculture production records Historical records of drought **Need for Desertification Hazard Assessment**
Phase I - Development Diagnosis Natural resource evaluation analysis of socio-economic and institutional characteristics, preparation of a development strategy and and identification of investment projects for high priority areas.	Preparation of maps which show aridity (Penman, Holdrigde) Together with livestock and agriculture sectors, evaluate condition and trend of actual land-use (using production data and rangeland plant species as index). **Need for Mitigation Design at the Project Level**
Phase II - Development Action Plan and Project Formulation Preparation of sector projects at prefeasibility or feasibility level and action plan for their implementation.	Together with sector specialists design projects and programs assuring that carrying capacity figures agree with the technology being applied. Design monitoring program as part of overall strategy.
Implementation Engineering design of infrastructure and building projects and their execution.	Assess projects implementation to include adherence to guidelines and mitigation projects Oversee installation and operation of monitoring strategy

Figure 9-6

MAP SHOWING AREAS OF POTENTIAL DESERTIFICATION IN SOUTH AMERICA



Source: Adapted from Dregne, H.E. Desertification of Arid Lands, Vol. 3 of Advances in Desert and Arid Land Technology and Development (Chur, Switzerland: Harwood Academic Publishers, 1983).

Figure 9-7

AREAS OF POTENTIAL DESERTIFICATION IN SOUTH AMERICA BY STATE, PROVINCE, OR DEPARTMENT [a/]

COUNTRY	Hyperarid Region	STATUS OF DESERTIFICATION: Slight	Moderate	Severe	Very Severe
ARGENTINA		Catamarca Chaco Chubut Formosa Jujuy La Rioja Mendoza Neuquén Río Negro Salta San Juan Santa Cruz Santiago del Estero	Chubut La Pampa Mendoza Neuquén Río Negro	Catamarca Córdoba Jujuy La Pampa La Rioja Mendoza Salta San Juan San Luis Santiago del Estero	La Pampa
BOLIVIA		Cochabamba Chuquisaca La Paz Oruro Potosí Santa Cruz Tarija		Cochabamba Chuquisaca La Paz Potosí Tarija	
BRAZIL			Alagoas Bahía Ceará Paraíba Pernambuco Piauí Rio Grande do Norte Sergipe		
COLOMBIA			Atlántico Guajira Magdalena		
CHILE	Antofagasta Atacama Tarapacá	Antofagasta Atacama Tarapacá	Aconcagua Coquimbo Valparaíso	Antofagasta Atacama	
ECUADOR		Esmeraldas Guayas Manabí			

Figure 9-7 (cont.)

COUNTRY	Hyperarid Region	STATUS OF DESERTIFICATION: Slight	Moderate	Severe	Very Severe
MEXICO	Sonora	Baja California Norte Baja California Sur Sonora	Baja California Norte Nuevo León Sinaloa Sonora	Aguas Calientes Baja California Norte Chihuahua Coahuila Durango Guanajuato Guerrero Hidalgo Michoacán Nuevo León Oaxaca Puebla Querétaro San Luis Potosí Sinaloa Sonora Tamaulipas Zacatecas	Chihuahua
PARAGUAY		Boquerón Chaco Nueva Asunción			
PERU	Ancash Arequipa Ica La Libertad Lima Moquegua Tacna	Ancash Arequipa Ayacucho Cajamarca Huancavelica Ica La Libertad Lambayeque Lima Moquegua Piura Puno Tacna Tumbes		Arequipa Ayacucho Moquegua Puno Tacna	
VENEZUELA			Falcón Zulia		

a/ Area is defined as the largest political subdivision of the country. The fact that an area appears with a specific status of desertification does not necessarily imply that the entire area is affected. Moreover, an area can have more than one status when different portions are affected to different degrees.

Source: Adapted from: Dregne, H.E. Desertification of Arid Lands (Chur, Switzerland: Harwood Academic Publishers GmbH, 1983).

PRELIMINARY MISSION

QUESTIONS PLANNERS NEED TO ASK:

- Is the study area included in a previously defined desertification hazard map or potential desertification hazard map?
- What basic resource information has been mapped (soils, geology, climate, vegetation, forests, life zones, topography)?
- What is the availability of satellite imagery? At what scale?
- Is information on hydrology available? Does basic climatic and hydrologic instrumentation exist in the region?
- What other information is available describing the region from a systems point of view? What is the history of occurrence of hazardous events contributing to desertification?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Creation of a base map and compilation of relevant thematic maps at appropriate scales.
- Formation of study team to treat desertification data scarcity in spatial and thematic terms.
- Preparation of an integrated work plan for next stage that includes desertification assessment.

in any of these life zones further desertification hazard analyses should be undertaken. A simplified method for identifying the various kinds of desertification hazard is given below (see Section C.2 Defining Desertification Potential).

If this preliminary analysis suggests that desertification is a present or potential problem in the study area, a more precisely defined objective to be met during the next stage of planning should be formulated. That is, an objective which specifically treats the problem of desertification should be made so that it can be treated in the overall regional plan. Terms of reference relevant to further study of the desertification hazard should be included for the work of the specialists assigned to the next stage of the study (see the Appendix to this chapter).

The member of the Preliminary Mission assigned to specifically evaluate desertification will need to answer the questions shown in the box above and to develop other information for an analysis of desertification hazard during subsequent stages.

b. Phase I. Diagnosis of the Study Area

The diagnosis phase of the study is designed to identify the principal problems, potentials, and constraints in the region being studied. It includes an evaluation of natural resources and socio-economic conditions; it delineates and studies subregions, generates new information on relevant subject areas, and identifies prospective development projects. Given the work of the earlier Preliminary Mission, all professionals on the study team should be aware of the potential for desertification and should include in their analyses an explicit concern for that potential.[2/] The team's environmental management adviser or natural hazard specialist should take full responsibility in this study. If neither position exists, the responsibility should reside with the agriculture or livestock management specialists. Several questions and decisions need to be addressed (see box below) which will help guide the team members in evaluating the overall desertification hazard as well as in assessing individual types of the hazard that may exist in the study area.

c. Phase II. Formulation of Development Projects

The previous stage identified the pressing issues and formulated a general strategy together with project ideas that address the problems with the available resources. Actions will have been suggested that are politically feasible within a time frame short enough to maintain the momentum required for decision making.

This stage is to formulate specific development projects based on the overall strategy and project

PHASE I

QUESTIONS PLANNERS NEED TO ASK:

- Can cause/effect relationships be shown between natural events, and between natural events and human activity, that have been responsible for desertification in the past?
- What are the natural goods and services provided to local populations from the ecosystems and how are these divided into the systems that represent environmental units?
- Who are the individuals at the local, regional, and national levels who are best informed about the structure and function of the regional and local ecosystems?
- What are the important linkages between the region under study and the neighboring regions?
- What is the distribution of desertification events according to sub-system?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Characteristics of any desertification abatement projects that should be considered.
- Identification of any desertification abatement projects that are to be a part of on-going programs or a new development program.
- Preparation of an integrated work plan that includes work on desertification specific for the next stage of the process.

ideas that were designed during Phase I. For purposes of the control of desertification, existing natural and man-made services that control the desertification process as well as the hazardous events that contribute to its progress will have been looked into. Cultural, social, and economic factors that could influence project execution and success need to be assessed at the appropriate level of feasibility. And the compatibility of the projects themselves needs to be evaluated in terms of their potential for intensifying or mitigating the desertification process.

Specialists in any sector should evaluate potential projects that explicitly treat mitigation of the desertification process and some specialists such as those in agriculture, range management, and forestry should have experience studying and proposing projects and programs relevant to the desertification process.

2. DEFINING DESERTIFICATION POTENTIAL

In this section short descriptions will be presented concerning two important aspects of the identification and evaluation of desertification potential: the zoning of hazard potential and the identification of the specific desertification hazards.

a. Hazard Zoning

The study area in which the desertification hazard evaluation is to be carried out should be zoned according to as many of the major variables active in the desertification process as possible (see B above). Climate data are especially important and a number of conventional systems of climate zoning exist. Bailey (1980) suggests several such classifications depending on the level of mapping being considered. For example, the methods of Koppen, Kuchler, and Hammond can be used to divide the landscape into a series of ecosystem levels (Figure 9-8). The Holdridge life zone method uses measurements of mean annual "bio-temperature," potential evapotranspiration ratio, and average total annual precipitation to divide an area into life zones and has a number of advantages. First, it is based on biotemperature and moisture--both highly correlated with desertification. Second, it now includes data on slope, soil texture, and soil depth. And, third, maps at varying scales exist for most of Latin America and some of the Caribbean.

b. A Descriptive Key to Identify Desertification Potential

During the Preliminary Mission, the decisions depend on the existence of different desertification

Figure 9-8

LEVELS OF GENERALIZATION IN A HIERARCHY OF ECOSYSTEMS

Levels of Generalization and Common Scales of Mapping	Current Definitions
1. Domain 1:3,000,000 and smaller (for use at Preliminary Mission level of planning)	Subcontinental areas of broad climatic similarity identified by zonal heat and water balance criteria.
2. Division 1:1,000,000 to 1:3,000,000 (for use at Preliminary Mission level of planning)	A part of a domain identified by macroclimatic criteria generally at the level of the basic climate types of Koppen.
3. Province 1:500,000 to 1:1,000,000 (for use in preliminary work during Phase I)	A part of a division identified by bio-climate and soil criteria at the level of soil orders and classes of vegetation during formations. Highland regions (e.g., mountain systems) with complex climate-vegetation zonation are distinguished at this level.
4. Section 1:250,000 to 1:500,000 (for use in Phase I and early Phase II)	A part of a province identified by a single climatic vegetation climax at the level of Kuchler's potential vegetation types.
5. District 1:150,000 to 1:250,000 (for use in Phase I and early Phase II)	A part of a section identified by Hammond's land-surface form types.
6. Landtype association 1:20,000 to 1:125,000 (for use in Phase I and Phase II)	A part of a district determined by isolating areas whose form expresses a climatic-geomorphic process (e.g., fluvial, glacial, etc.).
7. Landtype 1:10,000 to 1:20,000 (for use in Phase II and some design work)	A part of a landtype association having a fairly uniform combination of soils (e.g. soil series) and a chronological sequence of vegetation at the level of Daubenmire's (1964) habitat types.
8. Landtype phase 1:2,500 to 1:10,000 (for use in Phase II and some design work)	A part of a landtype based on variations of soil and landform properties such as soil drainage and slope that affect the productivity of the habitat type.
9. Site 1:2,500 and greater (for use in design work)	A part of a landtype phase that is homogeneous in respect to all components, their appearance, potential to produce biomass, limitations to use, and response to management. It is the basic geographic cell of the ecological classification.

Source: Modified from Bailey, R.G. "Integrated Approaches to Classifying Land as Ecosystems" in Proceedings of the Workshop of Land Evaluation for Forestry (Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement, 1980).

PHASE II

QUESTIONS PLANNERS NEED TO ASK:

- What are realistic levels of technology, credit, knowledge, information, market, etc., that will be available to the users of the land?
- What are the projects and programs that are being discussed by the other team members that would intensify or mitigate the desertification process?
- How can mitigation measures be designed to fit or even enhance these projects?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Make adjustments to current land use.
- Recommend levels of technology, credit, market, information, etc.
- Define the specific instruments of policy and management required for implementation of the overall strategy and individual projects.
- Design projects needed to monitor implementation of the program in terms of desertification.

hazards. Such decisions deal with the selection of specialists for Phase I and with the development of their terms of reference.

Figure 9-9 is a descriptive key or modified decision tree designed to help gain information on the kind and degree of the desertification that may be encountered in regional development studies. The method is based on easily measurable or existing data that are not normally subject to change due to human activity; and it is totally objective from the point of view of the evaluator.

The method uses data from the region being studied and is based on an understanding of the regional system, including existing conditions and development activities, thus enabling one to identify which desertification hazards are present. With this information, actions may be designed at later stages that would evade and/or help ameliorate the desertification processes.

In the key (Figure 9-9), numbers in the right margin (2, 2*, 3, 3*, 4, 4*...15, 15*) indicate where to go in the key given the data at hand. The letters correspond to general descriptions of desertification potential and discussions of land use that may be related to the site being described.

Information derived from Figure 9-9 can help in choosing the specialists and developing the terms of reference for these Phase I specialists; and, depending on the scale, quality, and quantity of this information, it could be mapped to indicate the location of each different desertification hazard encountered in the study.

(a) Annual average precipitation >1500mm; >50% sand; >10° slope:

An annual average precipitation of over 1500mm generally indicates a site situated in the wet forest life zone of the Holdridge (1967) classification system. In addition, however, the timing, duration, and intensity of each precipitation event as well as the characteristics of the soil, air temperatures, and topography can dictate the potential of a given site to suffer initiation of the desertification process. Consequently, even if annual precipitation is near 1500mm, its overall distribution should be evaluated, since marked wet and dry periods could indicate potential desertification problems in terms of soil loss, through erosion by water or wind. Soil erosion will also depend on the characteristics of land use and land-use management. That is, the lack of soil protection during the very wet or very dry parts of the year can increase soil loss and the use of soil conservation measures may help to control or ameliorate soil loss. Infrastructure such as buildings and other structures may be lost because of wind and water erosion or slope failure because of the high sand content of the soil and the relatively steep slopes. Waterlogging, however, should not be a problem because the high sand content of the soil and the relatively steep slopes provide more than adequate drainage.

Figure 9-9

DESCRIPTIVE KEY TO THE IDENTIFICATION OF DESERTIFICATION POTENTIAL

A dichotomous key is presented below in which several factors are identified which can influence the desertification process. In the key a decision is forced at each number that depends only on the value of the factor being considered. The numbers between 1 and 15 are given in pairs and one of each pair has an asterisk (*) which can also be chosen depending on the quantitative value of the factor being considered. Text corresponding to the letters of the alphabet discusses each individual site and its potential for suffering initiation of the desertification process.

IF:	GO TO:
(1) Precip >1500mm/yr	2 or 2*
(2) > 50% sand	3 or 3*
(3) >10° slope	(a) in the text.
(3*) <10° slope	(b) in the text.
(2*) < 50% sand	4 or 4*
(4) >10° slope	(c) in the text.
(4*) <10° slope	(d) in the text.
(1*) Precip <1500mm/yr	5 or 5*
(5) P/PET ≥1.0	6 or 6*
(6) >50% sand	7 or 7*
(7) >10° slope	(e) in the text.
(7*) <10° slope	(f) in the text.
(6*) <50% sand	8 or 8*
(8) >10° slope	(g) in the text.
(8*) <10° slope	(h) in the text.
(5*) P/PET <1.0	9 or 9*
(9) P/PET .76-.99	10 or 10*
(10) >50% sand	11 or 11*
(11) >10° slope	(i) in the text.
(11*) <10° slope	(j) in the text.
(10*) <50% sand	12 or 12*
(12) >10° slope	(k) in the text.
(12*) <10° slope	(l) in the text.
(9*) P/PET .01-.75	13 or 13*
(13) >50% sand	14 or 14*
(14) >10° slope	(m) in the text.
(14*) <10° slope	(n) in the text.
(13*) <50% sand	15 or 15*
(15) >10° slope	(o) in the text.
(15*) <10° slope	(p) in the text.

(b) Average annual precipitation >1500mm; >50% sand; <10° slope:

Native vegetation would again be classified as wet forest. Both agriculture and livestock ranching are often tried under these characteristics. These activities work best, if at all, at the drier end of the precipitation range. Given the low angle of slope, trampling by livestock could reduce infiltration rates--if the remaining soil fraction is clay--and problems similar to those of waterlogging are created. However, water erosion would be minimal because of the reduced slope, and where the soil is very sandy, waterlogging would not be a problem unless the area happened to be in a geographic depression with a high water table. Problems of salinity and alkalinity would generally be limited because of the high rainfall. Construction requires well engineered roads, bridges, and foundations because of erosion along river borders in areas of relatively flat terrain.

(c) Average annual precipitation >1500mm; <50% sand; >10° slope:

Areas having these characteristics suffer the same potential hazards as the areas described in (a) with the slight difference that the lower sand content may reduce the potential for water erosion on the steeper slopes. Soils having a greater percentage of clay or loam contain more nutrients despite precipitation rates greater than 1500mm per year and, therefore, such areas generally have good vegetative cover in their natural state. Consequently, both conversion of the forest to pasture and pasture maintenance are difficult and expensive. And, under the kinds of grazing pressures required to keep down the woody vegetation, such areas suffer from trampling and the creation of terraces, or trails, by the livestock. This allows runoff to be concentrated and the trails then become susceptible to the formation of gullies. Soils in this group are a bit more stable than those having a higher percentage of sand, and buildings and other infrastructure would generally be at less risk to erosion and slope failure.

(d) Average annual precipitation >1500mm; <50% sand; <10° slope:

Under these conditions the major desertification hazard is caused by waterlogging. The high precipitation, relatively heavier soils (soils having a higher percentage of clay), and less steep slopes all lead to excess water and waterlogging: more water, less runoff, and slower infiltration rates. A potential for waterlogging can be aggravated by certain land uses. Tree removal diminishes evapotranspiration; trampling by livestock increases bulk densities of the less sandy soil; and water collects in areas of little or no slope. In terms of infrastructure, any roads will require construction of a large number of culverts to allow free passage of runoff.

(e) Average annual precipitation <1500mm; P/PET 1.0+; >50% sand; >10° slope:

The low rate of evapotranspiration compared to the amounts of precipitation that these areas receive indicates regions that have fairly low temperatures. Even if annual average precipitation is low, excess water may exist. The high sand fraction and steep slopes work against waterlogging. However, these same characteristics would promote water erosion. If, in the cooler areas, growing seasons are shortened, certain kinds of agriculture and ranching (heavy grazing, trampling, plowing, clean fallow, and some construction activities) would eliminate or reduce ground cover during certain parts of the year. If these periods coincide with seasons of wind, erosion, and the formation and movement of sand dunes can be expected.

(f) Average annual precipitation <1500mm; P/PET 1.0+; >50% sand; <10° slope:

Under these characteristics, there is limited potential for nearly all kinds of desertification--especially near the upper end of the precipitation range and at the higher P/PET ratios. Again, because of the high P/PET ratios, the general climate would be cool to cold and this would place the area at either high altitude or high latitude. The major desertification hazard would be wind causing erosion problems if the land is left unvegetated. Growing seasons would generally be short, and clean fallow would be more likely to coincide with periods of wind. Waterlogging could be a problem in the flatter areas having less sand content in the soil.

(g) Average annual precipitation <1500mm; P/PET 1.0+; <50% sand; >10° slope:

Despite the large variation in precipitation that could occur in these areas, the key to understanding desertification hazard here is the P/PET ratio above 1.0. A high ratio of precipitation to potential evapotranspiration would mean a surplus of water during parts of the year. If this excess water were allowed to run off slopes of greater than 10°, water erosion would occur and this would generally be intensified under land uses which disturb vegetative cover. The P/PET ratio again indicates a fairly cold climate and a short growing season. As a consequence, soils may remain uncovered for lengthy periods. Despite the excess water as indicated in the P/PET ratio, periods of seasonal drought can occur. Wind during such dry periods can cause erosion, the formation of sand dunes, and, in cases of high and sustained wind velocities, the movement of sand dunes. Agricultural and livestock management practices as well as the design, construction, and maintenance of infrastructure should be undertaken with this in mind.

(h) Average annual precipitation <1500mm; P/PET 1.0+; <50% sand; <10° slope:

The characteristics of these areas are similar to those described in (e), (f), and (g): cool or cold temperatures and location at high altitude, high latitude, or both. In Latin America parts of the very high Andes or far Southern Cone would correspond to these characteristics. Due to short growing seasons, and low temperatures, such areas have excess water despite low total precipitation figures. Waterlogging may, therefore, be a hazard on the flatter areas. Agriculture is difficult because of the short growing seasons although grazing of livestock may be possible. In some areas trampling by livestock could aggravate waterlogging problems. These areas also usually have high wind velocities during portions of the

year. As a consequence, artificial protection of the soils may be necessary.

(i) Average annual precipitation < 1500mm; P/PET = 0.76-0.99; > 50% sand; > 10° slope:

Because of the potentially low precipitation, higher risk of drought, and lower P/PET ratios, these are the areas that are normally thought of in conjunction with the desertification process. Certain combinations of these characteristics (very low precipitation and P/PET ratio near .76) present conditions that are extremely favorable for initiation of the desertification process. This is especially a problem on steep slopes and sandy areas where water erosion can occur if vegetation is removed. In Latin America, large-scale clearing by fire or by bulldozer to create range-land for livestock grazing intensifies desertification hazards. Clearing of vegetation for rain-fed or irrigated agriculture, by heavy browsing and/or grazing by livestock, by the use of woody biomass for firewood and/or the production of charcoal, and by clearing for construction of infrastructure or housing are also causal factors. In Latin America, overgrazing by wildlife probably does not play a significant role except in isolated cases (vicuña or deer confined to publicly managed reserves or privately held protected areas). In areas receiving rainfall at the high end of the range and at high intensities, surface erosion is a potential threat. In the drier areas, a desertification threat may also be occasioned from wind.

(j) Average annual precipitation < 1500mm; P/PET = 0.76-0.99; > 50% sand; < 10° slope:

The significant difference between areas having these characteristics and the areas described in (i) above is the degree of slope. Consequently, areas falling within the previous description have problems of water and wind erosion and the areas described here have problems of surface salinity--particularly in areas having precipitation levels and P/PET ratios at the lower end of the stated ranges. Irrigation in poorly drained areas or poorly designed infrastructure such as roads, railroads, and dikes which inhibit the flow of water would worsen the salinity condition. Although surface salinity may be the major desertification hazard of concern here, subsurface soil salinity (caliche) could also be a problem if precipitation is at the higher end of the range and if the soils are heavy. These conditions allow leaching of salts from the upper soil levels but they also prohibit leaching from the total soil profile.

(k) Average annual precipitation < 1500mm; P/PET = 0.76-0.99; < 50% sand; > 10° slope:

Areas having these characteristics are relatively free from desertification hazards although they may be arid or semi-arid. Under the lower rainfall conditions and the resulting scarcity of vegetation, intense precipitation events cause water erosion and such erosion is more severe if the soil surface is disturbed by trampling, plowing, fire, or soil movement for construction purposes. Likewise, if the soil is uncovered during periods of drought and wind, as it often is, erosion will occur.

(l) Average annual precipitation < 1500mm; P/PET = 0.76-0.99; < 50% sand; < 10° slope:

Because of the low slope angle, desertification problems are, (1) wind erosion, depending on how the seasons of drought coincide with those of reduced vegetative cover because of human activities (farming practices) or low temperatures; and (2) salinity of soils in areas having less rainfall and greater potential evapotranspiration. If the soil clay fraction is high (as it often is due to deposition of the finer soil material on areas of little or no slope), puddling, soil expansion, and vertical soil movement decrease vegetative cover. Land use may include rain-fed agriculture in areas at the higher precipitation levels, although production is low and decreases with decreasing levels of precipitation and/or increasing rates of evapotranspiration. At the lower precipitation levels, then, irrigation would be necessary and this could increase the probability of salinization and waterlogging.

(m) Average annual precipitation < 1500mm; P/PET = 0.01-0.75; > 50% sand; > 10° slope:

These characteristics describe areas having a high potential for desertification. Because of the low precipitation, high potential evapotranspiration, rapid infiltration beyond the root zone of any precipitation entering the soil, and even more rapid runoff of precipitation that stays on the surface because of the steep slopes, the desertification process is easily initiated in these areas. The amount of moisture available for biomass production is small. Wind and direct insolation reduce available moisture even further and these are influenced by human activity which disturbs ground cover, be it vegetation or erosion pavement. Disturbance of ground cover can also initiate the formation of blow-outs (areas excavated by the force of wind). Over-grazing, plowing, trampling, and clearing for construction can all initiate the process. Even irrigation is potentially harmful, 1) because of the amount of water that probably will be necessary and the salinity of its residues; and 2) because of the erosivity of the sandy soils on steep slopes even if modern irrigation technology is used. Furthermore, given the low precipitation totals and the sparse cover of the soils by vegetation, incoming radiation will often be high and cultural practices for crops, livestock, and construction will need to consider

shade and insolation in project design. Slope angle and orientation are important in that slopes which face the sun will be much drier and warmer and, except in the very cold latitudes, will have much less vegetative growth.

(n) Average annual precipitation <1500mm; P/PET=.01-.75; >50% sand; <10°slope:

Conditions in these areas are similar to those found in areas described in (m) above except that, here, slopes are much less steep. The landscape is generally less well defined geomorphically as well. As a consequence, these flatter areas may have a higher level of soil moisture because they receive runoff from the slopes above and because insolation will generally be less direct. Wind erosion and the formation of sand dunes could be a problem if the soil is without cover during the periods of wind and little or no precipitation. Soil salinity could be a problem, although the sandier soil allows rapid infiltration that would wash the salts to lower levels in the soil profile, where they will form a layer of caliche. In areas where vegetation or desert pavement is disturbed by agriculture, grazing pressure, or construction activities, wind can create blow-outs and these often increase in size unless remedial efforts are made to restore the ground cover. Gathering of woody vegetation for charcoal and/or firewood could also initiate a cycle of reduced effective surface moisture because of the higher insolation and albedo.

(o) Average annual precipitation <1500mm; P/PET=0.01-0.75; <50% sand; >10° slope:

The major difference in the characteristics of these areas from those described in (n) above is in the amount of sand in the soil. A smaller percentage of sand in a soil means that the percentages of clay and silt are higher. The clay and silt fractions contain more nutrients and this may be reflected in the amount of vegetation that is present. On the other hand, if the soils are predominantly clay, runoff of precipitation is increased due to low infiltration rates. As a consequence, the areas described here may be drier than those described in (n) above. Additionally, root penetration may be reduced because higher percentages of clay generally mean that the soil is much harder and less friable under dry conditions. In any case, effective moisture in these areas is low and human activity could reduce it even more through exposing the land surface to radiation (higher temperatures) and wind.

(p) Average annual precipitation <1500mm; P/PET=0.01-0.75; <50% sand; <10° slope:

The characteristics of this area are very similar to those presented in (o) above except that slope steepness is much less. This difference is significant in that higher salinity levels will be encountered in the soil, subsoil, and open water. Given the higher clay content and less steep slopes, high soil alkalinity levels may also be present and these should be considered when proposing more intensive land use, especially irrigated agriculture. Beyond this, the common problems of desertification are all a potential in these areas: waterlogging (with irrigation); water erosion (especially along the edges of intermittent water courses); wind erosion; dune formation and movement; and reduced effective moisture. All of these will negatively affect the production of biomass.

3. INTEGRATED ANALYSIS OF DESERTIFICATION HAZARDS

Desertification is a complex phenomenon requiring the expertise of specialists from several different disciplines if it is to be understood and managed. Climatology and meteorology, soils, agronomy, range management, anthropology, political science, and economics are all appropriate for undertaking a study of the desertification process, and input from these and others will be required if development planning is to adequately treat the subject.

To be useful, each specialist must look toward a common objective and the information obtained must be shared. As in any integrated study, the output from one discipline serves as input to another and the output of one stage of planning serves as input to the next planning stage (OAS, 1978, 1984).

Each planning stage will require information from the sectors which these specialists represent but the information must be progressively more detailed and more narrowly focused in each succeeding stage. The Preliminary Mission, of course, will not have individuals from all specialties. Rather, the individuals who make up the Preliminary Mission must account for this information. Phase I may well have specialists from each sector to gather and organize information required by the specialists who will compose the Phase II mission. These specialists would make use of the information in developing strategies, projects, and programs. Further on, much of this information will serve as base-line data for integrated monitoring programs. (See the chapter appendix for explicit terms of reference for the work of selected specialists in Phase I of the planning exercise.)

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Appendix

TERMS OF REFERENCE FOR SELECTED SPECIALISTS IN DESERTIFICATION HAZARD ANALYSIS

As described in the text, the desertification process is a complex of several different phenomena leading to a decrease in a site's capability to produce biomass. As a consequence, an evaluation of this process for the purposes of planning will require the expertise of specialists from several different disciplines, including climatology and meteorology, soils, agronomy, range management, anthropology, political science, and economics. Any information that is sought must lead to the same end and any information gained must be shared--even debated--if the end result is to ameliorate rather than intensify desertification. Each planning stage will require information from these sectors but with progressively more detail in each succeeding stage. Thus, in general, these terms of reference will serve all planning stages, though for each specific stage they should be modified to fit the requirements of scale and objective.

The Preliminary Mission, of course, does not have representation from all specialties. Rather, individuals who are members of the preliminary mission must be "generalist" enough to understand the kinds of information needed by any specialists helping with the later stages of planning. Phase I, on the other hand, will require specialists from a number of sectors to gather and organize the information requested during the Preliminary Mission and to prepare that information for Phase II.

In the sections that follow, the informational input of each sector specialist to the work of other sectoral specialists for Phases I and II is given. In doing this, the output of information required of each sector is also identified.

INPUT OF CLIMATOLOGY/METEOROLOGY INFORMATION TO THE SECTORS OF:

1. HYDROLOGY: Precipitation and temperature records, especially monthly averages; conclusions as to whether or not storms are frontal or orographic. Information concerning the location and histories of stations in the region (important for interpretation of the data and for filling in data that may be missing).

2. SOILS: Total precipitation and average high and low temperature. Indications of the type and seasonal distribution of precipitation and the type and intensities of wind.

3. RANGE MANAGEMENT: Precipitation and temperature records, with monthly averages. An indication of wind characteristics.

4. AGRONOMY: Precipitation and temperature records especially monthly averages. Extreme temperature lows. Indications of photoperiod and optimum intensities of sunlight as they influence the life cycles of major native species and any exotics being recommended. Conclusions as to whether or not storms are frontal or orographic.

5. ECONOMICS: Precipitation and temperature averages by month and any indication of geographic variation.

6. ANTHROPOLOGY: Seasonal variation in temperature and precipitation. Geographical variation in periods of particularly heavy rainfall or extreme temperatures conditions sustained for lengthy periods.

7. POLITICAL SCIENCE: Records indicating extremes of precipitation or temperature which would highlight periods of drought or flooding. Names and addresses of officers and programs of national, regional, and local agencies covering management and operation of climatological/meteorological stations, projects, and programs.

INPUT OF HYDROLOGY INFORMATION TO THE SECTORS OF:

1. CLIMATOLOGY/METEOROLOGY: Location and relevance of any stations, projects, programs and institutions in the region being studied which have mandate, projects, programs in climatology/meteorology.

2. SOILS: Inventory of existing maps which outline river basins/watersheds, topography, and geology; indicate scales, date, source, and, if possible, examples of such maps.

3. RANGE MANAGEMENT: Similar needs to those of soils. Actual and potential sources of surface and ground water which could be used in livestock management.

4. AGRONOMY: Indication of actual and potential sources of water for irrigation and agroindustry, including some data on periodicity of low flows.

5. ECONOMICS: Physical data (flows, storage, water use for ener gy, irrigation, industry, urban centers, recreation, wildlife, fishing) to calculate reliability of costs and profit figures. Information given to water sector for the past construction, operation, and maintenance of structures. Estimates of outputs such as water used for irrigation, energy, industrial, or urban purposes.

6. ANTHROPOLOGY: Use of water by population. Sources of ground and surface water. Indication of the most common source (spring, open well, river, lake, deep well, cistern), reliability of sources.

7. POLITICAL SCIENCE: Numbers of communities/individuals using the water resource and for what purposes. Average rise and fall in reservoir depth over the year. Names and addresses of agencies having mandates in management of water resources and/or the operation of dams and reservoirs.

INPUT OF INFORMATION OF THE SOILS SPECIALIST TO THE SECTORS OF:

1. CLIMATOLOGY/METEOROLOGY: Identify, locate, and secure any available topographic and vegetation maps.

2. HYDROLOGY: Location, type, and extent of erosion. Location, type of sedimentation.

3. RANGE MANAGEMENT: Present land use. General soil-use capability. Topographic maps. Erosivity of soils.

4. AGRONOMY: Present land use. General soil-use capability. Topographic and land-use maps.

5. ECONOMICS: Production data with reference to soil-capability classes.

6. ANTHROPOLOGY: Present land use. General soil-use capability.

7. POLITICAL SCIENCE: Information on all agencies having mandate, projects, and programs dealing with soil science.

INPUT OF INFORMATION OF THE RANGE MANAGEMENT SPECIALIST TO THE SECTORS OF:

1. CLIMATOLOGY/METEOROLOGY: Dates of problems for the livestock enterprise, especially if they were related to climate/weather.

2. HYDROLOGY: Map showing distribution of livestock. Livestock numbers and classes.

3. SOILS: Map showing distribution of livestock by class and numbers.

4. AGRONOMY: Maps showing agricultural land use, including information on intensity of use, and projections of future use.

5. ECONOMICS: Production data by region/zone and by livestock class. Estimates of the inputs required by livestock sector (fencing, disease control, barns, etc.).

6. ANTHROPOLOGY: Information on the activities relating to livestock throughout the year. Livestock classes and numbers by household. Special uses or significance of livestock to the owner or herder.

7. POLITICAL SCIENCE: Information on any agency or institution having a mandate on livestock management, research or marketing, and their projects and programs (national and international as well as public and private agencies).

INPUT OF INFORMATION OF THE AGRONOMY SPECIALIST TO THE SECTORS OF:

1. CLIMATOLOGY/METEOROLOGY: Definition of data requirements by the agriculture sector.

2. HYDROLOGY: Distribution of agricultural land use in the region, including data on the kinds of crops (annual, perennial) and cultural methods being used (mapped if possible). Information on the agricultural year (periods of land preparation, seeding or planting, cultivation, harvest).

3. SOILS: Information as for the hydrologist, including general data on soil stability (eroded and eroding areas).

4. RANGE MANAGEMENT: Relationships between agriculture and livestock activities. Potential sources of fodder, either cut or standing. Information on the agricultural year.

5. ECONOMICS: Production data (historical as well as current). General information concerning both inputs (agricultural chemicals, labor, credit, subsidies, etc.) and outputs (prices, production and marketing figures). Use of labor and middlemen.

6. ANTHROPOLOGY: Information regarding the use of familial labor during the agriculture year; use of migrant labor; use of produce and services from the farm (private or collective) and from neighboring wildlands (wild species for food, fiber, medicine, firewood, building materials).

7. POLITICAL SCIENCE: Information on relevant agricultural legislation and policies affecting the farmers of the region. Copies of legislation or policies. Information on the organization of any public institutions which deal directly with the agriculture sector.

INPUT OF INFORMATION OF THE ECONOMIST
TO THE SECTORS OF:

1. CLIMATOLOGY/METEOROLOGY: Statement by the economist of specific data needs from the climatological/meteorological sector.

2. HYDROLOGY: Generalized information on costs and prices of inputs and outputs for the water-use sector. Information on discount rates, indebtedness, and historical economic behavior of the water-use sector. Costs of sedimentation of water-use infrastructure and to whom the costs are assigned.

3. SOILS: Statement by the economist of specific data that an economics review would require from the soils specialist.

4. RANGE MANAGEMENT: Statement by the economist of the data that an economics review would require from the range management sector. General information on the historical economic behavior (indebtedness, market success and failure, etc.) of the range management sector.

5. AGRONOMY: Statement by the economist of the data that an economics review would require from the agriculture sector. General information on the historical economic behavior (indebtedness, market success and failure, etc.) of the agriculture sector.

6. ANTHROPOLOGY: General information on the participation of the regional population in the formal and informal economic sectors. Income distribution; indebtedness; role of credit and credit institutions. Source and availability of energy (firewood, charcoal, other biomass).

7. POLITICAL SCIENCE: Data on economic trends. Structure and policies of public economic institutions. Information on the economic status of government ministries.

INPUT OF INFORMATION OF THE ANTHROPOLOGIST
TO THE SECTORS OF:

1. CLIMATOLOGY/METEOROLOGY: Outline of data requirements the anthropologist has from the climatological/meteorological sector.

2. HYDROLOGY: Statement from the anthropologist on requirements from the hydrology sector. Information on the abilities and disposition of the regional population to adapt to specific water uses (different types of irrigation). Generalized information on sources and use of domestic water (including water quality, abilities to use and pay for hydro-derived energy).

3. SOILS: Outline of the requirements of the anthropologist from the soils specialist. Information on areas of the region that have a special historical social/cultural significance to the population.

4. RANGE MANAGEMENT: Provide information on the special characteristics, beliefs, and needs of the regional population that would indicate adaptation to, or use of, livestock management practices. Information on existing cultural mores that would dictate livestock management practices.

5. AGRONOMY: Provide information on the characteristics, beliefs, and needs of the regional populations that would indicate adaptation to, or use of, special agricultural practices. Information on existing cultural mores that would indicate acceptable and unacceptable agricultural practices. Sources and supply of energy (firewood, charcoal, other biomass).

6. ECONOMICS: Information on the special characteristics, beliefs, and needs of the regional populations that would indicate their participation in economic activities of the region. Information on land tenure. Source and supply of energy, especially firewood and charcoal.

7. POLITICAL SCIENCE: Information on any special tribal or other group relationships that would influence political organization, decision-making, and action in the region.

INPUT OF INFORMATION OF THE POLITICAL SCIENTIST
TO THE SECTORS OF:

1. CLIMATOLOGY/METEOROLOGY: Institutional arrangements (international, national, regional; scientific, line agency) that deal with the general subject of climatology and meteorology.

2. HYDROLOGY: Institutional arrangements, structures, and policies of international, national, regional, scientific, and line agencies that deal with the general subject of hydrology.

3. SOILS: Institutional arrangements and policies at all levels of government that deal with the general subject of soils (which agencies undertake soil surveys, which have responsibility for soil conservation activities, which perform research, etc.)

4. RANGE MANAGEMENT: Institutional arrangements and policies at all levels that deal with the general subject of range management.

5. AGRONOMY: Institutional arrangements and policies at all government levels that deal with the general subject of agriculture.

6. ECONOMICS: Institutional arrangements and policies at all levels that deal with the general subject of economics, finance, and marketing.

7. ANTHROPOLOGY: Institutional arrangements and policies of governments at all levels relevant to the region in question that deal with the health and welfare of the regional populations, including indigenous peoples, and their migrations and activities.

OTHER SPECIALISTS

Other specialists may also be necessary depending on what is found in each of the planning stages. For example, based on an expertise in systems analysis, an environmental management advisor will probably be needed early in the process to help develop mutually compatible terms of reference for the sectoral specialists.

During the Preliminary Mission, the work of the environmental management advisor would be to :

- Prepare a short description of the major ecosystems where the actual and proposed human interventions are to take place;
- Review proposed and existing development activities within and surrounding the systems of interest;
- List the natural hazards that have occurred previously in the systems being intervened including wind, erosion, fire, medium and long term drought;
- List the natural services that control or ameliorate to some degree the natural hazards listed above.

At later stages and with the help of other sectors and disciplines the specialist would describe and evaluate the relationships between these services and the system structure and function which positively or negatively influence the desertification hazard and how the proposed human activities would influence the services of control (amelioration or intensification). During the later stages of Phase I and in Phase II the specialist should suggest studies which would lead to the successful "management" of the of the desertification process.

Some of the activities of the above specialists can be undertaken by others. For example, a forestry specialist should be involved in much of the activity of data gathering regarding use and supply of firewood, charcoal and other biomass for energy purposes as well as the use of forest products in other activities (building materials, construction of all kinds). In many cases a geomorphologist or fluviomorphologist should study erosion and sedimentation processes.

CHAPTER 10

LANDSLIDE HAZARD ASSESSMENT

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Contents

List of Figures

LANDSLIDE HAZARD ASSESSMENT

SUMMARY

This chapter presents (1) key terms, concepts, and important considerations related to landslide susceptibility; (2) a technique--hazard zonation mapping--for examining landslide risks; and (3) the critical issues that need to be addressed in integrating landslide hazards into the development planning process.

In 1974, one of the largest landslides in recorded history occurred in the Mantaro River valley in the Andes Mountains of Peru (Hutchinson and Kogan, 1975). A temporary lake was formed when the slide dammed the Mantaro River, resulting in the flooding of farms, three bridges, and twelve miles of roadway. Almost five hundred people in and around the village of Mayunmarca lost their lives. This disaster is one example of the destructive potential of landslides and why they are considered hazards. While not every landslide results in catastrophe, the damage from many small ones may equal or exceed the impact of a single major failure. Thus, both large and small landslides are capable of causing significant damage and loss of life.

Assessing relative landslide hazard is the objective of the method described in this chapter. Its primary product, a landslide hazard map, provides planners with a practical and cost-effective way to zone areas susceptible to landsliding.

This method can be used both by planners and by landslide technical specialists. The planner will gain a working knowledge of concepts and considerations for incorporating landslide hazard evaluation into the planning process, using a level of evaluation suitable for each stage of the process, and thus should be able to ask the appropriate questions of the technical specialist and prepare terms of reference to ensure that the needed information is obtained. The technical specialist will find a review of landslide hazard issues and guidelines for conducting a landslide zonation. As is often the case in natural hazards management, planning studies are often the link between scientific information and the general development planning process.

The method presented, one of several that are available, has the following characteristics:

- Various thematic maps and remote sensing information usually available to a development study are used.
- It is designed to provide landslide hazard information appropriate for each of the stages of the planning process.
- Relative susceptibility to landsliding is used as a measure of the potential hazard within an area.
- It is applicable to regions with different geomorphologic and vegetation characteristics.
- It can usually be used within the time and budget constraints of a planning study.

A. Overview of Landslide Hazard Mapping and the Development Planning Process

The susceptibility of a given area to landslides can be determined and depicted using hazard zonation. A landslide hazard map can be prepared early in the planning study and developed in more detail as the study progresses. It can be used as a tool to help identify land areas best suited for development by examining the potential risk of landsliding. Furthermore, once landslide susceptibility is identified, investment projects can be developed which avoid, prevent, or substantially mitigate the hazard.

Determining the extent of landslide hazard requires identifying those areas which could be affected by a damaging landslide and assessing the probability of the landslide occurring within some time period. In general, however, specifying a time frame for the occurrence of a landslide is difficult to determine even under ideal conditions. As a result, landslide hazard is often represented by landslide susceptibility (Brabb, 1985). Similar to the concept of flood-prone areas (see Chapter 8), landslide susceptibility only identifies areas potentially affected and does not imply a time frame when a landslide might occur. To simplify these concepts, landslide susceptibility will be referred to as landslide hazard in this chapter. Comparing the location of an area of proposed development to the degree of landslide hazard present enables the planner

DEFINITIONS

- **Landslide Hazard**: as represented by susceptibility, which is the likelihood of a potentially damaging landslide occurring within a given area.
- **Vulnerability**: the level of population, property, economic activity, including public services, etc., at risk in a given area resulting from the occurrence of a landslide of a given type.
- **Risk (specific)**: the expected degree of loss due to a particular landslide phenomenon.

to estimate the landslide risk. This can be used to define land use capability and identify appropriate mitigation measures.

A landslide hazard map which identifies areas of differing landslide potential may be generated. The need for such landslide hazard information may vary according to the future land use. The degree of landslide hazard present is considered relative since it represents the expectation of future landslide occurrence based on the conditions of that particular area. Another area may appear similar but, in fact, may have a differing landslide hazard due to a slightly different combination of landslide conditions. Thus, landslide susceptibility is relative to the conditions of each specific area, and it cannot be assumed to be identical for a similar appearing area.

Even with detailed investigation and monitoring, it is extremely difficult to predict landslide hazards in absolute terms. Sufficient understanding of landslide processes does exist, however, to be able to make an estimation of landslide hazard potential. The planner can use this estimation to make certain decisions regarding site suitability, type of development, and appropriate mitigation measures. Thus, the planner is determining acceptable risk.

1. DETERMINING ACCEPTABLE RISK

Determining whether there is a need for landslide hazard information is the first step in ensuring that landslide risk does not exceed an acceptable level in planning future land use. The objective of landslide information is to identify which relatively landslide-susceptible areas are best suited for what types of development activities. For example, assessing landslide hazard would have a low priority in planning areas to be set aside for national parks or game preserves. Conversely, landslides can be an important factor in the development of newly cleared forest areas or in building infrastructure in mountainous or hilly terrain. Clearly, the amount of landslide hazard information needed is based on the level and type of anticipated development for an area. Failure to understand the potential effects landsliding can have on a project or how the project might affect landslide potential can bring increased risk.

Natural changes as well as human-induced changes can affect the susceptibility to landslides and must be understood when assessing the landslide potential of an area. It is critical for a planner to appreciate these issues early in the planning process. A decision is ultimately made regarding the degree of risk that is acceptable or unacceptable to a project. Mitigation strategies are then designed to reduce risk. These concepts are discussed at more length later in this chapter.

Early consultation with landslide technical specialists is recommended so that they can assess the risk of proposed activities in a landslide hazard area. The planner, while not expected to be a technical expert, must know the questions to ask of a landslide specialist. By asking the appropriate questions, the planner will be able to identify and evaluate measures to minimize or avoid landslide vulnerability.

2. LANDSLIDE HAZARD MAPPING

Interpretation of future landslide occurrence requires an understanding of conditions and processes controlling landslides in the study area. Three physical factors--past history, slope steepness, and bedrock--are the minimum components necessary to assess landslide hazards. It is also desirable to add a hydrologic factor to reflect the important role which ground water often plays in the occurrence of

landslides. An indication of this factor is usually obtained indirectly by looking at vegetation, slope orientation, or precipitation zones. All of these factors are capable of being mapped. Specific combinations of these factors are associated with differing degrees of landslide hazards. The identification of the extension of these combinations over the area being assessed results in a landslide hazard map. The technique used to prepare hazard maps is called a combined factor analysis and is described in detail in Section C of this chapter.

3. INTEGRATING LANDSLIDE HAZARD ZONATION MAPS INTO THE DEVELOPMENT PLANNING PROCESS

Landslide hazard information serves as one of the many components in an integrated development planning study. Since landslide activity can adversely affect or interfere with human activity, landslide hazards constrain or limit land-use capability. For this reason, it is important to identify relative landslide hazard levels early in the planning process. This permits planners to determine the degree of landslide risk that is acceptable or unacceptable to a development program. Decisions can then be made regarding which of these measures will be taken: avoidance, prevention, or mitigation of existing and future landslide hazards in the development program. The method described in this chapter places emphasis on landslide hazard identification and its use in an integrated planning study as natural resources are evaluated, a development strategy is formulated, and investment projects are identified at the profile level.

a. Preliminary Mission

During the Preliminary Mission of an integrated development planning study, an initial review is made of the type and content of available information, including natural hazard information (see Appendix A). The availability of geologic, topographic, hydrologic, and vegetation maps and aerial photographs is usually ascertained. This information is essential for executing a landslide hazard zonation (see Figure 10-1). Also during this stage of the study, available information should be collected and reviewed concerning assessments of natural hazards, including landslides and disasters, which are known to have affected the study area. See Chapter 1 for a more detailed discussion of the integrated development planning process.

b. Phase I--Development Diagnosis

In the context of planning the development of a river basin, province, or other planning unit, a development diagnosis assists in identifying areas with highest development potential. These are designated "target areas," in which subsequent, more detailed studies are concentrated. Part of the development diagnosis process involves identifying and delineating natural resource factors that favor or constrain development in a particular area. Landslide hazard is an undesirable factor, and the greater the hazard, the more it may shape the development potential.

When a potential hazard is present in the study area, the first step is to undertake a brief survey to establish whether landslides have occurred in recent

PRELIMINARY MISSION (STUDY DESIGN)

QUESTIONS PLANNERS NEED TO ASK:

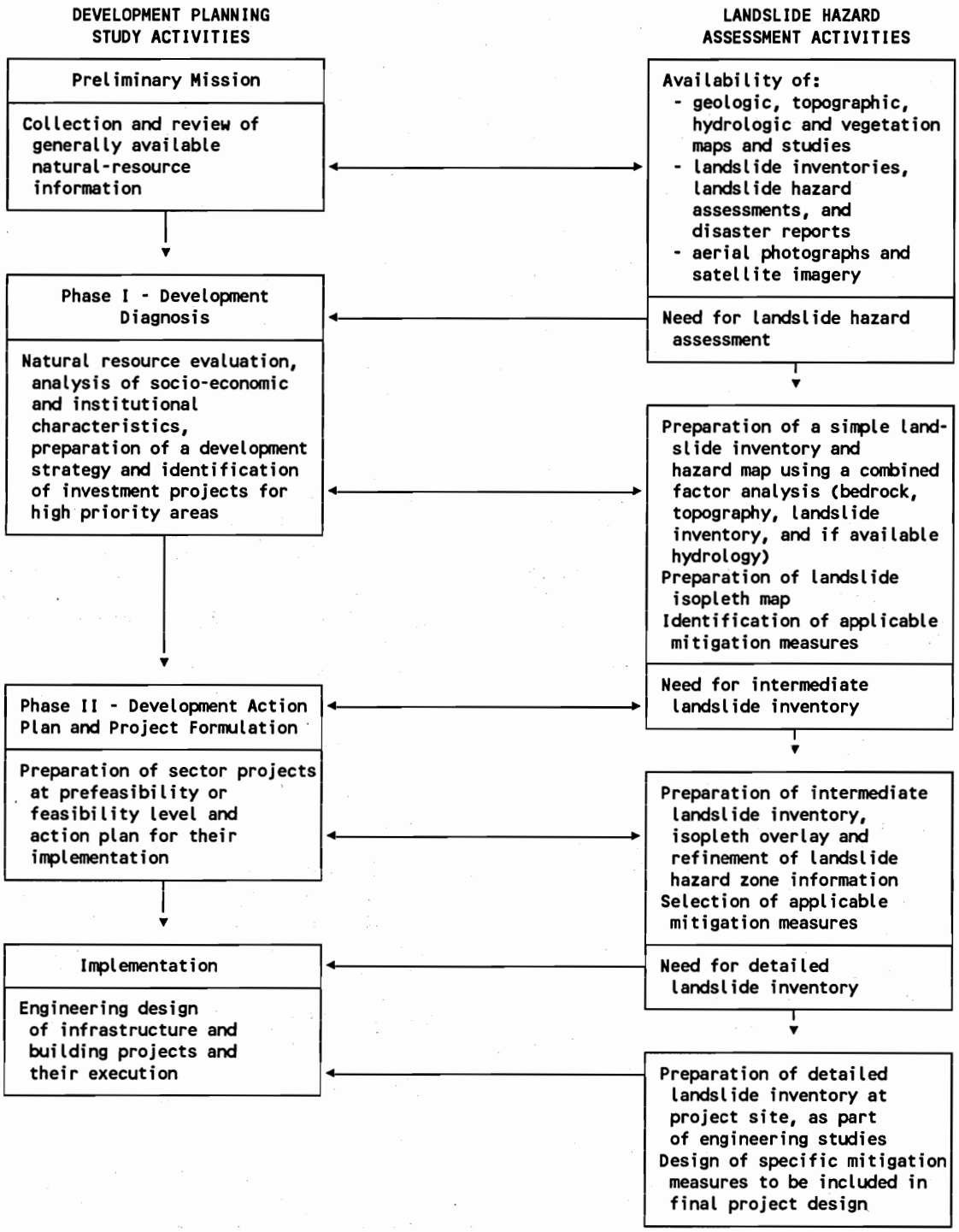
- Are geologic, topographic, hydrologic, and vegetation maps available? At what scale?
- Are aerial photographs available? At what scale?
- Does the study area have a history of landslides and/or disasters caused by landslide events?
- Is landslide hazard assessment information available?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Is it likely that landslides will affect major and/or significant portions of the study area?
- Will the study have access to landslide hazard assessment information other than what it may produce?

Figure 10-1

DEVELOPMENT PLANNING STUDY AND LANDSLIDE HAZARD ASSESSMENT ACTIVITIES



PHASE I: DEVELOPMENT DIAGNOSIS
(STRATEGY AND PROJECT IDENTIFICATION)

QUESTIONS PLANNERS NEED TO ASK:

- Is sufficient information to prepare a landslide inventory map, an isopleth map of existing landslides, and/or a landslide hazard map using factor analysis available?
- How will the assessment be carried out? During what time period?
- How will the assessment information be integrated into the overall study development strategy and project identification activities?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Is a landslide hazard map necessary?
- At what scale should the map be prepared?
- Who will execute the assessment?
- Who will be responsible for incorporating the assessment information into the overall study activities?

times. Roads, railroads, and river banks are good sites for seeking signs of past landslide occurrence. Discussions with local authorities responsible for public works, forestry, and agricultural activities can prove to be a valuable source of information since they may be familiar with past landslides in an area. However, it is important to bear in mind that new development activities may increase landslide hazards, and the absence of evidence from past landslides does not guarantee that landslides will not pose any problems in the future.

The areal extent and variety of development activities being considered make determining the landslide susceptibility based on all existing landslides, regardless of type, an appropriate approach (DeGraff, 1982). A simple inventory of past landslides, along with data regarding bedrock, slope steepness, and--when available--the hydrologic factor, produces a landslide hazard map that will satisfy the needs of the development diagnosis (see Figure 10-1). Suitable scales for the landslide hazard map range from 1:250,000 to 1:50,000. (See Figure 10-2 for a description of hazard identification needs and appropriate map scales for the different planning stages).

Having limited or insufficient data for preparing the combined factor analysis is most likely to be a problem encountered at the development diagnosis level. When this situation arises, there are two options: (1) invest the money and human resources to obtain the data needed to produce a landslide hazard map, or (2) prepare an isopleth map of existing landslides (described in Section C of this chapter). The isopleth map shows areas of frequent or infrequent landslide occurrence. While this type of map provides some idea of where landslides can be a major influence on development, it is only a rough approximation of where a problem can be encountered during development. Isopleth maps are an acceptable option at this stage of development but are wholly unsuitable for use in the more detailed planning stages.

The degree of landslide hazard in an area is a limiting factor only for those activities that may alter the existing balance between forces driving and resisting movement on an unfailed slope. Planners need to understand what effects development activities may have on this balance of forces. For example, placing a fence around a field is not going to produce a landslide, nor will it prevent one. Removing forest cover to create a field for cultivating crops is much more likely to lead to landslide occurrence, since it alters the balance of forces and may increase the susceptibility to slope failure by some triggering event, such as prolonged rainfall, which would not have produced the landslide under the original conditions. This increased susceptibility may not be immediately apparent since there may be a lag time before this is evident.

Landslide hazard zonation can be represented as an individual factor limiting land capability or it can be combined with hazard zonation for other natural hazards as an aggregate hazard. There are at least 10 different approaches that have been used to generate land capability maps (Hopkins, 1977).

Figure 10-2

LANDSLIDE HAZARD CONSIDERATIONS AT DIFFERENT PLANNING STAGES

Planning Stage	Hazard Identification Need	Landslide Inventory Level	Suitable Scales For Hazard Maps
Preliminary Mission	Identify hazard issue	As available	As available
Phase I-- Development Diagnosis	Degree of hazard from all types of landslides	Simple	1:250,000 to 1:62,500
Phase II-- Action Plan and Project Formulation	Degree of hazard from all types of landslides supplemented by hazard from some specific types	Intermediate	1:62,500 to 1:10,000
Project Implementation	Site-specific hazard based on geotechnical models	Detailed	1:12,500 to 1:500

Chapter 3 discusses land capability in more detail. The method for landslide hazard assessment presented in this chapter results in the production of a map. Thus, it can be considered in the application of land-use capability approaches.

There are two main applications of a landslide hazard assessment in land-use capability that includes relative surveys. First, it is used in overall development planning to emphasize the subjective nature of assigning land-use capability. For example, at the development diagnosis stage, the relative classification of "highest" capability can be assessed in relation to the constraints that possible increased landslide hazards may pose to proposed development activities. Second, it can show where existing development may face some risk previously unidentified. This enables prioritizing mitigation activities to be assigned to different development activities.

c. Phase II--Development Strategy and Project Formulation

An action plan is defined with the objective of facilitating development of target areas identified in Phase I. Development projects considered for the target area are formulated at this stage. Also at this time, landslide hazard evaluation within the study area is refined. The general landslide hazard assessment must be supplemented with an intermediate inventory to show the degree of hazard for specific types of landslides that may impact on proposed development activities. For example, introducing widespread agricultural activities into a forested environment requires a greater understanding of the hazard from shallow landsliding rather than from deep-seated rockslides.

In developing areas with landslide hazards, mitigation measures should be selected if they are not already part of the project identification information. It is possible to reduce the possible impact of natural landslide activity and limit landslides which occur as a result of human activity (Kockelman, 1985). There are two basic approaches: first, to avoid landslide-susceptible areas, and second, to design measures to compensate for the inducement of landslides (see the box below). For example, make location decisions so as to avoid building in certain areas, such as placing dwellings and critical infrastructure outside areas with a high likelihood of natural landslide activity. In some instances, the potential effects of a landslide can be

LANDSLIDE TRIGGERING ACTIONS, MITIGATION APPROACHES, AND DEVELOPMENT VARIABLES

- **Triggering Actions:**
  - From other hazards:
    - Earthquakes
    - Floods
    - Fire (and resulting loss of vegetation)
    - Volcanoes
  - Development related:
    - Changes in vegetation cover
    - Earthen dams
    - Excavation and mining
    - Irrigation
    - Infrastructure and structure construction
    - Liquid disposal (sanitary, sewers, latrines, etc.)
    - Pilings
    - Soils deposits
- **Mitigation Approaches:**
  - Avoidance
  - Insurance and taxation
  - Land-use zoning
  - Stabilization
  - Structural design
- **Development Variables:**
  - Available information
  - Economic, social, and political concerns
  - Existing development
  - Proposed development

mitigated. Landslide hazards resulting from development can be reduced by designing changes to counteract the impact that development may have on slope integrity. This might take the form of permitting only warehouses and storage facilities in higher hazard areas, to reduce the vulnerability to the population should a landslide occur.

In formulating investment projects, a more detailed hazard zonation map is needed. An intermediate landslide inventory is needed which provides greater detail to distinguish different landslide types. This data can be used for a reanalysis of the combined factor analysis. This reanalysis yields an improved landslide hazard map. If the hydrologic factor was not part of the earlier landslide hazard analysis, its inclusion at this stage would greatly improve the resulting hazard map.

At this stage, the value of a landslide hazard map to planners can be enhanced by representing areas where specific landslide types are prevalent. This is accomplished by preparing an isopleth map, as mentioned in Phase I. Preparation, however, should be altered to meet the specific needs of this planning stage. Alteration of the isopleth map is described in detail in Section C's discussion of "Compensating for Insufficient Data--The Isopleth Map". This produces a map representing the intensity of past landslide occurrence in a form resembling a topographic map. The isopleth lines appear similar to the contour lines showing elevation. The final isopleth map is used as an overlay on the landslide hazard map.

It should be noted that the isopleth map does not alter the basic hazard zones determined previously. It is still an analytic map, which in this instance shows the varying prevalence of a specific landslide type in an area. It provides an additional criterion for the planner to make use of in deciding which area may be best suited for certain development activities. This is especially helpful in evaluating moderate hazard zones.

PHASE II: PROJECT FORMULATION AND ACTION PLAN DEFINITION

QUESTIONS PLANNERS NEED TO ASK:

- Does the initial combined factor analysis landslide hazard map provide sufficient information to proceed with investment project formulation?
- If not already included, is there a hydrologic factor which could be added for further detail on hazard zones?
- Should an isopleth overlay be added to the hazard zonation map?
- Are there certain proposed land uses for which recommendations for mitigation should be included in the formulation of investment projects?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Who will execute the intermediate landslide hazard assessment?
- Which areas should be included in the additional assessment?
- Who will be responsible for incorporating additional information in investment project formulation activities?

Where proposed land use is recognized as susceptible to a specific landslide type, the proposed activity is best located in a low hazard zone or moderate hazard zone with the lowest occurrence, i.e., smallest isopleth value, of that landslide type. The improved landslide hazard map and isopleth overlay require that an intermediate landslide inventory be prepared at this planning level. The landslide hazard map suitable for formulating development projects should be at a scale of 1:62,500 to 1:12,500 (see Figure 10-2).

d. Project Implementation

The landslide hazard map can contribute to planning for a project's implementation. There are two situations when this map may prove beneficial, both of which are related to mitigating the potential effects of landslides. In one case, it is conceivable that if areas identified with a moderate landslide hazard are targeted for development, greater detail of those areas is needed to ensure the project design compensates for this greater hazard potential. For example, moderate or higher hazard areas may not be entirely avoidable along a proposed road. Detailed investigation can provide information on groundwater conditions and on the stability characteristics of soil and rock to ensure a stable design (Morgenstern and Sangrey, 1978).

In another case, existing infrastructure or communities may be located in previously unidentified high hazard zones. These areas should be given priority for introducing some measure of mitigation. For example, the effect of landslides issuing into an inhabited area from nearby mountain canyons might be mitigated by constructing debris basins to trap most of the material. Where such mitigation is impossible and the risk is identified as being extremely high, relocation to a safer area may be considered.

A detailed hazard map for the specific site in question is necessary at this stage of project design. Preparation of a detailed landslide inventory is now necessary. The large-scale features represented on landslides mapped in this detailed inventory are valuable for test drilling of a site and other sampling activities of engineering design work. Detailed landslide inventories and related interpretation of test results require map scales from 1:12,500 to 1:500 (see Figure 10-2).

The next section provides a detailed discussion of the types and nature of landslides, the basis for assessing landslide hazards, and the factors associated with landslide activity.

B. Landslides, Landslide Hazard Assessment, and Areas of Concern

1. LANDSLIDES AND LANDSLIDE SUSCEPTIBILITY

Landslides are caused when the force of gravity pulls rock, debris or soil down a slope. They are one

PROJECT IMPLEMENTATION

QUESTIONS PLANNERS NEED TO ASK:

- What type of landslide problems exist?
- What site-specific conditions need to be known for final design of an investment project with low landslide vulnerability?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Who will execute the detailed landslide hazard assessment?
- Which mitigation measures should be considered to reduce the risk to an acceptable level?
- Who will be responsible for incorporating the additional information in project implementation activities?

of the forms of erosion called mass wasting, which is broadly defined as erosion involving gravity as the agent causing movement. Because gravity constantly acts on a slope, landslides only occur when the stress produced by the force of the gravity exceeds the resistance of the material. This is distinct from some other forms of erosion caused by running water, for instance, which occurs when precipitation falls on a slope or within a channel carrying a stream or river. Figure 10-3 depicts a list and diagram with terminology commonly used for describing landslides.

Landslide movement is perceptible and may take the form of falls, topples, slides, or flows. It can consist of free-falling material from cliffs, broken or unbroken masses sliding down mountains or hillsides, or fluid flows. Materials can move up to 120mph or more, and slides can last a few seconds or a few minutes, or can be gradual, slower movements over several hours or days. Accordingly, landslides are recognized on the basis of type of movement.

The most widely used classification scheme divides landslides into different types according to the material being moved and type of movement (Varnes, 1978). Speed of movement and amount of water mixed with the material are secondary parameters defining some landslide types. Recognizing the types of landslides presents in an area helps explain how and where factors have contributed to natural slope instability in the past.

Factors influencing where landslides occur can be divided into two sets, permanent and variable (Sharpe, 1938). Permanent factors are characteristics of the landscape which remain unchanged or vary little from a human perspective. The steepness of a slope or the type of rock, for example, presents changes only with the passage of long periods of time. Permanent factors such as rock type and slope steepness can be recognized and identified for specific landslides long after their occurrence (DeGraff, 1978). By examining existing landslides in an area, it is possible to recognize how permanent factors contributed to these slope failures. Identifying conditions and processes promoting past instability makes it possible to use these factors to estimate future landslides (Varnes, 1985).

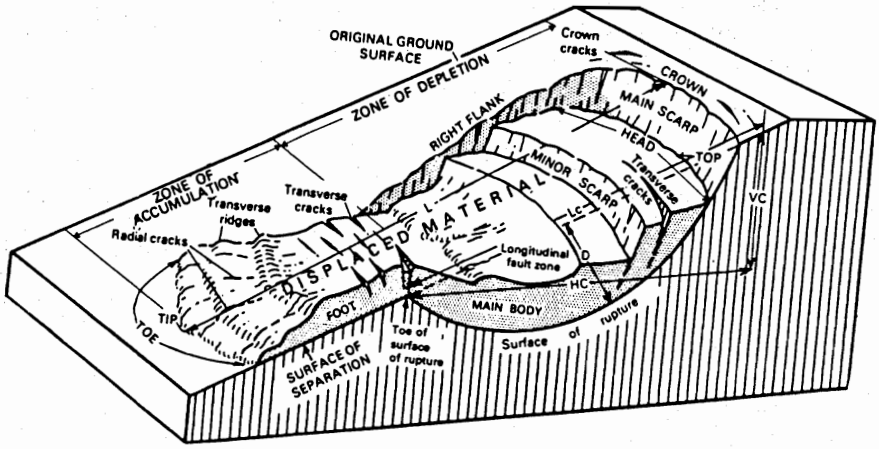
Variable factors are landscape characteristics that change quickly as a result of some triggering event. Ground vibration due to earthquakes, a rapid rise in groundwater levels, and increased soil moisture due to intense precipitation are examples of variable factors. It is often necessary to be present at the time a landslide occurs or shortly thereafter to assess these factors. Due to the lack of long-term records relating landslide activity to historic earthquakes, storms, or other initiating factors, permanent factors are usually used to estimate landslide hazard. As such, identifying landslide areas is not an accurate science and leads, in general, to depicting hazard-prone areas based on an estimation. At best, landslide and landslide susceptible areas can be identified along with expected triggering events. At worst, some areas may not be detected at all.

2. HAZARD ASSESSMENT OF LANDSLIDES

Landslides are not currently amenable to risk assessment since there is no basis to determine the probability of landslides occurring within a given time period. Hazard assessments are possible and can be used in place of risk assessments. Hazard assessments are estimations of an area's susceptibility

Figure 10-3

DEFINITION OF BASIC LANDSLIDE TERMS



NOMENCLATURE

Main Scarp: A steep surface on the undisturbed ground around the periphery of the slide, caused by the movement of slide material away from undisturbed ground. The projection of the scarp surface under the displaced material becomes the surface of rupture.

Minor Scarp: A steep surface on the displaced material produced by differential movements within the sliding mass.

Head: The upper parts of the slide material along the contact between the displaced material and the main scarp.

Top: The highest point of contact between the displaced material and the main scarp.

Toe of Surface of Rupture: The intersection (sometimes buried) between the lower part of the surface of rupture and the original ground surface.

Toe: The margin of displaced material most distant from the main scarp.

Tip: The point on the toe most distant from the top of the slide.

Foot: The portion of the displaced material that lies downslope from the toe of the surface of rupture.

Main Body: That part of the displaced material that overlies the surface of rupture between the main scarp and toe of the surface of rupture.

Flank: The side of the landslide.

Crown: The material that is still in place, practically undisplaced and adjacent to the highest parts of the main scarp.

Original Ground Surface: The slope that existed before the movement which is being considered took place. If this is the surface of an older landslide, that fact should be stated.

Left and Right: Compass directions are preferable in describing a slide, but if right and left are used they refer to the slide as viewed from the crown.

Surface of Separation: The surface separating displaced material from stable material but not known to have been a surface of which failure occurred.

Displaced Material: The material that has moved away from its original position on the slope. It may be in a deformed or undeformed state.

Zone of Depletion: The area within which the displaced material lies below the original ground surface.

Zone of Accumulation: The area within which the displaced material lies above the original ground surface.

Source: Adapted from Varnes, D. "Slope Movement and Processes" in Landslides: Analysis and Control, Special Report 176, Chapter 2 (Washington, D.C.: National Academy of Sciences, 1978).

TYPES OF LANDSLIDES

- **Falls**: a mass detaches from a steep slope or cliff and descends by free-fall, bounding, or rolling.
- **Topples**: a mass tilts or rotates forward as a unit.
- **Slides**: a mass displaces on one or more recognizable surfaces, which may be curved or planar.
- **Flows**: a mass moves downslope with a fluid motion. A significant amount of water may or may not be part of the mass.

to landslides based on a few key factors. These are each capable of being mapped and allow land areas to be evaluated on their relative susceptibility to landslides.

Three principles guide landslide hazard assessment. First, landslides in the future will most likely occur under geomorphic, geologic, and topographic conditions that have produced past and present landslides. Second, the underlying conditions and processes which cause landslides are understood. Third, the relative importance of conditions and processes contributing to landslide occurrence can be determined and each assigned some measure reflecting its contribution (Varnes, 1985). The number of conditions present in an area can then be factored together to represent the degree of potential hazard present.

Landslide hazard has been determined with a high degree of reliability for only a few locations. These have required careful, detailed study of the interaction of pertinent permanent and variable conditions in the target area. This can be a very expensive and time-consuming process that is unjustified for the purpose of broad-scale development planning. Landslide hazard zonation is one technique that can be used in the early stage of a planning study.

Most assessment procedures for landslide hazard zonation employ a few key or significant physical factors to estimate relative landslide hazard. The method described here requires a minimum of three factors mentioned earlier: distribution of past landslides, type of bedrock, and slope steepness, and a fourth, hydrologic factor may be added to reflect the important role which groundwater often plays in landslide occurrences (Varnes, 1985, and USGS, 1982).

Each factor is represented in a quantitative or semi-quantitative manner to facilitate the identification of different degrees of landslide hazard in an area. Since all of these are permanent features, it is usually possible to map each factor. Specific combinations of these factors can be associated with differing degrees of landslide hazard. By extending these combinations over an entire area, a landslide hazard map is produced.

3. FACTORS ASSOCIATED WITH LANDSLIDE ACTIVITY

The distribution of past landslides within the area, type of bedrock, and slope steepness represent, respectively, geomorphic, geologic, and topographic factors (Varnes, 1985, and USGS, 1982). Each of these factors is described in more detail below to give the planner a better understanding of their contribution to landsliding. The final section, "C. Mapping Physical Factors and Preparation of a Landslide Hazard Map," provides information on mapping them.

a. Past Landslides and Their Distribution

Interpreting the likelihood of future landslide occurrences requires an understanding of conditions and processes controlling past landslides in the area of interest. This can be achieved by examining and mapping past landslide activity in the area. Geologic, topographic, and hydrologic circumstances associated with past landslides indicate which natural or artificially created circumstances are likely to produce landslides in the future.

A primary consideration of the planner is the effect of existing land use on landslide activity. Certain types of landslides may be associated with specific land uses. For example, certain slides may only occur in road cuts or excavations. There may even be a critical height-to-inclination relationship for cutslopes below which these landslides will not occur. Field studies can provide insight into how different factors have contributed to failures. In some investigations special

IN ORDER TO PLAN FOR DEVELOPMENT IN LANDSLIDE AREAS, A PLANNER NEEDS TO KNOW:

- Past distribution of landslides
- Types of bedrock
- How steep the slopes are
- Indirect measures of the area's hydrologic characteristics that are available
- Effects development activity can have on landslide susceptibility

forms have been employed to ensure consistent collection of this ancillary information (see Figure 10-4). A summary of observations about landslide conditions and processes are incorporated into each landslide inventory, e.g., as in Pomeroy (1979), and mapped.

b. Bedrock

Bedrock influences landslide occurrence in several ways. Weak, incompetent rock is more likely to fail than strong, competent rock. (See Figure 10-5 for an example of this.) On slopes where weak rock overlain by strong rock is exposed, the difference in strength increases the potential for landsliding in the stronger rock as well since the weak rock tends to erode and undermine the stronger rock.

The strength of a rock mass depends on the type of rock and the presence and nature of discontinuitiessuch as joints or other fractures. The more discontinuities present in bedrock, the greater the likelihood of rock instability. Rock type may exert control on landsliding by influencing the strength of surface material in the area. For example, soils (in the engineering rather than agricultural sense of the term) derived from schists or shales will contain high percentages of clay. These soils will have different strength characteristics than coarser-grained soils such as those derived from granitic bedrock. There are many ways, then, that rock type or structure contributes to the instability, which can be represented on a map.

c. Slope Steepness or Inclination

The influence of slope steepness on landslide occurrence is the easiest factor to understand. Generally, steeper slopes have a greater chance of landsliding (see Figure 10-6). This does not prevent failures from occurring on gentler slopes. Other factors may make a gentle slope especially sensitive to failure, and thus in this situation could be determined to have a relatively high hazard potential. For example, high ground water conditions occurring in sandy soils may liquefy during an earthquake. This can cause a landslide on a slope as gentle as 5 to 10 percent. Conversely, the steepest slopes may not always be the most hazardous. Steep slopes are less likely to develop a thick cover of superficial material conducive to certain types of landslides. Slope steepness can be mapped using generally available topographic maps.

d. Hydrologic Factor

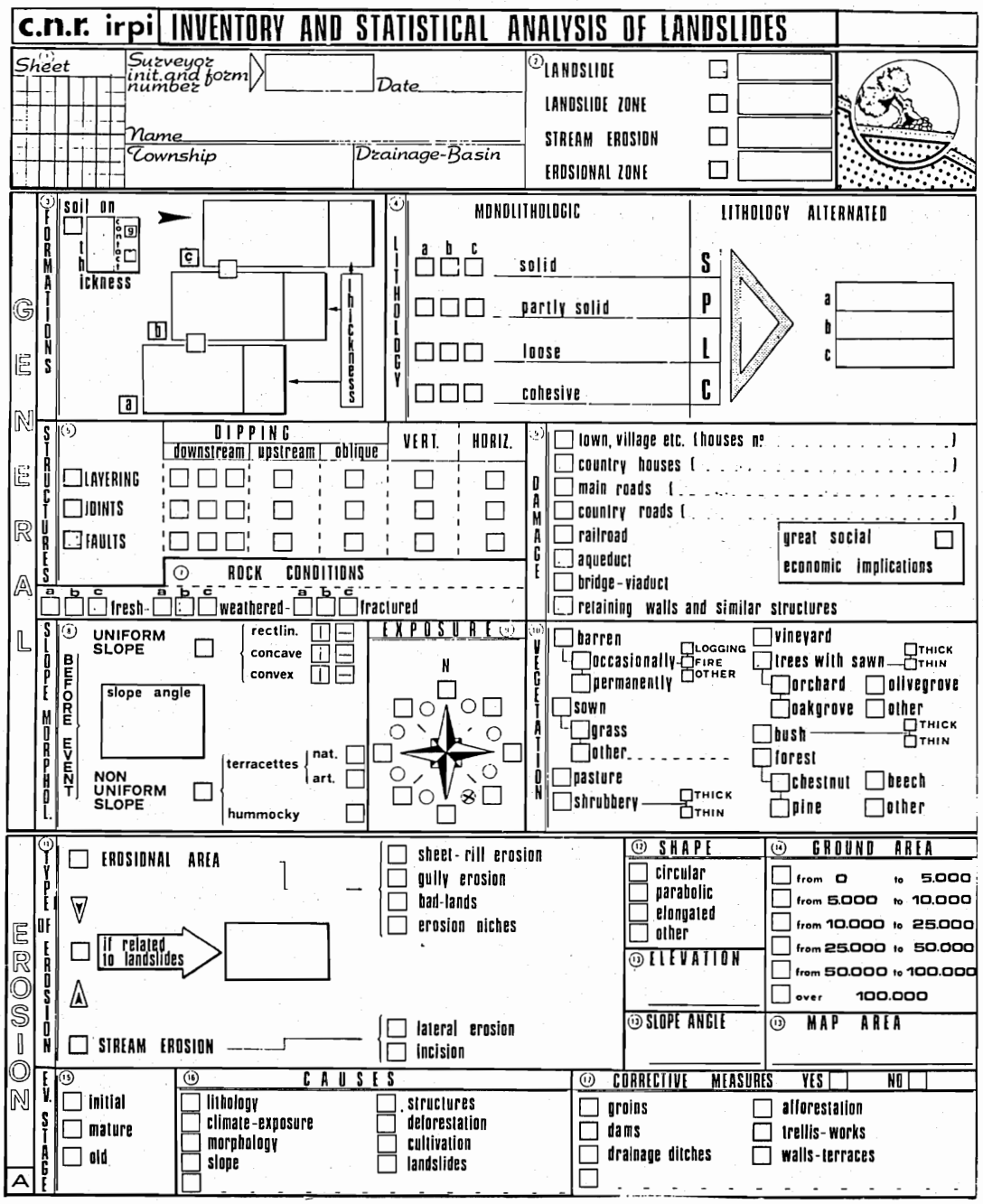
Water is recognized as an important factor in slope stability--almost as important as gravity. Information on water table levels and fluctuations is rarely available. To represent the hydrologic factor in landslide hazard assessments, indirect measures can be used which can be mapped to show the influence of the area's hydrology, such as vegetation, slope orientation (aspect), or precipitation zones.

The type of vegetation and its density over an area will often reflect the variation in subsurface water. Certain species are water-loving or phreatophytes. Presence of these species shows near-surface water table conditions and springs. In mountainous regions, microclimatic differences produce different hydrologic conditions which in turn result in plant communities that vary according to the moisture available to the slope and its distribution throughout the year.

Slope orientation (aspect) refers to the direction a slope faces. It can be an indirect measure of climatic influence on the hydrologic characteristics of the landscape. Important characteristics associated with landslides are related to such factors as subsurface recharge resulting from prevailing winds and their influence on local frontal storms or accumulated snow. In other cases, a slope may experience more freeze/thaw cycles or wet/dry cycles which can reduce the strength of the soil and make the area more susceptible to landslides. In general, due to the complexity of these factors and existing development

Figure 10-4

INVENTORY AND STATISTICAL ANALYSIS INFORMATION FORM FOR LANDSLIDES



Source: Carrara, A., and Merenda, L. "Landslide Inventory in Northern Calabria, Southern Italy" in Geological Society of American Bulletin, vol. 87 (1976), pp. 1153-1162.

Figure 10-5

BEDROCK AS A FACTOR IN LANDSLIDE OCCURRENCE

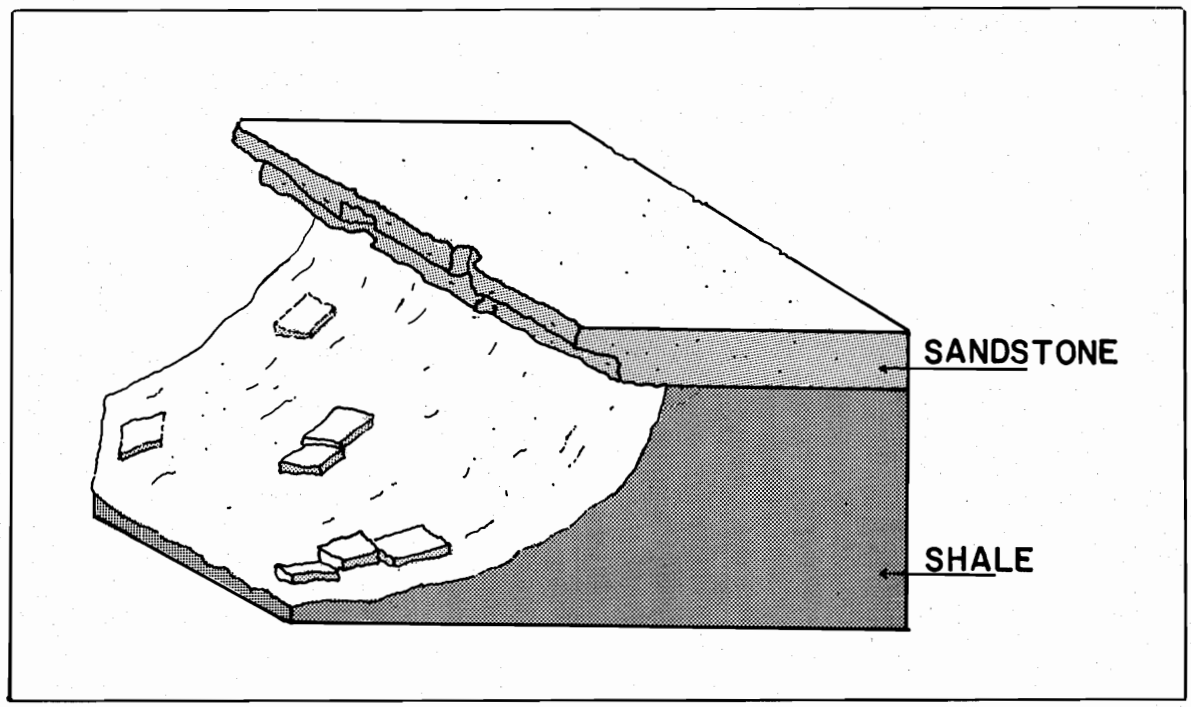
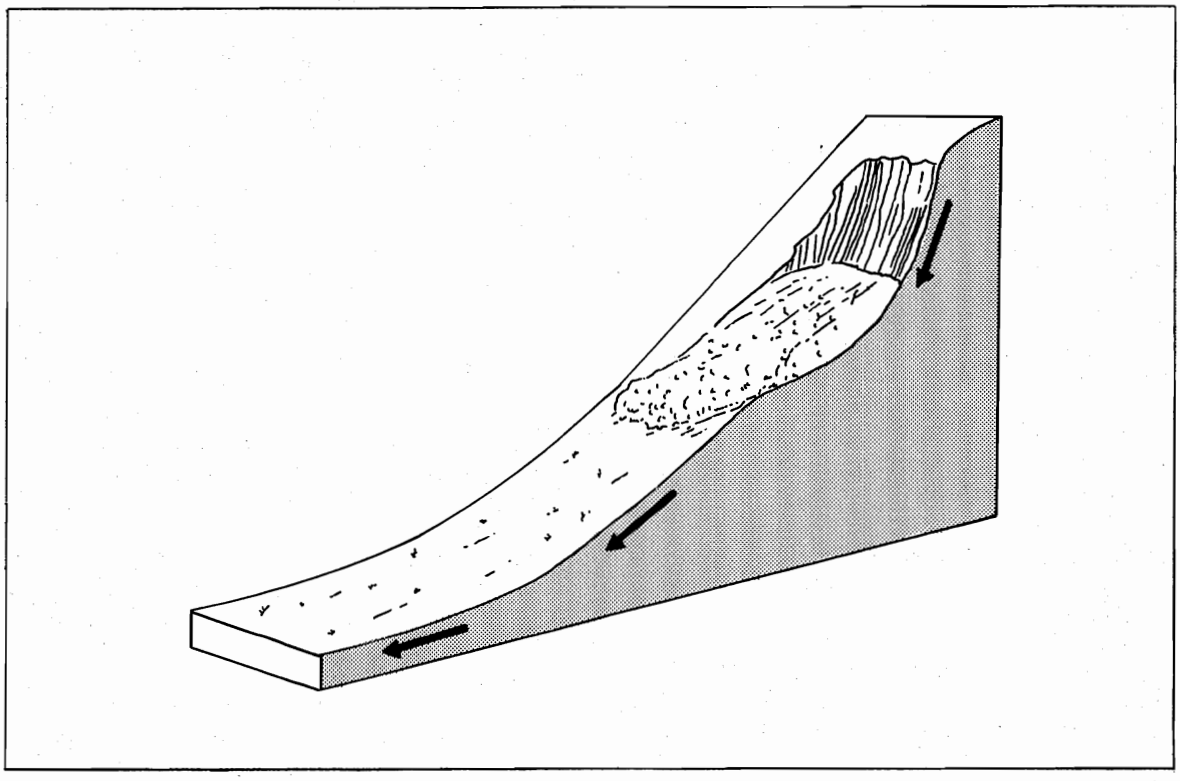


Figure 10-6

SLOPE STEEPNESS ASSOCIATED WITH LANDSLIDE ACTIVITY



activities, there is usually no direct observable correlation between slope orientation and landslide hazard.

e. Human-Initiated Effects

In addition to natural phenomena, human activities may increase the natural tendency for a landslide to occur. Landslides which result from development activities are usually the result of increasing moisture in the soil or changing the form of a slope. Development activities such as cutting and filling along roads and the removing of forest vegetation are capable of greatly altering slope form and ground water conditions (Swanson and Dyrness, 1975). These altered conditions may significantly increase the degree of landslide hazard present (Varnes, 1985, and Sidle, Pearce, and O'Loughlin, 1985).

For example, converting a forested area to grassland or one where crops are cultivated can increase the moisture in the soil enough to cause landslide problems (DeGraff, 1979). Or building a road which cuts off the toe of a steep slope can increase landslide susceptibility. It is possible to reduce the potential impact of natural landslide activity and limit development-initiated landslide occurrence by early consideration of these effects (Kockelman, 1985).

Now that the general points with regard to mapping the various land characteristics have been covered, the final section provides details on the techniques to do so in addition to presenting a step-by-step approach for preparing a landslide hazard map.

C. Mapping Physical Factors and Preparation of a Landslide Hazard Map

A landslide inventory produces a descriptive or data map (Cotecchia, 1978). By overlaying the landslide inventory map on the maps of the type of bedrock, slope steepness, and indirect hydrologic measures, the association of past landslides with the factors controlling landslide occurrence can be recognized. The method described below employs these associations in synthesizing a landslide hazard map. Extrapolating the data to areas with characteristics similar to those found associated with past landslides is an effective tool for forecasting where, but not when, landslides are more likely to occur in the future.

This section presents the techniques used to map each of the key factors associated with landslides. With these maps, a landslide hazard map can be prepared. Hazard zonation is a means of identifying areas with differing landslide hazards. The step-by-step approach, or factor analysis, used to prepare a landslide hazard map is described.

1. MAPPING THE PHYSICAL FACTORS ASSOCIATED WITH LANDSLIDES

Each factor is mapped separately by a different technique.

a. Mapping the Inventory of Existing Landslides

A map of existing landslides serves as the basic data source for understanding conditions contributing to landslide occurrence. Normally such a map is prepared by the interpretation of aerial photography and field examination of selected locations. While this map could also be compiled by field methods alone, the time and expense involved would only be justified by the unavailability of photo coverage. Either means of map preparation requires the skills of a geologist with experience in landslide or landform interpretation.

Aerial photography can serve as the source for data on existing landslides, type of bedrock, and vegetation cover. Typically, large-scale photography is necessary to be useful for existing landslides. The photo scale depends on the size of landslides common to the study area. Small-scale photography is less of a concern where bedrock and vegetation exist, since delineating areas with similar texture and appearance is easier than recognizing discrete features. Satellite imagery is generally unsuitable for landslide mapping except where data products can be enlarged to at least 1:50,000 scale. Photographic and satellite information is valuable in mapping other spatial information and for use in conjunction with computer mapping techniques as part of the development planning study (see Chapters 4 and 5 for a more detailed discussion).

Depending on vegetative cover, photo quality, and the skill of the interpreter, overall identification accuracy of 80 to 85 percent is realistic using aerial photography (Rib and Liang, 1978). The range of useful scales of aerial photography for landslide inventory work is limited to about 1:40,000 or larger. The selected scale will depend on the size of landslides common to the study area and, to some extent, the relief of the area. Large failures of four or more square kilometers are extremely difficult to detect on aerial photography smaller than 1:40,000. Where the majority of landslides are one hectare or smaller in size, large-scale photography on the order of 1:4,800 is necessary. The usefulness of black and white,

color, or color-infrared photography for landslide inventory work will vary with local conditions and the individual making the interpretation. Each type ofphotography has advantages and disadvantages that will vary in their importance according to the characteristics of the area being mapped.

The map may be prepared at different levels of detail concerning existing landslides (USGS, 1982). A simple inventory identifies the definite and probable areas of existing landslides and is the minimum level required for a landslide hazard assessment. A map is produced in which each landslide is outlined and an arrow is drawn to denote the direction it moved. (See Figure 10-7 for a simple inventory map.)

More information can be provided by producing an intermediate inventory. The map produced at this level would show the outlined landslide types and distinguish between areas of landslide origin and deposit. The former is the area where material once existed as the source of the landslide and appears as a scar. The latter is deposited material from the landslide. (See Figure 10-8 for a sample intermediate inventory map.) The most information is obtained by producing a detailed inventory (Wieczorek, 1984). Large-scale features such as secondary scarps, sag ponds, and ground-crack patterns may be represented on individual landslides. (See Figure 10-9 for a detailed landslide map.)

These three types of inventories can be prepared as the development study progresses. To reiterate what was presented in Section A of this chapter: the simple inventory is adequate for Phase I development diagnosis activities; the intermediate inventory provides greater detail for an improved hazard map of a target area in Phase II; and the large-scale features of the detailed inventory are necessary for final project design in the implementation stage. Refer to Figure 10-2 for the appropriate map scales.

There are several considerations to keep in mind when gathering data on existing landslides. First, the time and effort required to conduct an inventory varies with (1) geologic and topographic complexity; (2) size of an area; and (3) desired level of inventory detail (Varnes, 1985). Figure 10-10 characterizes the relationship between the amount of time and level of effort for these three variables. Second, more detailed inventories will require larger map scales to reveal the small features of this added detail. Third, additional data gathering can add detail to an existing inventory. This enables a previously completed simple inventory to be transformed into an intermediate inventory with less time and effort than producing the intermediate inventory solely from field work and aerial photography.

b. Mapping the Types of Bedrock Contributing to Instability

By using bedrock as one factor in the landslide hazard assessment, the many different ways rock type or structure contribute to instability are represented. Comparing a bedrock map with the landslide map, one can discriminate between rock units associated with existing landslides and those devoid or largely free of landslide activity.

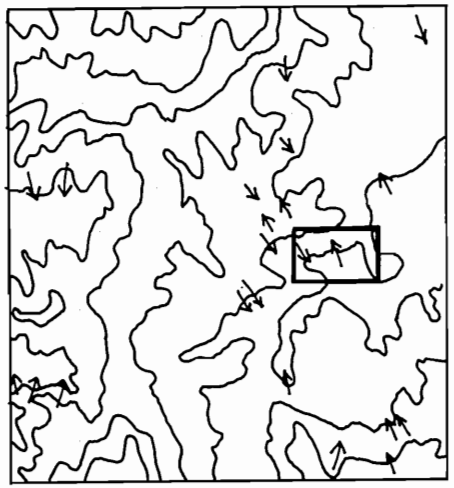
To produce a usable bedrock map for a hazard assessment, bedrock unit boundaries should be traced to produce new, more suitable units. Existing standard geologic maps define units according to factors such as age, composition or lithology (rock type), and structure (faulting, folding, etc.). For example, a standard geologic map may show a series of volcanic ash deposits of similar mineral compositions which vary only slightly in age. In most instances, these different units will affect landslide occurrence in a similar way and should be delineated as a single bedrock unit in a revised map for hazard assessment work. The geologist must use professional judgement to ensure that the number of bedrock units is sufficient to distinguish differences in their effect on landslide occurrence.

When a geologic map does not exist, a bedrock map based on aerial photography with limited field verification is needed. This map may be no more detailed than a delineation of sedimentary, igneous, and metamorphic rock types. Obviously, a bedrock map generalized from a more detailed map is preferable, but this is an acceptable alternative under such circumstances. Delineating areas with similar texture and appearance is easier than recognizing discrete features. Scales as small as 1:62,500 are useful for this work. Photos at scales of 1:20,000 or larger are difficult to use because the limited area shown restricts comparison with adjacent contrasting areas. It also significantly increases the number of photographs to examine in mapping the area. Black and white, color, and color infrared photography are all suitable for bedrock mapping. Satellite imagery is generally unsuitable for this mapping except when the imagery is enlarged to usable scales. For example, imagery at a 1:50,000 scale produced from satellite imagery is acceptable for this mapping (see Chapter 4).

A soils map is an inadequate substitute for a bedrock map. Soils maps are based on factors concentrated in the upper meter or less of superficial material that affects agricultural activities. Generally, there is little or no correlation between "agricultural" soil characteristics and the likelihood of failures originating along surfaces a few meters to tens of meters deep in superficial material.

Figure 10-7

SIMPLE LANDSLIDE INVENTORY MAP



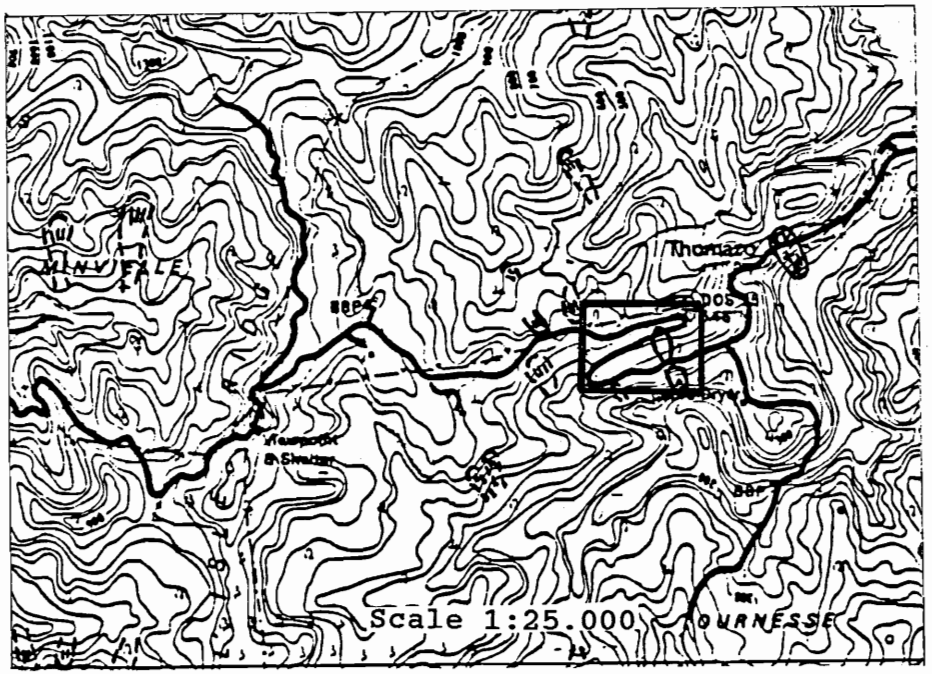
Scale 1:50.000

EXPLANATION

Landslide

Figure 10-8

INTERMEDIATE LANDSLIDE INVENTORY MAP



SYMBOLS AND EXPLANATION OF INTERMEDIATE LANDSLIDE INVENTORY MAP

ROCKFALL or ROCKSLIDE	DEBRIS FLOW	DEBRIS SLIDE
scar	scar	scar
deposit	deposit	deposit

Shallow Failure

LANDSLIDE COMPLEX

May consist of many landslides too small to represent individually, an old eroded landslide feature, or a landslide displaying more than one type of movement.

Deep-seated Failure

ROCKSLIDE or EARTH FLOW

scar

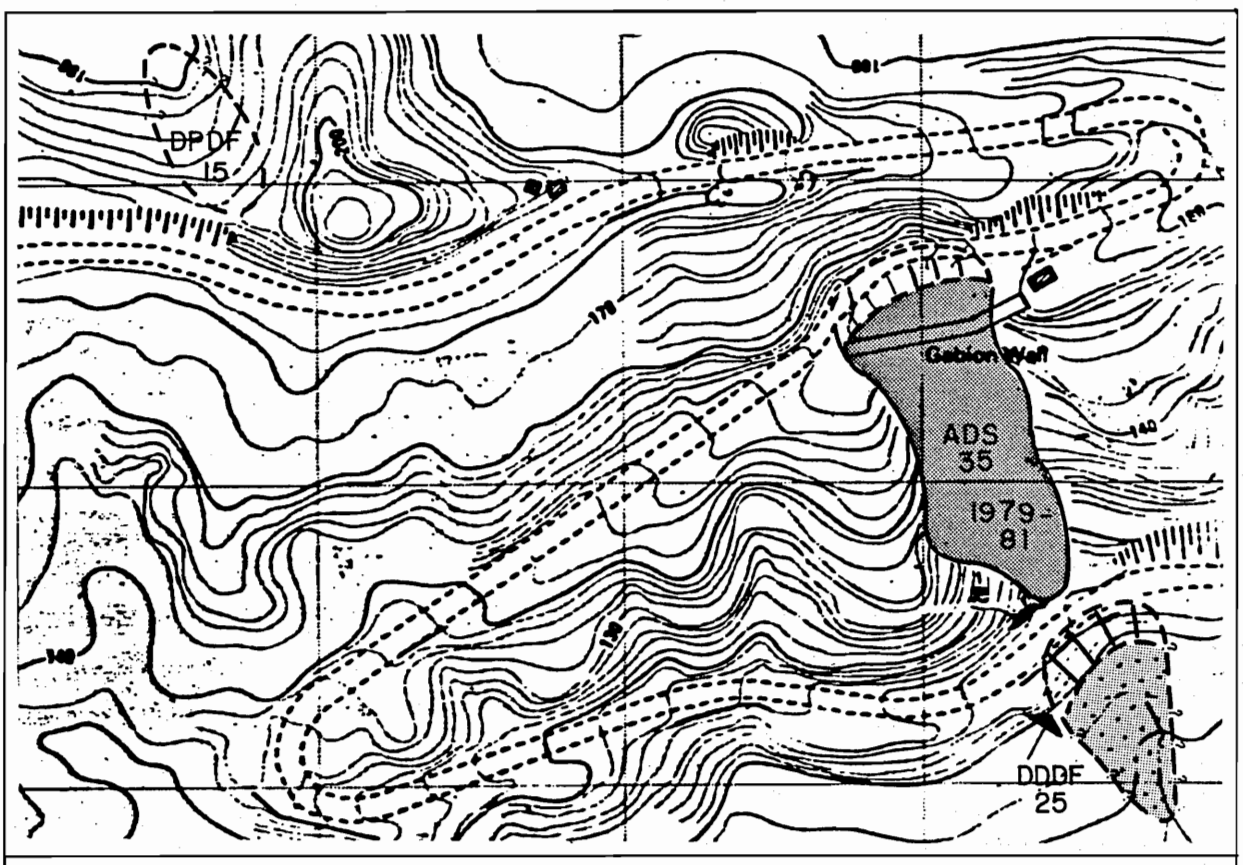
deposit

NOTE:

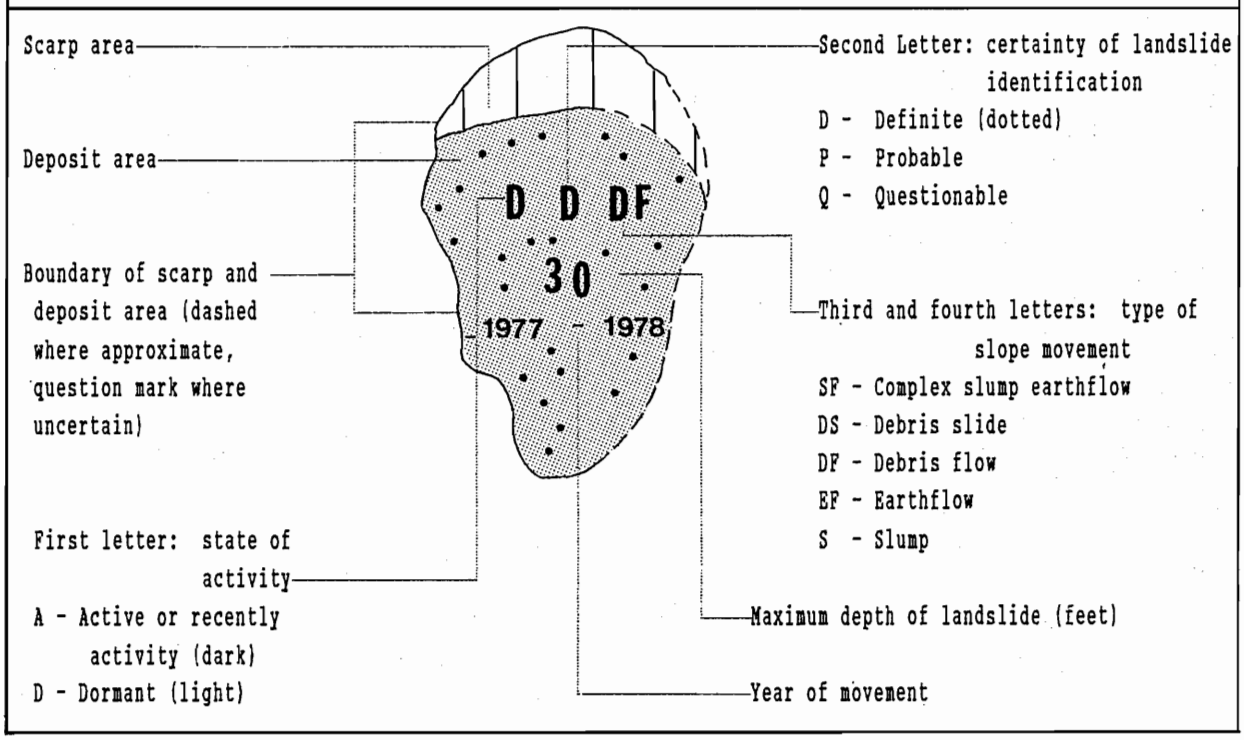
Landslides outlined with solid lines are identifiable as definite landslides. Dashed lines signify a possible landslide.

Figure 10-9

DETAILED LANDSLIDE INVENTORY MAP



EXPLANATION OF LANDSLIDE SYMBOLS



c. Mapping Slope Steepness or Inclination

Slope steepness is a factor which associates the effectiveness of gravity acting on a slope to landslide susceptibility. A topographic map is the source for preparing a slope steepness map. The slope steepness map displays the steepness values associated with the majority of existing landslides and is derived from an existing topographic map. Steepness for landslide hazard assessments is commonly expressed as a percentage rather than in degrees. The categories or grouping of steepness values for use in analyzing landslide hazards should approximate those of the slopes present in the study area. Too many classes will make it difficult to identify slopes critical to landslide occurrence and too few will be equally useless.

d. The Optional Hydrologic Factor--Mapping Indirect Measures

Since information on water table levels and fluctuations is rarely available, mapping indirect measures such as vegetation and slope orientation can reveal the influence of hydrology on an area. Any vegetation map used to represent the hydrologic factor in the landslide hazard assessment must employ units that are dependent on water. This may be as simple as representing phyreatic and non-phyreatic plant communities or as complex as distinguishing different forest types. Selection of the appropriate vegetation map units to indicate the effects of water in causing landslides requires careful field observation by the geologist.

Aerial photography is an appropriate source of data for preparing vegetation maps. In preparing vegetation maps, as in mapping bedrock, scale is less of a concern. Here, too, delineating areas with similar features is easier than recognizing discrete features. Scales of 1:62,500 are useful in identifying vegetation since 1:20,000 and larger scales do not reveal the contrasting characteristics of adjacent areas. Black and white, color, and color-infrared photography are all suitable for this mapping. Satellite imagery is acceptable only when enlarged to usable scale.

The direction in which a slope faces can also be mapped and used as an indirect indicator of the hydrologic factor. Slope orientation or aspect is described in terms of the eight cardinal directions, i.e., north, northeast, etc. For convenience in establishing a data base, slope orientation is measured in degrees of azimuth from 0 to 360 degrees. Each cardinal direction is defined by a set of azimuth values. For example, slopes facing the northeast can have an azimuth reading ranging from 22.5 degrees to 67.5 degrees.

2. INTERPRETING LANDSLIDE HAZARDS: THE LANDSLIDE HAZARD MAP

A landslide hazard map is generated to identify areas with differing landslide hazards. A hazard map is produced for each stage of the planning process, from the more generalized map in the initial stage to a detailed zonation map for specific site use. As the name suggests, this map divides the entire study area into sub-areas based on the degree of a potential hazard from landslides. The landslide hazard map is produced by interpreting the data represented by the maps of the inventoried landslides and the permanent factors found to influence the occurrence of landslides.

As with any map, scale is an important consideration. There are two points to keep in mind concerning the scale of the landslide hazard map. First, such a map should be produced at a scale capable of representing the information needed at a particular planning level. Compatibility of scale would be important when the hazard map is to be combined with other maps to yield a land capability map (see Chapter 3). Second, the landslide hazard map should be at a scale not markedly different from the data maps used to produce it. In other words, reliability may be questionable when a landslide hazard map produced at a scale of 1:50,000 has been based on a 1:250,000 slope steepness map.

Four levels of relative hazard are identified on a landslide hazard map: (1) low; (2) moderate; (3) high; and (4) extreme hazard. The level of landslide hazard is measured on the ordinal scale with this method and is a quantitative representation of differing hazard levels that shows only the order of relative hazard at a particular site and not absolute hazard. Predicting absolute hazard is impractical with current capabilities.

As a consequence, there is no way to compare hazard zones at different sites or to determine the likelihood that a high hazard area, for example, is two or ten times more likely to fail in the future than low hazard areas. It should be stressed that these relative hazard zones are based on the existing landslides and conditions influencing their occurrence in a specific area. The hazard zones which are determined for an area hold true only for the area for which they were prepared. Similar conditions found outside the assessed area may not produce the same degree of hazard because of some seemingly minor difference in one of the factors.

3. FACTOR ANALYSIS: THE TECHNIQUE TO PREPARE A HAZARD MAP

A factor analysis is a step-by-step approach used to prepare a landslide hazard zonation map of an area.

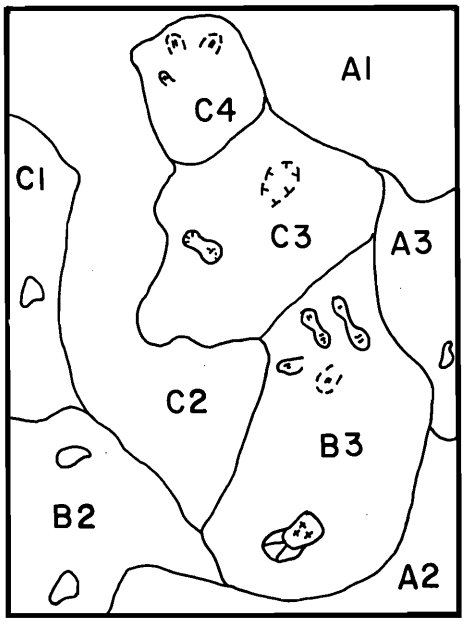
There are four steps to complete the factor analysis and produce a hazard map: (1) map the existing landslides and prepare a map combining the permanent factors (bedrock, slope steepness, and, when available, the hydrologic factors) into individual map units; (2) overlay the landslide inventory on the combined factor map; (3) prepare a combined factor analysis for all combinations of the factors and group combinations of these factors in a way that defines the four levels of landslide hazard; and (4) produce a map with four landslide hazard zones from the grouped combinations.

a. Step One: Combined Map of Permanent Factors

The first step is to prepare a map of the inventoried existing landslides. Also, compile a map which combines the bedrock, slope steepness, and, when included, hydrologic factor units or categories into individual cartographic units. As an example, assume that only bedrock and slope steepness are being used. The compiled map will be composed of cartographic units delineating certain bedrock type and slope values, e.g., Bedrock B3 on slopes between 25-50 percent (see Figure 10-10).

Figure 10-10

STUDY AREA MAP



$$\frac{\text{Landslide Area}}{\text{Bedrock / Slope Area}} = \text{Proportion}$$

(Permanent Factor Area)

Legend

A representation of how the proportion of bedrock slope combinations subject to past landslide activity is determined. Note that while combination B3 obviously has more landslides than combination C4, the smaller size of C4 area will likely result in its having a higher proportion than B3.

b. Step Two: Overlay of Landslide Inventory

The second step is to overlay the landslide inventory map with this combined factor map. This will identify which combinations are associated with past landslides and which are not. A landslide inventory table is developed indicating total area of landslides occurring on each specific bedrock unit and slope steepness combination (and other factors, if considered) (see Figure 10-12). When a hydrologic factor such as vegetative zone or slope orientation is used, the table will include the area of landslides for each specific combinations of bedrock, slope steepness, and the hydrologic factor. Summing the areas from all combinations found in the table will yield the total area of landslides in the study area. This is a way to check that all combinations are included in the analysis. Figure 10-11 shows the extent to which each combination is present in the study area. For example, Bedrock B on slopes between 25 and 50 percent has 784 hectares of landslides.

c. Step Three: Group Combinations Using a Factor Analysis

The third step is to group combinations of these factors in a way that will define four levels of landslide hazard. This grouping is achieved by performing a combined factor analysis or matrix assessment (DeGraff and Romesburg, 1980). This analysis permits incorporating the interaction among factors affecting landslide occurrence without explicitly understanding those interactions.

To start, measure the total area for every combination of bedrock, slope steepness, and hydrologic factors in the study area represented in the table prepared in Step 2. The total area with these combinations is to be calculated, not just those associated with landslide activity. Continuing with the example, assume a total area of 2,327 hectares of bedrock B on slopes greater than 25 percent but less than 50 percent was found. The landslide inventory table prepared in Step 2 shows only the area of past landslides present for each combination. Then the total area for every combination associated with landslides found in the landslide inventory table is divided by the area for the same combination of factors found in the study area (see Figure 10-12). In the example, this would be 784 divided by 2,327. This yields a proportion of each combination which is subject to past landslide occurrence, e.g., 0.34. This represents the proportion of the combination disturbed by past landslides in that area (see Figure 10-11).

The combination of bedrock, slope steepness, and hydrologic factors associated with the largest area disturbed by landslides may not, in fact, be the most

Figure 10-11

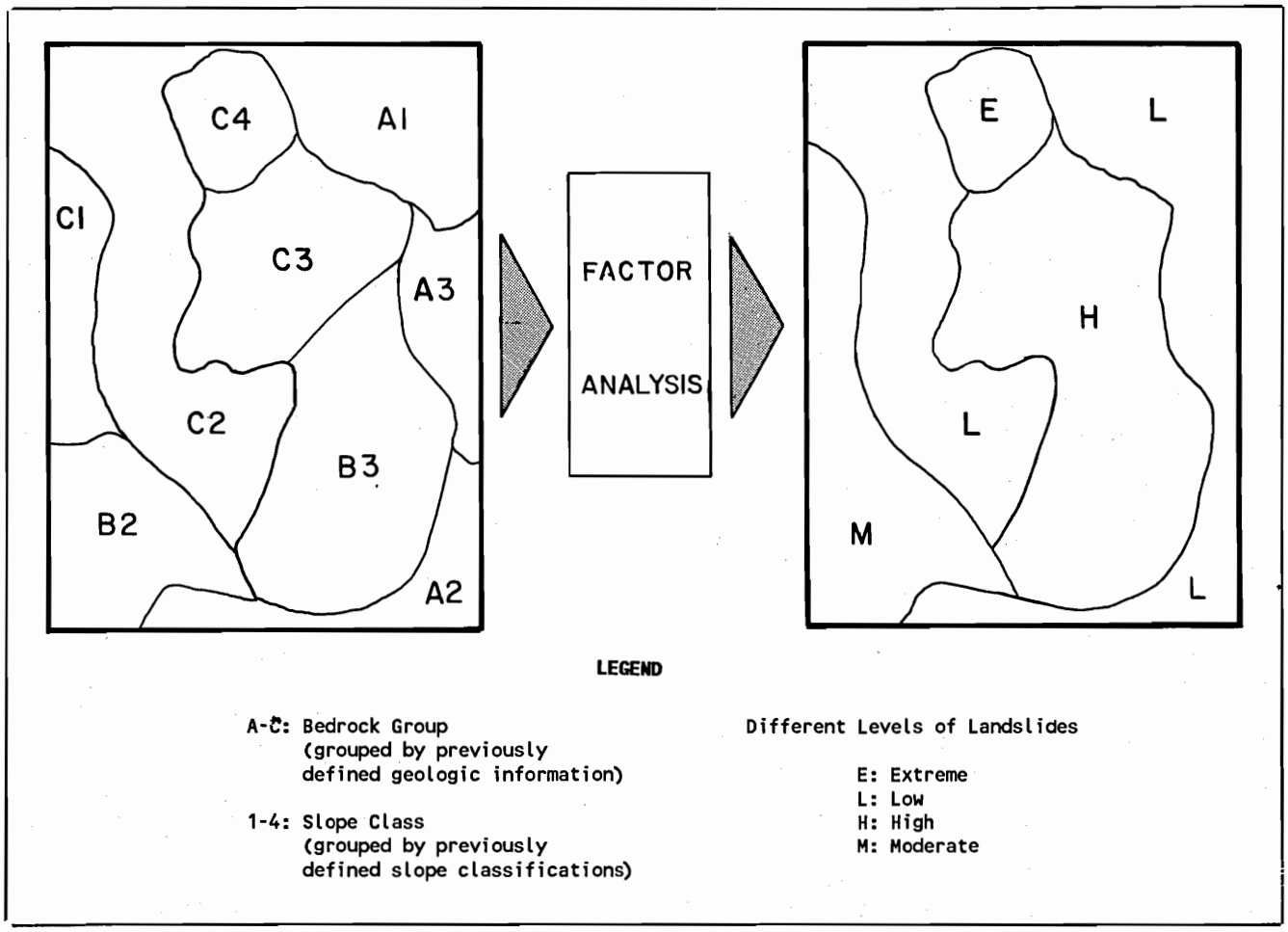
COMBINED PERMANENT FACTOR (SAMPLE BEDROCK AND SLOPE CLASS) AND LAND AREA COVERAGE (IN HECTARES)

BEDROCK GROUP	SLOPE CLASS 0<12% (1)	12<25% (2)	25<50% (3)	>50% (4)	TOTAL AREA (HA)
A	--	52	78	--	130 Landslide Area
	1,570	722	512	237	3,041 Combined Area[a]
B	--	301	784	--	1,085 Landslide Area
	--	1,776	2,327	--	4,103 Combined Area[a]
C	78	--	351	180	609 Landslide Area
	673	2,450	1,790	793	5,706 Combined Area[a]

[a] Combined Area = Combined Permanent Factor Area

Figure 10-12

LANDSLIDE HAZARD ZONES



hazardous: it may simply be the combination which is most common to the study area. Since such an area is the most prevalent combination, it has the greatest chance for being associated with past landslides rather than being most hazardous. The process described above ensures that comparison of landslide hazard among different combinations takes place on an equal basis.

There will be a proportional value for each combination of bedrock, slope steepness, and other factors associated with existing landslides ranging from .01 to 1.0. The proportions are sorted from the smallest to the largest. This range of values is broken into three groups to represent the relative landslide hazard in the study area. To ensure that the points used to define the three groups are determined objectively, a non-hierarchical cluster analysis is used. (See the Appendix of this chapter for a sample computation.)

An initial division into three groups is achieved by breaking equally the range of proportional values present. The upper and lower boundaries of each group are retained or adjusted to ensure that the final division represents the minimum sum of the squared deviations around the three group means. This is based on the W function (Anderberg, 1973).

d. Step Four: Producing Landslide Hazard Zones

The fourth, and final, step uses the grouped combinations to produce landslide hazard zones--extreme, high, moderate, and low. Once the proportions are divided into three groups, bedrock, slope steepness, and hydrologic factor combinations representing different degrees of relative landslide hazard are identified. The group of proportions with the larger values, i.e., toward the 1.0 end of the range, represent combinations defining extreme landslide hazard. The group of proportions with the next

THE W FUNCTION TO DEFINE FOUR LEVELS OF LANDSLIDE HAZARD

$$W = \sum_{i=1}^{i=3} \sum_{j=1}^{j=n_i} (X_{ij} - X_i)^2 = W_1 + W_2 + W_3$$

smaller values represents combinations defining high landslide hazard. The group of proportions with the smallest values, i.e., toward the 0.1 end of the range, represents combinations defining moderate landslide hazard. All bedrock, slope, and hydrologic factors not found to be associated at all with existing landslides define low landslide hazard.

The map overlays used to determine areas of bedrock, slope steepness, and hydrologic factor present in the entire study area can now be revised to make the hazard zonation map. Figure 10-12 shows the original maps redrawn into hazard zones. Combinations with extreme hazard are redrawn and relabeled as extreme hazard zones. Redrawing and relabeling for combinations representing other hazard zones produces a completed hazard zonation map displaying four levels of relative hazard. The empirical relationship of the physical factors, as defined by the factor analysis, is valid for only the area evaluated, and cannot be extrapolated to cover additional areas.

Once these hazard areas are identified, a decision can be made regarding the appropriate development activities, type of mitigation measures to be included in the process, or the areas which should be avoided. It is important to note that the essential bedrock and slope steepness maps are not always available. Without these maps, an isopleth map can be produced which is an acceptable substitute.

4. COMPENSATING FOR INSUFFICIENT DATA: THE ISOPLETH MAP

In the absence of bedrock and slope steepness maps, the landslide inventory map can be used to produce an analytical map suitable for representing landslide activity in an area. An isopleth map of landslide frequency is recommended for this purpose. An isopleth or any other analytic map can only serve as an initial assessment of landslide activity and not as a substitute for a landslide hazard map. The underlying conditions producing landslides will remain unknown and prevent making the distinction between the relative degrees of landslide hazard.

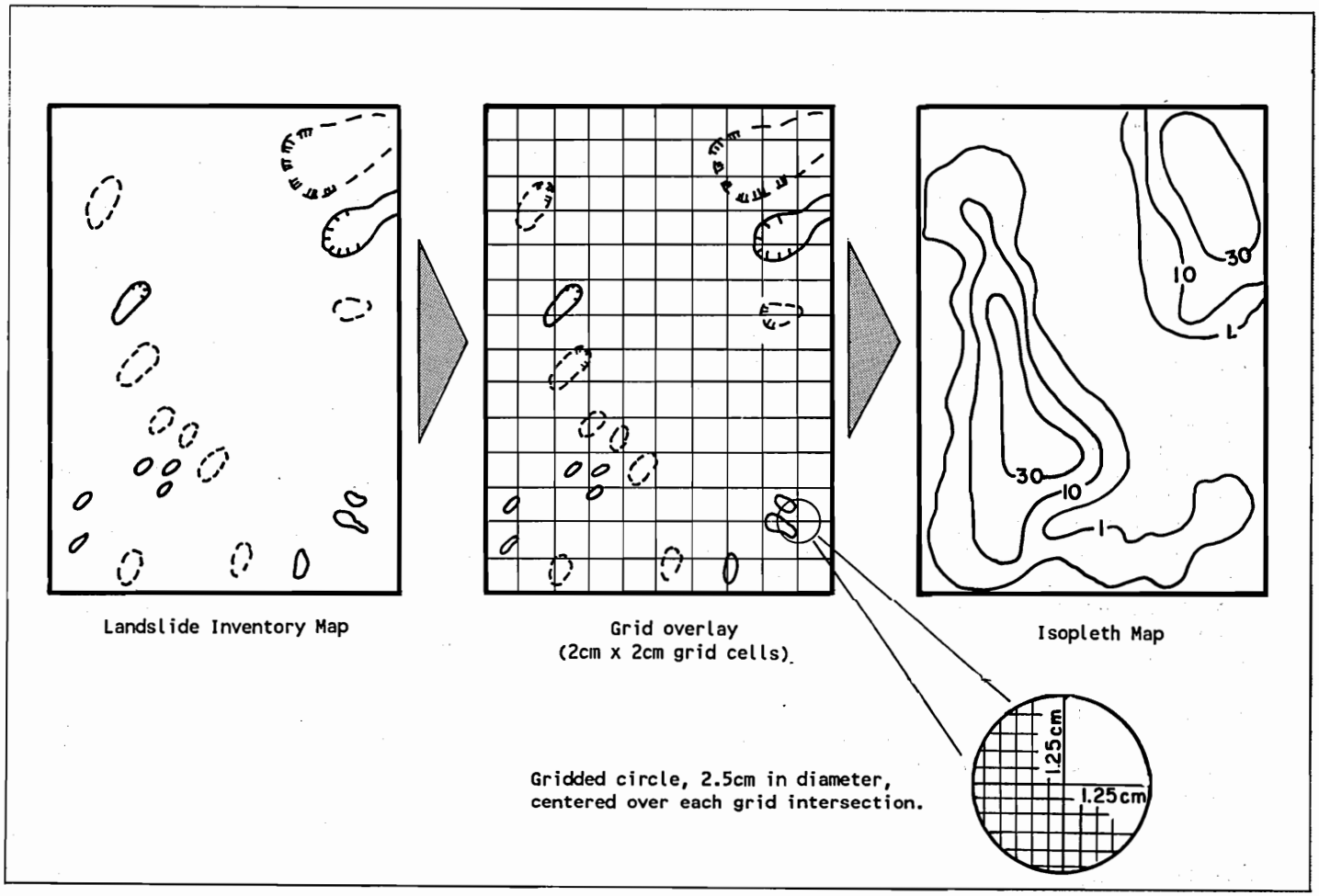
It is reasonable to assume that areas with a high frequency of landslide activity represent areas with a greater chance of future landslides than those areas with a low frequency. An isopleth map can be made based on this assumption. Preparing an isopleth map begins with the map of inventoried landslides (Wright et al., 1974). A transparent overlay with a 2cm x 2cm grid is placed over the landslide inventory map. (See Figure 10-13 for a graphic depiction of each step.) At each grid intersection a transparent gridded circle 2.5cm in diameter is centered on each grid intersection on the transparent overlay. The number of grid squares in the circle through which landslide deposits are visible is counted. Divide this number by the total number of grid squares within the inscribed circle. This yields the proportion of the unit area within the circle that is underlain by landslide deposits. This proportion is multiplied by 100 and rounded off to the nearest whole number to compute the percentage of landslide-disturbed terrain. The percent value is written on the gridded overlay next to the grid intersection.

Once all grid intersections are marked with percent values, the isopleth lines can be drawn. Isopleth lines connect the points of equal value. These show the generalized frequency of landslide activity as represented by the percent of landslide-disturbed area. The interval between isopleths drawn to produce the map will depend on the proposed use. A single value representing a boundary between areas of frequent landsliding and infrequent landsliding shows areas where this phenomenon is a major factor in shaping the landscape and areas where it is not. This serves as an initial assessment of areas subject to landslide problems when additional factors are not available for a study area. It is important to remember that this is an analytic technique producing a limited assessment of an area rather than a technique developed by an interpretative process.

During Phase II of the planning process, in addition to the intermediate landslide inventory, the preparation of an isopleth map which would enhance the information available to planners is recommended. Using the technique described above, preparation is

Figure 10-13

STEPS TO PREPARATION OF AN ISOPLETH MAP



altered in two ways: (1) only the specific landslide types identified in the intermediate inventory which are likely to be initiated by the land use proposed would be used in compiling this isopleth map; the choice of landslide types should be governed by the information on landslide activity developed by the geologist completing the intermediate inventory of existing landslides and by existing and proposed land use; and (2) isopleths are drawn at regular intervals similar to the way elevation is represented by a contour interval instead of the single value used in the isopleth map. For example, an interval of 10 percent has been used with some isopleth maps applied to land-use planning (Campbell, 1980, and Pomeroy, 1978). This produces a map representing the intensity of past landslide occurrence in a form resembling a topographic map. The isopleth lines would appear like the contour line showing elevation. The final isopleth map is used as an overlay on the landslide hazard map.

5. COMPUTER-GENERATED MAPPING

The method described in this chapter can be readily adapted to computer-generated mapping (Brabb, 1984). The factor maps used to generate the landslide hazard map can be encoded to a geographic information system (GIS) and manipulated by a computer. (See Chapter 5 for a discussion of computer mapping applications and GIS.) This enables the rapid preparation of tables showing the area for different factor combinations. In some cases, data maps used in landslide hazard assessment may be part of the GIS created for generated land-use planning, for instance a vegetation map. A second advantage of this approach is that the scales for maps to be overlaid in a landslide hazard assessment can be matched regardless of their original scale. For example, the scale of a published bedrock map may differ from the other factor maps. Using manual

techniques, redrafting the bedrock map at the same scale would be necessary, whereas a computer-based system permits the matching of map scales regardless of their original scale and the maps can be overlaid.

Computerized matching of map scales requires that certain reference points on each map be identified to ensure proper registration of points between maps. Once maps are computerized, they are capable of being updated or used to improve landslide hazard assessments. A more detailed landslide inventory map could be encoded and used to produce an improved hazard zonation map with the already encoded data maps.

The single major limitation of using a computer-based system is the amount of time and expense that is required to encode the maps and establish the data base for a landslide hazard assessment at a scale sufficiently large to permit the calculation of the percentage of the area covered by existing landslides. Creating such a data base usually dictates that a major project or series of projects be planned to justify this commitment of resources, or that a data base of computerized maps already exists. One final consideration is the ability to gain access to computer equipment, since computers may be scarce or in great demand for many uses. Nevertheless, readily available and relatively inexpensive micro-computers and software programs which are adequate for a landslide hazard assessment make it possible for some planning studies to have their own system.

Conclusion

Areas susceptible to landslides can be projected, based on the physical factors associated with landslide activity: past landslide history, bedrock, slope steepness, and hydrology. Predicting where and when landslides are going to occur is not possible even with the best available information. It is, however, possible to identify landslide-susceptible areas. This chapter has discussed some of the concepts related to landslide susceptibility: the different types of landslides; the relative nature of landslide hazard zonation; its relationship to development activity; and ways to mitigate the effects of landslides. The essential point has been to demonstrate the importance of considering landslides early in the planning study and to provide one technique which can be used at all stages of the planning process. The different questions that need to be asked at the different planning stages were highlighted. Many answers can be generated from the use of landslide hazard zonation at each stage of the planning study. The step-by-step combined factor analysis to prepare hazard maps was presented. All of this will enable the planner to have a working knowledge of terms, concepts, and the important considerations related to landslides and landslide hazard mapping.

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Appendix

SAMPLE COMPUTATION OF W FUNCTION

As noted in Section C-3, Factor Analysis, the W function is computed from the formula:

$$W = \sum_{i=1}^{i=3} \sum_{j=1}^{j=n_i} (X_{ij} - X_i)^2 = W_1 + W_2 + W_3$$

where: X_{ij} = j^{th} observation i^{th} group
n_i = number of observations in the ith group

For the example, it is assumed the combined factor analysis yielded the following sixteen proportions:

.53, .01, .19, .03, .39, .04, .05, .88, .11, .01, .21, .03, .61, .01, .04, .11

Step 1: The proportions are then arranged in ascending order:

.01, .01, .01, .03, .03, .04, .04, .05, .11, .11, .19, .21, .39, .53, .61, .88

The data range from .01 to .88. This range is divided equally to form three groups based on an equal interval partition: $.01 \leq X < .29$, $.29 \leq X < .58$, and $.58 \leq X < .88$.

Step 2: The W factor is computed using the values in each group formed under the initial equal interval partition:

[.01≤X<.29]	**[.29≤X<.58]**	**[.58≤X<.88]**
.01, .01, .01, .03, .03, .04, .04, .05, .11, .11, .19, .21	.39, .53	.61, .88
X1 = .07	X2 = .46	X3 = .745
W1 = .0534	W2 = .0098	W3 = .0365

W = W1 + W2 + W3 = .0534 + .0098 + .0365 = .0996

The objective is to minimize the value of W. In other words, find the smallest W values that can be computed for three groups of the proportional values. This applies the principle of least squares, a common statistical approach, to this one-dimensional problem through minimizing the sum of squared deviations about the group means.

Step 3: The boundary is shifted to the right to seek the desired decrease in W function:

[.01≤X<.39]	[.39≤X<.58]	[.58≤X<.88]
.01, .01, .01, .03, .03, .04, .04, .05, .11, .11, .19, .21, .39	.53	.61, .88
X1 = .0946	X2 = .53	X3 = .745
W1 = .1479	W2 = 0	W3 = .0365

W = W1 + W2 + W3 = .1479 + 0 + .0365 = .18435

Because the recomputed value is more than the W value initially computed, this is the wrong direction move. The boundary will be shifted to the left of the initial boundary seeking a decrease in the W value.

Step 4: The left-most boundary is moved to the left by one value. The W function is recomputed and compared to the initial W value to determine whether the desired decrease occurred:

[.01≤X<.19]	[.19≤X<.58]	[.58≤X<.88]
.01, .01, .01, .03, .03, .04, .04, .05, .11, .11, .19	.21, .39, .53	.61, .88
X1 = .0573	X2 = .3767	X3 = .745
W1 = .0320	W2 = .0515	W3 = .0365

W = W1 + W2 + W3 = .0320 + .0515 + .0365 = .12

This is not a decrease. Therefore, the partition for the left-most boundary is kept at the initial value.

Step 5: Now the second or right-most boundary is moved to the right:

[.01≤X<.29]	[.29≤X<.61]	[.61≤X<.88]
.01, .01, .01, .03, .03, .04, .04, .05, .11, .11, .19, .21	.39, .53, .61	.88
X1 = .07	X2 = .51	X3 = .88
W1 = .0534	W2 = .0248	W3 = 0

W = W1 + W2 + W3 = .0534 + .0248 + 0 = .0782

This is a decrease in the W value. If any other values remained in the third group, the boundary would be shifted in single moves to the right until no further decrease in W values was obtained. With no other values present, this minimizes the sum of squared deviations about the group means to the greatest extent possible and

retains three groups. If the shift to the right had resulted in an increased W value, a move to the left on the right-most boundary would have been tried. Having determined the boundaries for obtaining the smallest W value, the best grouping of the proportional values present is achieved.

As a result of this iterative process, the initial partition into groups with the following ranges:

$$.10 \leq X < .29$$
$$.29 \leq X < .58$$
$$.58 \leq X < .88$$

is changed to a grouping more consistent with the proportional values involved based on the range of values below:

$$.01 \leq X < .29$$
$$.29 \leq X < .61$$
$$.61 \leq X < .88$$

CHAPTER 11

GEOLOGIC HAZARDS

CHAPTER 11

GEOLOGIC HAZARDS

Contents

List of Figures

GEOLOGIC HAZARDS

SUMMARY

The chapter presents planners with (1) a description of the most hazardous geologic phenomena--earthquakes, volcanoes, and tsunamis--and their effects; (2) a discussion of how to use existing information to assess the hazards associated with these phenomena and incorporate mitigation measures early in an integrated development study; (3) sources of geologic data and maps; and (4) information with which to make key decisions early in the planning process.

The processes that have formed the earth continually act on or beneath its surface. The movement of plates in the earth's crust and local concentrations of heat are a continuing source of hazards to people and their structures. A simplified classification of the major hazard-related geologic phenomena and the hazards they cause is presented in the box below.

This chapter focuses on the use of information about earthquakes and earthquake-induced landslides, volcanic eruptions, and tsunamis (ocean waves caused by earth movement) to improve development planning in Latin America and the Caribbean. For each hazard the chapter presents physical characteristics, information sources, data available for determining the threat posed, and mitigation measures; Chapter 10 provides a more detailed discussion of landslides. Not considered here are certain other geologic phenomena--such as expansive soils, uplift, and subsidence--which are less common, less hazardous, or less amenable to general assessment and mitigation.

The results of the extensive research on geologic hazards that has been conducted to date have been translated into a form accessible to non-scientists, and small-scale maps displaying historic, actual, and potential hazard levels are available. While this chapter does not go into specific geologic hazard assessment techniques, most of which are well beyond the technical, temporal, and budgetary constraints of integrated development planning studies, it presents and discusses existing information which can and should be used during the Preliminary Mission and Phase I stages of a planning study. This information is sufficient to show the planning team whether a hazard constitutes a significant problem in development area and, if so, what detailed studies requiring the services of a specialist are needed.

A. Overview of Geologic Hazards and the Development Planning Process

Geologic hazards are responsible for great loss of life and destruction of property. In the twentieth century more than a million people worldwide have been killed by earthquakes alone, and the value of the property destroyed by earthquakes, volcanoes, and tsunamis amounts to scores of billions of dollars. Latin America suffers its share of this destructive force: during the period 1985-1987, earthquakes in Ecuador, Mexico, and El Salvador and a volcanic eruption in Colombia killed more than 36,000 people.

The Nazca Plate, sliding slowly eastward on the earth's mantle, slips under the South American Plate along the Peru-Chile Trench. Friction produces stress and temperature increases; the subducted rock melts and expands, causing additional stress and upward movement of the magma. The magma reaches the surface, erupting to form volcanoes, and the crustal rocks respond to the stresses by breaking and moving. Thus the crust above the subduction zone is demarcated by volcanoes and active faults. Movement along the faults causes earthquakes.

This zone of volcanism and earthquakes, involving several plates and trenches and manifested in Latin America by the Andes Mountains and their extension into Central America and Mexico, virtually encircles the Pacific Ocean and is known as the "Ring of Fire." Geologic hazards--earthquakes, the landslides they induce, and volcanic eruptions--are concentrated in this region, and the seismic sea waves called tsunamis most commonly originate from earthquake shocks there as well. Similar geologic conditions extend into the Caribbean, which is considered a part of the Ring of Fire even though not a part of the Pacific Basin.

A SIMPLIFIED CLASSIFICATION OF MAJOR GEOLOGIC HAZARDS

Geologic Event	Hazards They Cause
Earthquake	A. Ground shaking B. Surface faulting C. Landslides and liquefaction 1. Rock avalanches 2. Rapid soil flows 3. Rock falls D. Tsunamis
Volcanic Eruption	A. Tephra falls and ballistic projectiles B. Pyroclastic phenomena C. Lahars (mud flows) and floods D. Lava flows and domes E. Poisonous gases

With the present state of technology, most geologic events cannot be prevented or even predicted with any precision. Landslides are an exception: they can often be prevented. Areas prone to such events can be identified as earthquake fault zones, active volcanoes, and coastal areas susceptible to tsunamis. However, not all earthquake faults have been identified. Estimates of an occurrence of a given hazardous event are probabilistic, based on consideration of the magnitude of an event and its occurrence in time and space. Other measures--duration, areal extent, speed of onset, geographic dispersion, frequency--can be anticipated with even less precision.

Nevertheless, appropriate mitigation measures can enormously reduce the damage caused by geologic hazards. The City of Los Angeles, California, for example, instituted a system of grading regulations that has resulted in a 90 percent reduction of landslide-related damage to structures that were built after it went into effect (Hays, 1981). High density of population and infrastructure increases the risk, making hazard mitigation even more important.

Geologic events are distinctive for their extremely rapid onset. Unlike a flood or hurricane, whose impact at a site can be forecast hours or days in advance, earthquakes give virtually no warning. Volcanoes often show signs of a general increase in activity but give little or no warning of the actual eruption. (In a few areas where known hazards exist, e.g., Nevado del Ruiz, Mt. St. Helens and the San Andreas Fault, instrumentation has been installed which can give an indication of impending activity.) Tsunamis travel great distances over the open ocean; one triggered off the cost of Peru might hit the coast of Japan 18 hours later, giving reasonable warning time, but the same tsunami would hit the coast of Peru with almost no warning at all.

In addition to speed of onset, geologic hazards also tend to have impacts covering large areas. Earthquakes can cause damage over millions of square kilometers, and tsunamis travel the entire ocean and cause major damage thousands of kilometers from their point of origin. For these reasons, non-structural mitigation measures, such as land-use zoning or the development of monitoring systems, tend to be particularly effective.

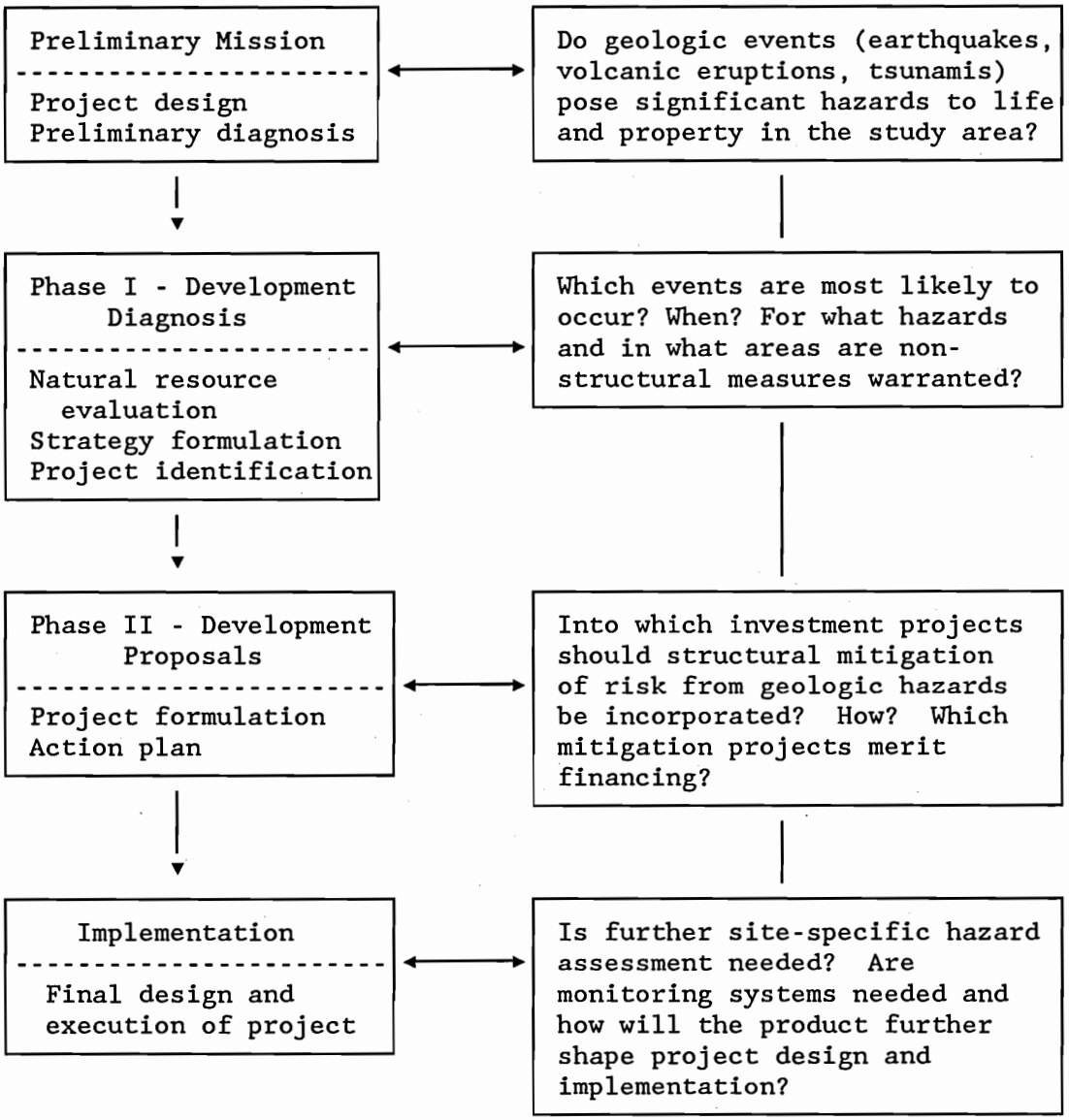
DEVELOPMENT PLANNING

The earlier geologic hazard mitigation is incorporated into the development planning process, the more effective it is. Figure 11-1 summarizes the major issues involved and indicates the most appropriate phase in the process for their consideration in a development planning study.

It must be emphasized that "consideration" means that hard decisions representing real money must be made at each step along the way: Is ground faulting a serious hazard here? Should something be done to avoid it? To mitigate its effects? How much will mitigation works cost? What are the potential costs of not taking action? The planner must provide the information on which to base a decision at each point, but it should be the minimum necessary for a decision of acceptable reliability, since gathering information is

Figure 11-1

RELATIONSHIP OF GEOLOGIC HAZARDS ISSUES TO AN INTEGRATED DEVELOPMENT PLANNING STUDY



expensive. Furthermore, it must be available at the right time, since integrated development planning, if it is to be efficient, operates on a tight schedule.

The ideal type of information for a particular decision may not be available or may be too expensive or too time-consuming to obtain as a part of the development planning study. In that situation it may be possible to substitute other information which, even if not ideal, yields a result with a degree of reliability suitable to the level of the study. This chapter offers a framework for arriving at decisions on the mitigation of geologic hazards at various stages of the development planning process with a minimum expenditure for information gathering. In the successive stages of development planning, the hazard mitigation work becomes more detailed and specialized. Thus, the chapter concentrates on the early phases of development studies, in which the assessment of geologic hazards and the identification of mitigation measures fit comfortably within a planning study.

B. Earthquakes

An earthquake is caused by the sudden release of slowly accumulating strain energy along a fault within the earth's crust. Areas of surface or underground fracturing that can experience earthquakes are known as earthquake fault zones. Some 15 percent of the world's earthquakes occur in Latin America, concentrated in the western cordillera. The Regional Seismologic Center for South America (Centro Regional de Sismología para América del Sur--CERESIS), based in Lima, Peru, has produced a map entitled "Significant Earthquakes, 1900-1979" which shows the significant earthquakes that have occurred in Latin America during this period.

1. EARTHQUAKE EFFECTS AND THE HAZARDS THEY CAUSE

Depending on its size and location, an earthquake can cause the physical phenomena of ground shaking, surface fault rupture, and ground failure and, in some coastal areas, tsunamis. Smaller earthquakes, aftershocks, may follow the main shock, sometimes several hours, months, or even several years later.

a. Ground Shaking

Ground shaking or ground motion, a principal cause of the partial or total collapse of structures, is the vibration of the ground caused by seismic waves during an earthquake. Four different types of waves are propagated through and on the surface of the earth at different velocities, arrive at a site at different times, and vibrate a structure in different ways. The first wave to reach the earth's surface is the sound wave or P wave and is the first to cause a building to vibrate. The most damaging waves are shear waves, S waves, which travel near the earth's surface and cause the earth to move at right angles to the direction of the wave and structures to vibrate from side to side. Unless a structure is designed and constructed to withstand these vibrations, ground shaking can cause damage. The third and fourth types are slow low-frequency surface waves, usually detected at great distances from the epicenter, which cause buildings to sway and waves to form in bodies of water.

Characteristics (Parameters)

Four principal characteristics which influence the damage that can be caused by an earthquake's ground shaking--size, attenuation, duration, and site response--are discussed here. A fifth parameter, the potential for ground failure (or the propensity of a site to liquefaction or landslides) is dealt with separately later in this section. These factors are also related to the distance of a site from the earthquake's epicenter--the point on the ground above its center.

(1) Earthquake Severity or Size: The severity of an earthquake can be measured two ways: its intensity and its magnitude. Intensity is the apparent effect of the earthquake at a specific location. The magnitude is related to the amount of energy released.

Intensity is measured on various scales. The one most commonly used in the Western Hemisphere is the twelve-level Modified Mercalli Index (MMI), on which the intensity is subjectively evaluated by describing the extent of damage. Figure 11-2 shows the approximate relationships of magnitude, intensity at the epicenter, and other seismic parameters, comparing energy release with equivalent tons of TNT.

The Richter Scale, which measures magnitude, is the one most often used by the media to convey to the public the size of an earthquake. Magnitude is easier to determine than intensity, since it is registered on seismic instruments, but it does present some difficulties. While an earthquake can have only one magnitude, it can have many intensities which affect different communities in different ways. Thus, two earthquakes with an identical Richter magnitude may have widely different maximum intensities at different locations.

(2) Attenuation: Attenuation is the decrease in the strength of a seismic wave as it travels farther from its source. It is influenced by the type of materials and structures the wave passes through (the transmitting

Figure 11-2

APPROXIMATE RELATION CONNECTING EARTHQUAKE MAGNITUDE, INTENSITY, ACCELERATION, ENERGY RELEASE, AND INCIDENCE

MODIFIED-MERCALLI INTENSITY SCALE I	GROUND ACCELERATION a	MAGNITUDE M	ENERGY E Ergs	TNT EQUIVALENT METRIC TONS	WORLDWIDE EXPECTED ANNUAL INCIDENCE
I Detected only by sensitive instruments.	cm/sec a/g				
II Felt by a few persons at rest, especially on upper floors; delicate suspended objects may swing.	2, 3		10^{14}		
III Felt noticeably indoors, but not always recognized as a quake; standing autos rock slightly, vibration like passing truck.	4, 5, 6, 7 .005g	M-3 CLASS E	10^{15}	20	
IV Felt indoors by many, outdoors by a few; at night some awaken; dishes, windows, doors disturbed; motor cars rock noticeably.	8, 9, 10 .01g		10^{16}		49,000
V Felt by most people; some breakage of dishes, windows and plaster; disturbance of tall objects.	20, 30	M-4	10^{17}	600	
VI Felt by all; many frightened and run outdoors; falling plaster and chimneys; damage small.	40, 50, 60	M-5	10^{18}		6,200
VII Everybody runs outdoors; damage to buildings varies, depending on quality of construction; noticed by drivers of autos.	70, 80, 90, 100 .1g	CLASS D	10^{19}	20,000	
VIII Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected; drivers of autos disturbed.	200, 300	M-6 CLASS C	10^{20}	600,000	800
IX Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken.	400, 500, 600 .5g		10^{21}		120
X Most masonry and frame structures destroyed; ground cracked; rails bend; landslides.	700, 800, 900, 1000 1g	M-7 CLASS B	10^{22}	20,000,000	18
XI New structures remain standing; bridges destroyed; fissures in ground; pipes broken; landslides; rails bent.	2000, 3000	M-8 CLASS A	10^{23}	600,000,000	
XII Damage total; waves seen on ground surface; lines of sight and level distorted; objects thrown up into air.	4000, 5000, 6000 5g	M-9	10^{24}	20,000,000,000	1

Sources: Adapted from U.S. Atomic Energy Commission, TID-7024. Nuclear Reactors and Earthquakes (August, 1963), pp. 13-14; Gutenberg, B., and Richter, C.F. Seismicity of the Earth and Associated Phenomena (Princeton, New Jersey: Princeton University Press, 1954), p. 18; and U.S. Department of Defense. The Effects of Nuclear Weapons (Washington, D.C.: S. Glasstone ed., Government Printing Office, 1962); pp. 14.

medium) and the magnitude of the earthquake. Figure 11-3 shows that a given degree of ground shaking can be expected over a much greater area in the eastern United States than in the West, where geologic conditions differ. The figure also shows that structural damage caused by a large earthquake can extend over a million square kilometers. The largest earthquakes have caused damage in areas three to four million square kilometers in extent.

(3) Duration: Duration refers to the length of time in which ground motion at a site exhibits certain characteristics such as violent shaking, or in which it exceeds a specified level of acceleration measured in percent of gravity (g). Larger earthquakes are of greater duration than smaller ones. This characteristic, as well as stronger shaking, accounts for the greater damage caused by larger earthquakes.

(4) Site Response: The site response is the reaction of a specific point on the earth to ground shaking. This also includes the potential for ground failure, which is influenced by the physical properties of the soil and rock underlying a structure and by the structure itself. The depth of the soil layer, its moisture content, and the nature of the underlying geologic formation--unconsolidated material or hard rock--are all relevant factors. Furthermore, if the period of the incoming seismic wave is in resonance with the natural period of structures and/or the subsoil on which they rest, the effect of ground motion may be amplified.

In the 1985 Mexico City earthquake, the period of the seismic wave was close to the natural period of the Mexico City basin, considering the combination of soil type, depth, and shape of the old lake bed. The wave reached bedrock under the city with an acceleration level of about 0.04g. By the time it passed through the clay subsoil and reached the surface, the acceleration level had increased to 0.2g, and the natural vibration period of the buildings with 10 to 20 floors increased the force to 1.2g, 30 times the acceleration in the bedrock. Most buildings would have resisted 0.04g acceleration, and the earthquake-resistant buildings destroyed would have resisted 0.2g, but the waves that were amplified to 1.2g caused all buildings they reached to collapse (Anderson, 1985).

Effects of Ground Shaking

Buildings, other types of structures, and infrastructure are all subject to damage or collapse from ground shaking. Fire is a common indirect effect of a large earthquake since electrical and gas lines may be ruptured. Furthermore, firefighting efforts may be impeded by blocked transportation routes and broken water mains. Damage to reservoirs and dams may result in flash flooding. The damage caused by ground shaking, however, is amenable to mitigation by a number of approaches which will be discussed later in this section. In general, structural measures such as earthquake-resistant design, building codes, and retrofitting are effective. Less costly non-structural measures such as land-use zoning and restrictions can also greatly reduce risk.

An important, if little-appreciated, effect of earthquakes is damage to aquifers. The 1985 Mexico City earthquake undermined major aquifers. It not only broke the encasing impermeable layers, allowing the trapped water to escape, but also permitted the infiltration of contaminants.

b. Surface Faulting

Surface faulting is the offset or tearing of the ground surface by differential movement along a fault during an earthquake. This effect is generally associated with Richter magnitudes of 5.5 or greater and is restricted to particularly earthquake-prone areas. Displacements range from a few millimeters to several meters, and the damage usually increases with increasing displacement. Significant damage is usually restricted to a narrow zone ranging up to 300 meters wide along the fault, although subsidiary ruptures may occur three to four kilometers from the main fault. The length of the surface ruptures can range up to several hundred kilometers.

In addition to buildings, linear structures such as roads, railroads, bridges, tunnels, and pipelines are susceptible to damage from surface faulting. Obviously, the most effective way to limit such damage is to avoid construction in the immediate vicinity of active faults. Where this is not possible, some mitigation measures such as installing pipelines above ground or using flexible connections can be considered. This is discussed in greater detail later in this section.

c. Earthquake-Induced Ground Failure: Landslides and Liquefaction

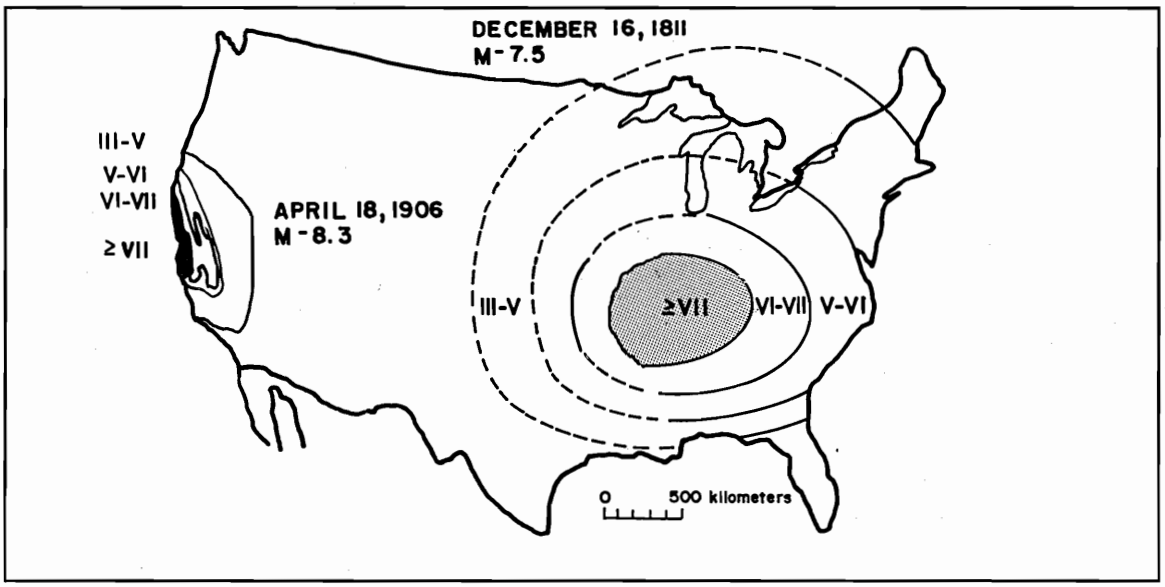
Landslides occur in a wide variety of forms. The focus of this section is on those induced by earthquakes, but they can also be triggered by other mechanisms. (For a detailed discussion of landslides see Chapter 10.) Not only can earthquakes trigger landslides, they can also cause the soil to liquefy in certain areas. Both of these forms of ground failure are potentially catastrophic.

Earthquake-Induced Landslides

Earthquake-induced landslides occur under a broad range of conditions: in steeply sloping to nearly flat land; in bedrock, unconsolidated sediments, fill,

Figure 11-3

ISOSEISMIC CONTOURS FOR THE 1906 SAN FRANCISCO AND THE 1811 NEW MADRID EARTHQUAKES



Source: Algermissen, S.T. "Integration, Analysis, and Evaluation of Hazard Data" in Proceedings of the Geologic and Hydrologic Hazards Training Program, Open File Report 84-760 (Reston, Virginia: U.S. Geological Survey, 1984), p. 20.

and mine dumps; under dry and very wet conditions. The principal criteria for classifying landslides are types of movement and types of material. The types of landslide movement that can occur are falls, slides, spreads, flows, and combinations of these. Materials are classified as bedrock and engineering soils, with the latter subdivided into debris (mixed particle size) and earth (fine particle size) (Campbell, 1984).

Moisture content can also be considered a criterion for classification: some earthquake-induced landslides can occur only under very wet conditions. Some types of flow failures, grouped as liquefaction phenomena, occur in unconsolidated materials with virtually no clay content. Other slide and flow failures are caused by slipping on a wet layer or by interstitial clay serving as a lubricant. In addition to earthquake shaking, trigger mechanisms can include volcanic eruptions, heavy rainstorms, rapid snowmelt, rising groundwater, undercutting due to erosion or excavation, human-induced vibrations in the earth, overloading due to construction, and certain chemical phenomena in unconsolidated sediments.

Figure 11-4, which is designed for practical use by planners, contains a simplified classification of earthquake-induced landslides indicating the more damaging and/or more common types. The salient characteristics of these landslide types and why each is of concern (degree of damage, frequency of occurrence[1], velocity) are listed in Figure 11-5. This figure, again designed for use by the planner, provides information on the mode of occurrence--under what conditions each type can be expected to occur (geomorphic, topographic, parent materials, moisture content), and their causative factors, including the smallest earthquake that can cause that type of landslide and common trigger mechanisms.

Rock avalanches, rock falls, mudflows, and rapid earth flows (liquefaction) account for over 90 percent of the deaths due to earthquake-induced landslides.

(1) Rock Avalanches: Rock avalanches originate on over-steepened slopes in weak rocks. They are uncommon but can be catastrophic when they occur. The Huascarán, Peru, avalanche which originated as a rock and ice fall caused by the 1970 earthquake was responsible for the death of approximately 20,000 people.

(2) Rock Falls: Rock falls occur most commonly in closely jointed or weakly cemented materials on

1/ The frequency of occurrence of earthquake-induced landslides is related primarily to the magnitude of the earthquake and aftershock but also to local geologic conditions. The frequency scale used here is based on a survey of landslides associated with 40 historic earthquakes.

Figure 11-4

CLASSIFICATION OF PRINCIPAL EARTHQUAKE-INDUCED LANDSLIDES INDICATING DEGREE OF DAMAGE PRODUCED[a/]

	Type of Material and Moisture Content		
	Bedrock	Engineering Soil (Earth and Debris)	
Type of Movement	Dry to Wet	Dry to Wet	Very Wet
Falls	ROCK FALL	Earth fall	
Slides	Rock slump Rock slide	EARTH SLUMP Debris slide Earth block slide	
Lateral spreads		EARTH LATERAL SPREAD	
Flows		Dry sand flow Loess flow	MUD FLOW Debris flow RAPID EARTH FLOW Earth flow (mudslide)
Complex	ROCK AVALANCHE, moist to very wet		

a/ Historical damage caused by earthquake-related landslides.
UNDERLINED CAPITALS: these landslides have caused many casualties and large economic losses.
CAPITALS: these landslides have caused a moderate number of casualties and moderate economic losses.
Upper and lower case: these landslides have caused few casualties and minor economic losses.

Sources: Modified from Campbell, R.H., et al. "Landslides Classification for Identification of Mud Flow and Other Landslide Hazards" and Keefer, P.K. "Landslides Caused by Earthquakes" in Proceedings of the Geologic and Hydrologic Training Program, Open File Report 84-760 (Reston, Virginia: U.S. Geological Survey, 1984).

slopes steeper than 40 degrees. While individual rock falls cause relatively few deaths and limited damage, collectively, they rank as a major earthquake-induced hazard because they are so frequent.

(3) Mud Flows: Mud flows are rapidly moving wet earth flows that can be initiated by earthquake shaking or a heavy rainstorm. While the term is used in several ways, in this chapter "mud flow" is used to designate the phenomena associated with earthquake shaking. Underwater landslides, also classified as mud flows, may occur at the margins of large deltas where port facilities are commonly located. Much of the destruction caused by the 1964 Seward, Alaska, earthquake was caused by such a slide. The term "mudflow," in keeping with common practice, is used as a synonym for "lahar," a phenomenon associated with volcanoes.

Liquefaction

Certain types of spreads and flows are designated as liquefaction phenomena. Ground shaking may cause clay-free soil deposits to lose strength temporarily and behave as a viscous liquid rather than as a solid. In the liquefied condition soil deformation may occur with little shear resistance. Deformation large enough to cause damage to constructed works (usually movement of about ten centimeters) is considered ground failure.

The occurrence of liquefaction is restricted to certain geologic and hydrologic environments, primarily in areas with recently deposited sands and silts (usually less than 10,000 years old) with high ground-water levels. It is most common where the water table is at a depth of less than ten meters in

Figure 11-5

CHARACTERISTICS OF PRINCIPAL EARTHQUAKE-INDUCED LANDSLIDES[a]

General Characteristics			Mode of Occurrence			Causative Factors	
Landslide Type and Degree of Damage[b]	Frequency of Occurrence[c]	Velocity	Landform and Geologic Environment	Parent Material	Moisture	Smallest Earthquake (Intensity)	Common Triggers[d] and Comments
			OCCURS ON VERY STEEP TO GENTLE SLOPES				
1. ROCK AVALANCHE	4	Extremely rapid	Slopes steep to very steep	Unsorted colluvium	Moist to very wet	6.0	Earthquake shaking, volcanic eruption, heavy rainstorm
2. Debris slide (debris avalanche)	1	Extremely rapid to rapid	Slopes steep to very steep	Colluvium	Wet to dry	4.0	Earthquake shaking, volcanic eruption, heavy rainstorm
3. Debris flow (debris avalanche)	2	Extremely rapid to rapid	Slopes steep to moderately steep	Colluvium	Very wet to wet	NA	Earthquake shaking, volcanic eruption, heavy rainstorm
4. MUD FLOW	NA	Extremely rapid to rapid	Slopes steep to gentle	Colluvium, alluvium	Very wet	NA	Earthquake shaking: Landslides in saturated materials, landslides into or beneath water
5. Rock slump	3	Slow to rapid	Slopes steep to moderately steep	Unconsolidated to poorly consolidated bedrock	Moist to wet	5.0	Groundwater rise; undercut/surcharge
6. EARTH SLUMP	2	Slow to rapid	Slopes steep to moderately steep, sometimes gentle	Unconsolidated deposits	Moist to wet	4.5	Groundwater rise; undercut/surcharge
7. Earth flow (or mudslide)	3	Rapid to slow	Slopes steep to moderately steep, sometimes gentle	Clay-bearing unconsolidated material	Wet to moist	5.0	Groundwater rise; undercut/surcharge
8. RAPID EARTH FLOW (including wet sand and silt flows)	3	Extremely rapid to rapid	Gentle slopes	Unconsolidated clay, silt, and sand	Very wet to wet	5.0	Earthquake or other dynamic lode; changes in pore water chemistry
			OCCURS PARALLEL TO GEOLOGIC DISCONTINUITIES				
9. Rock slide	1	Extremely rapid to moderate	Steep to very steeply dipping	Consolidated bedrock	Wet to dry	4.0	Earthquake shaking; groundwater rise; frost/root wedging
10. Earth block slide	2	Extremely rapid to rapid	Gently, moderately or steeply dipping	Unconsolidated material	Wet to dry	4.5	Groundwater rise; undercut/surcharge
11. Rock block slide	4	Extremely rapid to rapid	Gently, moderately or steeply dipping	Consolidated bedrock	Wet to dry	5.0	Groundwater rise; undercut/surcharge
12. EARTH LATERAL SPREAD	2	Extremely rapid to rapid	Flat to gently dipping	Unconsolidated material	Wet to moist	5.0	Earthquake shaking; undercut/surcharge
			OCCURS IN STEEP LOCAL RELIEF				
13. ROCK FALL	1	Extremely rapid to slow	Steep to vertical cliffs	Consolidated bedrock	Moist to dry	4.0	Earthquake shaking; undercut/surcharge
14. Earth fall	5	Extremely rapid to slow	Bluff faces	Unconsolidated deposits	Moist to dry	4.0	Earthquake shaking; undercut/surcharge
15. Dry sand flow	5	Extremely rapid to rapid	Very steep to steep local relief	Unconsolidated deposits	Dry	NA	Earthquake shaking; undercut/surcharge
16. Loess flow	5	Extremely rapid to rapid	Very steep to steep local relief	Unconsolidated deposits	Dry	NA	Earthquake shaking; undercut/surcharge

a/ Figure does not include landslides for which movement is extremely slow or for which earthquake-induced occurrence is very rare.
b/ Degree of damage from earthquake-induced landslides: Landslide types presented in UNDERLINED CAPITALS - great damage; landslide types presented in CAPITALS - moderate damage; landslide types presented in lower case letters - little damage.
c/ The frequency scale used here is based on a survey of landslides associated with 40 historic earthquakes: (1) very abundant (more than 100,000 landslides associated with the 40 earthquakes); (2) abundant (10,000 landslides); (3) moderately common (1,000 to 10,000 landslides); (4) uncommon (100 to 1,000 landslides); (5) rare (less than 100 landslides); NA - data not available.
d/ All landslides shown can be induced by earthquakes. For some landslides, other trigger mechanisms are more common.

Source: Modified from Campbell, R.H. et al. "Landslides Classification for Identification of Mud Flow and Other Landslide Hazards"; and Keefer, P.K. "Landslides Caused by Earthquakes" in Proceedings of the Geologic and Hydrologic Training Program, Open File Report 84-760 (Reston, Virginia: U.S. Geological Survey, 1984).

Holocene deltas, river channels, areas of floodplain deposits, eolian material, and poorly compacted fills.

Ground failures grouped as liquefaction can be subdivided into several types. The two most important are rapid earth flows and earth lateral spreads.

(1) Rapid Earth Flows: Rapid earth flows are the most catastrophic type of liquefaction. Large soil masses can move from tens of meters to several kilometers. These flows usually occur in loose saturated sands or silts on slopes of only a few degrees; yet they can carry boulders weighing hundreds of tons.

(2) Earth Lateral Spreads: The movement of surface blocks due to the liquefaction of subsurface layers usually occurs on gentle slopes (up to 3 degrees). Movement is usually a few meters but can also be tens of meters. These ground failures disrupt foundations, break pipelines, and compress or buckle engineered structures. Damage can be serious with displacements on the order of one or two meters.

In areas susceptible to earthquakes, liquefaction may be one of the most critical effects. Flow failure in loess (wind-blown silt) in the 1960 earthquake in China caused 200,000 deaths. Liquefaction was also a major factor in the earthquakes of 1960 in Chile and 1985 in Mexico and in major earthquakes in California, Alaska, India, and Japan.

In general, liquefaction can be prevented by ground-stabilization techniques or accommodated through appropriate engineering design, but both are expensive methods of mitigation. Avoidance is, of course, the best approach, but it is not always practical or possible in areas already developed or with existing transportation routes, pipelines, etc.

2. EARTHQUAKE HAZARD PREDICTION, ASSESSMENT, AND MITIGATION

Minimizing or avoiding the risks from earthquakes involves three subject areas. First is the ability to predict their occurrence. While scientists cannot routinely predict earthquakes, this area is of growing interest and may be a key factor in reducing risks in the future. The second area is seismic risk assessment, which enables planners to identify areas at risk of earthquakes and/or their effects. This information is used to address the third area of earthquake risk reduction--mitigation measures. Following a discussion of prediction, assessment, and mitigation, the types and sources of earthquake information are presented.

a. Earthquake Prediction

A report on an erroneous prediction of an earthquake in Lima, Peru, states:

> Earthquake prediction is still in a research and experimental phase. Although a few successful predictions have been made, reliable and accurate predictions having a long lead time, and useful location and magnitude estimates, are many years in the future (Gersony, 1982).

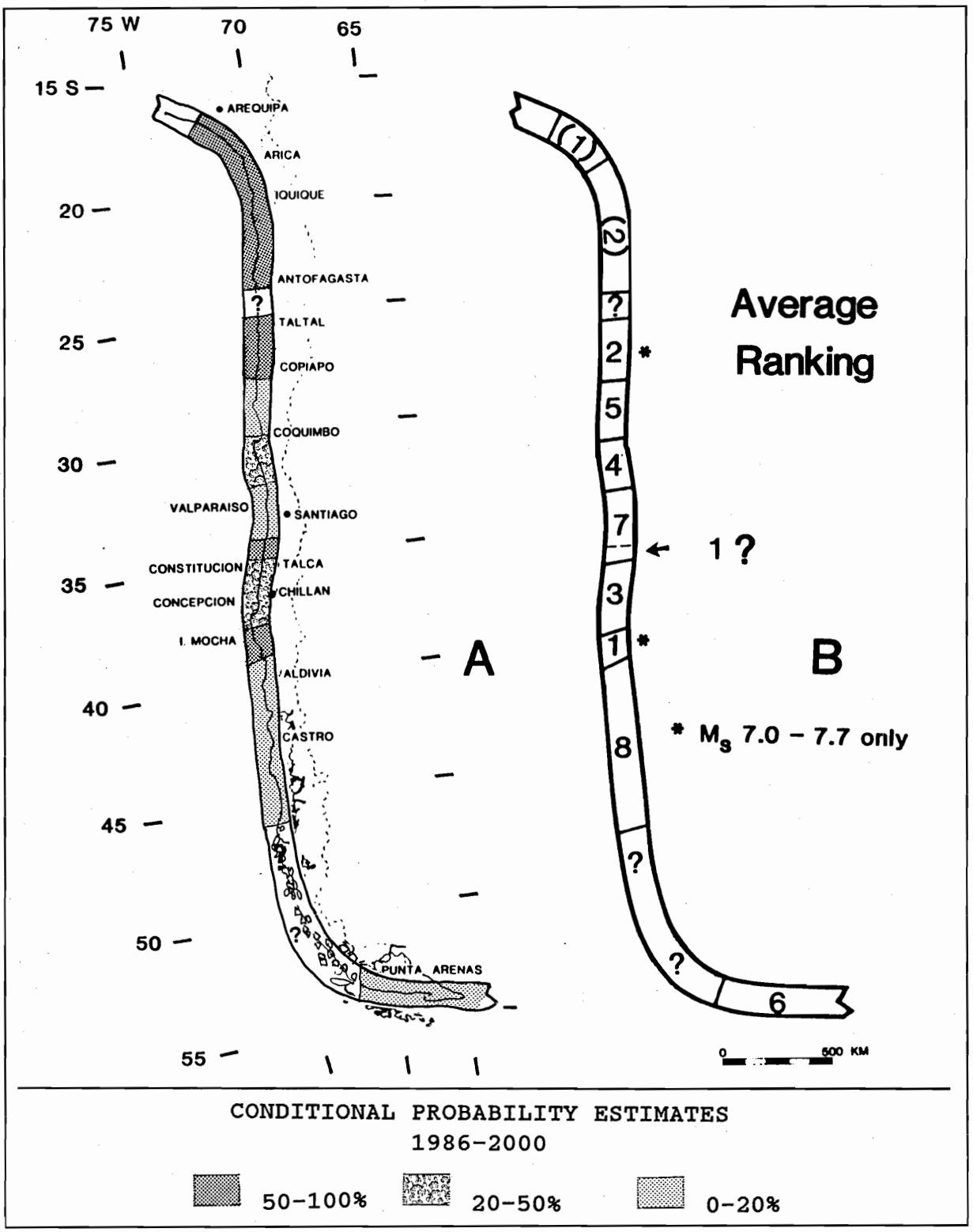
Some progress is being made in regional, long-term prediction and forecasting. "Seismic gaps" along major plate boundaries have been identified: areas with histories of prior large earthquakes (greater than 7 on the Richter scale--Ms7) and great earthquakes (Ms7.75) which have not had such an event for more than 30 years (McCann et al., 1979; Nishenko, 1985; and United Nations, 1978). Recent studies show that major earthquakes do not recur in the same place along faults until sufficient time has elapsed for stress to build up, usually a matter of several decades. In the main seismic regions, these "quiet" zones present the greatest danger of future earthquakes. Confirming the seismic gap theory, several gaps that had been identified near the coasts of Alaska, Mexico, and South America experienced large earthquakes during the past decade. Moreover, the behavior of some faults appears to be surprisingly constant: there are areas where earthquakes occur at the same place, but decades apart, and have nearly identical characteristics. Monitoring these seismic gaps, therefore, is an important component of learning more about earthquakes, predicting them, and preparing for future ones.

On the basis of the seismic gap theory, the U.S. Geological Survey has prepared maps of the coast of Chile and parts of Peru for the U.S. Agency for International Development's Office of Foreign Disaster Assistance (USAID/OFDA), adapted from a study by Stuart Nishenko (Nishenko, 1985). These maps give probability estimates and rank earthquake risk for the time period 1986 to 2006 (see Figure 11-6). USAID/OFDA has commissioned studies to produce similar information for the remainder of the Latin American Pacific coast.

It can be seen, however, that forecasting of this type only delineates relatively large areas in which an earthquake could potentially occur in a general future period of time. There have been successful earthquake predictions, but these are the exception rather than the rule. Earthquake prediction involves monitoring many aspects of the earth, including slight shifts in the ground, changes in water levels, and

Figure 11-6

RANKING OF RISK FROM SEISMIC GAPS OF THE CHILEAN SUBDUCTION ZONE



Source: Nishenko, Stuart P. "Seismic Potential for Large and Great Interplate Earthquakes Along the Chilean and Southern Peruvian Margins of South America: A Quantitative Reappraisal" in Journal of Geophysical Research, Vol. 90, No. B5 (April, 1985).

emission of gases from the earth, among other things. At this stage, it is still a young science.

One successful short-term prediction is the often-mentioned case of Haicheng, China, in February 1975, in which people were evacuated six hours before a Ms7.3 earthquake struck. The worst-hit area was around the epicenter, where about 500,000 people lived, and half the buildings were damaged or destroyed. Among the indicators the Chinese had observed were changes in water level in deep wells, increased levels of radon gas, foreshocks, and unusual behavior of animals. Unfortunately, such successful predictions are offset by failures to predict: one year later in Tangshan, China, a great earthquake reportedly killed between 500,000 and 750,000 people.

b. Seismic Risk Assessment

A seismic risk assessment is defined as the evaluation of potential economic losses, loss of function, loss of confidence, fatalities, and injuries from earthquake hazards. Given the current state of knowledge of seismic phenomena, little can be done to modify the hazard by controlling tectonic processes, but there are a variety of ways to control the risk or exposure to seismic hazards. There are four steps involved in conducting a seismic risk assessment: (1) an evaluation of earthquake hazards and prepare hazard zonation maps; (2) an inventory of elements at risk, e.g., structures and population; (3) a vulnerability assessment; and (4) determination of levels of acceptable risk.

Evaluating Earthquake Hazards and Hazard Zonation Maps

In an earthquake-prone area, information will undoubtedly exist on past earthquakes and associated seismic hazards. This can be supplemented with existing geologic and geophysical information and field observation, if necessary. Depending on geologic conditions, some combination of ground shaking, surface faulting, landslides, liquefaction, and flooding (covered in Chapter 8) may be the most serious potential earthquake-related hazards in an area. Maps should be prepared showing zones of these hazards according to their relative severity. These maps provide the planner with data on such considerations as the spatial application of building codes and the need for local landslide and flood protection. A composite map can be compiled showing the relative severity of all seismic hazards combined (see Chapter 6).

(1) Assessing Ground Shaking Potential: Even though ground shaking may cause the most widespread and destructive earthquake-related damage, it is one of the most difficult seismic hazards to predict and quantify. This is due to the amplification of the shaking effects by the unconsolidated material overlying the bedrock at a site and to the differential resistance of structures. Consequently, the ideal way to express ground shaking is in terms of the likely response of specific types of buildings. These are classified according to whether they are wood frame, single-story masonry, low-rise (3 to 5 stories), moderate-rise (6 to 15 stories), or high-rise (more than 15 stories). Each of these, in turn, can be translated into occupancy factors and generalized into land-use types.

Alternative approaches can be used for planning purposes to anticipate where ground shaking would be most severe:

- The preparation of intensity maps based on damage from past earthquakes rated according to the Modified Mercalli Index.
- The use of a design earthquake to compute intensity.
- In the absence of data for such approaches, the use of information on the causative fault, distance from the fault, and depth of soil overlying bedrock to estimate potential damage.

(2) Assessing Surface Faulting Potential: This is relatively easy to do, since surface faulting is associated with fault zones. Three factors are

QUESTIONS PLANNERS NEED TO ASK TO EVALUATE EARTHQUAKE HAZARDS

- Where have earthquakes occurred in the region?
- How often do earthquakes of a certain magnitude occur?
- What kinds of seismic hazards are associated with the earthquakes?
- How severe have the hazards been in the past? How severe can they be in the future?
- How do the hazards vary spatially and temporally?

important in determining suitable mitigation measures: probability and extent of movement during a given time period, the type of movement (normal, reverse, or slip faulting), and the distance from the fault trace in which damage is likely to occur.

In areas of active faulting, fault maps should be prepared at scales appropriate for planning purpose (about 1:50,000 in developing areas and 1:10,000 in urban areas) and kept updated as new geologic and seismic information becomes available. The extent on the areas in jeopardy along the faults should be determined, and maps should be prepared showin the degree of hazard in each of them. Measures such as land-use zonation and building restrictions should be prescribed for areas in jeopardy.

(3) Assessing Ground Failure Potential: The mapping and evaluation of landslide hazards is described in Chapter 10. This method is applicable to earthquake-induced landslides. Liquefaction potential is determined in four steps: (1) a map of recent sediments is prepared, distinguishing areas that are likely to be subject to liquefaction from those that are unlikely; (2) a map showing depth to groundwater is prepared; (3) these two maps are combined to produce a "liquefaction susceptibility" map; and (4) a "liquefaction opportunity" is prepared by combining the susceptibility map with seismic data to show the distribution of probability that liquefaction will occur in a given time period.

Inventory of Elements at Risk

The inventory of elements at risk is a determination of the spatial distribution of structures and population exposed to the seismic hazards. It includes the built environment, e.g., buildings, utility transport lines, hydraulic structures, roads, bridges, dams; natural phenomena of value such as aquifers and natural levees; and population distribution and density. Lifelines, facilities for emergency response, and other critical facilities are suitably noted.

Vulnerability Assessment

Once an inventory is available, a vulnerability assessment can be made. This will measure the susceptibility of a structure or class of structures to damage. It is difficult, if not impossible, to predict the actual damage that will occur, since this will depend on an earthquake's epicenter, size, duration, etc. The best determination can be made by evaluating the damage caused by a past earthquake with known intensity in the area of interest and relating the results to existing structures.

Assessing Risk and Its Acceptability

It is theoretically possible to combine the hazard evaluation with the determination of the vulnerability of elements at risk to arrive at an assessment of specific risk, a measure of the willingness of the public to incur costs to reduce risk. This is a difficult and expensive process, however, applicable to advanced stages of the development planning process. For any particular situation, planners and hazard experts working together may be able to devise suitable alternative procedures that will identify approximate risk and provide technical guidance to the political decisions as to what levels are acceptable and what would be acceptable costs to reduce the risk. Thus, the appropriate mitigation measures can be recommended as part of a development study. Sub-section 4, "Earthquake Hazards and the Development Planning Process," provides a more detailed discussion of where seismic risk assessment fits into the development planning process.

c. Earthquake Mitigation Measures

There is no question that earthquake damage can be reduced. The questions are what techniques or mechanisms are appropriate in a given situation and how can they be applied. The range of mechanisms includes land-use zoning; engineering approaches such as building codes, strengthening of existing structures, stabilizing unstable ground, redevelopment; the establishment of warning systems; and the distribution of losses. In keeping with this chapter's focus on hazard-related aspects of the early phases of development studies, this sub-section discusses only the land use, or nonstructural, mechanisms such as avoiding hazardous areas or restricting types and intensities of land use. See Chapter 3 for a detailed discussion of land-use evaluation and hazards.

Some of these mitigation measures are applicable to new development, some to existing development, and some to both. Consideration must be given to the administrative and political aspects of applying mitigation techniques such as obtaining community support, mobilizing local interests, and incorporating the seismic aspects into a comprehensive zoning ordinance. These issues are discussed amply in a number of publications, including those listed in the box below. The mitigation measures included in this discussion focus on the most important earthquake-related hazards--ground shaking, surface faulting, landslides, and liquefaction. Again, mitigation measures for floods induced by earthquakes are the same as for flooding induced by any other cause. These are discussed in Chapter 8.

Ground Shaking Mitigation Measures

Once the potential severity and effects of ground shaking are established as explained above, several types of seismic zoning measures can be applied. These include:

ADDITIONAL EARTHQUAKE INFORMATION

The following publications are useful sources of information on earthquakes, other geologic hazards, and their mitigation:

UNDRO. Disaster Prevention and Mitigation: Land Use Aspects (New York: United Nations, 1978).

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

U.S. Geological Survey. Proceedings of the Geologic and Hydrologic Hazards Training Program, March 5-30, 1984, Denver, Colorado, Open File Report 84-760 (Reston, Virginia: U.S. Geological Survey, 1984).

W. W. Kockelman. Examples of Use of Geologic and Seismological Information for Earthquake Hazard Reduction in Southern California. U.S. Geological Survey Open File Report 83-82 (Reston, Virginia: U.S. Geological Survey, 1983).

- Relating general ground shaking potential to allowable density of building occupancy.
- Relating building design and construction standards to the degree of ground shaking risk.
- Adopting ordinances that require geologic and seismic site investigations before development proposals can be approved.
- In areas already developed, adopting a hazardous building abatement ordinance and an ordinance to require removal of dangerous parapets.

Surface Faulting Mitigation Measures

Since fault zones are relatively easy to delineate, they lend themselves to effective land-use planning. Where assessment of the consequences of surface rupture indicates an unacceptably high possibility of damage, several alternative mitigation measures are available:

- Restricting permissible uses to those compatible with the hazard, i.e., open space and recreation areas, freeways, parking lots, cemeteries, solid-waste disposal sites, etc.
- Establishing an easement that requires a setback distance from active fault traces.
- Prohibiting all uses except utility or transportation facilities in areas of extremely high hazard, and setting tight design and construction standards for utility systems traversing active fault zones.

Ground Failure Mitigation Measures

Land-use measures to reduce potential damage due to landslides or liquefaction are similar to those taken for other geologic hazards: land uses can be restricted, geologic investigations can be required before development is allowed, and grading and foundation design can be regulated. Stability categories can be established and land uses commensurate with these categories can be recommended or ordained. Land-use zoning may not be appropriate in some areas because of the potential for substantial variation within each mapped unit, but even without mandatory use restrictions, stability categories can indicate the precautions appropriate for the use of any parcel of land.

General Land-Use Measures

Where development has already taken place in areas prone to earthquake hazards, measures can be adopted to identify unsafe structures and ordain their removal, starting with those that endanger the greatest number of lives. Tax incentives can be established for the removal of hazardous buildings, and urban renewal policies should restrict reconstruction in hazardous areas after earthquake destruction. The political acceptability of zoning measures can be increased by developing policies which combine earthquake hazards with other land-use considerations.

3. TYPES AND SOURCES OF EARTHQUAKE INFORMATION

The following categories of information are discussed below: information on the occurrence of earthquakes as hazardous geologic events;

information on the hazards or effects of earthquakes; information for assessing seismic risk and undertaking a vulnerability assessment; and substitute data in the absence of other information. This sub-section is intended to identify for the planner the kind of information that might be available, where it might be sought, what it might be used for, and, if it does not exist, what other information can be helpful.

a. Information on Earthquakes (occurrence, size, characteristic effects, relation to geologic features)

Seismic Information

This information covers the occurrence of historic earthquakes and their characteristics.

(1) Earthquake Catalogues: There are several kinds of earthquake catalogues, covering world-wide, regional, national, or more geographically restricted occurrences. Earthquake catalogues normally provide information on location, time, and size for each earthquake recorded and an estimate of the completeness of the seismic record. Of particular relevance is the catalogue published in December 1985 by CERESIS, which includes entries for all earthquakes recorded in South America since 1900 and historical earthquakes dating back 400 years. This catalogue is accompanied by two maps: Seismicity (epicenters) and Large Earthquakes of South America (1520-1981).

(2) Maps Showing Damage Caused by Earthquakes; Maps of Notable or Historic Earthquakes: The U.S. Geological Survey has published such maps for South America and Middle America. The National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce has published a world map of significant earthquakes between 1900 and 1979. National maps are also available for some countries.

(3) Epicenter Maps, Data on Hypocenters (Earthquake Foci), Maps and Data on Earthquake Magnitude and Peak Horizontal Ground Acceleration, and Earthquake Recurrence Data: Seismicity information is available from a variety of sources such as CERESIS, national geologic surveys, national agencies of disaster preparedness, USAID/OFDA, and the United Nations Disaster Relief Coordinator (UNDRO).

Seismotectonic Information

This information covers indicators of seismic activity.

(1) Continental and Subregional Seismotectonic Maps: Geologic maps showing seismic indicators such as faults, volcanoes, hot springs and uplifted or down-dropped tectonic blocks are available from hemispheric, regional, and national geologic information sources. In 1985 CERESIS published a Neotectonic Map of South America at a scale of 1:5,000,000, and each of the participating countries produced similar national maps at a scale of 1:2,000,000. For planners, this map is particularly useful for delimiting areas prone to volcanic eruptions. (See Section C of this chapter, "Volcanic Eruptions.") A seismicity map of Middle America is also available.

(2) Seismic Provinces and Source Zones; Macrozonation Maps: Some large countries or those having markedly differentiated geology may be regionalized according to seismic hazard. The principal function of these maps is to distinguish areas with relatively minor hazard from those having a great hazard which requires mitigation. Argentina, for example, is divided into eleven seismotectonic provinces. One advantage of such information is that it permits the setting of priorities for subsequent assessment work. In Argentina the most seismically active provinces were studied to determine the nature and degree of specific seismic hazards in preparation for undertaking mitigation activities. Information on seismic provinces and source zones is available through national disaster mitigation agencies.

(3) Geologic and Geophysical Information: A wide range of geologic information is applicable to the determination of seismic hazard, including surface and subsurface geology (age and rock type), structural geology, stratigraphy, and tectonics. The mapping of quaternary sedimentary geology is useful for determining the liquefaction potential. Fault mapping can be used to approximate seismic parameters in lieu of other data. Geologic information is available from national, state, or urban municipal governments, universities, and private oil, mineral, and engineering firms.

High-resolution seismic reflecting surveys, gravity maps, magnetic maps, and seismic refraction surveys are useful in supplementing or substituting for geologic information in the delineation of seismotectonic features. In addition, information concerning "gaps" in active fault zones provides one of the most widely used means of forecasting earthquakes. National geologic survey agencies are sources of geophysical information, as are mineral and oil exploration companies and repositories of satellite imagery. See Chapter 4 for information on where to obtain satellite imagery.

b. Information on Seismic Hazards

This information covers maps and data on the effects of earthquakes.

Ground Shaking

(1) Intensity and Magnitude Data: The available information includes maps of maximum seismic intensities, intensity observations and maps of intensity distribution, and calculations of the magnitude's upper bound. Mapped data can range in scale from 1:5,000,000 maps suitable for delineating seismic provinces to large scale maps of 1:5,000 suitable for detailed land-use planning for seismic hazards.

In 1985 CERESIS published a Maximum Intensities Map of South America showing the geographic distribution of Modified Mercalli Index units. (See the discussion below on "Earthquake Hazards and the Development Planning Process.") Again, the continental map scale is 1:5,000,000, and the national map scale is 1:2,000,000. Peak ground acceleration can be used as a measure of the severity of ground motion. Maps showing intensity distribution can be constructed by using mathematical models and by plotting historical data.

(2) Seismic Attenuation Data: These include isoseismal maps (maps showing equal-intensity contours) of significant historic earthquakes and strong-motion accelerogram records when available. Since detailed strong-motion data are frequently not available, an interpretation of intensity distribution on isoseismal maps may be used as a substitute.

(3) Site Response Data: There are two general types of site response data: (1) observations of the effects of past earthquakes which correlate the total ground shaking (acceleration in the bedrock plus amplification effects) with the damage caused at a site; and (2) response spectra obtained from accelerogram data or theoretical calculations.

Ground Failure: Landslides and Liquefaction

(1) Continental Map: CERESIS published a map of potential landsliding and liquefaction in South America at a scale of 1:10,000,000 in 1985.

(2) Other Landslide Hazard Information: National maps of the occurrence of landslides and liquefaction at a scale of 1:2,000,000 have been produced by the South American countries under the coordination of CERESIS. Maps or reports on the potential for landslides at the local level are found in some urban areas that have a high potential for the hazard. In the absence of such data, slope maps and geology maps, together with information on soils, topography, vegetation, rainfall regime, groundwater level, and present land use can be used to estimate the landslide hazard. Chapter 10 describes the method to use for this purpose.

(3) Other Liquefaction Information: Liquefaction hazard maps can most commonly be found at the disaster preparedness agency of urban municipal governments. In the absence of such information, the liquefaction hazard can be estimated using maps of Holocene or Quaternary geology or other depictions of recent sediment deposition and maps of groundwater depth.

Other Data

Geologic, seismotectonic, and geophysical data can be used to evaluate the potential for surface faulting. Bathymetric data can be used to estimate tsunami runup in coastal areas and, together with offshore geologic information, provide insights into the potential for subaqueous landslides caused by earthquakes.

c. Information on Seismic Risk and Vulnerability

This information covers maps, records, reports, and data useful for making a seismic risk or hazard assessment and vulnerability analysis.

(1) Seismic Microzonation Maps: These large-scale maps delineate areas according to their seismic risk potential and are useful for estimating the population and property at risk and designating the land uses and earthquake-resistant structural designs appropriate for each land unit. Such maps are only rarely available, usually for metropolitan areas having a history of seismic events. Information for estimating lives and property at risk can be derived from census and land-use data.

(2) Instrumental Site Response Records: These provide information on how the bedrock and soil cover will influence seismic waves at a site. This information is necessary for determining suitable design parameters.

(3) Geotechnic Properties of Materials at Shallow Depth and Earthquake Damage Assessment Reports: In the absence of more definitive information on the seismic hazard of a site, this type of information can be used to make a rough evaluation of the hazard.

(4) Building Codes and Regulations: These legal statutes, which relate seismic hazard mitigation requirements to the degree of exposure to seismic hazards and type of construction, are normally prepared at the city, county, or provincial level, but national guidelines are often available as well.

d. Data Substitution

As was said above, when the necessary information is not available, an approximation can

often be made by interpretation from information that is available. Here are some examples: Maximum intensity can be estimated for sites from data on earthquake magnitude in specific areas. Magnitude or intensity can be estimated from the length of the causative fault, and peak ground acceleration can be estimated from the magnitude and distance from the causative fault. Duration of shaking can be correlated with magnitude (Hays, 1980).

4. EARTHQUAKE HAZARDS AND THE DEVELOPMENT PLANNING PROCESS

a. Preliminary Mission

In the Preliminary Mission of a development planning study, the planner wants to know if earthquakes pose enough of a great threat in all or part of the study area to warrant consideration in development planning. If it can be established that they do not, the planner can move on to other issues. See Figure 11-7 for a diagram of the relationship between development planning and the assessment of earthquake hazards.

Two kinds of information are needed to evaluate an earthquake threat: (1) the potential severity of an earthquake; and (2) the likelihood of a damaging earthquake during the timeframe of a project or planning application. While both are necessary for a full evaluation, one or the other may not exist for a given location, in which case a partial evaluation can be made with the information available.

Potential severity is usually defined historically; that is, the largest earthquake determined to have occurred in an area is taken as the maximum that is likely to occur there again. The severity of an earthquake can be measured in terms of intensity by the Modified Mercalli Index (MMI) or in terms of magnitude by the Richter Scale (see Figure 11-2 and the discussion of earthquake severity in sub-section B.1 above). In the figures below, MMI is used for South America and Middle America (Mexico to Panama) and Ms (surface-wave magnitude) for the Caribbean. MMI of VI or greater and Ms of 4 or greater are taken to indicate significant threat.

The likelihood of occurrence is measured in terms of conditional probability or seismic potential. Conditional probability is an estimate, expressed as a percentage, of how likely it is that a large or great earthquake will occur within a specified time period. In the following tables and maps, data generated by

PRELIMINARY MISSION (STUDY DESIGN)

QUESTIONS PLANNERS NEED TO ASK:

- Is there a history of significant earthquakes (Modified Mercalli Index of VI or greater or magnitude of 4 or greater) in the study area?
- In what part of the study area did they, or are they likely to, occur? Is there a significant population or infrastructure at risk?
- What is the likelihood of such a quake occurring during the timeframe of the development project (50-100 years)?
- What hazards are associated with these earthquakes: ground shaking, surface rupture, liquefaction, landslides, other?
- If earthquakes pose a threat in all or part of the study area, is there a national agency or institution that is responsible for data collection, monitoring, hazard mitigation, disaster planning?

KEY DECISIONS TO BE MADE AT THIS STAGE:

- Earthquakes are (or are not) a significant threat in the study area, and therefore consideration of earthquake hazards should (or should not) be included in the development planning process.
- If the information available is insufficient for making a recommendation on the above decision in the Preliminary Mission, Phase I should include a data collection effort designed to permit such a recommendation.
- If earthquake hazards are found to constitute a significant threat in the study area, mitigation efforts should be built into the study design.

Figure 11-7

RELATIONSHIP OF DEVELOPMENT PLANNING STAGES TO EARTHQUAKE-RELATED HAZARD ASSESSMENT

(Showing Direct and Indirect Sources of Information)

Integrated Regional Development Planning Stage	Hazard Assessment Activity
Preliminary Mission	Determination of Earthquake Potential (probability of occurrence of damaging earthquake) **Direct:** Seismic zones; Maximum intensity; Magnitude; Peak ground acceleration **Indirect:** Seismotectonics; Seismicity; Epicenters
Phase I Natural Resources Evaluation, Strategy Formulation, Project Identification	Specific Hazard Evaluation and Zoning **Ground Shaking/Surface Faulting — Direct:** Maximum intensity; Magnitude; Damage reports **Ground Shaking/Surface Faulting — Indirect:** Fault length **Landslides — Direct:** Landslide hazard map **Landslides — Indirect:** Bedrock geology; Interpretive soils; Slope; Hydrology **Liquefaction — Direct:** Liquefaction map **Liquefaction — Indirect:** Holocene sedimentary geology; Depth to ground water
Phase II Project Formulation, Action Plan Preparation	Multiple Hazards Zoning, Land Use Zoning, Building Codes Information Requirements for the Evaluation of Ground Shaking, Surface Faulting, and Ground Failure Seismic geology Seismological evaluation Maximum magnitude/Intensity recurrence Strong motion data Attenuation relationships Bedrock, soil, groundwater, topography Site response data Elements at risk
Implementation	Engineering Studies Building and grading regulations, retrofitting, redevelopment: not treated in this chapter

Stuart Nishenko of the U.S. Geological Survey are used for South and Middle America. William McCann of the University of Puerto Rico defines seismic potential as the likelihood of occurrence of a large or great earthquake in the near future and provides values for the Caribbean on a scale of 1 (high potential) to 6 (low potential).

The information presented below will usually be sufficient to guide a planner in answering the questions and arriving at decisions for the preliminary mission indicated in the box above.

South America

The best source of information for determining the seismic threat of an area is a seismic zone map, available for several South American countries such as Argentina, Peru, and Venezuela. The planner can locate the study area on such a map and use the seismic hazard ratings indicated. When a seismic zone map is unavailable, the CERESIS Map of Maximum Intensities covering all of South America can be used. More detail can be obtained from the national maps of maximum intensities available for individual South American countries. Figure 11-8 shows the geographic distribution of the historical occurrence of maximum intensities of VI or greater by political subdivision in South America. The figure also indicates the occurrence of soil liquefaction and significant landslides, although there may be other areas prone to landslides or liquefaction not shown on the table. Figure 11-9 shows by province and department the conditional probabilities of an

PRELIMINARY MISSION:
PROCEDURE FOR INITIAL SEISMIC HAZARD ASSESSMENT IN LATIN AMERICA AND THE CARIBBEAN

INITIAL REVIEW

- For French Guiana, Paraguay, and Suriname: seismic hazards are not a significant threat.
- For Brazil and Uruguay: GO TO NOTE 1.
- For Barbados, St. Vincent and the Grenadines, and Trinidad and Tobago: GO TO NOTE 2.
- For Argentina, Bolivia, Chile, Colombia, Ecuador,Guyana, Peru, Venezuela; and
- Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama; and
- Antigua and Barbuda, Cuba, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Puerto Rico, St. Barts, Saint Eustatius, Saint Lucia, the Virgin Islands: GO TO STEP 1.

NOTE 1 - In Uruguay, seismic hazards constitute a minor threat in the Department of Artigas. In Brazil, they constitute a minor threat in the states of Bahia, Ceará, Minas Gerais, Rio Grande do Norte, Santa Catarina, and São Paulo (see Figure 11-8). Elsewhere in these countries they are not considered a significant threat. They do not require study in the Preliminary Mission or in Phase I, but consideration of seismic hazards should be incorporated into the Project Formulation and Implementation phases of specific projects.

NOTE 2 - For these countries there is no record of large shocks (they are considered to have a relatively low potential for a large or great earthquake). There is no information on estimated maximum magnitude (see Figure 11-17). Earthquakes probably do not constitute a major threat.

STEP 1 - Determine if the study area is included in areas of MMI of VI or greater or of magnitude of 4 or greater on the maps and tables presented below. If not, earthquakes do not pose a significant hazard in the study area. If yes, go to Step 2.

STEP 2 - Incorporate seismic hazards in phases I and II of the planning study. Include suitable mitigation measures commensurate with historic maximum intensity. Conduct studies of specific seismic hazards, initiate earthquake zoning, modify building codes to incorporate seismic considerations, and recommend emergency preparedness actions. (Before undertaking these actions, go to Step 3.)

STEP 3 - Determine probability of a large or great earthquake occurring in the near future (see Figures 11-9, 11-11, 11-14 and 11-17). If the area has a high probability of a large earthquake in the near future, the actions described in Step 2 should be undertaken with greater urgency.

Figure 11-8

GEOGRAPHIC DISTRIBUTION OF MAXIMUM EARTHQUAKE INTENSITIES, SOIL LIQUEFACTION, AND SIGNIFICANT LANDSLIDES IN SOUTH AMERICA

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X	XI	A – Soil Liquefaction B – Significant Landslide
ARGENTINA							
Province							
Catamarca	x	x					
Chaco	x						
Chubut	x						
Córdoba	x	x		L			
Corrientes	x						
Entre Ríos	x						
Jujuy	x	x	x				A, B
La Rioja	x	x	x	L			B
Mendoza	x	x	x	x			A, B
Neuquen	x	x					
Río Negro	x						
Salta	x	x	x	x			A, B
San Juan		x	x	x			A, B
San Luis	x	x	x				
Santa Cruz	x						
Santiago del Estero	x						
Tierra de Fuego	x						
Tucumán	x		L				

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X	XI	A – Soil Liquefaction B – Significant Landslide
BOLIVIA							
Department							
Cochabamba	x	x					B
Chuquisaca	x	x	x				A, B
La Paz	x	x	x				B
Oruro	x	x					
Pando							
Potosí	x	x	x				B
Santa Cruz	x	x					A
Tarija	x	x	x	x			
BRASIL							
State							
Bahía	L	L					
Ceará	x	L					
Minas Gerais	L	L					
Rio Grande do Norte	L						
Santa Catarina	x						
São Paulo	L						

Legend:

x = Contour value covering all or part of the area.

L = Observed localized intensity greater than the contour values.

Figure 11-8 (continued)

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X	XI	A – Soil Liquefaction B – Significant Landslide
CHILE							
Province							
Aisén	x						
Aconcagua		x	x	x	x		
Antofagasta	x	x	x				
Arauco			x				A, B
Atacama	x	x	x	x	L		
Bio Bio	x	x	x				
Cautín	x	x	x				A, B
Chiloé	x	x	x				
Colchagua	x	x	x				
Concepción			x	x			
Coquimbo		x	x	x			
Curicó	x	x	x				
Linares	x	x	x	x			
Llanquihue	x	x	x			L	A, B
Magallanes	x	x					
Malleco	x	x	x		L		
Maule			x	x	L		
Ñuble	x	x	x	x	L		
O'Higgins	x	x	x				
Osorno	x	x	x				B
Santiago		x	x	x	L		B
Talca	x	x	x	x			
Tarapacá		x	x	x			B
Valdivia	x	x	x		L		A, B
Valparaíso			x	x	x	L	
COLOMBIA							
Department							
Antioquia	x	x	x	L			A, B
Arauca	x	x	x				
Atlántico	x	x					
Bolívar	x	x	x				
Boyacá	x	x	x				
Caldas			x	x			B
Caquetá	x	x	x				B
Cauca	x	x	x	x	x		B
Chocó		x	x	x			A, B
Córdoba	x	x	x				

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X	XI	A – Soil Liquefaction B – Significant Landslide
COLOMBIA (continued)							
Cundinamarca		x	x	x			B
Guajira	x	x	x				
Huila		x	x	x	x		A, B
Magdalena	x	x	x				B
Meta	x	x	x	x			B
Nariño		x	x	x	x		B
Norte de Santander		x	x	x	x		B
Putumayo	x	x					B
Santander	x	x	x	x			B
Tolima		x	x	x			
Valle del Cauca		x	x	x			
Vaupes	x						
Vichada	x						
ECUADOR							
Province							
Azuay		x	x				
Bolívar			x	x			B
Cañar		x					
Carchi		x	x	x			
Chimborazo			x	x	x	L	A, B
Cotopaxi		x	x	x	x	L	
El Oro			x				
Esmeraldas		x	x	x	x		B
Guayas		x	x	x			
Imbabura		x	x	x			A, B
Los Rios		x	x				
Loja	x	x	x				
Manabí			x	x			
Morona Santiago	x	x	x				
Napo	x	x	x				B
Pastaza	x	x					
Pichincha		x	x	x	L		
Tungurahua		x	x	x	x	L	B
Zamora-Chinchipe		x	x				

Figure 11-8 (continued)

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X	XI	A - Soil Liquefaction B - Significant Landslide
GUYANA		x	x				
PERU							
Department							
Amazonas	x	x	x	x			B
Ancash	x	x	x	x		L	A, B
Apurimac		x	x				
Arequipa		x	x	x	x	L	A, B
Ayacucho	x	x	x	x			B
Cajamarca	x	x		L			B
Cuzco	x	x	x	x			A
Huancavelica	x	x	x				B
Huánuco	x	x	x				
Ica		x	x	x	L		A
Junín	x	x	x	x	L	L	
La Libertad	x	x	x	x			
Lambayeque	x	x	x				
Lima	x	x	x	x	L	L	A
Loreto	x	x	x	x	x		
Madre de Dios	x	x					
Moquegua		x	x	x		L	
Pasco	x	x	x	L			
Piura		x	x	x			A
Puno	x	x	x				
San Martín	x	x	x	x	x		A
Tacna		x	x	x			
Tumbes			x	x			A, B

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X	XI	A - Soil Liquefaction B - Significant Landslide
URUGUAY							
Department							
Artigas	x						
VENEZUELA							
State							
Delta Amacuro	x	x	x	x			A
Amazonas	x						
Apure	x	x	x				
Aragua		x	x	x			A
Anzoátegui	x	x	x	x			B
Barinas		x	x	x			
Bolívar	x	x	x				
Carabobo		x	x				A
Cojedes		x	x				B
Distrito Federal				x	L		B
Falcón		x	x				B
Guarico	x	x	x				
Lara				x	x		B
Mérida				x	L		A, B
Miranda			x	x	x		A, B
Monagas			x	x			A
Portuguesa		x	x	x			B
Sucre				x	L		A, B
Táchira			x	x	x		B
Trujillo			x	x			A, B
Yaracuy			x	x			A
Zulia		x	x	x			A, B

Source: Adapted from Regional Seismological Center for South America (CERESIS). Maximum Intensity Map of South America (Santiago, Chile: CERESIS, 1985); and Regional Seismological Center for South America. Map of Soil Liquifaction and Landslides Associated with Earthquakes in South America (CERESIS, 1985).

Figure 11-9

MAXIMUM SEISMIC INTENSITY AND CONDITIONAL PROBABILITY OF OCCURRENCE OF A LARGE OR GREAT EARTHQUAKE FOR COASTAL LOCATIONS IN SOUTH AMERICA

Location	Maximum Likely Seismic Intensity	Conditional Probability[a] 1989-1994 (%)	1989-1999 (%)	1989-2009 (%)
COLOMBIA				
Department				
Cauca	X	≤1	≤1	≤1
Chocó	IX	?	?	?
Nariño				
North	X	≤1	≤1	≤1
South	X	8	19	6
Valle	IX	≤1	≤1	≤1
CHILE				
Province				
Aconcagua	X	≤1	≤1	≤1
Aisén				
North	VI	≤1	≤1	≤1
South	VI	?	?	?
Antofagasta				
North	VIII	(10)	(20)	(39)
South	VIII	≤1	≤1	15
Arauco	VIII	1	3	12
Atacama				
North	IX	≤1	≤1	15
South	IX	2	4	10
Cautín	VIII	1	3	12
Chiloé	VIII			
Colchagua				
North	VIII	≤1	≤1	≤1
South	VIII	17	33	59
Concepción	IX	1	3	12
Coquimbo				
North	IX	2	4	10
South	IX	11	24	49
Curicó	VIII	≤17	≤33	≤59
Llanquihue	VIII	≤1	≤1	≤1
Magallanes				
North	VII	?	?	?
South	VII	4	11	29
Maule	IX	1	3	12
Ñuble	IX	1	3	12
Osorno	VIII	≤1	≤1	≤1
Santiago	IX	≤1	≤1	≤1
Talca	IX	1	3	12
Tarapacá	IX	10	20	39

Figure 11-9 (continued)

Location	Maximum Likely Seismic Intensity	Conditional Probability 1989-1994 (%)	1989-1999 (%)	1989-2009 (%)
CHILE (Cont.)				
Valdivia				
North	VIII	1	3	2
South	VIII	≤1	≤1	≤1
Valparaíso	X	≤1	≤1	≤1
ECUADOR				
Province				
El Oro	VIII	?	?	?
Esmeraldas	X	(41)	(66)	(90)
Guayas	IX	?	?	?
Manabí				
North	IX	(41)	(66)	(90)
South	IX	?	?	?
PERU				
Department				
Ancash				
North	IX	?	?	?
South	IX	≤1-3	≤1-8	1-24
Arequipa				
North	X	(≤1)	(≤1)	(≤1)
Central	X	6	13	29
South	X	(≤1-12)	(≤1-23)	(≤1-43)
Ica				
North	IX	(14)	(27)	(47)
South	IX	(≤1)	(≤1)	(≤1)
La Libertad	IX	?	?	?
Lambayeque	VIII	?	?	?
Lima				
North	IX	≤1-3	≤1-8	1-24
South	IX	≤1	≤1	≤1
Moquegua	IX	(≤1-12)	(≤1-23)	(≤1-43)
Piura	VIII	?	?	?
Tacna				
North	IX	(≤1-12)	(≤1-23)	(≤1-43)
South	IX	4	11	29
Tumbes	IX	?	?	?

a/ Conditional probability refers to earthquakes caused by inter-plate movement.

? No information available.

( ) All values in parenthesis represent less reliable estimates.

Source: Adapted from Regional Seismological Center for South America (CERESIS). Maximum Intensity Map of South America (Santiago, Chile: CERESIS, 1985), and Nishenko, S.P. Summary of Circum-Pacific Probability Estimates (unpublished table) (Golden, Colorado: U.S. Geological Survey, 1989).

earthquake occurring in the next 5, 10, or 20 years and the maximum likely intensity of such a shock.

Middle America

Information for seismic hazard evaluation of Mexico includes published data on the Pacific Coast subduction zone and mapped data on maximum acceleration and maximum velocity of earthquake waves expected in 50-year, 100-year, and 500-year periods, available from the Instituto de Ingeniería of the Universidad Nacional Autónoma de México. For unpublished information planners should contact the Instituto de Geofísica and the Instituto de Ingeniería, Universidad Nacional Autónoma de México; the U.S. Geological Survey; the Institute for Geophysics at the University of California, Santa Cruz; or the Lamont Dougherty Geological Observatory in Palisades, New York.

Figure 11-10 presents the conditional probability of a large or great earthquake between 1986 and 1996 along the 13 segments of the Mexican Subduction Zone (Nishenko and Singh, 1987). The data on these segments are summarized in Figure 11-11.

New maps and reports by Randall White and Stuart Nishenko, both of the U.S. Geological Survey, on seismic hazards in Central America became available in 1988 and 1989. Figure 11-12 is a map of the region showing MMI values recorded historically and carefully analyzed by White. Figure 11-13 shows the occurrence by province and department of MMI of VI or greater for Belize, Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua (information on Panama is still limited). Figure 11-14 shows conditional probability and MMI by province and department.

Caribbean

Information for estimating seismic hazards of the Caribbean Basin is available from William McCann from the Department of Geology of the University of Puerto Rico. Figure 11-15, a map of seismic potential in the Caribbean region, rates potential in terms of the length of time since the last large earthquake (McCann, 1987). The map is a composite of two earlier ones: the 1982 Seismic Potential Map, which covers the whole basin, and the 1983 Seismic Potential Map, covering the area from Dominica to the eastern portion of the Dominican Republic.

Long-term seismic activity expressed in terms of magnitude is shown in Figure 11-16 from a 1984 map which covers the same area as the 1983 map. This map is close to the "model sources" map needed by engineers to estimate ground shaking (McCann, 1985). Combining data from two maps, Figure 11-17 categorizes the Caribbean countries in terms of their seismic potential (likelihood of experiencing a large earthquake) and long-term seismic activity (likely maximum size of an earthquake).

McCann, who has written extensively on Eastern Caribbean seismology, emphasizes:

> The eastern margin of the Caribbean from Trinidad to Puerto Rico has the potential for large earthquakes. The northern Lesser Antilles is in the category of highest seismic potential. This region appears ripe for a major earthquake. While this estimate may have an error of 25 years or more, it does indicate the strong likelihood of a great earthquake before the turn of the century in the northern Lesser Antilles (McCann, unpublished paper).

This is obviously a consideration that planners should bear in mind.

b. Phase I: Development Diagnosis

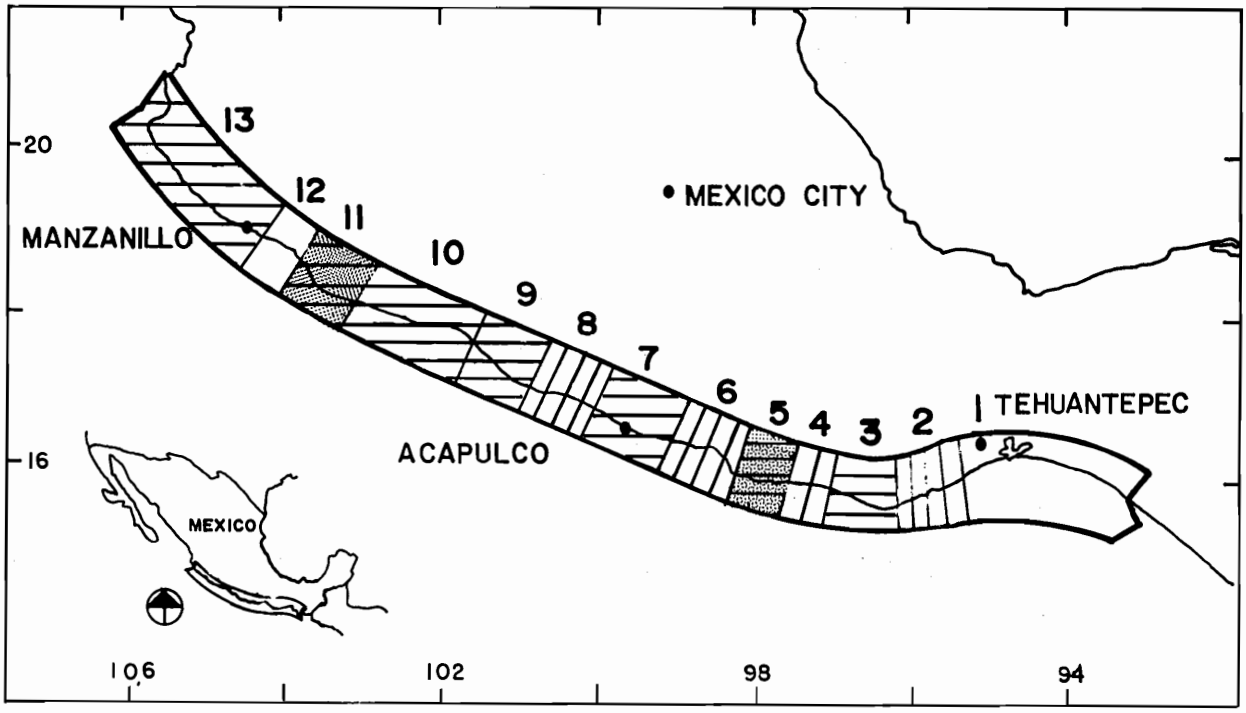
This phase of a planning study requires the diagnosis of a region, including spatial and natural resource stet. Further evaluation of earthquake-prone areas and areas where the data are insufficient for evaluating the seismic threat depends on the type of development programmed for the area and resource allocation considerations for subsequent studies. Parallel to the hazard studies, the planning study team may subdivide the study area into present and near-future use-intensity zones, and hazard studies should proceed in selected zones according to the judgment of the planner. Recommended mapping scales for this work are 1:250,000 to 1:50,000.

The evaluation and zoning of specific seismic hazards is conducted as an element of the natural resource evaluation in the selected areas. The hazards can be grouped as follows: ground shaking/fault rupture, landslides, and liquefaction. Since it has already been established that the selected areas are earthquake-prone, seismic data such as intensity and magnitude, strong motion, attenuation, site response, fault movement, and damage reports of past earthquakes are likely to be available, as are data on landslides and/or liquefaction. At this point a substantial effort in the collection of existing data is justified.

If the existing data on seismic hazards are inadequate, the use of some substitute data can provide adequate information for this stage of

Figure 11-10

CONDITIONAL PROBABILITY ESTIMATES ALONG THE MEXICAN SUBDUCTION ZONE



Legend:

- No historic record of large or great earthquakes
- Conditional probability = 0 - 10 %
- Conditional probability = 11 - 25 %
- Conditional probability = 26 - %

Map view of the conditional probability of the occurrence of a large or great earthquake in 13 segments of the Mexican Subduction Zone for the time interval 1986-1996. Probabilities are based on estimates of the expected recurrence time using either historically observed data or recurrence behavior extrapolated from other segments. Segmentation into separate source zones is based on the lateral extent of the last large or great earthquake in each segment.

Source: Adapted from Nishenko, S.P., and Singh, S.K. "Conditional Probabilities for the Recurrence of Large and Great Interplate Earthquakes Along the Mexican Subduction Zone," submitted to the Bulletin of the Seismological Society of America (1987).

Figure 11-11

CONDITIONAL PROBABILITY OF A LARGE OR GREAT EARTHQUAKE ALONG THE MEXICAN SUBDUCTION ZONE[a]

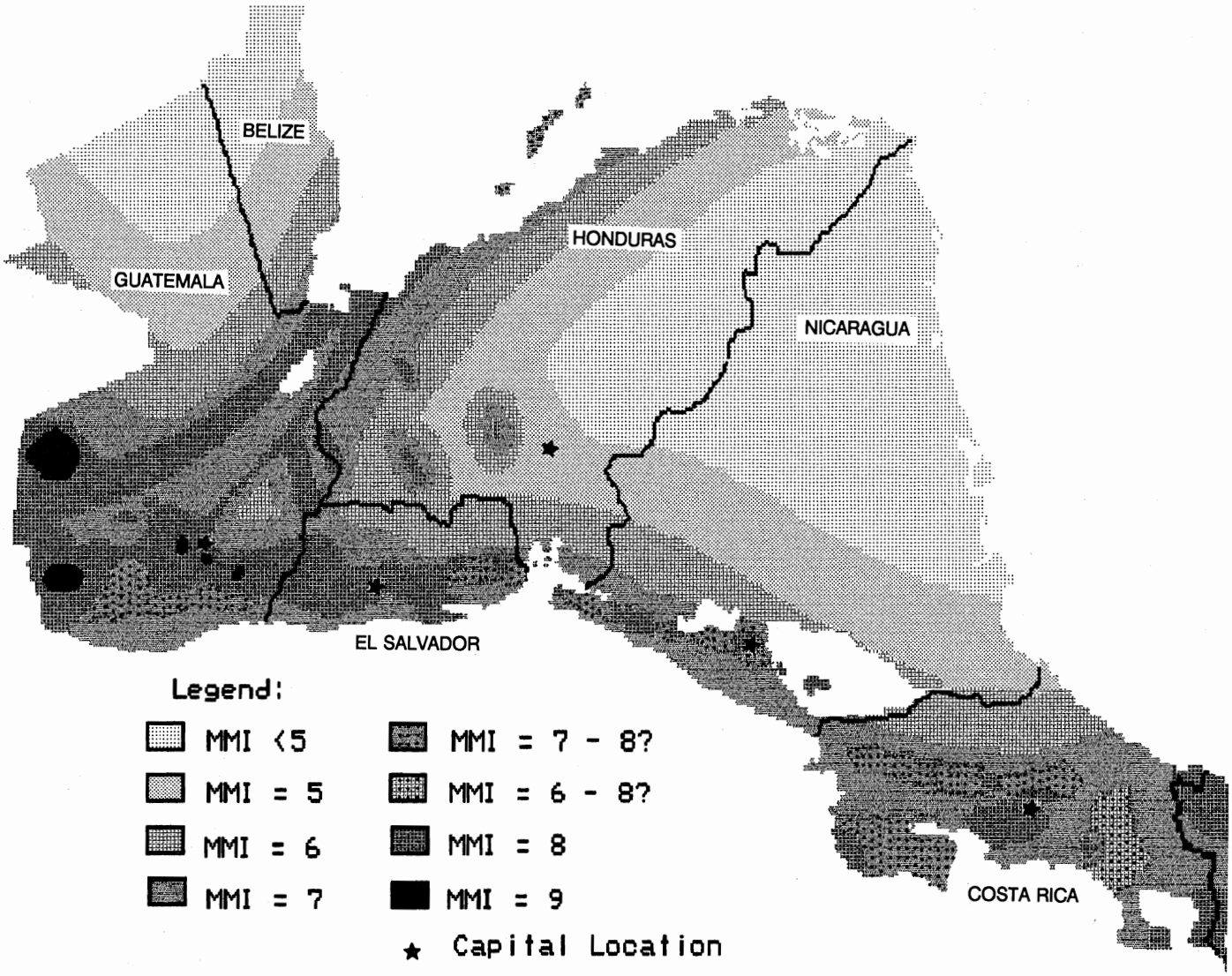
Segment Number	Region	Longitude	Date of Last Event	Magnitude	Forecast Window[c]	Conditional Probability: 5 year-Interval 1989-1994 (%)	Conditional Probability: 10 year-Interval[b] 1989-1999 (%)	Conditional Probability: 20 year-Interval 1989-2009 (%)
1.	Tehuantepec	94°-95.2°W	d/					
2.	East Oaxaca	95.2°-96.4°W	1965	7.8	1991-2026	15	35	70
3.	Central Oaxaca	96.4°-97.3°W	1978	7.8	2013-2060	<1	<1	2
4.	Central Oaxaca	97.3°-97.7°W	1928	7.8	(1990-2032)	(25)	(45)	(72)
5.	West Oaxaca	97.7°-98.2°W	1968	7.4	1994-2025	6	21	64
6.	Ometepec	98.2°-99.3°W	1950	7.3	1990-2030	26	47	74
7.	Acapulco	99.3°-100°W	1957	7.7	1994-2042	5	13	40
8.	Guerrero	100°-101°W	1899-1911	7.8	(1990-2068)	(16)	(30)	(52)
9.	Petatlan	101°-101.8°W	1979	7.6	2001-2038	<1	3	29
10.	Michoacan	101.5°-103°W	1985	8.1	2029-2106	<1	<1	<1
11.	Colima	103°-103.7°W	1973	7.5	1993-2025	8	25	66
12.	"	103.7°-104.5°W	d/					
13.	Jalisco	104.3°-105.7°W	1932	8.2	1992-2129	1-9	2-18	7-39

a/ All values in parenthesis reflect less reliable estimates.
b/ Forecast window represents the 90% confidence level about the expected recurrence time, and is conditional upon the event not having occurred by 1989.
c/ Interval shown on Figure 11-10.
d/ No historic record of large or great shocks.

Source: Nishenko, S.P. Circum Pacific Seismic Potential 1989-1999. U.S. Geological Survey, Open File Report 89-86 (Golden, Colorado: U.S.Geological Survey, 1989).

Figure 11-12

MAXIMUM SEISMIC INTENSITIES IN CENTRAL AMERICA



Source: Based on White, Randall A. Maximum Earthquake Intensities in Central America (draft map) (Menlo Park, California: U.S. Geological Survey, 1988).

Figure 11-13

GEOGRAPHIC DISTRIBUTION OF MAXIMUM EARTHQUAKE INTENSITIES IN CENTRAL AMERICA

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X
BELIZE					
District					
Stann Creek	x				
Toledo	x	x			
COSTA RICA					
Province					
Alajuela	x	x	x		
Cartago		x	x		
Guanacaste		x	x		
Heredia	x	x	x		
Limón	x	x	x		
Puntarenas	x	x	x		
San José	x	x	x		
EL SALVADOR					
Department					
Ahuachapán		x	x		
Cabañas	x	x			
Chalatenango	x	x			
Cuscatlán	x	x			
La Libertad		x	x		
La Paz		x	x		
La Unión	x	x	x		
Morazán		x	x		
San Miguel	x	x	x		
San Salvador	x	x	x		

Location	Maximum Earthquake Intensity VI	VII	VIII	IX	X
EL SALVADOR (Cont.)					
Department					
San Vicente		x	x		
Santa Ana	x	x	x		
Sonsonate		x	x		
Usulatán		x	x		
GUATEMALA					
Department					
Alta Verapaz	x	x	x		
Baja Verapaz		x	x		
Chimaltenango		x	x		
Chiquimula		x	x		
El Petén	x				
El Progreso	x	x	x		
El Quiché	x	x	x		
Escuintla		x	x		
Guatemala		x	x	x	
Huehuetenango		x	x	x	
Izabal		x	x		
Jalapa	x	x			
Jutiapa		x	x		
Quezaltenango		x	x	x	
Retalhuleu		x	x		
Sacatepéquez			x		
San Marcos			x	x	
Santa Rosa		x	x	x	
Sololá		x	x		
Suchitepéquez		x	x		
Totonicapán		x	x		
Zacapa		x	x		

Figure 11-13 (continued)

Location	Maximum Earthquake Intensity				
	VI	VII	VIII	IX	X
HONDURAS					
Department					
Atlántida	x	x	x		
Choluteca	x	x			
Colón	x	x			
Comayagua	x	x	x		
Copán	x	x	x		
Cortes	x	x	x		
Distrito Central	x				
El Paraíso	x				
Fco. Morazán	x				
Gracias a Dios	x				
Intibuca	x	x	x		
La Paz	x				
Lempira	x	x	x		
Ocotepeque	x	x	x		
Olancho	x				
Santa Barbara	x	x	x		
Valle	x	x			
Yoro	x				

Location	Maximum Earthquake Intensity				
	VI	VII	VIII	IX	X
NICARAGUA					
Department					
Boaco	x				
Carazo		x			
Chinandega	x	x	x		
Chontales	x				
Granada		x	x		
León	x	x	x		
Managua	x	x	x		
Masaya		x	x		
Matagalpa	x				
Río San Juan	x				
Rivas		x			

Source: Adapted from White, R.A. Maximum Earthquake Intensities in Central America (unpublished map). (Menlo Park, California: U.S. Geological Survey, 1988).

Figure 11-14

MAXIMUM SEISMIC INTENSITY AND CONDITIONAL PROBABILITY OF OCCURRENCE OF A LARGE OR GREAT EARTHQUAKE FOR SELECTED LOCATIONS IN CENTRAL AMERICA

Location	Maximum Likely Seismic Intensity	Conditional Probability[a/] 1989-1994 (%)	1989-1999 (%)	1989-2009 (%)
COSTA RICA				
Province				
Alajuela				
West	VIII	9	43	93
Central and East	VIII	≤1-3	≤1-8	4-25
Guanacaste				
West	VIII	16	31	55
East	VIII	9	43	93
Heredia (West)	VIII	≤1	≤1	≤4
Puntarenas				
North	VIII	3-9	8-43	25-93
Central	VIII	≤1	≤1	≤4
San José (West)	VIII	≤1	≤1	≤4
EL SALVADOR				
Department				
Ahuachapán	VIII	29	51	79
Cabañas	VII	≤1	≤1	≤1
Cuscatlán	VII	29	51	79
La Libertad	VIII	29	51	79
La Paz				
West	VIII	29	51	79
East	VIII	≤1	≤1	≤1
San Miguel (West)	VIII	≤1	≤1	≤1
San Salvador	VIII	29	51	79
San Vicente	VIII	≤1	≤1	≤1
Santa Ana	VIII	29	51	79
Sonsonate	VIII	29	51	79
Usulatán	VIII	≤1	≤1	≤1
GUATEMALA				
Department				
Alta Verapaz	VIII	(4)	(8)	(15)
Baja Verapaz	VIII	(4)	(8)	(15)
Chimaltenango	VIII	10	23	50
Chiquimula	VIII	29	51	79
El Progreso	VIII	29	51	79
Escuintla	VIII	10	23	50
Guatemala	X	10-29	23-51	50-79

Figure 11-14 (continued)

Location	Maximum Likely Seismic Intensity	Conditional Probability 1989-1994 (%)	1989-1999 (%)	1989-2009 (%)
GUATEMALA (Cont.)				
Department				
Huehuetenango				
East	X	(4)	(8)	(15)
West	X	5	13	34
Izabal				
East	VIII	≤1	≤1	≤1
West	VIII	(4)	(8)	(15)
Jalapa	VII	29	51	79
Jutiapa	VIII	29	51	79
Quezaltenango	IX	5	13	34
Quiché	VIII	(4)	(8)	(15)
Retalhuleu	VIII	5	13	34
Sacatepéquez	VIII	10	23	50
San Marcos	IX	5	13	34
Santa Rosa	IX	10-29	23-51	50-79
Sololá	VIII	10	23	50
Suchitepéquez	VIII	10	23	50
Totonicapán	VIII	10	23	50
Zacapa	VIII	(4)	(8)	(15)
HONDURAS				
Department				
Comayagua	VIII	?	?	?
Copán				
East	VII	≤1	≤1	≤1
West	VIII	(4)	(8)	(15)
Intibuca	VIII	?	?	?
Lempira	VIII	?	?	?
Ocotepeque				
East	VII	≤1	≤1	≤1
West	VIII	(4)	(8)	(15)
Santa Barbara (West)	VIII	≤1	≤1	≤1
NICARAGUA	VIII	?	?	?

a/ Conditional probability refers largely to earthquakes caused by inter-plate movement.

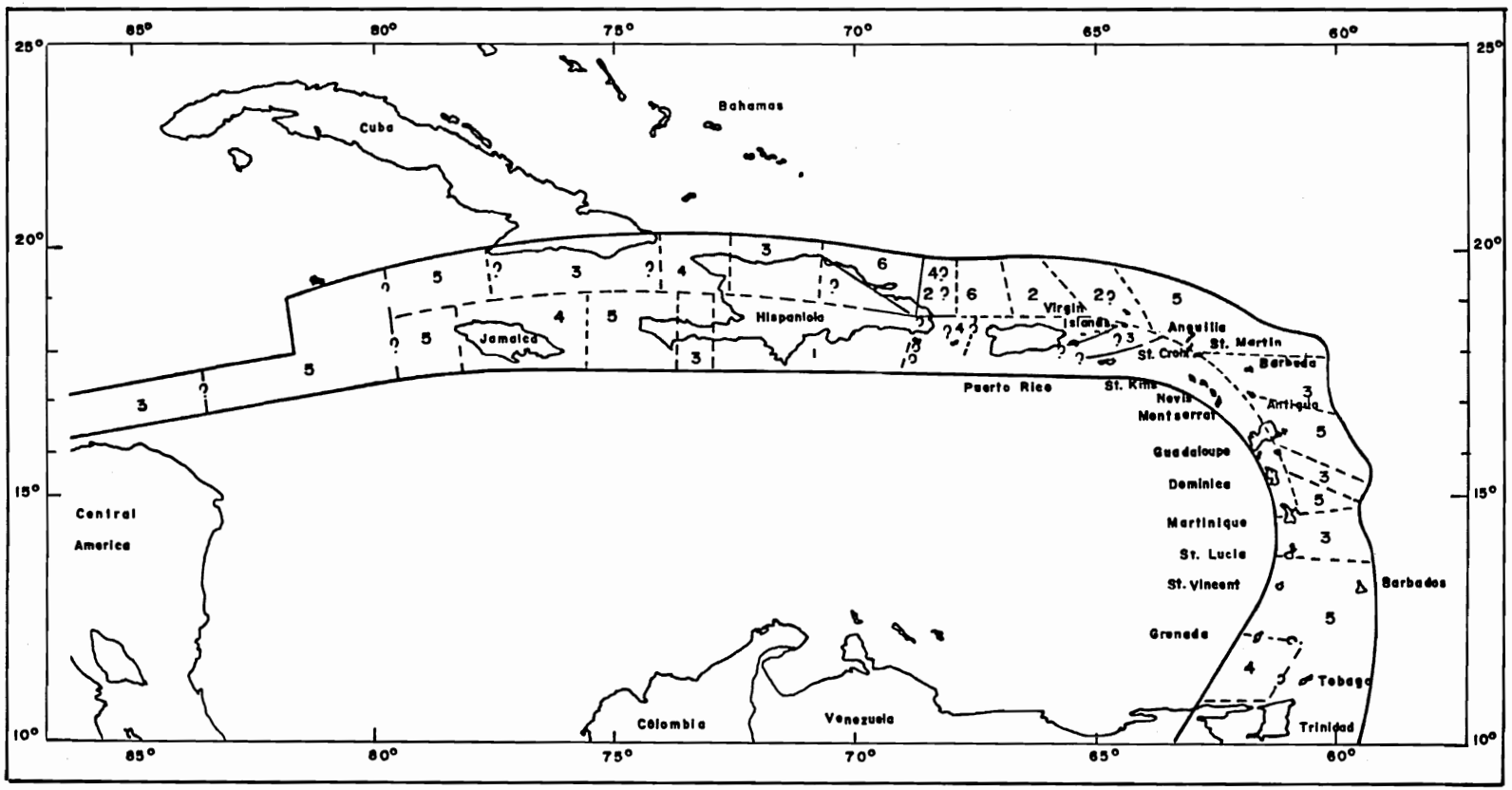
? No information available.

( ) All values in parentheses represent less reliable estimates.

Source: Adapted from White, R.A. Maximum Earthquake Intensities in Central America (unpublished map) (Menlo Park, California: U.S. Geological Survey, 1988), and Nishenko, S.P. Summary of Circum-Pacific Probability Estimates (unpublished table) (Golden, Colorado: U.S. Geological Survey, 1989).

Figure 11-15

SEISMIC POTENTIAL IN THE CARIBBEAN REGION: POTENTIAL FOR OCCURRENCE OF A LARGE EARTHQUAKE



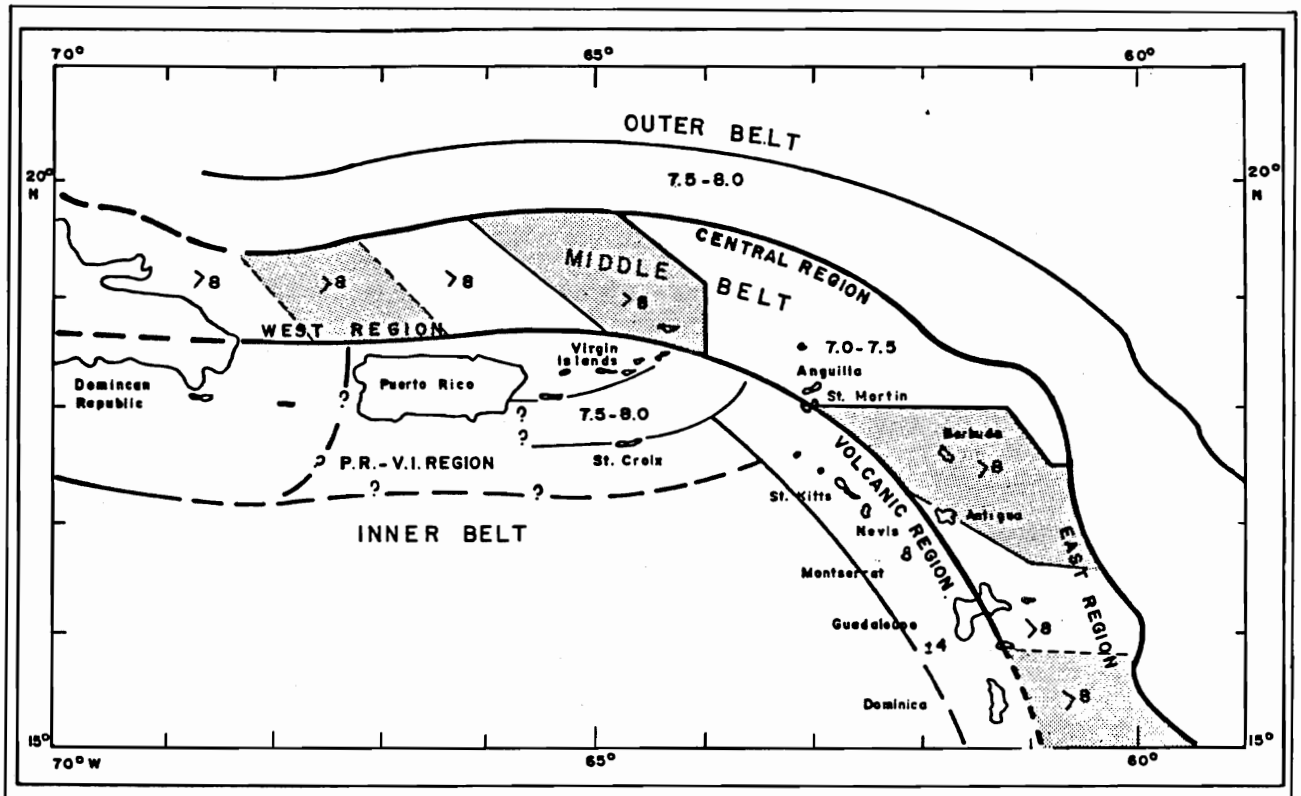
SYMBOL	SEISMIC POTENTIAL	YEARS SINCE LAST EARTHQUAKE
1	HIGH	≥ 200
2	MODERATELY HIGH	150 - 200
3	MODERATE	100 - 150
4	MODERATELY LOW	50 - 100
5	UNKNOWN	No record of large shocks
6	LOW	< 50

500 400 300 200 100 0 500 1000 Km

Source: McCann, William R. "On the Earthquake Hazards of Puerto Rico and the Virgin Islands" in Bulletin of the Seismological Society of America, Vol. 75, No. 1. (February 1985): pp.251-262.

Figure 11-16

LONG-TERM SEISMIC ACTIVITY IN THE CARIBBEAN REGION: ESTIMATED MAXIMUM MAGNITUDE



SYMBOL	SEISMIC BELT AND REGION	EARTHQUAKE SOURCE	ESTIMATED MAXIMUM MAGNITUDE	COMMENT
	OUTER BELT	Tectonic	7.5 - 8.0	
	MIDDLE BELT	Tectonic		
	Central Region	Tectonic	7.0-7.5	
	East and West Regions	Tectonic	> 8	
	"Hot Spot"	Tectonic	> 8	Smaller shocks (6-7Ms) occur more frequently than in rest of belt.
	INNER BELT			
	Southern region	Volcanic	Low (±4)	Unpredictable occurrence due to nature of source. Can cause great damage due to shallow hypocenters.
	Puerto Rico - Virgin Islands	Tectonic	V.I: P.R: Variable	Puerto Rico out of but surrounded by source regions. Damage depends on distance from source.
	Western region	Tectonic	?	Little information

100 0 100 200 300 400 Km

Source: McCann, William R. "On the Earthquake Hazards of Puerto Rico and the Virgin Islands" in Bulletin of the Seismological Society of America, Vol. 75, No. 1. (February 1985): pp.251-262.

Figure 11-17

SEISMIC HAZARD IN THE CARIBBEAN REGION

Country or Area	Seismic Potential[a/] (Likelihood of occurrence of a large earthquake in the near future)	Estimated Maximum Magnitude (Ms)
Anguilla	5	7 - 7.5
Antigua	3	>8
Barbados	5	NA
Barbuda	3	>8
Cuba:		
Extreme south	3	NA
Remainder	NA	NA
Dominica	3	>8
Dominican Republic	1, 3, 6	>8
Grenada	4	NA
Guadeloupe[b/]	3, ?	>8, ±4
Haiti	1, 3, 4, 5	NA
Jamaica	4	NA
Martinique	3, 5	NA
Montserrat[c/]	?	±4
Puerto Rico and Virgin Islands[d/]	2	8 - 8.25
St. Barts	3	>8
St. Eustatius[c/]	?	±4
St. Kitts and Nevis	?	±4
Saint Lucia	3	NA
St. Martin	5	7 - 7.5
St. Vincent and the Grenadines	5	NA
Trinidad and Tobago	5	NA

a/ Potential for Large or Great Earthquake
- 1 High potential; large earthquake more than 200 years ago
- 2 Moderately high potential; large earthquake 150-200 years ago
- 3 Moderate potential; large earthquake 100-150 years ago
- 4 Moderately low potential; large earthquake 50-100 years ago
- 5 No record of large shocks
- 6 Low potential; large earthquake less than 50 years ago

b/ Volcanic source in part of area: seismic potential unpredictable; maximum magnitude low but intensity high

c/ Volcanic source: seismic potential unpredictable; maximum magnitude low but intensity high

d/ Numerous seismic sources possible

? Indeterminate

NA Not available

Source: McCann, W.R. "On the Earthquake Hazards of Puerto Rico and the Virgin Islands" in Bulletin of the Seismological Society of America, vol. 75, no. 1 (February 1985), pp. 251-262.

evaluations. See the discussion on data substitution in the preceding sub-section, and Chapter 10 for a discussion of the factors associated with landslide activity. An indication of the susceptibility to liquefaction can be estimated from data on Holocene sedimentary geology and depth to groundwater.

The result of the work up to this point will enable a determination to be made of which hazards constitute a significant threat. For those that do, a rough zonation map (see Chapter 6) should be prepared; an appropriate scale is 1:50,000. This hazard zonation map is an important part of the overall regional diagnosis and constitutes a valuable element for strategy formulation and the identification of specific action proposals. It gives an idea of where intensive development is appropriate, which areas should be left relatively undeveloped, what precautions will be necessary where the development of hazardous areas is deemed necessary or unavoidable, and where mitigation is necessary in already developed areas.

c. Phase II: Development Strategy and Project Formulation

The analysis of the hazard information in conjunction with other elements of the regional development study at this point results in project actions and priorities which in turn create new demands for hazard information. This can include undertaking vulnerability studies which, together with the hazard zoning, can be used to produce earthquake risk maps for each hazard individually or the combination of hazards.

These maps can then be combined with maps of other hazards, e.g., flooding, to produce multiple hazard maps, and the hazard maps can be combined with maps of present and potential land use to produce land-use zoning maps. They serve to guide future development and provide the spatial units to which the elements of a building code can be addressed. At this stage, detailed data are required, including characteristics of bedrock and overlying soil, site-specific intensity, acceleration data, site response data, damage reports of previous earthquakes affecting the area. Appropriate scales are 1:50,000 to 1:10,000. See Chapter 6 for a further detailed discussion.

d. Project Implementation

Finally, projects are studied at the final design stage and are implemented. Parallel hazard activities such as the preparation of building and grading regulations, the retrofitting of existing structures to make them more earthquake-resistant, and the redevelopment of damaged areas are beyond the scope of this chapter.

C. Volcanic Eruptions

Even though ash from very large volcanic eruptions such as Krakatoa, in what is now Indonesia, can encircle the earth in a matter of a few days and may affect sunsets for years afterwards, serious damage is restricted to small areas compared with the extent of damage from large floods or great earthquakes. Yet volcanic eruptions can take a high toll in human life and property. There are reasons for this seeming contradiction.

The decomposition of most volcanic materials yields rich agricultural soils--particularly significant in tropical areas where other soils tend to be low in nutrient content--and to use them farmers are willing to risk the hazard of a new eruption. Furthermore, the densest rural population in Latin America and some of the largest cities are located in the Andean range and its extension into Mesoamerica along the zone of contemporary volcanism. Finally, many of the volcanoes in the small islands of the Caribbean are still very active. Three of the world's most catastrophic eruptions took place on Guadeloupe, Martinique, and St. Vincent, where there is not much room to hide. The seriousness of volcanic hazards in Latin America and the Caribbean is documented in Figures 11-18 and 11-19. Nearly 60,000 lives have been lost and 250,000 severely affected by eruptions during this century. In the past 10,000 years, 250 volcanoes in Latin America and the Caribbean have erupted nearly 1,300 times.

Since it is impossible to prevent the use of areas subject to volcanism, it becomes imperative to determine which of them are susceptible to particular hazards, to plan their development appropriately, and to establish systems of monitoring, warning and evacuation.

The restricted geographic distribution of volcanic eruptions makes it easier to mitigate their detrimental effects. Throughout Latin America and the Caribbean, only areas that have experienced eruptions since the Pliocene Epoch are subject to significant danger. These areas are indicated in Figure 11-20 by the location of active volcanoes in Latin America and the Caribbean.

Volcanic eruptions range from gentle outpourings of lava to violent explosions. The difference is determined largely by the viscosity of the magma, or molten rock, and its content of dissolved gas. Fluid magmas, rich in iron and magnesium, tend to allow the volcanic gases to escape and often reach the surface in the form of quiet lava flows. More viscous magmas, rich in silica, tend to trap the volcanic gases, resulting in a build-up of pressure, and thus have a greater propensity to violent eruptions. The ejecta of volcanic

Figure 11-18

SUMMARY OF IMPACTS OF RECENT VOLCANIC ERUPTIONS IN LATIN AMERICA AND THE CARIBBEAN

Date	Volcano, Country	Description
1985	Ruiz, Colombia	23,000 death toll caused by lahar (mudflow) through town of Armero.
1985	El Chichón, Mexico	Most of the 153 deaths resulted from roof collapse and fires ignited by incandescent tephra.
1979	Soufriere, St. Vincent	Evacuation of 20,000 people for a month.
1963-1965	Irazu, Costa Rica	Tephra fall forced the 230,000 inhabitants of San Jose to wear goggles, bandannas or even gas masks almost every day for months. Lahar (mudflow) 12m thick in places.
1961	Calbuco, Chile	Explosive eruption, phreatic explosion, lava flows, and mudflow resulted in destruction of extensive agricultural land.
1902	Soufriere, St. Vincent	Pyroclastic flow killed 1680 (77 km^2 impacted by pyroclastics).
1902	Mt. Pelee, Martinique	28,000 deaths caused by pyroclastic gases and mudflows; 58 km^2 destroyed.
1902	Santa María, Guatemala	About 40% of the more than 5,000 deaths resulted from collapsing house roofs under the weight of tephra. The town of Quezaltenango, 15 km from volcano, was destroyed. Eruption lasted 18 hours.

Source: Modified from Krumpe, P.F. Briefing Document on Volcanic Hazard Mitigation (Washington, D.C.: USAID/Office of Foreign Disaster Assistance, March 11, 1986).

explosions include blobs of molten lava, which solidify quickly to form glass, and solid fragments ranging from fine ash to house-size boulders. The nature of volcanic hazards is determined by the material ejected by an eruption and the force with which it is ejected.

1. VOLCANIC HAZARDS

Volcanic hazards include tephra falls and ballistic projectiles, pyroclastic phenomena (flows, surges, and laterally directed blasts), lahars (or mudflows), lava flows, hazards associated with lava domes, phreatic explosions, and emissions of poisonous or corrosive gases. Summary information on the characteristics, warning periods, and effects of these hazards can be found in Figures 11-21 and 11-22.

a. Tephra Falls and Ballistic Projectiles

Tephra includes all sizes of rock fragments and lava blobs ejected into the atmosphere by the force of

Figure 11-19

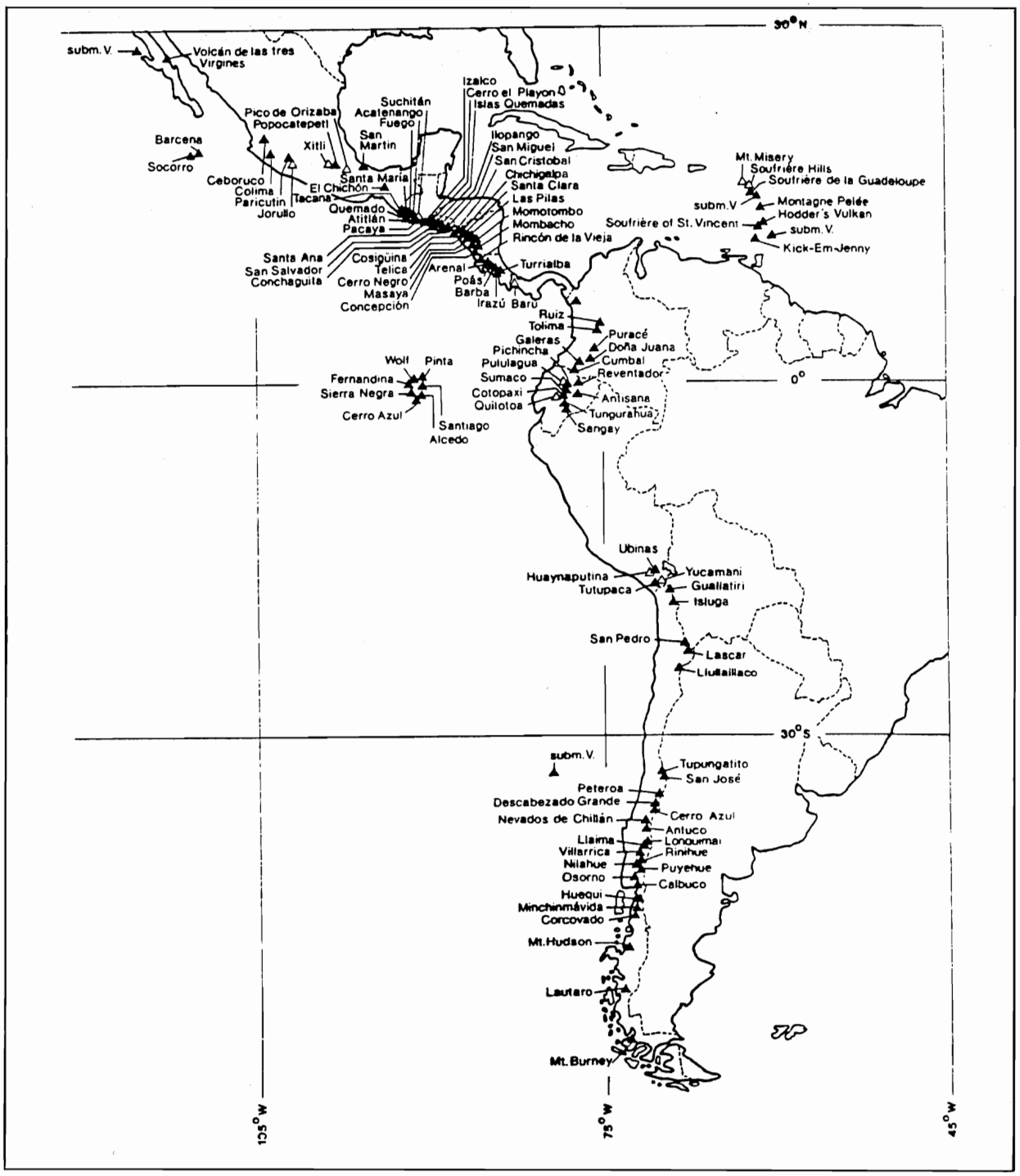
NUMBER OF VOLCANOES, ERUPTIONS, AND INCIDENTS OF VOLCANIC ERUPTIONS CAUSING SIGNIFICANT DAMAGE IN LATIN AMERICA AND THE CARIBBEAN DURING THE LAST 10,000 YEARS

Country	Number of Volcanoes	Number of Eruptions	Number of Eruptions Causing:			
			Fatalities	Agricultural Land Destruction	Mudslides	Tsunamis
Mexico	30	88		4	1	
Guatemala	24	120	5	10	3	
El Salvador	19	119	3	17		
Nicaragua	22	94		9	1	
Costa Rica	11	66	2	5	2	
Honduras	2	2				
Panama	1	3		2		
Colombia	13	62	4	4	3	
Ecuador	10	82	5	14	29	
Galápagos	13	61				
Peru	10	38	1	4	1	
Bolivia	15	15				
Chile	62	271	5	12	13	1
Argentina	3	3				
West Indies:						
Saba	1	1				
St.Eustatius	1	1				
St.Kitts and Nevis	2	4				
Montserrat	1	1				
Guadaloupe	1	10			2	
Dominique	4	4				
Martinique	1	24	1	2	3	
Saint Lucia	1	1				
St.Vincent	1	210	1	3	5	
Grenada	2	2				
	---	---				
	250	1282				

Source: Compiled from Simkin, T. et al. Volcanoes of the World (Stroudsburg, Hutchinson Ross Publishing Company, 1981): pp. 89-103.

Figure 11-20

LOCATION OF ACTIVE VOLCANOES IN LATIN AMERICA AND THE CARIBBEAN



Source: Krumpe, P.F. Briefing Document on Volcanic Hazards Mitigation (Washington, D.C.: USAID/Office of Foreign Disaster Assistance, 1988).

Figure 11-21

SUMMARY ESTIMATES OF THE PHYSICAL PROPERTIES OF SELECTED VOLCANIC HAZARDS

Hazard	Distances at Which Effects Experienced: Average (km^2)	Distances at Which Effects Experienced: Maximum (km^2)	Area Affected: Average (km^2)	Area Affected: Maximum (km^2)	Velocity: Average (ms^{-1})	Velocity: Maximum (ms^{-1})	Temperature (°C)
Tephra falls	20-30	800+	100	100,000+	15	30	Usually ambient air
Ballistic projectiles	2	15	10	80	50-10	100	1000
Pyroclastic flows and debris avalanches	10	100	5-20	10,000	20-30	100	600-7000
Lahars	10	300	5-20	200-300	3-10	30+	100
Lava flows	3-4	100+	2	1,000+	5	30	750-1150
Acid rains and gases	20-30	2,000+	100	20,000	15	30	ambient air
Airshock waves	10-15	800+	1,000	100,000+	300	500	ambient air
Lightning	10	100+	300	3,000	$12x10^5$	$12x10^5$	Above ignition point

Source: Modified from Blong, R.H. Volcanic Hazards (Sydney, Australia: Macquarie University Academic Press, 1984).

Figure 11-22

WARNING PERIODS AND LIKELY EFFECTS OF SELECTED VOLCANIC HAZARDS

Hazard	Warning Period	Capacity to Cause Severe Damage	Likelihood of Severe Injury or Death
Tephra falls	Minutes to hours	Minor-moderate	Low-moderate
Ballistic projectiles	Seconds	Extreme	Very high
Pyroclastic flows and debris avalanches	Seconds	Extreme	Extreme
Lahars	Minutes to hours	Very high	Very high
Lava flows	Usually hours or days	Extreme	Very high
Acid rains and gases	Minutes to hours	Very low	Usually very low
Airshock waves	Seconds to minutes	Minor	Very low
Lightning	None	Moderate	Very high

Source: Modified from Blong, R.H. Volcanic Hazards (Sydney, Australia: Macquarie University Academic Press, 1984).

an eruption which accumulate to form deposits as the airborne materials fall back to earth. Eruptions associated with major tephra falls can have main eruptive phases lasting from an hour to two or three days. The eruptions may occur as single events separated by long quiet intervals or as multiple events closely spaced in time over a period of months or years. Tephra deposits consist of variable proportions of low-density material (pumice and scoria) and high-density rock fragments with particle sizes ranging from ash (2mm) to blocks and bombs (up to several meters in diameter). These larger fragments, hurled with great force from the volcano, are considered ballistic projectiles.

Tephra can cause casualties or property damage by the impact of falling fragments, by forming a layer covering the ground, by producing a suspension of fine-grained particles in the air, and by heat close to the volcano. The greater the thickness and coarseness of the deposit, the more detrimental the effects.

Large bombs can fly as far as 15km from the vent. Small bombs and lapilli (rock fragments ranging in size up to 64mm) can be carried as far as 80km from the eruption. Ash may be deposited to a depth of 10cm as far as 30km from the eruption and to much greater depths closer by. Accumulation of tephra can cause buildings to collapse, break power lines, and kill vegetation. Deposits only a few centimeters thick can disrupt vehicular traffic. The addition of moisture worsens these effects. Suspended tephra in the air can cause serious respiratory problems, damage machinery, especially internal combustion engines, short-circuit electrical transmission equipment, and disrupt air, rail, and highway transportation. Fragments falling as far as 10km from the vent may still be hot enough to start fires.

b. Pyroclastic Phenomena

Pyroclastic Flows

Pyroclastic flows are masses of hot, dry pyroclastic material and hot gases that move rapidly along the ground surface. The term includes a range of volcanic phenomena known as pumice flow, ash flow, block-and-ash flow, nuee ardente, and glowing avalanches. Pyroclastic flows consist of two parts: a basal flow, which is the pyroclastic flow proper, and an overriding turbulent ash cloud that includes both hot pyroclastic surges and towering columns of ash. Basal flows are dense mixtures of ash, gas, and volcanic rock whose movement is controlled by gravity. They therefore tend to move along topographic depressions. Maximum temperatures of pyroclastic flows soon after deposition range from about 350°C to 700°C. Pyroclastic flows are common throughout the world, ranging in area from less than 1km^2 to more than 10,000km^2. The dangers associated with pyroclastic flows include asphyxiation, burial, incineration, and impact injury and damage.

Pyroclastic Surges

Pyroclastic surges are turbulent, low-density clouds of gases and rock debris that move above the ground surface at high speed. They are generally associated with pyroclastic flows, but because of their greater mobility they affect broader areas. Pyroclastic surges pose all the dangers of pyroclastic flows plus those of noxious gases and high-velocity clouds. Their great mobility makes escape impossible once they have formed. Zones of potential pyroclastic surge inundation should be evacuated at the start of an eruption that may be accompanied by such an event.

Laterally Directed Blasts

Laterally directed blasts are among the most destructive of volcanic hazards. They occur within a period of a few minutes, without warning, and can affect hundreds of square kilometers. Within areas affected by such blasts, virtually all life can be expected to be extinguished and all structures destroyed. Volcanic explosions can project material upward or at any other angle. Laterally directed blasts have an important low-angle component which contributes to their destructiveness.

Rock fragments may be ejected out of a blast site on ballistic trajectories, as pyroclastic flows or surges, or in some combination. Whatever the transport mechanism, the debris is carried at speeds that greatly exceed those expected from simple gravitational acceleration. At Mt. St. Helens, the blast cloud had an initial velocity of about 600km/hr, slowing to about 100km/hr at 25km from the volcano. The deposited material may be cold or may be hot enough to start fires.

c. Lahars and Floods

A lahar (or mudflow) is a flowing slurry of volcanic debris and water that originates on a volcano. The eruption of a snow-covered volcano can melt enough snow to cause a lahar. Similarly, an eruption in a crater lake can cause a flood which becomes a lahar as it entrains rock and eroded earth from the slopes of the volcano. Lahars in which at least 50 percent of the particulate matter is the size of sand or smaller are called mud flows, while those with a lower content of fine particles are called debris flows (see Figures 11-4 and 11-5).

Lahars can be produced in several ways: a sudden draining of a crater lake by an explosive eruption or the collapse of a crater wall, the melting of

snow or ice by the deposition of hot rock debris or lava, the mixing of a pyroclastic flow with water, the avalanching of water-saturated rock debris from a volcano, the fall of torrential rain on unconsolidated fragmental deposits, or the collapse of dams formed by lava flows (Crandall, 1984). A lahar was the principal cause of death in the 1985 eruption of the Nevado del Ruiz in Colombia.

The distance reached by a lahar depends on its volume, water content, and gradient, and may be as much as 300km. By incorporating additional sources of water, such as a reservoir in the case of Colombia, it can greatly augment its speed and length. The Ruiz lahar averaged 30km/hr for 90km. The shape and gradient of a valley will also affect lahar length: a steep narrow valley will permit a lahar of a given volume to move a greater distance.

Lahars sometimes reach astonishing speeds. One from a Japanese volcano had a velocity of 180km/hr. A lahar initiated by the eruption of Cotopaxi Volcano in Ecuador had an average speed of 27km/hr over a distance of 300km.

With their high-bulk density and velocity, lahars can destroy structures in their path such as bridges, bury towns and crops, and fill stream channels, thus decreasing their capacity to carry water. This can result in flooding as the water overflows the smaller channel or in the formations of dams by volcanic debris that back up the water and increase the potential for flash flooding.

d. Lava Flows and Domes

Fluid lava forms long thin flows on slopes and flat-topped lava lakes in flat areas and topographic depressions, while viscous lava forms short stubby flows on slopes and steep-sided domes around their vents. In either case lava flows seldom threaten human life because they move slowly and their path can be predicted. The distances they reach are determined by their volume and viscosity and by the local topography. Basalt flows may reach distances of a few hundred kilometers from their sources, but more viscous lava such as andesite rarely extends more than 20km. Lava flows can cause extensive damage by burning, crushing, or burying everything in their path.

A volcanic dome is formed when lava extruded from a vent is too viscous to flow more than a few tens or hundreds of meters so that movement is principally upwards towards the center of the dome. The sides become unstable and avalanches may form, which can be triggered by volcanic explosions or by the growth of the dome itself. Explosions may result in pyroclastic flows, which are the main source of damage associated with the development of domes.

e. Other Hazards

Phreatic explosions occur when magma heats groundwater to the point that it forms steam and blasts through the overlying rock or sediment. Volcanic gases may carry toxic elements that can kill humans and animals and acids that can harm vegetation and corrode metal. Nearly 3,000 deaths were attributed to the release of poisonous gas or carbon dioxide in the August 1986 eruption in the Cameroons. Indirect hazards include volcanic earthquakes, tsunamis, ground deformation, structural collapse due to the withdrawal of magma, airshock waves, and lightning.

2. CLASSIFICATION, ASSESSMENT, MAPPING, AND MITIGATION OF VOLCANIC HAZARDS

Understanding the nature of volcanoes and the hazards they present can lead to development-related mitigation. This sub-section discusses in general terms the classification of volcanoes by frequency of eruption, the assessment of volcanic hazards, the preparation of a hazard zonation map, and the focus of mitigation. Their relationship to the development planning process follows.

a. Classification of Volcanic Hazards

At the outset it is necessary to consider the periodicity of eruptions. The Sourcebook for Volcanic Hazards Zonation published by UNESCO distinguishes between short-term and long-term hazards. A short-term hazard is defined as a volcano that erupts more than once a century--people can expect to experience an eruption in their lifetime. Long-term hazards have a periodicity of more than 100 years (Crandall, 1984).

In this primer, the definitions are modified as follows: a short-term hazard is defined as having a periodicity of 100 years or less and/or as having erupted since 1800; a long-term hazard has a periodicity of more than 100 years and has not erupted since 1800. An additional category is also proposed: imminent hazard signifies volcanoes for which reliable geologic evidence indicates an eruption can be expected within a year or two.

b. Volcanic Hazards and Risk Assessment

An evaluation of the likelihood that a given volcano will erupt in a particular timeframe and an estimation of the severity of such an eruption is based on historic and prehistoric information and on the behavior of similar volcanoes elsewhere in the world. If data from the historic and prehistoric records are adequate, then the frequency of past eruptions can be determined and the possible frequency of future eruptions can be

estimated. This assumes that the future behavior of a volcano will reflect its history over the past few thousand years. The behavior of similar volcanoes elsewhere can provide an indication of events of low probability but great magnitude that could take place.

The volcanic hazard assessment involves establishing a stratigraphic record of the products of past eruptions and determining the aerial extent of deposits, their origin in the stratigraphic sequence, and the date of the eruptions. To accomplish this, information that exists in the historic record usually must be supplemented with field analysis.

Implicit in establishing the stratigraphic record is classifying the volcano type in terms of morphology and eruption characteristics[2/] and determining the rock types of the volcanic deposits, both of which are indicators of the propensity for violent explosions. Once the stratigraphic sequence is determined, the deposits are classified as to the type of hazard (tephra, pyroclastic flow, lava flow, etc.), dated (a number of techniques are available that can be used to supplement the historic record), and mapped. The resulting products are maps and reports which depict the volcanic hazards of an area. Finally, the volcanic hazard can be graded in terms of severity on a volcanic hazard zonation map.

c. Volcanic Hazard Zonation Map

The Sourcebook for Volcanic Hazards Zonation provides an excellent discussion of preparing hazard zonation maps:

> Volcanic hazards zonation maps have two primary purposes, namely, for long-range planning for uses of land around volcanoes that are thought to be compatible with the hazard from future eruptions, and for determining which areas should be evacuated and avoided during eruptions. Maps prepared for these two purposes have similarities as well as differences. A hazards-zonation map and an accompanying report designed to guide land-use planning could include estimates of the frequency of events anticipated in the future. Such reports could also include quantitative or other estimates of relative degrees of hazard. In contrast, a zonation map prepared chiefly for the purpose of evacuation could subdivide kinds of hazard, so that people could be removed selectively from different areas according to whether the eruption was expected to produce lava flows, airfall deposits, pyroclastic flows, lahars or combinations of these. Maps such as these could also be divided into zones based on the anticipated scales of future eruptions, or into sectors determined by which flank of a volcano, or which valley system, might be affected most often by eruptions. The expectable high cost and social disruption caused by evacuation might be reduced by the use of such maps. Both kinds of uses of hazards-zonation maps should be considered during their preparation; both kinds of maps can be prepared from the same basic data, and in some cases one map could be prepared that would serve both purposes (Crandall, 1984).

Examples of volcanic hazard zonation maps used for development planning purposes are shown in Figures 11-23 and 11-24. Suggestions for preparing hazard zonation maps for specific volcanic hazards together with numerous examples are available from the UNESCO Sourcebook.

d. Mitigation of Volcanic Hazards

Development-related aspects of volcanic hazard mitigation--reducing the potential loss of life and property damage that can be caused by a volcanic eruption--primarily involve hazard assessments and land-use planning. Other mitigation procedures such as the establishment of monitoring and warning systems, emergency evacuation measures, protective measures, insurance programs, and relief and rehabilitation measures are not treated in this chapter. Many of these activities are associated with preparedness, which is another phase of hazard management (see Chapter 1).

Volcanoes which present a short-term hazard and which clearly threaten life or property should be kept under surveillance, and restrictions should be placed on permanent habitation in the areas of greatest hazard. For volcanoes that have long-term periodicity and therefore may or may not pose a hazard during the lifetime of a project, land-use restrictions may not be warranted on purely economic grounds, but development should be planned with a knowledge of the potential consequences of future eruptions. Obviously, an imminent eruption requires constant monitoring and vigilance and the taking of suitable measures to cope with the impending event.

3. VOLCANIC HAZARDS AND THE DEVELOPMENT PLANNING PROCESS

Compared with earthquakes, volcanic hazards are simpler to cope with in development planning because

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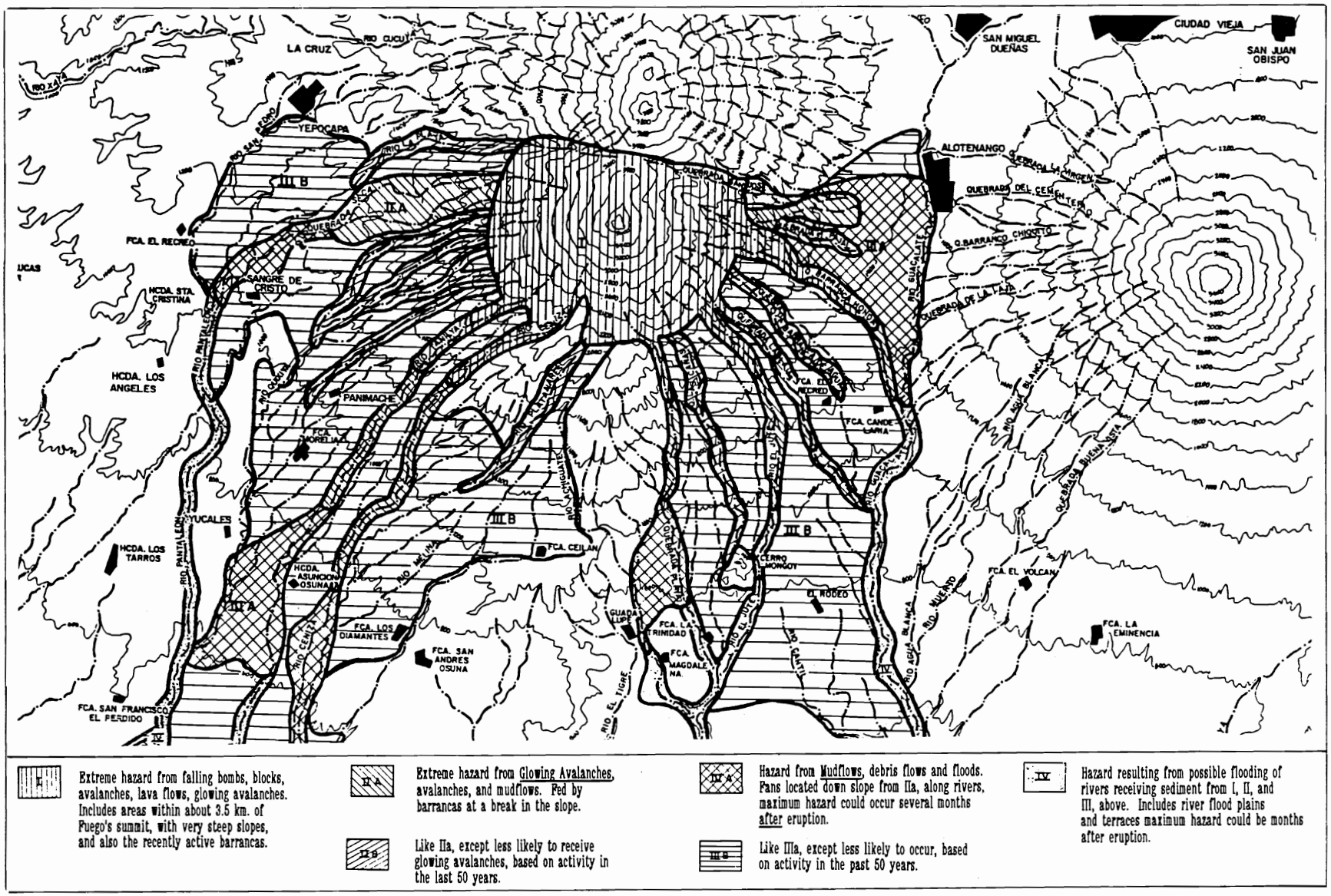
2/ For classifications of volcano types see Steinbrugge, 1982, and Simkin, et al., 1981.

Figure 11-23

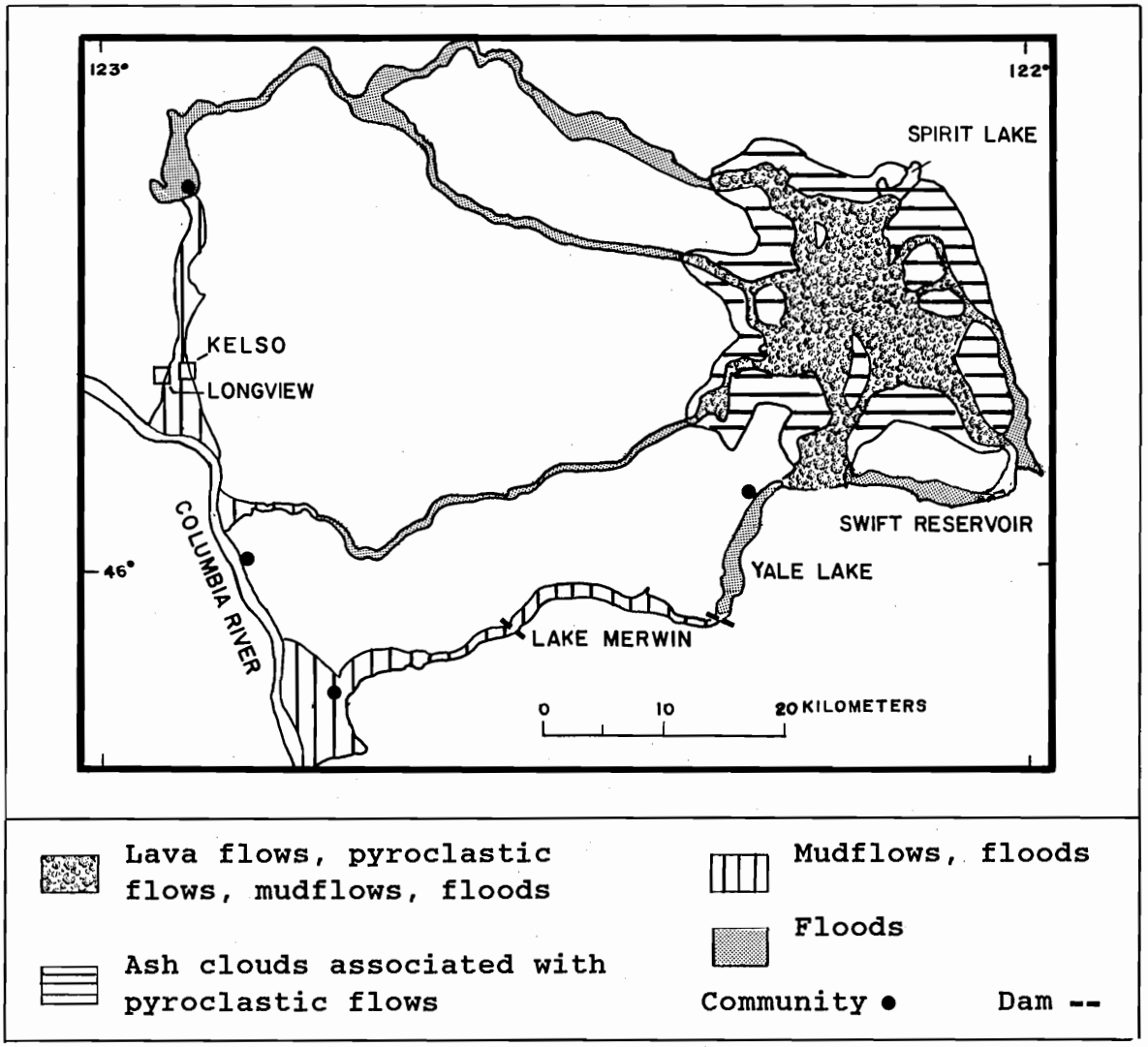
VOLCANIC HAZARD ZONES OF FUEGO VOLCANO, GUATEMALA



Source: Rose, W.I., et al. Volcanic Hazards of Fuego Volcano, Preliminary Report (Houghton, Michigan: Michigan Technological University, 1981).

Figure 11-24

VOLCANIC HAZARD ZONES OF MT. ST. HELENS VOLCANO, U.S.A.



Source: Adapted from Crandall, D.R. et al. Sourcebook for Volcanic-Hazards Zonation, Natural Hazards 4 (Paris, France: UNESCO, 1984).

KEY QUESTIONS PLANNERS NEED TO ASK SEQUENTIALLY ABOUT VOLCANOES AS PART OF A DEVELOPMENT STUDY

- Are volcanic eruptions a concern in the study area?
- How imminent is an eruption?
- What specific hazards present a danger and where?

of their point source, the limited extent of the area in which active volcanoes occur, and the limited distance from the source for which volcanic activity poses a serious hazard. The process involves addressing key questions listed in the box above.

a. Preliminary Mission

During the preliminary mission of an integrated development planning study, an initial review is made of the information available. At this time the first two questions shown in the box above can be answered with an acceptable degree of reliability by undertaking an initial volcanic hazard assessment. The procedure, outlined in the box on page 59, uses information from the Preliminary Neotectonic Map of South America and Figure 11-25, which is a listing of volcanoes active in the Holocene period, their periodicity, and other summary information on each. When necessary, local information can supplement this. No specialized expert is needed for this task.

b. Phase I--Development Diagnosis

Phase I of a development study requires a diagnosis of a region's development potential. The results of the initial volcanic hazard assessment will lead to different information needs if a volcano in the study area is identified as an imminent, short-term, or long-term threat.

If an eruption is determined by geologic evidence to be imminent, mitigation actions must take precedence over all other activities. The statement appears too self-evident to merit mention, yet surprisingly the principle is not always heeded. For example, the Nevado del Ruiz gave clear signs of the approach of a major eruption in November 1985, one year before the eruption that killed 23,000 people (Tomblin, 1986). The moment an eruption appears imminent, full-scale monitoring of the volcano must be initiated if it is not already being done. Warning and evacuation systems must be established. Large reservoirs in the path of potential lahars should be either drained or lowered sufficiently to serve as a trap rather than a lubricant to moving mud and water. People occupying the flanks of the volcano should be relocated. Planners can play a role in seeking suitable relocation sites and helping to define relocation mechanisms. Areas adjacent to the volcano that are vulnerable to any specific hazard, particularly lahars and pyroclastic phenomena, should be delineated--at first simply by topographic considerations--and suitable precautions taken. In short, if an eruption is found to be imminent in an area, the planner's focus abruptly changes from the future to the immediate present. When a short-term volcanic hazard is identified, additional information is needed.

Additional information on individual volcanoes can be found in the resources listed in the box on page 60. These sources may be supplemented by more detailed local data such as maps and studies of specific volcanic hazards or historical event and damage assessment studies. Additional information can be inferred from geologic, tectonic, and seismic maps, particularly maps of Holocene or Quaternary geology. Data on wind (prevalent direction and speed) are relevant to evaluating tephra hazard. Topography and interpretative soil studies are important for the evaluation of tephra, lava flow, pyroclastic flow, and lahar hazards. The location of reservoirs and other major sources of water that can cause flooding or contribute to the movement of lahars is particularly important data for volcanic hazard mitigation.

Information on elements at risk is the same as for earthquake hazards. In some areas with severe volcanic hazards, maps of volcanic hazards, risks, and volcanic hazard land-use zonation are available. Sources of information include national geologic agencies, national and international volcanic and hazard data centers, national disaster mitigation agencies, universities, and research centers.

Volcanoes posing a short-term hazard can be plotted on 1:10,000- to 1:100,000-scale topographic maps. Local information commonly exists for volcanoes in this category, and some hazard mitigation program may already have been instituted. In this

Figure 11-25

ACTIVE VOLCANOES IN LATIN AMERICA AND THE CARIBBEAN, ASSOCIATED VOLCANIC HAZARDS, AND PERIODICITY OF ERUPTIONS DURING THE LAST 10,000 YEARS

Country, Volcano, Periodicity (1)	Location Latitude	Location Longitude	Date Last Eruption (2)	Effects Fatl (3)	Effects Prop (4)	Volcanic Hazards Expl (5)	Pyro (6)	PhEx (7)	Lava (8)	Mdfl (9)	VEI (10)	Volcano Ni. (11)	Comments
Mexico													
Pinacate Peaks	31.75N	113.50W	Holocene										
San Quintin Volcanic Field	30.48N	116.03W	Holocene										
San Luis, Isla	29.97N	114.43W	Holocene										
Jaraquay Volcanic Field	29.33N	114.50W	Holocene										
Tortuga, Isla	27.39N	111.86W	Holocene										
TRES VIRGENES, VOLCAN DE LAS	27.47N	112.58W	1857?										
BARCENA (REVILLAGIGEDO IS)	19.27N	110.80W	1952			x	x		x		2		
SOCORRO (REVILLAGIGEDO IS)	18.75N	110.95W	1951					x			2		
CEBORUCO, VOLCAN	21.15N	104.50W	1870			x	x		x		3		
Brenal	24.15N	104.45W	Holocene										
SANGANGUEY	21.45N	104.98W	1859										
COLIMA, and EL VOLCANCITO	19.42N	103.72W	1977		x	x	x	x	x		1-4		
PARICUTIN VOLCANIC FIELD	19.48N	102.25	1943		x	x			x		3		
Jorullo	19.03N	101.67W	1759		x	x	x		x	x	4		
Zacapu Volcanic Field	19.80N	101.80W	Uncertain										
Valle de Santiago	20.38N	101.22W	Holocene			x			x				
Unnamed	19.10N	099.50W	Holocene			x			x		4		
Xitli	19.25N	099.22W	Holocene						x		0?		
Chichinautzin, Sierra del	19.08N	099.13W	Holocene										
Santa Catarina Range	19.20N	098.97W	Holocene										
Gordo, Cerro	19.75N	098.82W	Holocene										
Pitos, Sierra de las	19.92N	098.73W	Holocene										
POPOCATEPETL	19.02N	098.62W	1943			x					1-3		
ORIZABA, PICO DE	19.03N	097.28W	1687			x			x		3		
SAN MARTIN, VOLCAN DE	18.58N	095.17W	1838			x			x		2-4		
Catemaco, Lake	18.42N	095.07W	Uncertain										
Santa Marta, Volcán	18.30N	095.00W	Holocene										
CHICHON, EL	17.33N	093.20W	1985										
TACANA	15.13N	092.10W	1878?								1		On Guatemala border. Threatened eruption in 1985 and 1986.
Guatemala													
TAJUMULCO	15.043N	091.898W	1863?			x					2		
Siete Orejas	14.82N	091.62W	Holocene										
SANTA MARIA	14.758N	091.548W	1990	x	x	x	x		x	x	2-6		Very high VEI. Includes Santiaguito dome (SW Flank Santa Maria)
QUEMADO, CERRO	14.798N	091.52W	1823?		x	x			x		2		
Oro, Cerro de	14.88N	091.38W	Holocene										

Figure 11-25 (continued)

Country, Volcano, Periodicity (1)	Location Latitude	Location Longitude	Date Last Eruption (2)	Effects Fatl (3)	Effects Prop (4)	Volcanic Hazards Expl (5)	Pyro (6)	PhEx (7)	Lava (8)	Mdfl (9)	VEI (10)	Volcano Ni. (11)	Comments
Guatemala (continued)													
ATITLAN	14.588N	091.182W	1856?		x	x			x		2-3		
Tolimán	14.614N	091.117W	Holocene										
ACATENANGO	14.503N	090.873W	1972			x		x			1-3		
FUEGO	14.482N	090.882W	1977	x	x	x	x		x	x	0-4		
Agua	14.47N	090.742W	Holocene										
PACAYA	14.38N	090.603W	1989		x	x			x		0-3		
13 Minor volcanoes east of Guatemala City	14.03-14.83N	089.35-090.45W	Holocene										
El Salvador													
Ahuachapán Geothermal Field	13.90N	089.82W	1990	x	x	x							
3 Minor volcanoes	13.90-14.27N	089.47-089.77W	Holocene										
SANTA ANA	13.853N	089.630W	1920		x	x					2-3		
IZALCO	13.815N	089.635W	1966	x	x	x	x		x		0-3		
SAN MARCELINO	13.807N	089.577W	1722		x				x		0		
Coatepeque Caldera	13.87N	089.55W	Holocene										
SAN SALVADOR	13.738N	089.288W	1917	x	x	x			x		0-4		
Guazapa	13.90N	089.12W	Holocene										
ILOPANGO	13.672N	089.053W	1879	x	x	x	x		x		3-6?		Very high VEI
6 Minor volcanoes around San Vicente	13.42-13.623N	088.32-088.852W	Holocene										
SAN MIGUEL	13.437N	088.272W	1976		x	x		x	x		1-3		
Conchagua	13.227N	087.853W	Uncertain										
CONCHAGUITA	13.22N	087.765W	1892			x					2		
Nicaragua													
COSIGUINA	12.98N	087.57W	1852		x	x	x				2-5		Very high VEI
SAN CRISTOBAL	12.70N	087.00W	1977			x		x			1-3		
Casita	12.70N	086.97W	1550										
TELICA	12.60N	086.85W	1976			x		x	x		1-3		
Rota	12.55N	086.75W	Holocene										
NEGRO, CERRO	12.50N	086.70W	1971		x	x			x	x	1-3		
PILAS, LAS	12.50N	086.68W	1954			x		x			1		
MOMOTOMBO	12.42N	086.53W	1905		x	x			x		2-3		
Apoyeque	12.242N	086.342W	Holocene										
MASAYA, NINDIRI, SANTIAGO, and SAN PEDRO	11.98N	086.15W	1974		x	x			x		0-3		
Apoyo	11.92N	086.03W	Holocene										
MOMBACHO	11.83N	085.98W	1850?			x					2-3		
Zapatera Island	11.73N	085.82W	Holocene										
CONCEPCION	11.53N	085.62W	1978			x			x		2		
Madera, La	11.45N	085.52W	Uncertain										
3 Minor volcanoes	12.30-12.53N	085.73-086.138W	Holocene										

Figure 11-25 (continued)

Country, Volcano, Periodicity (1)	Location Latitude	Location Longitude	Date Last Eruption (2)	Effects Fatl (3)	Effects Prop (4)	Volcanic Hazards Expl (5)	Pyro (6)	PhEx (7)	Lava (8)	Mdfl (9)	VEI (10)	Volcano Ni. (11)	Comments
Costa Rica													
OROSI	10.98N	085.47W	1849			x					2		
RINCON DE LA VIEJA	10.83N	085.33W	1970		x	x		x			2-3		
Miravalles	10.75N	085.15W	Holocene										
Tenorio	10.67N	085.02W	Uncertain										
ARENAL	10.47N	084.73W	1968	x	x	x	x	x	x	x	3-4		
Poco Sol, Cerro	10.320N	084.660W	Uncertain										
Platanar, Cerro	10.299N	084.366W	Holocene										
POAS	10.20N	084.22W	1980			x		x			1-3		
BARBA	10.13N	084.08W	1867			x					2		
IRAZU	09.98N	083.85W	1974	x	x	x		x	x	x	1-3		
TURRIALBA	10.03N	083.77W	1866			x					2-3		
Honduras													
Yojoa, Lake	14.98N	087.98W	Holocene										
Utila Island	16.10N	086.90W	Holocene										
Panama													
Barú	08.80N	082.558W	1550?		x	x							
Colombia													
RUIZ	04.88N	075.37W	1985	x	x	x			x	x	2-4	2	
Mesa Nevada de Herveo	05.30N	075.47W	Holocene										
TOLIMA	04.65N	075.37W	1943			x					2	1	
Machín	04.15N	075.37W	Holocene										
Huila	03.00N	075.98W	Holocene										
PURACE	02.37N	076.38W	1977	x	x	x			x	x	2-4	3	
Sotara	02.22N	076.62W	Holocene										
Petacas	01.57N	076.78W	Uncertain										
DOÑA JUANA	01.52N	076.93W	1897	x		x	x		x	x	4	4	
GALERAS	01.22N	077.30W	1974			x			x		2-4	5	
Azufral de Tuquerres	01.08N	077.73W	Holocene										
CUMBAL	00.98N	077.88W	1926			x					2	6	
Negro de Mayasquer, Cerro	00.80N	077.95W	Holocene			x					2	7	
Ecuador													
REVENTADOR	00.08S	077.67W	1976			x	x		x	x	2-3	8	
Cuicocha	00.30N	078.37W	Holocene										
Pululagua	00.05N	078.48W	Holocene			x	x						

Figure 11-25 (continued)

Country, Volcano, Periodicity (1)	Location Latitude	Location Longitude	Date Last Eruption (2)	Effects Fatl (3)	Effects Prop (4)	Volcanic Hazards Expl (5)	Pyro (6)	PhEx (7)	Lava (8)	Mdfl (9)	VEI (10)	Volcano Ni. (11)	Comments
Ecuador (continued)													
GUAGUA PICHINCHA	00.17S	078.60W	1881			x	x				2-4	9	
ANTISANA	00.48S	078.13W	1801			x			x		0-2	10	
SUMACO	00.57S	077.65W	1933?			x					2-3?	11	
COTOPAXI	00.65S	078.43W	1942	x	x	x	x		x	x	0-4	12	
QUILOTOA	00.85S	078.90W	1759?			x					2-4?	13	
TUNGURAHUA	1.47S	078.45W	1944		x	x	x	x	x	x	2-4	14	
SANGAY	02.03S	078.33W	1976	x	x	x	x		x		2-3+	15	
FERNANDINA (GALAPAGOS)	00.37S	091.55W	1978			x		x	x		0-4		
6 VOLCANOES ON ISABELA IS.	00.02N-00.90S	091.12-091.55W	Holocene-1979	x		x		x	x		0-3		
9 VOLCANOES IN GALAPAGOS IS.	00.58N-00.88S	089.50-090.77W	Holocene-1958						x		0		
Peru													
4 Minor volcanoes	14.37-15.80S	071.17-072.70W	1990		x	x	x		x				Sabancaya Volcano
MISTI, EL	16.302S	071.414W	1870?		x	x					2-3	16	
UBINAS	16.355S	070.903W	1969		x	x					2-3?	17	
HUAYNAPUTINA	16.584S	070.87W	1667	x	x	x	x			x	2-4	18	
Ticsani	16.77S	070.60W	Holocene										
TUTUPACA	17.025S	070.358W	1902			x					2-3	19	
Yucamani	17.18S	070.20W	1787									20	
Northern Chile and Bolivia													
Chupiquina, Nevado	17.67S	069.80W	Holocene										
Tacora	17.72S	069.78W	Holocene										
6 Minor volcanoes	17.92-18.42S	068.53-069.80W	Holocene										On Chile-Bolivia border
GUALLATIRI	18.42S	069.10W	1960			x					2	21	
6 Minor volcanoes	18.38-19.15S	068.08-069.47W	Holocene										On Chile-Bolivia border
ISLUGA	19.15S	068.83W	1960		x	x			x		2	22	
11 MINOR VOLCANOES	20.73-21.78S	066.50-068.47W	Holocene-1865										On Chile-Bolivia border; one erupted in 1865. Volcano No. 23 is one of these 11 volcanoes
SAN PEDRO	21.88S	068.40W	1960?		x	x			x		2	24	
11 MINOR VOLCANOES	21.92-23.13S	067.18-068.23W	Holocene-1972										On Chile-Bolivia border; one erupted in 1972. Volcano No. 25 is one of these 11 volcanoes.
LASCAR	23.37S	067.73W	1986			x					2-3	26	
5 Minor volcanoes	23.58-24.45S	067.53-068.57W	Holocene										On Chile-Argentina border

Figure 11-25 (continued)

Country, Volcano, Periodicity (1)	Location Latitude	Location Longitude	Date Last Eruption (2)	Effects Fatl (3)	Effects Prop (4)	Volcanic Hazards Expl (5)	Volcanic Hazards Pyro (6)	Volcanic Hazards PhEx (7)	Volcanic Hazards Lava (8)	Volcanic Hazards Mdfl (9)	VEI (10)	Volcano Ni. (11)	Comments
Northern Chile and Bolivia (continued)													
LLULAILLACO	24.72S	068.55W	1877			x			x		0-2	27	
4 Minor volcanoes	25.17- 27.32S	067.88- 069.13W	Holocene										On Chile-Argentina border. Volcano No. 28 is one of these four volcanoes.
Central and Southern Chile, Argentina													
TUPUNGATITO	33.40S	069.80W	1980			x			x		2	29	
SAN JOSE	33.80S	069.92W	1895			x					2	30	On Chile-Argentina border. Fumarolic activity afterwards.
MAIPO	34.17S	069.87W	1912?			x						31	On Chile-Argentina border
TINGUIRIRICA	34.82S	070.35W	1917									32	
PETEROA	35.25S	070.57W	1967			x			x	x	1-4	33	On Chile-Argentina border
DESCABEZADO GRANDE	35.58S	070.75W	1932			x					2	34	
AZUL, CERRO	35.67S	070.77W	1967			x			x		2-5	35	Very high VEI
Maule, Laguna del	36.02S	070.58W	Holocene										
CHILLAN, NEVADOS DE	36.87S	071.38W	1973			x			x	x	1-3	36	
ANTUCO	37.40S	071.37W	1972			x			x		0-2	37	
CALLAQUI	37.92S	071.42W	1850?									38	On Chile-Argentina border
Copahues	37.85S	071.17W	1750?			x						39	
LONQUIMAY	38.37S	071.58W	1889			x			x		0-2	40	
LLAIMA	38.70S	071.70W	1979		x	x			x	x	2-4?	41	
VILLARRICA	39.42S	071.95W	1980	x	x	x	x		x	x	2-3	42	
Quetrupillán	39.485	071.70W	Holocene										
RINIHUE (or CHOSHUENCO MOCHO)	39.93S	072.03W	1864			x					2	43, 44	
NILAHUE	40.35S	072.07W	1979	x	x	x			x	x	2-4	45	
Casablanca, Volcán	40.75S	072.20W	Holocene									46	
PUYEHUE	40.57S	072.10W	1960			x			x		3-4	47	
PUNTIAGUDO, CERRO	40.95S	072.27W	1930?										
OSORNO	41.10S	072.50W	1869			x			x		0-2	48	
CALBUCO	41.32S	072.60W	1961		x	x		x	x	x	1-2	49	
Cayute-La Viguería	41.98S	072.27W	Holocene										
HUEQUI	42.37S	072.58W	1920?			x			x		0-2	50	
MINCHINMAVIDA	42.78S	072.43W	1835						x		2	51	
CORCOVADO	43.18S	072.80W	1835			x					2		
Maca	45.10S	073.20W	Holocene									52	
HUDSON, MT.	46.17S	072.92W	1971	x	x	x				x	3	53	
LAUTARO	49.02S	073.55W	1961			x					1-2	54	
BURNEY, MONTE	52.33S	073.40W	1910			x					2	55	
Palei-Aike Volcanic Field	52.15S	069.95W	Holocene			x			x				

Figure 11-25 (continued)

Country, Volcano, Periodicity (1)	Location Latitude	Location Longitude	Date Last Eruption (2)	Effects Fatl (3)	Effects Prop (4)	Volcanic Hazards Expl (5)	Pyro (6)	PhEx (7)	Lava (8)	Mdfl (9)	VEI (10)	Volcano Ni. (11)	Comments
West Indies													
Saba (Caribbean)													
Mountain, The	17.63N	063.23W	Holocene										
St. Eustatius													
Quill, The	17.48N	062.95W	Holocene										
St.Kitts and Nevis													
MISERY, MOUNT (ST. KITTS)	17.37N	062.80W	1843?			x		x					
Nevis Peak (Nevis)	17.15N	062.58W	Holocene										
Montserrat													
Soufriere Hills	16.72N	062.18W	Holocene			x							
Guadeloupe													
SOUFRIERE DE LA GUADELOUPE	16.05N	061.67W	1976			x	x	x		x	1-3		
Dominica													
Diable, Morne au	15.62N	061.45W	Holocene										
Diablotins, Morne	15.50N	061.42W	Holocene										
MICOTRIN	15.33N	061.33W	1880					x			3		
Patates, Morne	15.22N	061.37W	Holocene										
Martinique													
MONTAGNE PELEE	14.82N	061.17W	1929	x	x	x	x	x	x	x	3-4		
St. Lucia													
Qualibou (Soufriere)	13.83N	061.05W	1776					x			1		
St. Vincent													
SOUFRIERE	13.33N	061.18W	1979	x	x	x	x	x	x	x	0-4		
Grenada													
KICK-EM-JENNY (submarine)	12.30N	061.63W	1977								0		

Figure 11-25 (continued)

Notes:

1. Sources of information for name of volcano, location, periodicity, location, date of last eruption, effects, and volcanic hazards: Simkin, T. et al. Volcanoes of the World. (Stroudsburg, Pennsylvania: Hutchinson Ross Publishing Company, 1981), and Smithsonian Institution. Global Volcanism Network. (Washington D.C.: Smithsonian Institution, 1989-90)..
   Volcanoes with short-term periodicity are presented in capital letters. A volcano having short-term periodicity is defined for this table as one with an eruption periodicity of 100 years or less and/or one that has erupted since 1800.
2. Date of last eruption is simplified from Volcanoes of the World using three categories: (1) "Historic"-- the actual eruption date is given, sometimes qualified by "?" when data is questionable. (2) "Holocene"-- including the following subcategories: (a) eruptions dated by Carbon 14, hydrophone data, dendrochronology, varve count, anthropologic evidence, lichenometry, magnetism, tephrochronology, hydration rind or fission track analysis; (b) volcanoes now displaying fumarolic or solfataric activity and giving obvious evidence of recent, although undated, eruption; (c) volcanoes virtually certain to have erupted in postglacial time even though neither dated products nor thermal features are present. (3) "Uncertain"-- signifying possible Holocene activity but questionable documentation.
3. Fatalities caused by one or more eruptions.
4. Destruction of agricultural land or other property damage caused by one or more eruptions.
5. One or more eruptions were explosive.
6. Pyroclastic flows or surges and/or laterally directed blasts were associated with one or more eruptions.
7. Phreatic explosion was associated with one or more eruptions.
8. Lava flow, lava domes, or spines were associated with one or more eruptions.
9. Destructive mudflows were associated with one or more eruptions.
10. VEI = Volcanic Explosivity Index: the size or "bigness" of a historic eruption. The VEI combines total volume of products, eruptive cloud height, duration of eruption, tropospheric injection, stratospheric injection, and some descriptive terms to yield a 0-8 index of increasing explosivity as follows: 0 nonexplosive, 1 small, 2 moderate, 3 moderately large, 4 large, 5 very large, 6-8 cataclysmic.
11. Volcano number as per reference found on: Regional Seismological Center for South America (CERESIS). Preliminary Neotectonic Map of South America. (Santiago, Chile: CERESIS, 1985).

PRELIMINARY MISSION: PROCEDURE FOR INITIAL VOLCANIC HAZARD ASSESSMENT IN LATIN AMERICA AND THE CARIBBEAN

INITIAL REVIEW

- For Colombia, Ecuador, Peru, Bolivia, Chile, Argentina: GO TO STEP 1.
- For Mexico, Guatemala, El Salvador, Nicaragua, Costa Rica, Honduras, Panama: GO TO STEP 2.
- For Saba, St. Eustatius, St. Kitts and Nevis, Montserrat, Guadeloupe, Dominica, Martinique, Saint Lucia, St. Vincent, Grenada: GO TO STEP 3.
- For all other countries in Latin America and the Caribbean, volcanic hazards are not a significant concern.

STEP 1: Determine if any part of the planning area lies within the area designated "Pliocene-Holocene Volcanic Cover" on the Preliminary Neotectonic Map of South America and/or within 30km of an active volcano indicated on the map. If "no," volcanic hazards are not a significant concern in the study area. If "yes," go to Step 2.

STEP 2: Determine if any part of the study area includes or lies within 30km of any of the volcanoes listed in Figure 11-25. If "no," volcanic hazards are not a significant concern in the study area. If "yes," go to step 3.

STEP 3: Using Figure 11-25, classify the eruption periodicity of each volcano in the study area as short-term or long-term. Volcanoes with short-term periodicity are shown in capitals. If the volcano is classified as short-term, go to Step 4.

STEP 4: For short-term volcanoes, determine from local authorities if there is any geologic evidence that an eruption is imminent, and if hazard zonation maps have been prepared.

NOTE: The 30km distance is arbitrary, based on the distance from a volcano that lahars, ash, pyroclastic flows, etc., may be dangerous. The radius may be shorter or longer depending on such factors as the difference in elevation between the volcano and threatened areas, slope, channel morphology, and prevailing winds.

case, the task of the planner is to promote land uses and protective measures commensurate with the degree of risk of any area.

If a hazard zonation map does not exit, one should be prepared as part of the development planning study and should become an integral part of the integrated natural resource inventory. In this case it will be necessary to obtain the services of a volcanic hazard expert. Having completed the preliminary hazard work during the preliminary mission, the planner will be prepared to draft precise terms of reference for the specialist. With the results of additional studies, the planner can identify potential mitigation measures, comparing costs and potential benefits with all the other elements involved in the development of the study area.

If long-term volcanic hazards are determined to occur in the study area, incorporating hazard considerations into a development study can offer additional benefits. Long-term hazards are often ignored in spite of the fact that surprising eruptions from volcanoes considered dormant or inactive are responsible for tremendous damage. If no local information exists, a difficult decision will be required as to whether the preparation of a volcanic hazard zonation map is justified. A volcanic hazard expert can advise on the degree of risk and, commensurately, the effort that should be devoted to additional studies and mitigation measures.

c. Phase II: Development Strategy and Project Formulation

In developing areas with short-term volcanic hazards, mitigation measures should be selected if they are not already part of the project identification information. Land-use restrictions should be instituted for areas having a potential threat of pyroclastic phenomena. In areas where volcanic ash can constitute a hazard, building codes should stipulate appropriate roof construction. In many cases only lahars would merit mitigation measures. Valley areas in the path of potential lahars could be delineated and land-use restrictions or protective measures in keeping with economic rationality could be instituted. The mitigation measures that can be justified economically for these short-term hazards are limited, since "short-term" is still a lengthy period of time. Awareness of the potential danger may permit a more reasoned development plan.

ADDITIONAL VOLCANO INFORMATION

One of these two sources may provide details of a short-term volcano's history:

Simkin, T., et al. Volcanoes of the World, Smithsonian Institution (Stroudsburg, Pennsylvania: Hutchinson Ross Publishing Co., 1981).

International Association of Volcanology (ed.). Catalog of Active Volcanoes of the World Including Solfatara Fields (Rome: Istituto di Geologia Applicata, Facultà di Ingegneria).

D. Tsunamis

Tsunamis are water waves or seismic sea waves caused by large-scale sudden movement of the sea floor, due usually to earthquakes and on rare occasions to landslides, volcanic eruptions, or man-made explosions.

1. TSUNAMI HAZARDS AND THEIR ASSESSMENT AND MITIGATION

a. Tsunami Hazards

Life-threatening tsunamis have not been known to occur in the Atlantic Ocean since 1918, but are a serious problem in the Pacific. Although the Caribbean Basin's tectonic configuration indicates that the area is susceptible to seismic activity, these earthquakes are rarely tsunamigenic. Since 1690 only two significant occurrences have been registered. The 1867 tsunami swept away villages in Grenada, possibly killed 11 or 12 people in St. Thomas, and killed an additional five persons in St. Croix. The 1918 occurrence created abnormally large waves for two to three hours in different parts of the Dominican Republic, and killed 32 people in Puerto Rico (NOAA, 1989). In view of the rarity of these events, it would be difficult to establish an economic justification for mitigation measures. On the Pacific coasts of Mexico, Guatemala, El Salvador, Costa Rica, Panama, Colombia, Ecuador, Peru, and Chile, on the other hand, between 1900 and 1983, there were 20 tsunamis that caused casualties and significant damage. A devastating tsunami occurred in Arica, then in Peru, in 1868. Ships were carried five kilometers inland by a wave that exceeded 21m in height. This and subsequent waves 12m high swept over the city, killing hundreds of people. The earliest recorded tsunami in Latin America occurred in 1562, inundating 1,500km of the Chilean coastline.

Tsunamis differ from other earthquake hazards in that they can cause serious damage thousands of kilometers from the causative faults. Once they are generated, they are nearly imperceptible in mid-ocean, where their surface height is less than a meter. They travel at incredible speeds, as much as 900km/hr, and the distance between wave crests can be as much as 500km. As the waves approach shallow water, a tsunami's speed decreases and the energy is transformed into wave height, sometimes reaching as high as 25m, but the interval of time between successive waves remains unchanged, usually between 20 and 40 minutes. When tsunamis near the coastline, the sea recedes, often to levels much lower than low tide, and then rises as a giant wave.

The effects of tsunamis can be greatly amplified by the configuration of the local shoreline and the sea bottom. Since a precise methodology does not exist to define these effects, it is important to examine the historic record to determine if a particular section of coastline has been subjected to tsunamis and what elevation they reached. An attempt should also be made to determine the possible amplifying effects of the coastal configuration, even with the crude methodologies available (Nichols and Buchanan-Banks, 1974). It should be noted, as shown by the diagram in Figure 11-26, that because of the force of the wave, the runup can reach an elevation substantially higher than the crest of the wave at the shoreline.

Seiches are phenomena similar to tsunamis but occur in inland bodies of water, generally in elongated lakes. Seiche waves are lower (less than three meters high) than those of tsunamis and are oscillatory in nature. They can cause structural failure and flooding in low-lying areas.

b. Tsunami Hazard Assessment

Estimates of the risk of future tsunamis are based primarily on two types of information: the past history of tsunamis and the prediction of tsunamigenic earthquakes. This information must, of course, be

TSUNAMI INFORMATION SOURCES

World Data Center A for Solid Earth Geophysics, National Geophysical Data Center. Tsunamis in the Pacific Basin 1900-1983 (map) (Boulder, Colorado: July 1986) and Tsunamis in Peru-Chile (Boulder, Colorado: NOAA, 1985).

The Pacific Tsunami Warning Center, National Oceanic and Atmospheric Administration. Communication Plan for the Tsunami Warning System, Tenth Edition (Ewa Beach, Hawaii: NOAA, February, 1984).

The International Tsunami Information Center and Intergovernmental Oceanographic Commission, Tsunami Newsletter. (P.O. Box 58027, Honolulu, Hawaii 96850-4993).

The Pacific Marine Environmental Laboratory, National Oceanographic and Atmospheric Administration. THRUST, Third Annual Report (Seattle, Washington: NOAA, 1986).

TSUNAMI MITIGATION MEASURES

- Avoid tsunami runup areas in new development except marine installations and others requiring proximity to water. Prohibit setting of high-occupancy and critical structures.

- Place areas of potential inundation under floodplain zoning, prohibiting all new construction and designating existing occupancies as non-conforming.

- Where economically feasible, establish constraints to minimize potential inundation or to reduce the force of the waves. These measures include:

    * constructing sea walls along low-lying stretches of coast and breakwaters at the entrances of bays and harbors

    * planting belts of trees between the shoreline and the areas requiring protection

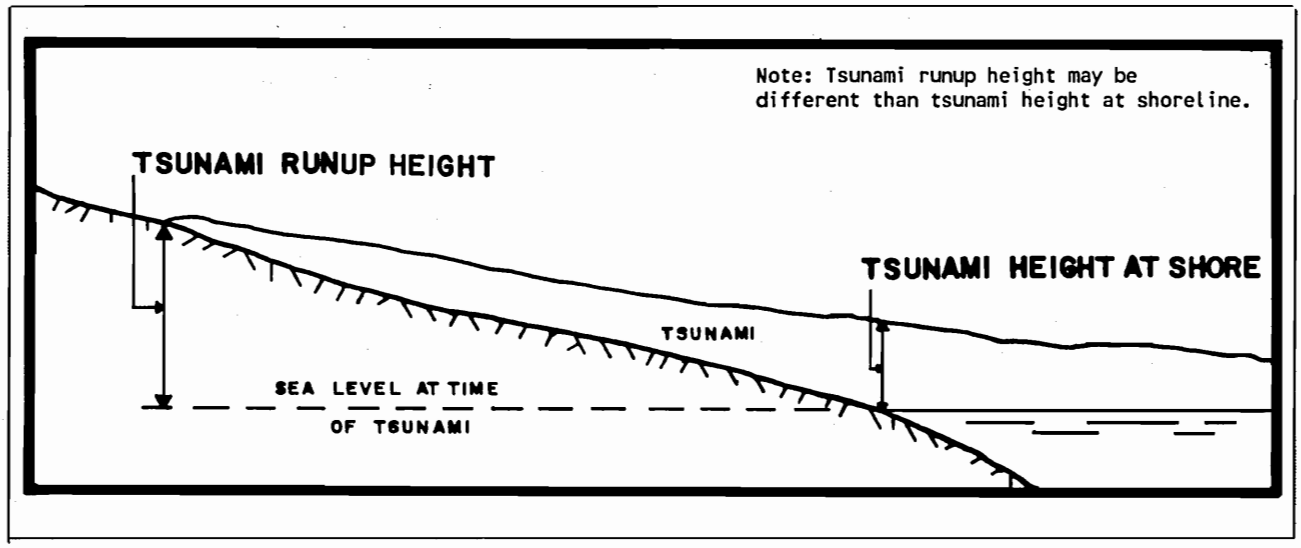
- Where development exists, establish adequate warning and evacuation systems.

- Set standards of construction for structures within harbors and known runup areas.

(Nichols and Buchanan-Banks, 1974; Blair, 1979)

Figure 11-26

TSUNAMI RUNUP HEIGHT



Source: Adapted from Steinbrugge, K.V. Earthquakes, Volcanoes and Tsunamis: An Anatomy of Hazards (Skancia, New York: 1982).

qualified by local conditions such as near-shore marine and terrestrial topography. The most readily available sources of information on historic tsunamis, including current activities in tsunami research, are listed in the box above.

The prediction of tsunamigenic earthquakes is principally based on the seismic gap theory discussed earlier in this chapter.

c. Mitigating the Effects of Tsunamis

While tsunamis cannot be prevented, the Pacific Tsunami Warning Center is constantly monitoring the oceans and in many cases can warn a local population of an impending tsunami with sufficient lead time to make evacuation possible. Such warnings, however, cannot prevent the destruction of boats, buildings, ports, marine terminals, and anything else within the runup area. The areas at risk can be identified, and stringent controls such as those proposed in the box above should be applied.

It should be emphasized, however, that such measures are generally more applicable in areas of high population concentration and that, since significant protection against a large tsunami is virtually impossible economically, avoidance and warning systems are the best mitigation measures for many areas.

To protect against seiches, land-use controls should be applied to low-lying areas of earthquake-prone regions on the borders of large lakes and to areas of potential inundation downstream from large water-retaining structures.

While it is beyond the scope of this chapter to deal with site-specific evaluation of tsunami hazard and design of mitigation measures, techniques for these purposes have been developed for planners. The box below identifies two sources of information.

2. TSUNAMIS AND THE DEVELOPMENT PLANNING PROCESS

Tsunamis can be neither prevented nor predicted. The low probability of a large tsunami striking a particular site, together with the potential for great damage if one does hit, makes incorporating tsunami considerations into development planning a tricky proposition. The problem is reduced somewhat in Latin America because of differential trans-Pacific transmission: while a large earthquake in Chile or Peru can generate a tsunami capable of causing damage in Alaska, Hawaii, and Japan, there is little likelihood that an earthquake in the western or northern Pacific will cause damage in Latin America. Of the 405 tsunamis recorded in the Pacific Basin from 1900 to 1983, 61 were recorded on the west coast of Latin America. The source region of all but five of these was the west coast of Latin America. Those five had low to moderate runup and caused negligible to little damage (Tsunamis in the Pacific Basin, 1986 map; and Hebenstreit, 1981). A large tsunami generated in Chile or Peru, however, can cause serious damage thousands of kilometers away on the same coast.

SOURCES FOR TSUNAMI EVALUATION AND THE DESIGN OF MITIGATION MEASURES

National Science Foundation. Comprehensive Planning for Tsunami Hazard Areas. Prepared by Urban Regional Research (1988).

National Science Foundation. Land Management in Tsunami Hazard Areas. Prepared by Urban Regional Research (1982).

KEY PROPOSITIONS FOR CONSIDERING TSUNAMIS IN A DEVELOPMENT PLANNING STUDY

- Any low-lying coastal population center within a zone subject to tsunamis is at risk.
- Mitigation measures other than land-use regulations are generally economically unfeasible except for major metropolitan areas.
- The Pacific Tsunami Warning System covers eight Latin American countries and is designed to alert eastern Pacific countries to tsunamis generated by earthquakes in the western Pacific and vice versa. The system is not designed to warn population centers on the west coast of Latin America of tsunamis generated on the same coast where there may only be about 30 minutes between an earthquake and the subsequent tsunami.
- A new warning system, THRUSH, designed to warn eastern Pacific localities of tsunamis generated on the same coast is in the experimental stage. When it becomes operational, warning lag time should be reduced to about ten minutes.

Studies are being conducted that should greatly enhance the capability for tsunami risk assessment. Until these studies are completed, however, the information in this chapter will serve as an interim guide for planners. Given the propositions listed in the box above, it is important for a planner to know whether or not the study area lies within a zone prone to tsunami damage. If it is, the planner needs to ensure that an adequate warning system is in place and can propose land-use regulations to the extent that they are economically reasonable.

Evaluation of the tsunami hazard is discussed below for two overlapping subregions: Mexico-Ecuador and Colombia-Chile.

a. Mexico-Ecuador

The best data available for estimating the likelihood of a damaging tsunami striking a given site within a given time period in this part of Latin America are found in the record of past tsunamis from the Tsunamis in Latin America Data File (National Geophysical Data Center, 1986). The data for Mexico to Ecuador, indicating 52 tsunamis between 1732 and 1985, are summarized in Figure 11-27.

Areas not included in this figure can be considered to have little threat of damaging tsunamis. While the data are insufficient for statistical prediction, they do provide a general indication of probability based on past events.

b. Colombia-Chile

The historical seismicity patterns and the seismic gap theory have been used in one study to estimate the tsunami hazard in the near future (about 50 years) on the Pacific coast of South America (Hebenstreit and Whitaker, 1981).

Figure 11-27

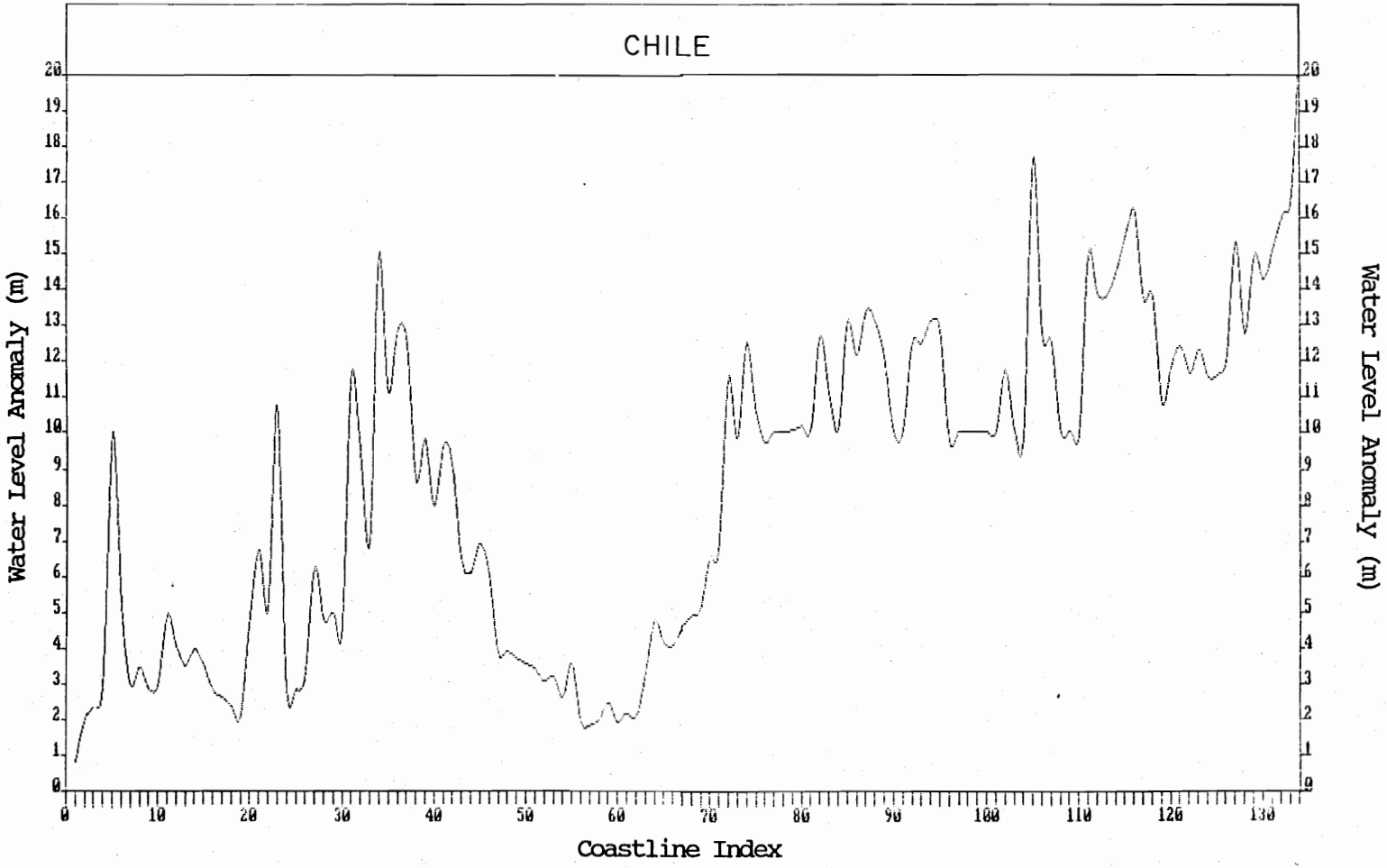
TSUNAMIS ON THE PACIFIC COAST OF LATIN AMERICA: MEXICO TO ECUADOR

Country	Area	Recorded Occurrences			Earthquake Magnitude (Range)	Distribution of Run up Height (Meters)			
		First	Most Recent	Number		0 - 1.9	2 - 5.9	6 - +	Unknown
Mexico	Pacific coast of the states of Colima, Michoacán, Guerrero, and western Oaxaca (possible extension to Golf of Tehuantepec); Islas Marias. Most frecuent and serious occurrences around Acapulco-San Marcos (Guerrero) and Manzanillo-Coyotlán (Colima).	1732	1985	24	6.2 - 8.6	9	6	2	7
Guatemala-El Salvador-Nicaragua	Pacific coast of Guatemala and El Salvador (serious occurrences at Acajutla, El Salvador) and northwest corner of Nicaragua, around Gulf of Fonseca.	1859	1950	4	6.2 - 7.1	1	1		2
Costa Rica	West coast of Nicoya Peninsula, Costa Rica.	1850	1952	2	7.0 - 7.7	2			
Panama	Osa Peninsula, Costa Rica, to Gulf of Chiriqui, Panama.	1854	1962	7	6.8 - 7.8	3	2		2
Colombia-Ecuador	Pacific coast from Tumaco, Colombia, to Gulf of Guayaquil, Ecuador. Serious occurrences from Tumaco, Colombia, to Esmeraldas, Ecuador.	1906	1979	6	6.9 - 8.6	3	3		

Source: Lockridge, Patricia A. and Smith, Ronald H. Tsunamis in the Pacific Basin - 1900-1983. (Map). (Boulder, Colorado: National Geophysical Data Center and World Data Center A for Solid Earth Geophysics, 1984); and Tsunamis in Latin America Data File (computer print-outs, Tables 1, 2 and 3) (Boulder, Colorado: National Geophysical Data Center, 1986).

Figure 11-28A

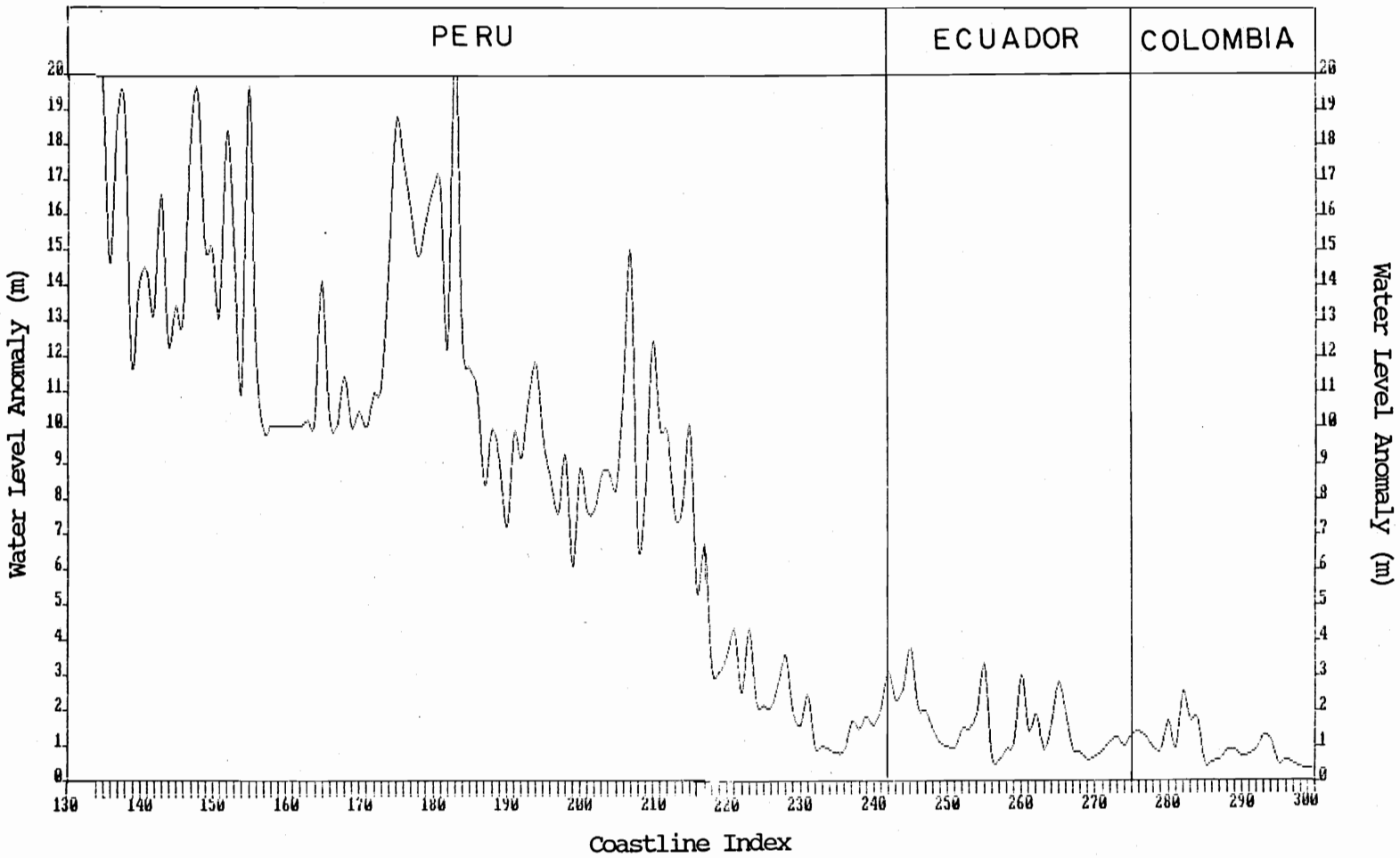
MAXIMUM WATER LEVEL ANOMALIES CALCULATED FOR TSUNAMIS GENERATED BY UNIFORM UPLIFT EARTHQUAKES IN PRINCIPAL SEISMIC GAP AREAS ON THE PACIFIC COAST OF SOUTH AMERICA



CHILE

Province	(index code)						
Valdivia	(1-6)	Ñuble	(26-28)	Colchagua	(36-39)	Coquimbo	(52-69)
Cautín	(6-12)	Maule	(28-33)	Santiago	(39-43)	Atacama	(69-88)
Arauco	(12-18)	Talca	(33-34)	Valparaíso	(43-48)	Antofagasta	(88-116)
Concepción	(18-26)	Curicó	(34-36)	Aconcagua	(48-52)	Tarapacá	(116-134)

Figure 11-28B

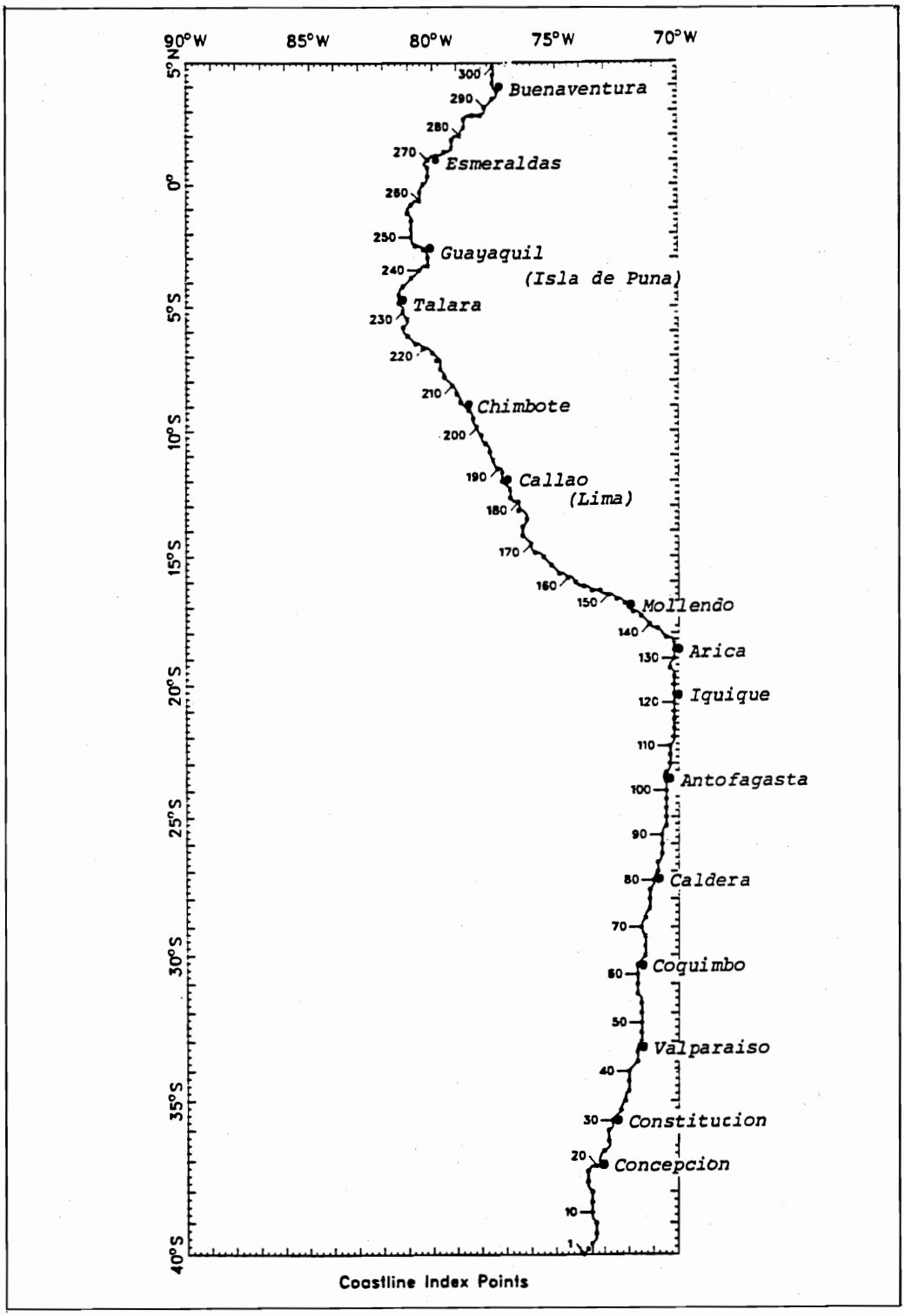


PERU				ECUADOR		COLOMBIA	
Department	(index code)			Province	(index code)	Department	(index code)
Tacna	(134-140)	Ancash	(196-205)	El Oro	(242-244)	Nariño	(275-286)
Moquegua	(140-143)	La Libertad	(205-215)	Guayas	(244-253)	Cauca	(286-291)
Arequipa	(143-164)	Lambayeque	(215-224)	Manabí	(253-266)	Valle	(291-296)
Ica	(164-178)	Piura	(224-236)	Esmeraldas	(266-275)	Choco	(296-300)
Lima	(178-196)	Tumbes	(236-242)				

Source: Adapted from Hebenstreit, G.T., and Whitaker, R.E. Assessment of Tsunami Hazard Presented by Possible Seismic Events: Near Source Effects (McLean, Virginia: Science Applications, 1981).

Figure 11-29

COASTLINE INDEX POINTS AND MAIN POPULATION CENTERS FOR THE AREA COVERED BY FIGURES 28A AND 28B



Source: Hebenstreit, G.T., and Whitaker, R.E. Assessment of Tsunami Hazards Presented by Possible Seismic Events: Near Source Effects (McLean, Virginia: Science Applications, 1981).

Figure 11-30

TSUNAMI HAZARDS FOR POPULATION CENTERS IN SOUTH AMERICA

COUNTRY, Department or Province	Location of Calculated and/or Reported Wave Height 2-3m	3-5m	Above 5m
COLOMBIA			
Cauca	Guapi (h)		
Nariño	San José (c)	Pizarro (h)	
	Majagual (c)	La Chorrera (h)	
	San Juan (c)	Chagui (h)	
		Trapiche (h)	
		Tumaco (h)	
		Papayal (h)	
ECUADOR			
Esmeraldas	Muisne (c)	Esmeraldas (h)	
Manabí	Pedernales (c)	Isla Salango (c)	
		Bahía de Caraquez (c)	
		Manta (c)	
Guayas	Guayaquil (h)	Isla Puna (c)	
El Oro	Machala (c)		

COUNTRY, Department or Province	Location of Calculated and/or Reported Wave Height 2-3m	3-5m	Above 5m	
PERU				
Tumbes	Pto. Pizarro (c)			
Piura	Paita (c)	San Pedro (c)		
	Bayóvar (c)	Balneario Leguía (c)		
		Sechura (c)		
Lambayeque		San José (c)	Pimentel (b)	
			Santa Rosa (c)	
			Puerto de Etén (b)	
La Libertad		Trujillo (h)	Pacasmayo (c)	
		Tambo (h)	Puerto Chicama (c)	
			Santiago de Cao (c)	
			Huanchaco (c)	
			Víctor Larco Herrera (c)	
			Salaverry (c)	
Ancash	Chimbote (h)	Santa (h)	Santa (c)	
		Samancos (h)	Chimbote (c)	
		Casma (h)	Samancos (c)	
		Caleta Tortuga(h)	Caleta Tortuga (c)	
			Casma (c)	
			Culebras (c)	
			Huarmey (c)	
Lima			Pativilca (c)	Ancón (c)
			Barranca (c)	Callao (a
			Supe (b)	Lima (c)
			Huaura (c)	Lurín (c)
			Huacho (c)	Pucusana
			Hualmay (c)	Chilca (c)
			Salinas (b)	Mala (c)
			Chancay (c)	San Vicén

Figure 11-30 (continued)

COUNTRY, Department or Province	Location of Calculated and/or Reported Wave Height 2-3m	3-5m	Above 5m
PERU (cont.)			
Ica		Pisco (h)	Tambo de Mora (c) Pisco (c) San Andrés (c) Paracas (c) Pto. Caballos (c) San Juan (c)
Arequipa	Lomas (h)	Mollendo (h)	Lomas (c) Quilca (c) Yauca (c) Matarani (c) Chala (b) Islay (b) Atico (c) Mollendo (c) Camaná (c) Mejía (c)
Moquegua			Ilo (b)
Tacna			Los Baños (c) La Yarada (c) Pascana del Hueso (c)

COUNTRY, Department or Province	Location of Calculated and/or Reported Wave Height 2-3m	3-5m	Above 5m
CHILE			
Tarapacá			Arica (b) Pisagua (b) Iquique (b) Chanabaya (h) Caleta Pabellón de Pica (h) Punta Lobos (b) Guanillo del Norte (h)
Antofagasta			Tocopilla (b) Cobija (h) Mejillones (b) Antofagasta (b) Taltal (c)
Atacama		Huasco (h)	Chanaral (b) Caldera (b) Carrizal Bajo (c) Huasco (c)
Coquimbo	Tongoy (c)	La Serena (c) Coquimbo (c) Los Vilos (c)	Coquimbo (h)
Aconcagua		Papudo (c) Zapallar (c)	
Valparaíso		Quintero (c) Valparaíso (h)	Juan Fernández Is. (h) Concón (c) Viña del Mar (c) Valparaíso (c) Laguna Verde (c) Algarrobo (c) El Quisco (c)

Figure 11-30 (continued)

COUNTRY, Department or Province	Location of Calculated and/or Reported Wave Height 2-3m	3-5m	Above 5m
CHILE (cont.)			
Santiago			El Tabo (c) Las Cruces (c) Cartagena (c) San Antonio (c) Llolleo (c)
Colchagua			Pichilemu (c)
Curicó			Iloca (c)
Maule		Chanco (c)	Constitución (b) Curanipe (c)
Ñuble			Buchupureo (c) Coloquecura (c)
Concepción	Laraquete (c)	Dichato (c) Tomé (b) Coronel (h)	Coelemu (h) Cerro Verde (c) Penco (c) Talcahuano (b) Concepción (b) Coronel (c) Schwager (c) Lota (c)
Arauco	Arauco (c)	Lebu (b) Pto. Tirna (h)	
Cautín		Pto. Saavedra (c) Nahuentue (c)	Isla Mocha (h) Mehuín (b) Toltén (c) Pto. Saavedra (h)
Valdivia	Mancera Is.(h)	Niebla (c) Corral (c)	Corral (h) Valdivia (h)
Osorno			Mansa River (h)
Chiloé	Pindo Is. (h)		Ancud (h) Chiloé Is. (h) Guafo (h)
Aisén	Puerto Aisén (h)		

Legend:
- c: Calculated wave height
- h: Historically recorded wave height
- b: Both c and h

Source: Based on Hebenstreit, G.T., and Whitaker, R.E. Assessment of Tsunami Hazard Presented by Possible Seismic Events: Near Source Effects (McLean, Virginia: Science Applications Inc., 1981); and Lockridge, P.A. Report SE-39 - Tsunamis in Peru-Chile (Boulder, Colorado: World Data Center A for Solid Earth Geophysics, 1985).

A mathematical model combines hypothetical earthquakes with ocean-bottom topography to estimate the height of tsunamis that could be generated by different mechanisms in six gap areas, giving both near-source and far-field heights along the coast from central Colombia to southern Chile. While the study does not attempt to predict actual earthquakes and resulting tsunamis, the results are probably representative of those that could occur in a given area. The water-level anomaly, or wave height above mean sea level, calculated for tsunamis generated by uniform-uplift earthquakes in the principal seismic gap areas of the Pacific coast of South America is shown in Figures 11-28A and 11-28B. Figure 11-28A covers Chile from the Department of Valdivia to the northern border. Figure 11-28B covers the area from the southern border of Peru to the Department of Chocó in Colombia. The approximate location of population centers is shown in Figure 11-29; Figure 11-30 summarizes the results in tabular form. Certain areas seem to be threatened by all or most tsunamis, regardless of the location of the earthquake that generated them. Such locations include the stretch from Guayaquil, Ecuador, to Chimbote, Peru; Callao and Pisco, Peru; and Arica, Iquique, Taltal, Caldera, and Coquimbo-to-Valdivia, Chile.

Of course, as the author of the study, Gerald Hebenstreit, points out, the threat is not uniform, but "making a distinction between a seven meter wave and a twelve meter wave seems pointless. Both are going to be highly destructive in most cases" (Hebenstreit, 1981).

Conclusions

A great deal of information on geologic hazards and their mitigation now exists for Latin America and the Caribbean. There is a gap, however, between the existence of this information and its use by development planners: planners may find it difficult to obtain it or incorporate it into the development process.

This chapter has provided guidelines on the use of geologic hazard information for development planning, and catalogues information at a general level. The next obvious step is to proceed to the national level. For each member state, a compilation should be made of existing information and information being prepared on hazards associated with ground shaking, landslides, liquefaction, volcanic eruptions, and tsunamis and on mitigation, monitoring, and warning measures now in place. Such a catalogue could also include a brief guide on how to use the information in a development planning study. These guides could be prepared cheaply and quickly. Yet they could greatly increase the value of expenditures already made for scientific and engineering studies of geologic hazards.

References

Key to symbols found at the beginning of selected citations:

H = General Hazards
G = General Geologic Hazards
E = General Earthquake Hazards
EG = Ground Shaking and Fault Rupture
V = Volcanic Hazards
EL = Landslides and Liquefaction
T = Tsunami Hazards
* = Important reference (any category)

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CHAPTER 12

HURRICANE HAZARDS

CHAPTER 12

HURRICANE HAZARDS

Contents

List of Figures

HURRICANE HAZARDS

SUMMARY

This chapter describes the nature of hurricanes and their destructive capability. It outlines measures that can be taken to reduce the impact of a hurricane and, in particular, identifies appropriate mitigation measures for small towns and villages.

The destruction caused by hurricanes in the Caribbean and Central America is a force that has shaped history and will shape the future of the region. The danger arises from a combination of factors that characterize tropical cyclonic storms: rise in sea level, violent winds, and heavy rainfall. In the Greater Caribbean Basin from 1960 through 1988 (excluding the United States and U.S. territories) hurricanes caused more than 20,000 deaths, affected 6 million people, and destroyed property worth over US$9.5 billion (OFDA, 1989). The great bulk of this harm was done to the Caribbean island countries, whose small economies are least able to withstand such impacts.

Data on hurricane damage have been collected since the discovery of the Americas, and recent statistics show that mitigation measures have made a difference since the 1930s. While the ferocity of the storms has not abated over the years, and population has increased substantially in the area, the casualty rate has decreased as a result of the incorporation of mitigation measures and the increased effectiveness of preparedness activities. This improvement in saving lives has been countered by a marked increase in property damage. This is a clear indicator that structural mitigation measures are not keeping pace with the rapid increase in development in vulnerable areas.

A important feature of this chapter is its detailed discussion of hurricane hazard mitigation in small towns and villages. In this setting, largely beyond the reach of national mitigation activities, simple strategies are both essential and highly effective.

A. Hurricane: the Phenomenon

"Tropical cyclone" is the scientific term for a closed meteorological circulation that develops over tropical waters. These large-scale non-frontal low-pressure systems occur throughout the world over zones referred to as "tropical cyclone basins" (NOAA, 1987). The name for them varies: in the Atlantic and northeast Pacific they are called "hurricanes" after the Mayan word for devil, in the northwest Pacific "typhoons," and in the South Pacific and Indian Ocean simply "cyclones." Of all tropical cyclone occurrences, 75 percent develop in the northern hemisphere, and of these, only one out of three are hurricanes in the northeast Pacific or northwest Atlantic (UNDRO,1978). The storms of the northern hemisphere travel westward; those of the southern hemisphere move eastward.

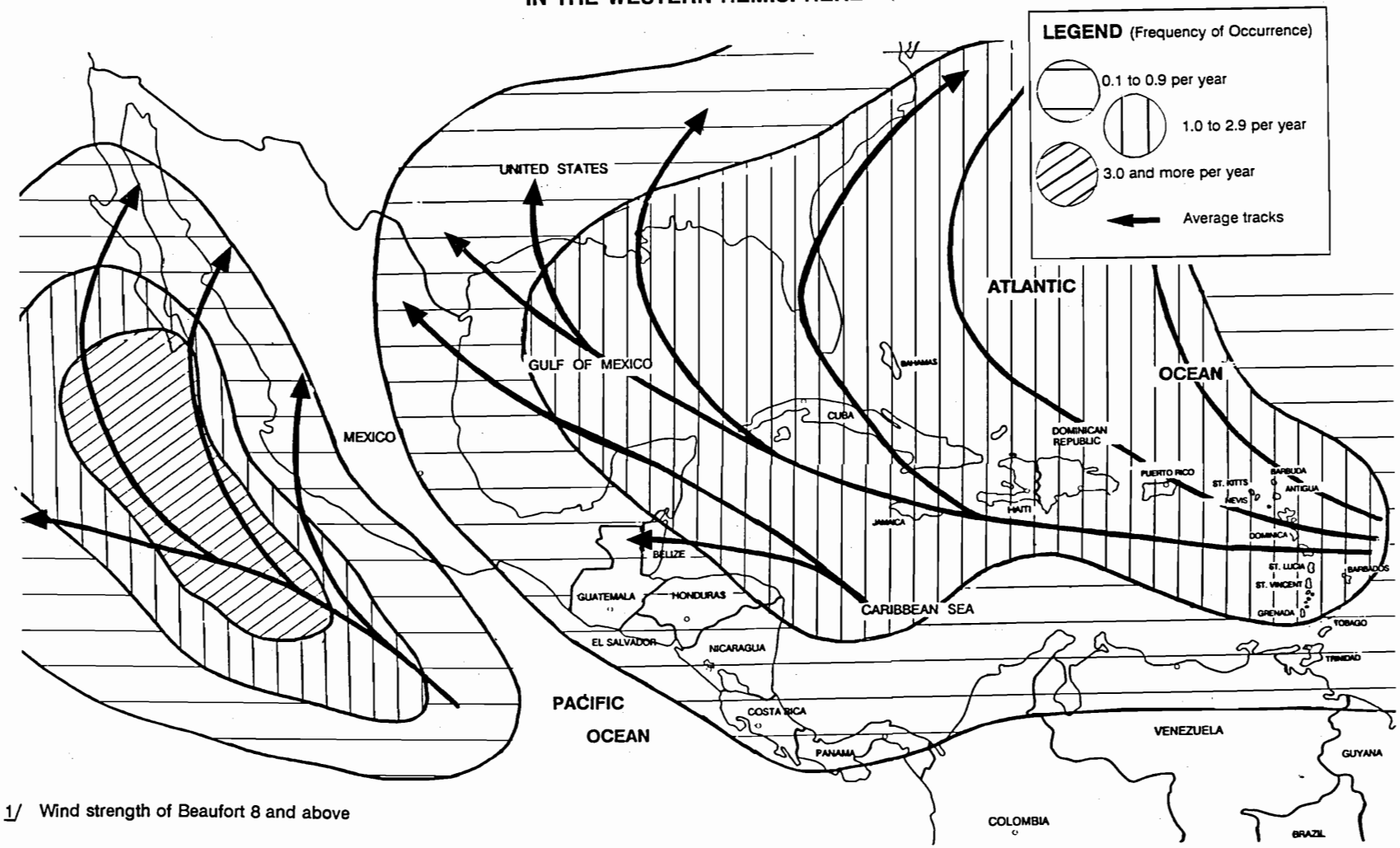
In the Atlantic tropical cyclone basin, which includes the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico, hurricanes originate mostly in the northern Atlantic and to a lesser degree in the Caribbean. The areas most at risk are the Caribbean island countries north of Trinidad (73 strikes by major hurricanes between 1900 and 1988), Mexico and the southeastern United States, Central America north of Panama, and to a limited extent the northern coast of South America (Tomblin, 1979). Hurricanes also originate in the northeast Pacific, where they can affect the west coast of Mexico. Most of South America is essentially at no risk, because the tropical southwestern Atlantic and the southeastern Pacific are devoid of these meteorological occurrences, but systems originating on the west coast of Africa can potentially strike the northernmost part of the continent; for example, in 1988 Hurricane Joan formed on the northwestern coast of Africa and struck the coast of Venezuela and Colombia before hitting eastern Nicaragua. Figure 12-1 shows the paths of the hurricanes originating in the Atlantic, the Pacific, and the Caribbean.

1. HURRICANE DEVELOPMENT

All of the embryonic tropical depressions that develop into hurricanes originate in similar meteorological conditions and exhibit the same life cycle. The distinct stages of hurricane development are defined by the "sustained velocity" of the system's winds--the wind velocity readings maintained for at least one minute near the center of the System. In the

Figure 12-1

OCCURRENCE OF TROPICAL STORMS AND CYCLONES IN THE WESTERN HEMISPHERE 1/



1/ Wind strength of Beaufort 8 and above

Source: Munchener Ruck. Mapa Mundial de los Riesgos de la Naturaleza. (Munich, Federal Republic of Germany, Munchener Ruckversicherungs: 1988)

formative stages of a hurricane, the closed isobaric circulation is called a **tropical depression**. If the sustained velocity of the winds exceeds 63km/h (39 mph), it becomes a **tropical storm**. At this stage it is given a name and is considered a threat. When the winds exceed 119km/h (74 mph), the system becomes a **hurricane**, the most severe form of tropical storm. Decay occurs when the storm moves into nontropical waters or strikes a landmass. If it travels into a nontropical environment it is called a **subtropical storm and subtropical depression**; if landfall occurs, the winds decelerate and it becomes again a **tropical storm and depression**. Figure 12-2 summarizes this classification.

a. Birth: Tropical Depression

Hurricanes are generated at latitudes of 8 to 15 degrees north and south of the Equator as a result of the normal release of heat and moisture on the surface of tropical oceans. They help maintain the atmospheric heat and moisture balance between tropical and non-tropical areas. If they did not exist, the equatorial oceans would accumulate heat continuously (Landsberg, 1960).

Hurricane formation requires a sea surface temperature of at least 27 degrees Celsius (81 degrees Fahrenheit). In the summer months, the sea temperatures in the Caribbean and Atlantic can reach 29 degrees (84 degrees), making them prime locations for inception. The surface water warms the air, which rises and then is blocked by warmer air coming from the easterly winds. The meeting of these two air masses creates an atmospheric inversion. At this stage, thunderstorms develop and the inversion may be broken, effectively lowering the atmospheric pressure.

b. Growth: Tropical Storm and Hurricane

The growth of the system occurs when pressure in the center of the storm drops well below 1000 millibars (mb) while the outer boundary pressure remains normal. When pressure drops, the trade winds are propelled in a spiral pattern by the earth's rotation. The strong torque forces created by the discrepancy in pressure generate wind velocities proportional to gradient of pressure. As the energy level increases, the air circulation pattern is inward towards the low pressure center and upward, in a counter-clockwise spiral in the northern hemisphere and clockwise in the southern hemisphere. The cycle perpetuates itself and the organized storm begins a translational movement with velocities of around 32 km/h during formation and up to 90km/h during the extra-tropical life.

The zone of highest precipitation, most violent winds, and rising sea level is adjacent to the outer wall of the "eye." The direction of the winds, however, is not towards the eye but is tangent to the eye wall about 50km from the geometric center (Mathur, 1987). The organized walls of clouds are composed of adjoining bands which can typically reach a total diameter of 450km (Earthscan No. 34-a, 1983). The central eye, unlike the rest of the storm, is characterized as an area of relatively low wind speeds and no cloud cover with an average diameter of 50-80km and a vertical circulation of up to 15km.

Hurricane classification is based on the intensity of the storm, which reflects damage potential. The most commonly used categorization method is the one developed by H. Saffir and R.H. Simpson (Figure 12-3). The determination of a category level depends mostly on barometric pressure and sustained wind

Figure 12-2

CLASSIFICATION OF HURRICANE DEVELOPMENT

ENVIRONMENT	DEVELOPMENT	CRITERIA
Tropical	Depression	max sustained winds < or = 63km/h (39 miles/h)
	Tropical Storm	63km/h < sustained winds < 119km/h (74 miles/h)
	Hurricane	sustained winds > or = 119km/h (74 miles/h)
	Tropical Depression (dissipation)	max sustained winds < or = 63km/h (39 miles/h)
Nontropical	Subtropical Storm (dissipation)	63km/h < sustained winds < 119km/h (74 miles/h)
	Subtropical Depression (dissipation)	max sustained winds < or = 63km/h (39 miles/h)

Source: Adapted from Neumann, C.J. et al. Tropical Cyclones of the North Atlantic Ocean, 1871-1986 (Washington, D.C.: U.S. Department of Commerce, NOAA, 1987).

Figure 12-3

SAFFIR-SIMPSON HURRICANE SCALE (SSH)

Hurricane Category Number	Sustained Winds (km/h)	Sustained Winds (miles/h)	Atmospheric Pressure in the Eye (millibars)	Storm Surge (meters)	Storm Surge (feet)	Damage Level
1	119 - 153	74 - 95	980	1.2 - 1.5	4.0 - 4.9	Low
2	154 - 177	96 - 110	965 - 979	1.8 – 2.4	5.9 - 7.9	Moderate
3	179 - 209	111 - 130	945 - 964	2.7 – 3.7	8.9 - 12.2	Extensive
4	211 - 249	131 - 155	920 - 944	4.0 – 5.5	13.0 - 18.0	Extreme
5	> 249	> 155	< 920	> 5.5	> 18.0	Catastrophic

Source: Adapted from Oliver, J., and Fairbridge, R. The Encyclopedia of Climatology (New York: Van Nostrand Reinhold Co., Inc., 1987).

velocities. Levels of storm surge fluctuate greatly due to atmospheric and bathymetric conditions. Thus, the expected storm surge levels are general estimates of a typical hurricane occurrence.

c. Death: Landfall or Dissipation

Typically, a hurricane eventually dissipates over colder waters or land about ten days after the genesis of the system. If it travels into a non-tropical environment, it loses its energy source and falls into the dominant weather pattern it encounters. If, on the other hand, it hits land, the loss of energy in combination with the increased roughness of the terrain will cause it to dissipate rapidly (Frank, 1984). When it reaches land in populated areas, it becomes one of the most devastating of all natural phenomena.

2. TEMPORAL DISTRIBUTION OF HURRICANE OCCURRENCE IN THE CARIBBEAN

The official hurricane season in the Greater Caribbean region begins the first of June and lasts through November 30, with 84 percent of all hurricanes occurring during August and September (Frank, 1984). Figure 12-4 shows the seasonal character of hurricanes. The greatest risk in Mexico and the western Caribbean is at the beginning and end of the season, and in the eastern Caribbean during mid-season.

Every year over 100 tropical depressions or potential hurricanes are monitored, but an average of only ten reach tropical storm strength and six become hurricanes. These overall averages suggest that activity is uniform from year to year but historical records indicate a high degree of variance, with long periods of tranquillity and activity (Figure 12-5). The Atlantic basin has the widest seasonal variability. In 1907, for example, not a single tropical storm reached hurricane intensity, while in 1969, there were 12 hurricanes in the northern Atlantic (NOAA, 1987). Because the cycles vary in periodicity and duration, prediction is difficult. Recent forecasting developments, connecting hurricane activity levels with El Niño and the Quasi-biennial Oscillation have made it possible to predict the variance in Atlantic seasonal hurricane activity with an accuracy of 40 to 50 percent (American Meteorological Society, 1988), but this degree of accuracy, while considered high by meteorological standards, is not good enough for planners trying to develop appropriate emergency response systems. There is no doubt that the quality of forecasting will continue to improve, but until that happens planners must rely on historical information to calculate the probability of occurrence in a given year. Simpson and Lawrence in 1971 used historical data to make these calculations for the entire east coast of the United States and Gulf of Mexico coast, using 80km (50 miles) segments (ESCAP/WMO, 1977).

3. HAZARDOUS CHARACTERISTICS OF HURRICANES

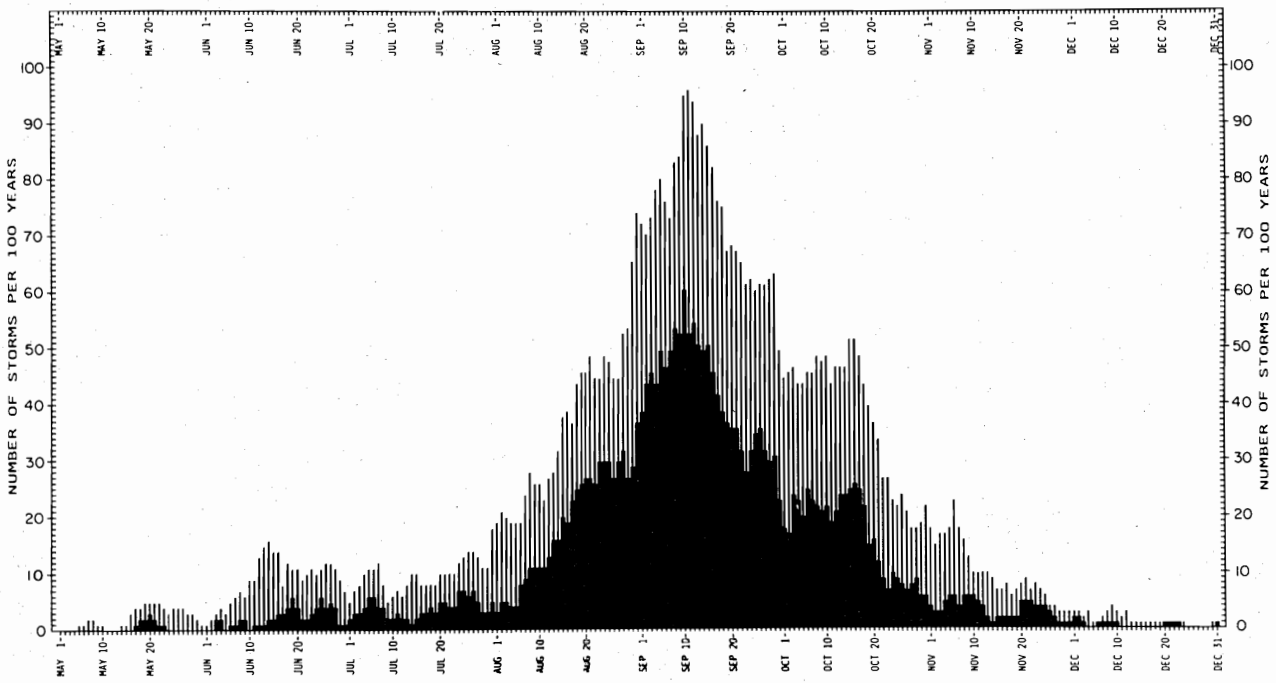
a. Winds

Hurricane wind speeds can reach up to 250km/h (155mph) in the wall of the hurricane, and gusts can exceed 360km/h (224mph).The destructive power of wind increases with the square of its speed. Thus, a tripling of wind speed increases destructive power by a factor of nine. Topography plays an important role: wind speed is decreased at low elevations by physical obstacles and in sheltered areas, while it is increased over exposed hill crests (Davenport, 1985; see Figure 12-6). Another contributor to destruction is the upward vertical force that accompanies hurricanes; the higher the vertical extension of a hurricane, the greater the vertical pulling effect.

Destruction is caused either by the direct impact of the wind or by flying debris. The wind itself primarily damages agricultural crops. Entire forests have been

Figure 12-4

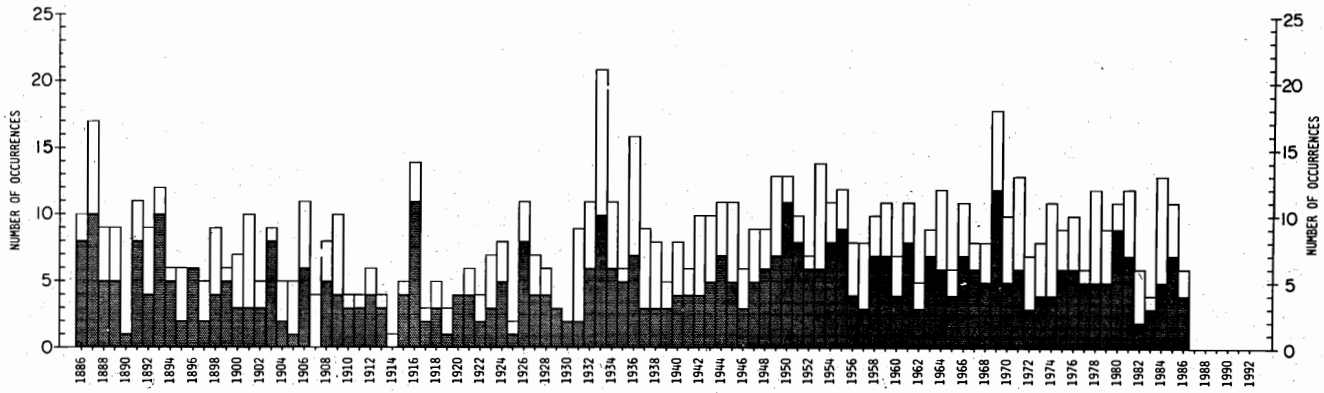
NUMBER OF TROPICAL STORMS AND HURRICANES (open bar) AND HURRICANES (solid bar) OBSERVED ON EACH DAY, MAY 1-DECEMBER 31, 1886 THROUGH 1986, IN THE NORTH ATLANTIC OCEAN



Source: Neumann, C.J. et al. Tropical Cyclones of the North Atlantic Ocean, 1871-1986 (Washington, D.C.: U.S. Department of Commerce, NOAA, 1987).

Figure 12-5

ANNUAL DISTRIBUTION OF THE 845 RECORDED TROPICAL CYCLONES IN THE NORTH ATLANTIC REACHING AT LEAST TROPICAL STORM STRENGTH (open bar) AND THE 496 REACHING HURRICANE STRENGTH (solid bar), 1886 THROUGH 1986

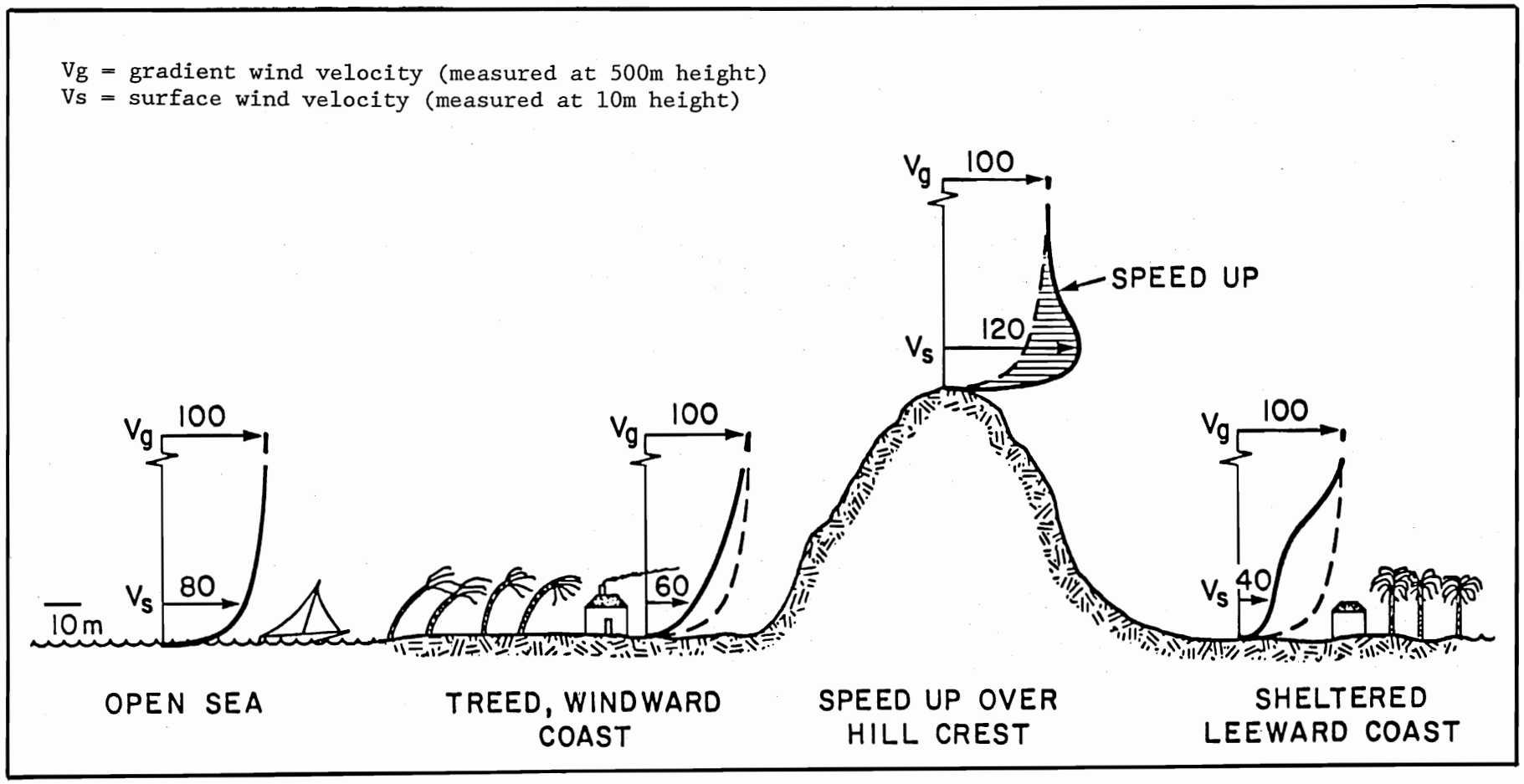


Note: The average number of such storms is 8.4 and 4.9 respectively.

Source: Neumann, C.J. et al. Tropical Cyclones of the North Atlantic Ocean, 1871-1986 (Washington, D.C.: U.S. Department of Commerce, NOAA, 1987).

Figure 12-6

ISLAND TOPOGRAPHIC EFFECTS ON MEAN SURFACE WIND SPEEDS



Source: Davenport, A.G. Georgiou, P.N., and Surry, D. A Hurricane Wind Risk Study for the Eastern Caribbean, Jamaica and Belize with Special Consideration to the Influence of Topography. (London, Ontario, Canada: Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, 1985).

flattened by forces that pulled the tree roots from the earth. Man-made fixed structures are also vulnerable. Tall buildings can shake or even collapse. The drastic barometric pressure differences in a hurricane can make well-enclosed structures explode and the suction can lift up roofs and entire buildings. But most of the destruction, death, and injury by wind is due to flying debris (ECLAC/UNEP, 1979), the impact force of which is directly related to its mass and the square of its velocity. The damage caused by a flying car to whatever it strikes will be greater than if the wind had acted alone. Improperly fastened roof sheets or tiles are the most common projectiles. Other frequent objects are antennas, telephone poles, trees, and detached building parts.

Building standards to withstand high wind velocities are prescribed in almost all countries that face a high risk. The codes recommend that structures maintain a certain level of strength in order to withstand the local average wind velocity pressure, calculated by averaging wind pressure over a period of ten minutes for the highest expected wind speed in 50 years. The Caribbean Uniform Building Code (CUBIC) under consideration by the Caribbean countries, prescribes the reference wind velocity pressure for each country. Figure 12-7 shows the relationship between wind speed, expressed in the codes in terms of meters per second rather than kilometers or miles per hour, and general property damage. Note the correlation between this and the SSH scale in Figure 12-3.

b. Rainfall

The rains that accompany hurricanes are extremely variable and hard to predict (ECLAC/UNEP, 1979). They can be heavy and last several days or can dissipate in hours. The local topography, humidity, and the forward speed of a hurricane in the incidence of precipitation are recognized as important, but attempts to determine the direct connection have so far proved futile.

Intense rainfall causes two types of destruction. The first is from seepage of water into buildings causing structural damage; if the rain is steady and persistent, structures may simply collapse from the weight of the absorbed water. The second, more widespread and common and much more damaging, is from inland flooding, which puts at risk all valleys along with their structures and critical transportation facilities, such as roads and bridges. Chapter 8 describes flooding in more detail.

Landslides, as secondary hazards, are often triggered by heavy precipitation. Areas with medium to steep slopes become oversaturated and failure occurs along the weakest zones. Thus, low-lying valley areas are not the only sites vulnerable to precipitation. Chapter 10 is devoted to this phenomenon.

c. Storm Surge

A storm surge is a temporary rise in sea level caused by the water being driven over land primarily by the on-shore hurricane force winds and only secondarily by the reduction in sea-level barometric pressure between the eye of the storm and the outer region. A rough relationship between atmospheric pressure and the storm surge level was shown in Figure 12-3. Another estimate is that for every drop of 100 millibars (mb) in barometric pressure, a 1m (3.28 feet) rise in water level is expected. The magnitude of the surge at a specific site is also a function of the radius of the maximum hurricane winds, the speed of the system's approach, and the foreshore bathymetry. It is here that the difficulty arises in predicting storm surge levels. Historical records indicate that the increase in mean sea level can be negligible or can be as much as 7.5 meters (24.6 feet) (ECLAC/UNEP, 1979). The most vulnerable coastal zones are those with the highest historical frequencies of landfalls. Regardless of its height, the great dome of water is often 150km (93 miles) wide and moves toward the coastline where the hurricane eye makes landfall.

Figure 12-7

RELATIONSHIP BETWEEN WIND SPEED AND GENERAL PROPERTY DAMAGE

Wind Speed	Damage
22-35m/sec	minor
36-45m/sec	intermediate (loss of windows)
>45m/sec	structural

Source: ECLAC/UNEP. Natural Disasters Overview. Meeting of Government-Nominated Experts to Review the Draft Action Plan for the Wider Caribbean Region, Caracas, Venezuela, 28 January - 1 February (Caracas: ECLAC/UNEP, 1979).

Storm surges present the greatest threat to coastal communities. Ninety percent of hurricane fatalities are due to drowning caused by a storm surge. Severe flooding from a storm surge affects low-lying areas up to several kilometers inland. The height of the surge can be greater if man-made structures in bays and estuaries constrict water flow and compound the flooding. If heavy rain accompanies storm surge and the hurricane landfall occurs at a peak high tide, the consequences can be catastrophic. The excess water from the heavy rains inland creates fluvial flooding, and the simultaneous increase in sea level blocks the seaward flow of rivers, leaving nowhere for the water to go.

B. Historical Occurrence and Impact on the Americas: Hurricane Gilbert

Hurricanes are by far the most frequent hazardous phenomena in the Caribbean. Tomblin (1981) states that in the last 250 years the West Indies has been devastated by 3 volcanic eruptions, 8 earthquakes, and 21 major hurricanes. If tropical storms are also taken into account, the Greater Caribbean area has suffered from hundreds of such events.

The economic and social consequences of this phenomenon are severe, especially in less developed countries, where a significant percentage of the GDP can be destroyed by a single event. Figure 12-8 lists the major hurricanes and tropical storms in the Americas and the damage they caused.

Without a comprehensive list of costs and casualties, the economic and social disruption caused by a disastrous event is hard to grasp. It is not the purpose of this chapter to provide all this information, which can be found in the great volume of literature on individual events. But a brief review of how one hurricane affected various sectors in Mexico and Jamaica will help planners to understand the complexities of the turmoil that such a natural event can cause.

Hurricane Gilbert struck the Caribbean and the Gulf Coast of Mexico in 1988, causing comprehensive damage in Mexico, Jamaica, Haiti, Guatemala, Honduras, Dominican Republic, Venezuela, Costa Rica, and Nicaragua. Arriving in Saint Lucia as a tropical depression, it resulted in damage estimated at US$2.5 million from the flooding and landslides caused by the heavy rain (Caribbean Disaster News No.15/16, 1988).

The physical variations in this hurricane resulted in different types of damage. It was considered a "dry" hurricane when it struck Jamaica, discharging less precipitation than would be expected. Thus, most of the damage was due to wind force which blew away roofs. By the time it approached Mexico, however, it was accompanied by torrential rains, which caused massive flooding far inland.

Hurricane Gilbert began as a tropical wave on September 3, 1988, on the north coast of Africa. Six days later, the system was across the Atlantic and had evolved into Gilbert as a tropical storm. It struck Jamaica on September 12 as a Category 3 (SSH Scale) hurricane and traveled westward over the entire length of the island. Gaining strength as it moved northwest, it hit the Yucatan Peninsula, in Mexico, on September 14, as a Category 5 (SSH Scale) hurricane. By September 16 it had been weakened and finally dissipated after moving inland over the east coast of Mexico.

Sustained winds in Jamaica were measured at 223 km/h, and greater across high ridges. The barometric pressure was the lowest ever recorded in the Western Hemisphere at 888mb, 200km east-southeast of Jamaica. The barometric pressure when it hit Jamaica was 960mb. The forward speed was 31 km/h. The eye had a 56km diameter, but little storm surge occurred in Jamaica. Average rainfall registered from 250mm to 550mm. Serious flooding due to storm surge and heavy rains was not a problem. Landslides occurred at high elevations where most of the rainfall was concentrated.

By the time Hurricane Gilbert hit Mexico it had changed characteristics. In the Yucatan the storm surge reached 5 meters in height and rainfall averaged 400mm. By the time Gilbert struck the northern coast of Mexico, the winds had increased to 290km/h and the storm surge had reached 6 meters.

1. JAMAICA

a. Affected Population and Damage to Social Sectors

Even though the loss of life was limited to 45 reported deaths, 500,000 people lost their homes when approximately 280,000 houses--almost 55 percent of the housing stock--were damaged. Of these, 14,000, or 5 percent, were totally destroyed and 64,000 were seriously damaged.

b. Impact on the Economy and Damage to Productive Sectors

The Planning Institute of Jamaica estimated the total direct damage at US$956 million. Nearly half was accounted for by losses from agriculture, tourism, and industry; 30 percent from housing, health, and

Figure 12-8

MAJOR TROPICAL STORMS AND HURRICANES OF THE ATLANTIC TROPICAL CYCLONE BASIN

REGION/COUNTRY	YEAR/MONTH	CASUALTIES	PEOPLE AFFECTED	DAMAGE THOUSANDS/US$	HURRICANE NAME	SOURCE
CARIBBEAN						
Antigua	1792 00					Tomblin
	1950 09	2		1,000	Dog	OFDA
	1960 09	2			Donna	OFDA
	1966 09					OFDA
Barbados	1780 00	4,326				Tomblin
	1786 00					Tomblin
	1831 00	2,000				Tomblin
	1955 09	57			Janet	OFDA
Belize	1931 09	1,500		7,500		OFDA
	1955 09	16		5,000	Janet	OFDA
	1961 09	275		60,000		OFDA
	1974 09		70,000	4,000	Carmen, Fifi	OFDA
	1978 09	5	6,000	6,000	Greta	OFDA
Cuba	1768 00	1,000				Tomblin
	1844 00					Tomblin
	1846 00	500				Tomblin
	1926 10	600				OFDA
	1932 11	2,500				OFDA
	1935 09	35	500			OFDA
	1948 09	3		12,000		OFDA
	1948 10	11	300	6,000		OFDA
	1963 10	1,750				Tomblin
	1966 09	5	156,000	18,000	Inez	OFDA
	1968 10	0			Gladys	OFDA
	1982 06	24	105,000	85,000		OFDA
	1985 11	4	476,891		Kate	OFDA
Dominica	1806 00					Tomblin
	1834 00	200				Tomblin
	1963 09			2,600	Edith	OFDA
	1979 08	40	70,000	44,650	David, Frederick	OFDA
	1984 10	2	10,000	2,000	Klaus	OFDA
Dominican Republic	1930 09	2,000	6,000	40,000		OFDA
	1963 10	400		60,000	Flora	OFDA
	1964 08	7		1,000	Cleo	OFDA
	1966 09	74	7,000	5,000	Inez	OFDA
	1979 08	1,400	1,200,000	150,000	David, Frederick	OFDA
	1987 09	3		23,700	Emily	OFDA
Grenada	1963 09	6			Flora	OFDA
Haiti	1909 11	150				OFDA
	1915 08	1,600				OFDA
	1935 10	2,150				OFDA
	1954 10	410	250,000		Hazel	OFDA
	1963 10	5,000		180,000	Flora	OFDA
	1964 08	100	80,000	10,000	Cleo	OFDA
	1966 09	480	67,000	20,000	Inez	OFDA
	1979 08	8	1,110		David	OFDA
	1980 08	300	330,000	40,000	Allen	OFDA
	1988 09	54	870,000	91,286	Gilbert	OFDA
Jamaica	1722 00	400				Tomblin
	1780 00	300				Tomblin
	1786 00					Tomblin
	1880 00	30				Tomblin
	1903 08	65				OFDA
	1912 11	142				OFDA

Figure 12-8 (continued)

REGION/COUNTRY	YEAR/MONTH	CASUALTIES	PEOPLE AFFECTED	DAMAGE THOUSANDS/US$	HURRICANE NAME	SOURCE
Jamaica (cont.)	1917 09	57				OFDA
	1933 10	10				OFDA
	1935 10		2,000			OFDA
	1944 08	32				OFDA
	1951 08	154	20,000	56,000	Charlie	OFDA
	1963 10	11		11,525	Flora	OFDA
	1980 08	6	30,000	64,000	Allen	OFDA
	1985 11	7		5,200	Kate	OFDA
	1988 09	49	810,000	1,000,000	Gilbert	OFDA
St. Kitts/Nevis	1772 00					Tomblin
	1792 00					Tomblin
	1928 09					OFDA
	1955 01					OFDA
Saint Lucia	1960 07				Abby	OFDA
	1963 09	10		3,465	Edith	OFDA
	1980 08	9	70,000	87,990	Allen	OFDA
St. Vincent	1898 00	300				Tomblin
	1955 09	122			Janet	OFDA
	1980 08		20,000	16,300	Allen	OFDA
	1987 09		200	5,300	Emily	OFDA
Trinidad/Tobago	1933 06	13		3,000		OFDA
	1963 09	24		30,000	Flora	OFDA
CENTRAL AMERICA						
Costa Rica	1988 10	28	120,000		Joan	OFDA
El Salvador	1969 09	2	4,600	1,600	Francelia	OFDA
Guatemala	1969 09	269	10,200	15,000	Francelia	OFDA
Honduras	1969 09		8,000	19,000	Francelia	OFDA
	1974 09	8,000	600,000	540,000	Fifi	OFDA
	1978 09		2,000	1,000	Greta	OFDA
Nicaragua	1971 09	35	2,800	380	Edith	OFDA
	1988 10	120	300,000	400,000	Joan	OFDA
Panama	1988 10	7	7,000	60,000	Joan	OFDA
NORTH AMERICA (EXCLUDING THE UNITED STATES)						
Mexico	1951 08	50				OFDA
	1955 09	300			Hilda	OFDA
	1955 09	500		40,000	Janet	OFDA
	1960 10	960				OFDA
	1961 11	436			Tara	OFDA
	1966 10	14	80,000	24,000	Inez	OFDA
	1967 08	77	271,000	184,000	Katrina, Beulah	OFDA
	1975 10	29			Olivia	OFDA
	1976 10	600	175,000	100,000	Liza	OFDA
	1977 09	10	50,000		Anita	OFDA
	1982 09	225	50,000	30,000	Paul	OFDA
	1983 10	135			Tico	OFDA
	1988 09	240	100,000		Gilbert	OFDA

Sources: Tomblin, J. "Natural Disasters in the Caribbean: A Review of Hazards and Vulnerability," in Caribbean Disaster Preparedness Seminar, St. Lucia, June, 1979 (Washington, D.C.: OFDA/USAID, 1979); and Office of Foreign Disaster Assistance, U.S. Agency for International Development (OFDA/USAID). Disaster History: Significant Data on Major Disasters Worldwide, 1900-Present. July, 1989. (Washington, D.C.: OFDA/USAID, 1989).

education infrastructure;and 20 percent from economic infrastructure. The economic projections for 1988 had to be adjusted dramatically, to allow for expected losses of US$130 million in export earnings, and more than US$100 million in tourism earnings; therefore, instead of the expected 5 percent growth in GDP, a decline of 2 percent was projected. Other estimates were for increases in inflation (30 percent), government public expenditures (US$200 million), and public sector deficit (from 2.8 percent to 10.6 percent of GDP).

As expected, the economic activity most affected was agriculture, with the total destruction of banana and broiler production and of more than 50 percent of the coffee and coconut crops. Capital losses to the sector were estimated at J$0.7 billion. According to some calculations, the loss of revenue through 1992 will be US$214 million.

Other productive sectors were also affected seriously. Manufacturing suffered J$600 million (in 1989 dollars) in losses, mainly from a decline of 12 percent in its exports. Tourism lost US$90 million in foreign exchange, with 5 percent fewer visitor arrivals in the third quarter of 1988 than during the same time period in 1987. Loss of electricity decreased bauxite production by 14.2 percent for that quarter compared to the third quarter of the previous year, and alumina exports declined by 21 percent.

c. Damage to Natural Resources

The coastal resources of Jamaica suffered extensive damage from hurricane forces. It is estimated that 50 percent of the beaches were seriously eroded, with the northeast coast being the most affected. An estimated 60 percent of all the trees in the mangrove areas were lost, 50 percent of the oyster culture was unsalvageable, and other non-measurable harm occurred to coral reefs and the water quality of the island (Bacon, 1989).

2. MEXICO

a. Affected Population and Damage to Social Sectors

The Government of Mexico reported that the hurricane caused 200 deaths and approximately 200,000 homeless. In the state of Nuevo León, where the Monterrey area suffered from extensive flooding, 100 people died and 30,000 housing units were destroyed.

b. Impact on the Economy and Damage to Productive Sectors

The tourism industry suffered the greatest damage. The tourist areas of the state of Quintana Roo, for example, suffered US$100 million in direct damage and lost an estimated US$90 million in revenues. The Inter-American Development Bank, after evaluating the damage to infrastructure in this sector, lent US$41.5 million for reconstruction.

c. Damage to Natural Resources

The impact across the Yucatan Peninsula in terms of damage to wildlife, beaches, and coral reefs was much higher than on the coasts of Jamaica. Extensive reduction in beaches and coral reefs was reported, and large numbers of birds lost their lives.

C. Risk Assessment and Disaster Mitigation

1. DETERMINING THE RISK POSED BY HURRICANES

The risk posed by hurricanes to a particular country is a function of the likelihood that a hurricane of a certain intensity will strike it and of the vulnerability of the country to the impact of such a hurricane. Vulnerability is a complex concept, which has physical, social, economic and political dimensions. It includes such things as the ability of structures to withstand the forces of a hazardous event, the extent to which a community possesses the means to organize itself to prepare for and deal with emergencies, the extent to which a country's economy depends on a single product or service that is easily affected by the disaster, and the degree of centralization of public decision-making (Wilches-Chaux, 1989).

Population centers and economic activities in the region are highly vulnerable to disruption and damage from the effects of extreme weather. They are largely concentrated in coastal plains and low-lying areas subject to storm surges and landborne flooding. High demands placed on existing lifeline infrastructure, combined with inadequate funds for the expansion and maintenance of these vital systems, have increased their susceptibility to breakdowns. Uncontrolled growth in urban centers degrades the physical environment and its natural protective capabilities. Building sites safe from natural hazards, pollution, and accidents have become inaccessible to the urban poor, who are left to build their shelters on steep hillsides or in flood-prone areas (Bender, 1989). Agriculture, particularly the cultivation of bananas for export, is often practiced without the necessary conservation measures corresponding to the soil, slope, and rainfall characteristics of the area.

Communities, countries, or regions differ greatly in vulnerability, and hence in the effects they may suffer from hurricanes of similar strength. The very size of a country is a critical determinant of vulnerability: small island nations can be affected over their entire area, and major infrastructure and economic activities may be crippled by a single event. Scarce resources that were earmarked for development projects have to be diverted to relief and reconstruction, setting back economic growth.

To assess future risks, planners must study historical trends and correlate them with probable future changes. The main cause of increasing vulnerability is the population movement to high-risk areas. Most cities in the West Indies are in low coastal zones threatened by storm surge (Tomblin, 1979), and they continue to grow.

The economic sectors most affected by hurricanes are agriculture and tourism. Together, these represent a major portion of the economy for the countries in the Caribbean. Particularly for island countries, agriculture is the most vulnerable activity (ECLAC/UNEP, 1979). Hurricanes have disastrous effects on banana crops in particular. During Hurricane Allen, in August of 1980, Saint Lucia suffered US$36.5 million in damage, with 97 percent of the banana plantations destroyed. In St. Vincent 95 percent, and in Dominica 75 percent, of the banana plantations were ruined (Earthscan No. 34a, 1983). Damage to the tourism industry is more difficult to quantify since it includes many other economically identifiable sectors such as transportation and hotel services.

Crop statistics rarely account for long-term losses. The increased salinity in the soil due to the storm surge can have detrimental effects on production in subsequent years. For example, Hurricane Fifi decreased production in Honduras by 20 percent the year it occurred, but in the following year production was down by 50 percent. How much of this reduction was due to the increase in salinity is unclear, but it is known that salt destroys vegetation slowly.

2. MITIGATING AGAINST HURRICANE RISK

Once the risk posed by hurricanes is understood, specific mitigation measures can be taken to reduce the risk to communities, infrastructure, and economic activities. Human and economic losses can be greatly reduced through well-organized efforts to implement appropriate preventive measures, in public awareness and in issuing timely warnings. Thanks to these measures, countries in the region have experienced a drastic reduction in the number of deaths caused by hurricanes.

Mitigation measures are most cost-effective when implemented as part of the original plan or construction of vulnerable structures. Typical examples are the application of building standards designed for hurricane-force winds, the avoidance of areas that can be affected by storm surge or flooding, and the planting of windbreaks to protect wind-sensitive crops. Retrofitting buildings or other projects to make them hurricane-resistant is more costly and sometimes impossible. Once a project is located in a flood-prone area, it may not be feasible to move it to safer ground.

The overall record on mitigation of hurricane risk in the Caribbean and Central America is not very encouraging. Cases abound of new investments in the public or productive sectors that were exposed to significant hazard risk because of inappropriate design or location, and even of projects that were rebuilt in the same way on the same site after having been destroyed a first time. Other cases can be cited of schools and hospitals funded with bilateral aid that were built to design standards suitable for the donor country but incapable of resisting hurricane-strength winds prevalent in the recipient country.

The tourism sector in the Caribbean is notorious for its apparent disregard of the risk of hurricanes and associated hazards. A hotel complex built with insufficient setback from the high-water mark not only risks being damaged by wave action and storm surge, but interferes with the normal processes of beach formation and dune stabilization, thus reducing the effectiveness of a natural system of protection against wave action. After the first serious damage is incurred the owners of the hotel will most likely decide to rebuild on the same site and invest in a seawall, rather than consider moving the structure to a recommended setback.

a. Reduction of Risk at the International Level

In the past three decades the technological capacity to monitor hurricanes has improved dramatically, and along with it the casualty rate has declined. New technology permits the identification of a tropical depression and on-time monitoring as the hurricane develops. The greatest advance has occurred in the United States, but developing countries benefit greatly because of the effective warning mechanism. The computer models also generate vast quantities of information useful for planners in developing nations.

Computer models that estimate tracking, landfall, and potential damage were first implemented in 1968 by the U.S. National Hurricane Center (NHC). At this point there are five operational track guidance models: Beta and Advection Model (BAM), Climatology and

Persistance (CLIPER), a Statistical-dynamical model (NHC90), Quasi-Lagrangian model (QLM) and the barotropic VICBAR. They vary in capacity and methodology and occasionally result in conflicting predictions, though fewer than formerly. The NHC evaluates incoming data on all tropical storms and hurricanes in the Atlantic and eastern Pacific tropical cyclone basin and issues an official track and intensity forecast consisting of center positions and maximum one-minute wind speeds for 0, 12, 24, 48, and 72 hours.

The NHC has also developed a hurricane surge model named Sea, Lake and Overland Surges (SLOSH) to simulate the effects of hurricanes as they approach land. Its predecessor SPLASH, used in the 1960s, was useful for modeling hurricane effects along smooth coastlines, but SLOSH adds to this a capability to gauge flooding in inland areas. These results can be used in planning evacuation routes.

A computerized model that assesses the long-term vulnerability of coastal areas to tropical cyclones has also been developed. This model, the National Hurricane Center Risk Analysis Program (HURISK), uses historical information on 852 hurricanes since 1886. The file contains storm positions, maximum sustained winds, and central pressures (unavailable for early years) at six-hour intervals. When the user provides a location and the radius of interest, the model determines hurricane occurrences, dates, storm headings, maximum winds, and forward speeds. Vulnerability studies begin when the median occurrence date, direction distribution, distribution of maximum winds, probability of at least $\underline{x}$ number of hurricanes passing over $\underline{n}$ consecutive years, and gamma distribution of speeds are determined. Planners can use these objective return period calculations to evaluate an otherwise subjective situation.

b. Reduction of Risk at the National Level

One of the most important steps a country can take to mitigate the impact of hurricanes is to incorporate risk assessment and mitigation measure design into development planning. The design of basic mitigation measures begins with the compilation of all historical records of former hurricane activity in the country, to determine the frequency and severity of past occurrences. Reliable meteorological data for each event, ranging from technical studies to newspaper reports, should be gathered. With all the information in place, a study of (1) the distribution of occurrences for months of a year, (2) frequencies of wind strengths and direction, (3) frequencies of storm surges of various heights along different coastal sections, and (4) frequencies of river flooding and their spatial distribution should be undertaken. The statistical analysis should provide quantitative support for planning strategies.

The design of mitigation measures should follow the statistical analysis and consider long-term effects. Both non-structural and structural mitigation measures should be considered, taking into account the difficulties of implementation.

Non-structural measures consist of policies and development practices that are designed to avoid risk, such as land use guidelines, forecasting and warning, and public awareness and education. Much credit for the reduction of casualties from hurricanes in the Caribbean should be given to the Pan Caribbean Disaster Preparedness and Prevention Project (PCDPPP), which has worked effectively with national governments on motivating the population to take preventive measures, such as strengthening roof tie-downs, and on establishing forecasting and warning measures.

Structural mitigation measures include the development of building codes to control building design, methods, and materials. The construction of breakwaters, diversion channels, and storm surge gates and the establishment of tree lines are a few examples of mitigation from a public works standpoint.

c. Reduction of Risk at the Local Level

The effectiveness of national emergency preparedness offices of countries in the region is often seriously limited because of inadequate institutional support and a shortage of technical and financial resources. In the smaller Caribbean islands, these offices are mostly one-person operations, with the person in charge responsible for many other non-emergency matters. It would be unrealistic to expect them to be able to act effectively at the local level in cases of area-wide emergencies, such as those caused by hurricanes. It is therefore essential to enhance the capacity of the population in small towns and villages to prepare for and respond to emergencies by their own means.

From 1986 through 1989, the OAS/Natural Hazards Project has worked with several Eastern Caribbean countries to evaluate the vulnerability of small towns and villages to natural hazards, and train local disaster managers and community leaders in organizing risk assessments and mitigation in their communities. These activities have resulted in the preparation of a training manual with accompanying video for use by local leaders. This effort has focused on lifeline networks--transportation, communications, water, electricity, sanitation--and critical facilities related to the welfare of the inhabitants, such as hospitals and health centers, schools, police and fire stations, community facilities, and emergency shelters.

The remainder of this chapter is dedicated to a summary overview of the process by which the leadership in a small town or village can introduce effective hazard mitigation.

D. Coping with Hurricanes in Small Towns and Villages

The degree to which local communities can survive damage and disruption from severe storms and hurricanes also depends to a large extent on how well the basic services and infrastructure, the common goods of the community, stand up to the wind and rain accompanying these storms. Whereas individual families bear full responsibility for preparing their own shelter to withstand the effects of storms, they have a much more limited role in ensuring that their common services are safeguarded, yet one that cannot be neglected.

Non-governmental agencies involved in low income housing construction and upgrading have developed practical and low cost measures for increasing the resistance of self-built houses to hurricane force winds. Typical of efforts of this nature is the work performed by the Construction Resource and Development Centre (CRDC) in Jamaica, which produced educational materials and organized workshops on house and roof reconstruction following Hurricane Gilbert.

The principal responsibility for introducing an awareness and concern in the community regarding the risk posed by hurricanes to the common good rests with the community leadership and local--or district--disaster coordinator, if such a function exists. It involves a lengthy process of identifying the issues, mobilizing resources from within the community and from outside, and building support for common action.

Such a process consists of six steps: (1) making an inventory of lifeline networks and critical facilities; (2) learning the operation of these and their potential for disruption by a hurricane; (3) checking the vulnerability of the lifelines and critical facilities through field inspection and investigation; (4) establishing a positive working relationship with the agencies and companies that manage the infrastructure and services of the community; (5) developing an understanding of the total risk to the community; (6) formulating and implementing a mitigation strategy.

1. INVENTORY OF LIFELINE NETWORKS AND CRITICAL FACILITIES

Lifeline networks and critical facilities are those elements in the economic and social infrastructure that provide essential goods and services to the population in towns and villages. Their proper functioning is a direct concern of the community, since disruption affects the entire population.

The community leadership should gradually build up an inventory of these elements by locating them in a first instance on a large-scale map (1:5,000 or 1:2,500) of the community. The base maps can be obtained from the town and country departments or physical planning offices. The road network should indicate the road hierarchy (highway, principal access to settlement, local streets) and the location of bridges and other civil works such as major road cuts and retaining walls. Similar treatment should be given to the electricity and telephone networks and the water system. Residential areas and areas of economic activity should also be identified.

Various sources can be tapped to obtain this information. Water, electricity, and telecommunication companies can be called upon to draw their networks on the maps for the area in question. The local representative of the ministry of public works or physical planning office can assist with the identification of the road network and the location of public facilities housing important services.

2. LEARNING THE OPERATION OF LIFELINES AND FACILITIES AND THEIR POTENTIAL FOR DISRUPTION BY HURRICANE

Community leaders should periodically organize brief sessions in which the engineers or managers responsible for the different lifelines and facilities can explain the workings of their systems to selected residents who may be involved in disaster preparedness and response. The maps that were prepared earlier should be helpful during these sessions, while at the same time particular details can be reviewed and updated. The focus of these sessions should be:

- Identification of the different elements that make up the system, their interaction, and their interdependency.
- How the different elements function, what can go wrong, and what the normal repair and maintenance procedures are.
- How each of the elements of the system can be affected by the forces accompanying a hurricane.
- What the consequences of a hurricane could be for the functioning of the system and for the users.

WHAT ARE THE LIFELINE NETWORKS:

Road network, with roads, bridges, road cuts and retaining walls, elevated roads, drainage works.

Water system, with surface intakes, wells, pipelines, treatment plants, pumping stations, storage tanks or reservoirs, water mains, and distribution network.

Electricity system, with generating plant, transmission lines, substations, transformers, and distribution network.

Telecommunication, with ground station, exchanges, microwave transmission towers, aerial and underground cables, and open line distribution network.

Sanitation system, with collector network, treatment plant and sewage fallout; public washrooms and toilet facilities; solid waste collection and disposal.

WHAT ARE THE CRITICAL FACILITIES:

Hospitals, health centers, schools, churches.

Fire stations, police stations, community centers, shelters, and other public buildings that house vital functions that play a role in emergencies.

3. CHECKING THE VULNERABILITY OF THE LIFELINES AND FACILITIES THROUGH FIELD INSPECTION AND INVESTIGATION

The vulnerability of buildings and infrastructure elements will be determined first of all by their location with respect to hazard-prone areas. Storm surges and wave action can inflict severe damage in waterfront and low-lying coastal areas; heavy rains accompanying the hurricanes can cause flash flooding or riverine flooding along the river banks and in low-lying areas; rain can also cause land slippages and mudslides on steep slopes and unstable roadcuts; and structures in exposed areas such as ridges and bluffs are particularly vulnerable to wind damage.

Hazard-prone areas should be systematically identified and located on the lifeline and critical facilities map, to show where lifeline networks and critical facilities may be especially vulnerable.

The next step consists of a visual inspection and observation of all important infrastructure elements and critical facilities. Details of location and construction that may affect vulnerability should be noted and recorded on a sheet, together with a brief description of the possible damage that may occur.

4. ESTABLISHING A POSITIVE WORKING RELATIONSHIP WITH THE AGENCIES AND COMPANIES THAT MANAGE THE INFRASTRUCTURE AND SERVICES OF THE COMMUNITY

Once the community leadership has collected a fair amount of information, a series of consultations should be organized with the engineers or managers responsible for each of the lifeline and critical facilities of the settlement, or with their local representatives, and further elaboration of the information collected thus far should take place.

Such consultations provide an opportunity for the community leadership to learn about the maintenance and emergency repair policies practiced in their settlements by the different agencies and utility companies, to get to know the officers responsible for carrying out emergency repairs, and to find out how to contact them under normal circumstances as well as in emergencies.

Good contacts between agency representatives and community leadership are of great help in exploring the coincidence of interest between the residents on the one hand and the service agencies

LEARNING FROM PAST DISASTERS

Very valuable information about the vulnerability of small towns and villages can be obtained by inquiring into the local hurricane damage history. This is done through interviews with older residents in the community, retired public works officials familiar with the area, and other informants; by searching in old newspapers, and documents; and other means that may be appropriate in the particular setting.

The information should be organized by event, and within each event by infrastructure element that was affected. Damage that resulted from that particular impact should be briefly described. An effort should be made to collect at least the following data:

a. The **EVENT**:
- date of occurrence
- duration
- areas affected
- measures of strength (wind speed, height of flood waters)
- other characteristics that distinguish the event from others

b. The particular **ELEMENT** that was affected:
- class and type of element
- physical characteristics
- any information on what may have made the element vulnerable at that time--for example, poor state of repair or accumulated debris

c. The **DAMAGE** that was caused:
- quantitative and qualitative description of direct physical damage
- description of indirect damage, such as loss of function, interruption of service, loss of jobs

and companies on the other. Through effectively managed participation by the residents in such tasks as monitoring the state of repair of the infrastructure or keeping drains clear, the community can receive better services at a lower cost to the agencies responsible. The actual hiring of workers or small firms from the settlement to execute some of the agencies' tasks should be encouraged wherever possible.

5. DEVELOPING AN UNDERSTANDING OF THE TOTAL RISK TO THE COMMUNITY

To be meaningful, the view of the risk posed by hurricanes to a settlement should include the perspective of the population and its economic activities. In such an integrated view, vulnerability is obviously more than the sum of the technical deficiencies experienced by structures or equipment in the face of excessive natural forces. The traditional sectoral organization of the public system provides a poor basis for an integrated vulnerability analysis, since it tends to overlook the dependency and interaction between different infrastructure systems, which are often major determinants of the vulnerability of a society.

The different pieces of information collected so far will have to be put together to create an understanding of the total risk to which the settlement can be subject, and of the variations of this risk within the settlement according to the location and vulnerability of specific elements of the infrastructure. The following techniques have proved helpful in this exercise.

- Creating a visual image

  All the information collected earlier is compiled on the large-scale base map of the settlement, either directly on the same map, on acetate overlays, or

INVOLVING THE COMMUNITY IN VULNERABILITY REDUCTION

In St. Kitts and Nevis, the Ministry of Education, the Ministry of Public Works, and the Disaster Preparedness Office organized local residents to repair the schools with materials donated by USAID. The school children benefited from safer, more operable buildings, while the community as a whole benefited from having safer hurricane shelters, a function which school buildings across the island automatically acquire during the hurricane season.

EXAMPLES FOR COMMUNITY ACTION

Contributions that local communities can make to reducing the vulnerability of their basic services are typically non-structural, and are built around routine monitoring and maintenance. Some examples:

- Avoid throwing garbage, especially large objects such as tires, tree branches, and appliances, into gullies and rivers. These tend to accumulate near bridges and culverts, forming obstacles to normal water flow.
- Do not remove natural vegetation from river and gully banks, and from cut slopes, in order to avoid accelerated erosion of the banks.
- Keep roadside drainage clear of silt and other objects; pay special attention to crossover culverts.
- Do not remove sand and stones from beaches.
- Keep overhanging branches away from electricity and telephone lines.
- Do not tamper with electricity/telephone poles; report any visible signs of deterioration of the poles or their stays.
- Report any visible signs of deterioration to public buildings, paying special attention to roofs and windows.
- Do not interfere with water intakes; report excessive silting or obstructions.

a few different copies. The final number of maps depends on the scale of the base map and the complexity of the information.

The maps will highlight where hazardous events can strike, who suffers the risks, what functions are threatened, where direct damage can be experienced, and what the level of risk is.

- Creating impact scenarios

  With the help of the maps, much can be learned about the risk to which the community is subject by formulating realistic scenarios of the impact of a hurricane on the settlement and simulating the consequences for population, lifelines, and critical facilities.

These scenarios can be reviewed with various groups in the community. Discussion of the different scenarios creates the perfect background against which to start thinking about what the community can do to reduce the risk, which is after all the purpose of the exercise.

6. FORMULATING A MITIGATION STRATEGY

The formulation of a strategy to introduce appropriate mitigation measures that respond to the community's priorities is the culmination of all the efforts expended on the vulnerability analysis and risk assessment.

It is important that the community leadership focus on identifying realistic mitigation measures and proposing a simple implementation strategy. The common pitfall of identifying measures that require substantial funding should be avoided by concentrating on non-structural measures. Typical of the measures that should be emphasized are those that can be integrated into routine maintenance or upgrading of infrastructure; the avoidance of environmental degradation that can decrease the natural protective capacity of resources such as sand dunes, mangroves, and other natural vegetative coverage; and prevention by means of proper planning and design of new investments.

It is also important to establish the role of the different governmental levels and agencies in the country in the implementation of a mitigation strategy. The range of actions under the control of a small community is obviously quite limited, and depends on the degree of autonomy of the local government, the level of resources it controls, and the expertise it is able to mobilize.

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APPENDIX A

SOURCES OF INFORMATION ON NATURAL HAZARDS

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Contents

List of Figures

A. Types and Level of Detail of Natural Hazard Information

Most of the information used in natural hazard assessments is generated by three principal networks: international and national natural phenomena research and monitoring centers and universities; disaster management entities; and multisectoral and sectoral planning agencies, ministries, and public utilities. While some may appear in scientific language or as statistical data, other readily usable information may be found in the form of maps, reports, newspaper and magazine articles, proceedings from hazard-related workshops, historical records, etc. Users of hazard information include many agencies at the community, regional, national, and international levels, a number of which are also important produces of information. Examples of potential users are listed in Figure A-1. Sources of specific information on each natural hazard addressed in this study--hurricanes, floods, droughts, desertification, earthquakes, landslides, and volcanoes--are identified in the individual chapters on those hazards.

Analysis of the location, frequency, and severity of a hazard may require more than one type of information. In addition to information on the hazards themselves, the planner will also require information on vulnerability (the potential impact on human life and property caused by a natural event) and risk (the probability that a natural event will occur within a specified time period and cause a specified degree of damage). More precise definitions of these terms are given in Chapter 1.

Information on natural hazards can be obtained from maps and studies of the hazards themselves and also from maps and studies of natural resources, population, and infrastructure. Analysis of vulnerability and risk requires multiple sources. While all the types of maps and studies mentioned are important, it is not necessary to collect them all. Some can substitute for others in providing the information required. The cardinal rule is that the planning team should collect only the information needed to answer the development questions posed.

1. NATURAL RESOURCE MAPS

a. Climate Maps

Data on a wide variety of climatic factors (including changes, extreme observations, and probabilities) can be obtained in the form of maps, reports, and statistics. Factors include precipitation, temperature, evapotranspiration, wind (velocity and direction), cloudiness, and relative humidity.

b. Geologic Maps

These maps show the distribution, composition, structure, and age of rock units that constitute the foundation of all human activities in the study area. They are useful in determining the location of mineral deposits and construction materials, stability and bearing capacity (and thus the suitability of a location for large engineering structures), soil-forming parent materials, the capacity to store and yield underground water, and the possibility of liquefaction. Large-scale faults and folds are associated with earthquakes, and information on the age and composition of volcanic rocks facilitates volcanic hazard analysis. Small-scale regional tectonic maps show the relative stability of great crusted plates and indicate zones of collision between plates which are the loci of intensive volcanic and earthquake activity.

c. Hydrologic Maps

Surface hydrology maps indicate natural and man-made bodies of water, and may show stream flow (volume, seasonality) and irrigated areas. Groundwater maps show the location and depth of aquifers, water wells, quality of groundwater, etc. These maps can be important in evaluating the potential for floods and drought and also play a role in a vulnerability analysis. They help the planner identify changes in floodplains and recurring flood areas.

d. Landform or Geomorphic Maps

These maps depict the physiographic forms of an area (e.g., mountains, plateaus, mesas, ridges, piedmont, valleys), often relating the form to its geologic origin (e.g., anticlinal ridge, volcanic highlands, alluvial valleys) and thus providing the basis for comprehensive interpretation of soils, land-use potential, and propensity for landslides. The morphological maps are important to planners since they describe the sculpturing of the land by indicating, for example, how the natural forces of erosion have worked towards the establishment of slopes that are relatively stable. They can also reflect the impact of man-made changes. When development unbalances the equilibrium of a stable slope, natural forces immediately set about restoring its equilibrium. The most important use of these maps for natural hazard management is that the users can identify potentially unstable soils.

e. Life Zone Maps

Life zone maps, also called ecological maps, use a combination of precipitation, temperature, and evapotransporation to delineate life zones or "ecologic" zones. The literature on life zones indicates the natural vegetation, and suitable crops and grasses for each zone. Important for development planning, these maps have limited applicability to a hazard analysis.

f. Soils Maps

Two different types of soils maps provide planners with valuable information: agricultural soils maps and engineering soils maps. The former can be classified as basic maps and interpretative maps. The basic, or soil unit classification, maps show soil mapping units, usually soil types and phases, and provide information on each unit that usually includes parent material, chemical composition, texture, moisture holding capacity, slope, drainage, and limitations for agricultural use at specified management levels. A wide variety of interpretative maps can be prepared from the soil classification maps, on topics including land classification, suitability for irrigation, trafficability, and erosiveness.

Engineering soils maps show the bearing capacity of soils. They also show the cohesion and resistance of the soils units which affect slope gradient and stability and liquefaction. Engineering soils maps can reflect the impact of changes on soil conformation.

g. Topographic Maps

These maps provide information on elevations, relief, drainage patterns, and culture of an area. They are essential for both vulnerability and risk analyses involving hazards such as high winds, floods, erosion, earthquakes, landslides and volcanic activity. The detail of the information depends upon the scale of the map. Topographic maps are often used as the base maps upon which a variety of thematic maps can be constructed. The features depicted on topographic maps can be grouped under the following heads:

- The hydrography, or water features (ponds, stream, lakes, etc.).
- The hypsography, or relief of surface forms (hills, valleys, plains, etc; elevation above sea level shown by contour lines).
- The cultural features constructed by humans (towns, roads, canals, power lines, etc.).

2. HAZARD-RELATED MAPS

a. Bathymetric Maps

These maps show the depth and slope of the ocean floor near the shore and are used to assess the potential impacts of storm surges and tides on coastal areas. For example, gently sloping sections of the ocean floor near the shoreline may facilitate storm surge run-up under certain tidal and weather conditions.

b. Desertification Maps

These maps identify areas currently or potentially subject to desertification.

c. Epicenter Maps

These maps show the location of earthquake epicenters. Usually they give the date and depth of an epicenter and the magnitude of the related earthquake.

d. Fault Maps

These maps, which show the location of the major geological fault systems and related geological features, are used to identify the loci of earthquakes and zones of earth movement.

e. Flash Flood Maps

These maps contain information on areas historically affected by flash floods. They delimit traditionally affected areas and identify floodplains.

f. Floodplain Maps

These maps show rivers, channels, and streams that are susceptible to flooding. They may include information on historical floods, and may also delimit the floodplains and their changes over time.

g. Landslide Maps

These maps show the areas where landslides have occurred. They can also include potential areas of landsliding based on geological/hydrological information or on changes related to past development. For these purposes they may illustrate slope stability, gradient and levels of moisture absorption, and the impact of development-induced changes, cohesion, and undermining of soils.

h. Maximum Observed Intensity Maps

These maps demarcate zones where earthquake damage over hundreds of years can be observed or inferred.

i. Seismotectonic Maps

These maps delimit seismic zones and trace lines of major dislocations and secondary fractures. They include information on observed tectonic movement.

j. Storm Surge Maps

These maps contain information on the heights of past storm surges. They can also provide information on erosion and structural damage caused by storms in coastal areas.

k. Volcano Maps

These maps identify the locations of volcanoes and the damage zones where damage from volcanic activity can be observed or inferred.

l. Windstorm Maps

These maps include information on the wind direction and velocity of past hurricanes. They may also provide information on structural damage and damage to the forest or the agricultural sector caused by past storms.

3. REFERENCE MAPS FOR VULNERABILITY AND RISK ASSESSMENT

a. Built Structure Maps

These maps illustrate the distribution of buildings in the study area. Usually they are based on data collected from engineering surveys, local directories, land-use maps, inventories of properties, and census data. They may be limited to the buildings themselves, or may extend to other significant features such as age, function, architectural form, and historical or cultural significance. In some instances they provide engineering information such as the distribution and thickness of underlying formations; slopes and slope stability; drainage patterns, permeability, and water table depth; susceptibility to frost; stability in earthquakes; excavation characteristics; suitability for foundations, sub-grade, and fill; and compaction characteristics.

b. Cadastral Maps

These maps define the property and ownership boundaries of an area. Although they are often at scales larger than is needed for general regional development planning, they are excellent for hazard management because of their accuracy and detail, especially of lifeline elements and other cultural features.

c. Demographic Maps

Maps with information on single or multiple demographic aspects of an area, usually based on census data, can often be found. As a rule, because of representation problems, they show only certain categories of information. Information on vital statistics is more commonly found in tabular form.

d. Drainage and Irrigation

These maps show coastal and lake zones and river deltas where irrigation, hydrologic energy, and transportation works are often present. They identify natural drainage systems and networks which may be threatened by flooding.

e. Infrastructure Maps

These maps provide essential data on the location, type, and configuration of basic infrastructure (transportation, communication, and energy systems) of the area. Service infrastructure maps show water, sanitation, health, education, and public safety facilities. Coastal infrastructure maps show port and harbor facilities

and may include information on historical tides and storm surges. Maps of critical infrastructure show structures which if damaged would endanger lives (e.g., chemical facilities, nuclear plants, dams, and reservoirs).

f. Land-Use and Vegetation Maps

Land-use maps show human use of the land. Depending on the scale, they may indicate various subdivisions of settlement use, cropping patterns, pasture lands, forest plantations, etc. Maps of actual vegetation (as opposed to theoretical maps of potential natural vegetation) show areas of forest, brush, and grasslands, and they may be presented separately or in combination with land-use maps. The depiction of ground cover is useful in determining evapotranspiration, rate of absorption of rainfall, and runoff. They help the planner identify wet and dry season areas.

g. Lifeline and Critical Facilities Maps

Designed to facilitate response to emergencies, these maps show the most important installations necessary for the maintenance of health and public safety. In addition to the basic infrastructure these maps show potable water and sanitation systems, police and fire stations, military posts, emergency management facilities, emergency shelters, and medical services.

B. The Use of Hazard Information in the Development Planning Process

The type, level of detail, and scale of hazard information that is needed in each stage of the planning process are determined by the objectives of that particular stage and by the available resources and information. While different planning contexts dictate the need for specific types of information, some general guidelines can be offered.

As planning activities evolve from a general assessment of the study area's natural resource base to the preparation of development strategies and the formulation of investment projects, the information required becomes increasingly detailed. Figure A-2 summarizes the relationship between natural hazard assessments and each phase of the development planning process.

1. PRELIMINARY MISSION (Study Design)

In the preliminary mission, the first stage of the development planning process, the primary objective is to identify existing natural hazards and potential natural events that can produce future disasters. Once the existence of potentially hazardous conditions or events has been recognized, constraints and opportunities for future development can be identified.

For this purpose, general information pertaining to the occurrence or potential for natural hazards and natural phenomena should be collected. Existing information such as maps, remotely sensed images, and reports can be used to illustrate historical and current conditions. From this the planner can identify potentially hazardous conditions and conduct qualitative and quantitative assessments of the probable impacts of the hazards on the natural resource base and economic development potentials of the target development area. Gathering all existing hazard-related information during the preliminary mission provides an inventory of what is available and enables the planner to determine what else will be needed for the subsequent phases.

A list of useful studies and maps for a hazard assessment in the preliminary mission is presented in Figure A-3, together with the desirable level of detail and scale of each map, which will differ according to the type of hazard and the size of the region under study. In general, small-scale maps on the order of 1:1,000,000 are appropriate for examining areas larger than 25,000 square kilometers. While large-scale maps, ranging from 1:10,000 to 1:50,000, are useful for identifying the presence of natural hazards in relatively small areas up to 2,500 square kilometers.

2. PHASE I (Development Diagnosis)

In the later stages of the development planning process, the objective of collecting natural hazard information shifts from a qualitative to a quantitative assessment: the location, frequency, and severity of occurrence of specific natural hazards, and the vulnerability of the population and the natural and built environment. Information collected and generated during the Preliminary Mission can be used as the basis for Phase I activities, the objectives of which are to prepare a development diagnosis, formulate a development strategy, identify investment projects for the study area, and assess the areas and proposed project's vulnerability to natural hazards.

The development diagnosis involves an analysis of the resource base, to determine the development potential and constraints--including natural hazards--in the study area. If adequate information exists, it must be synthesized into a form suitable for the planning study. Where data are limited, they must be supplemented with field studies. This analysis, in turn, leads to the identification of projects that will resolve the problems or capture the opportunities. Information on natural hazards is used at this point in selecting the location of the projects and in their preliminary formulation. Some projects, such as the preparation of detailed hazard zone maps or the modification of building codes, may be directly related to natural hazards.

In already developed areas, the hazard assessment is used to determine the vulnerability of vital human structures such as lifeline networks, settlements, production facilities, infrastructure, and other types of activity. Vulnerability maps, created by integrating meteorological or geological information with information on human use and occupation, can be overlaid on lifeline maps to show critical facilities, production areas and population centers, and to identify vulnerable sites. After vulnerability levels for lifeline networks and areas of human activity have been assessed, a development strategy can be devised aimed at maximizing the development potential while reducing their vulnerability to natural hazards. Such a strategy includes (1) determining under what circumstances the development activities can and should alter natural phenomena, and (2) deciding what types of structural and non-structural mitigation measures should be executed as part of the development project.

The specific types of natural hazard information needed for Phase I are enumerated in Figure A-4. The information needed on vulnerability and risk, which tends to be similar for Phases I and II, is shown in Figure A-6.

3. PHASE II (Project Formulation and Sector Plan Preparation)

The principal activity of Phase II is the preparation of an action plan and the detailed formulation of investment projects that were identified in Phase I and selected by the government for further study. Risk criteria based on vulnerability analysis, the assessments of different hazards, and the expected economic life of the investment project can be used to distinguish risk levels for different development activities and to define the constraints associated with the projects.

After acceptable risk levels have been determined, specific mitigation measures applicable to the particular hazard (see Chapters 8, 9, 10, 11, and 12) should be identified and a disaster preparedness plan, consisting of activities to minimize loss of life and property and to identify lifeline network components that need reinforcement, should be formulated.

Figure A-5 presents a summary of natural hazard information needs for Phase II of the planning process, and Figure A-6 shows the information needed to undertake vulnerability and risk assessments.

4. IMPLEMENTING THE STUDY RECOMMENDATIONS

In the final stage of the planning process, when the approved development projects are implemented, the related disaster preparedness and mitigation measures identified in Phase II are executed. Specific preparedness activities should be designed for development activities that are not amenable to major reductions in vulnerability levels. In addition to these measures, the hazards identified should be monitored for early warning, and seminars and disaster preparedness information exchanges should be conducted.

Figure A-1

EXAMPLES OF POTENTIAL USERS OF HAZARD INFORMATION

Development and Investment Users

Capital donors
Capital investors
Development assistance agencies
Insurers and reinsurers
Preliminary mission teams
Private consulting firms
Underwriters

Community Users

Building, engineering, planning, and safety departments
Disaster preparedness agencies
Flood control districts
Governing bodies
Offices of emergency services
Police and fire departments
Provincial and district councils
Public works and highway departments
School districts

Regional Government Users

Building, housing, and community development agencies
Coastal protection agencies
Departmental development corporations
Emergency services agencies
Legislatures and legislative committees
Planning and research agencies
Transportation, water resources, mining, and geological agencies
Utility regulatory agencies

National Government Users

Agrarian research, promotion, and development centers
Congresses and congressional staffs
Development corporations
Economic policy affairs ministries
Emergency management agencies
Environmental protection agencies
Foreign affairs ministries
Extractive, manufacturing, and processing industries
Forest ministries or departments
General services administrations
Housing and urban development ministries
Human settlements ministries
Industry and commerce ministries
Insurance administrations
Land management and reclamation ministries
Military corps of engineers
National expansion, colonization, and development institutes
Natural resources agencies and councils
Oceanic and atmospheric administrations
Planning boards or agencies
Power commissions
Research and promotion institutes
Rural, agricultural, and livestock ministries
Science and technology institutes
Small farmers' affairs ministries
Transportation, communication, and public works ministries
Water resources councils and institutes

Other National Users

Applied technology councils
Associations of engineering geologists
Associations of highway and transportation officials
Associations of state geologists
Earthquake engineering research institutes
International conferences of building officials
National associations of cities, counties, and states
National associations of insurance commissioners
National institutes of building sciences
Natural hazards research and applications centers
Professional and scientific societies
Public works associations
Red Cross
Research institutes

International Users

Inter-American Training Center for Formulation and Evaluation of Projects
Inter-American Center for Integrated Development of Land and Water Resources
Inter-American Center for Regional Development
Inter-American Development Bank
International Bank for Reconstruction and Development
International development assistance agencies
Organization of American States
United Nations Development Programme
United Nations Economic Commission for Latin America
United Nations Educational, Scientific, and Cultural Organization
United Nations Food and Agriculture Organization
U.S. Agency for International Development and its Office of Foreign Disaster Assistance

Public and Quasi-Public Users

Civic and voluntary groups
Communication and transportation industries
Concerned citizens
Construction companies
Consulting planners, geologists, architects, and engineers
Financial and insurance institutions
Landowners, developers, and real-property sales persons
Structural engineers' associations
University departments (including geography, geology, civil engineering, economic development, architecture, urban and regional planning, national resources, forestry, and environmental studies)
Utility companies

Figure A-2

RELATIONSHIP BETWEEN NATURAL HAZARD ASSESSMENTS AND THE DEVELOPMENT PLANNING PROCESS

PHASE	ROLE OF HAZARD ASSESSMENT	
Preliminary Mission	Hazard-related objective:	To collect information to establish the presence of natural events in the study area and the limitations imposed by hazards.
	Effect on development planning activities:	Presence of hazards indicates the need for further qualitative and quantitative assessment of this potential effect on development.
Phase I: Development Diagnosis, Strategy Formulation, and Project Identification	Hazard-related objective:	To assess those hazards present in the study area and identify existing critical segments or elements of production facilities, infrastructure, and settlements (lifeline network mapping). To include vulnerability in the determination of development potential and strategy (for example, by identifying floodplains, landslide areas, incipient desertification). To identify alternative non-structural and structural mitigation measures in initial project identification.
	Effect on development planning activities:	Presence of hazards will affect the overall strategy. Hazard mitigation should influence identification of sectoral projects, particularly agriculture and infrastructure. Presence of hazards will affect the identification, type, and location of investment projects, which may require modification of the lifeline network.
Phase II: Action Plan Preparation Project Formulation	Hazard-related objective:	To determine specific mitigation measures for selected investment projects and identify critical elements of lifeline network disaster preparedness activities.
	Effect on development planning activities:	Presence of hazards will affect the action plan for project implementation, the specific site selection of investment projects at the local level, the project engineering design, and the economic feasibility.
Implementation	Hazard-related objective:	To follow through on implementation of mitigation measures and disaster preparedness.
	Effect on development planning activities:	Monitoring of natural phenomena for early warning against possible damage, and formulation of future risk assessment and disaster preparedness activities.

Figure A-3

NATURAL HAZARD INFORMATION FOR THE PRELIMINARY MISSION [a]

SUBJECT	INFORMATION TYPE	DESCRIPTION	PREFERRED MAP SCALE	SCALE RANGE
Hurricane	Maps	Historical events (paths)	1:1 000 000	1:5 000 000 or larger
		Risk	1:1 000 000-1:50 000	1:5 000 000 or larger
	Studies	Event histories		(as provided by the study)
Flood	Maps	Drainage	1:500 000-1:50 000	1:1 000 000 or larger
		Floodplain	1:500 000-1:50 000	1:1 000 000 or larger
		Historical events	1:500 000-1:50 000	1:1 000 000 or larger
		Event-related inundation	1:500 000-1-50 000	1:1 000 000 or larger
	Studies	Event histories		(as provided by the study)
Drought and Desertification	Maps	Historical events	1:1 000 000-1:250 000	1:10 000 000 or larger
	Studies	Drought assessment		(as provided by the study)
		Desertification assessment		(as provided by the study)
		Event histories		(as provided by the study)
Natural Resource Information Related to Hydrologic and Atmospheric Hazards [b]	Maps	Life zones (ecology)	1:1 000 000-1:50 000	1:3 000 000 or larger
		Land use	1:1 000 000-1:50 000	1:3 000 000 or larger
		Land capability	1:1 000 000-1:50 000	1:3 000 000 or larger
		Precipitation	1:1 000 000-1:50 000	1:3 000 000 or larger
		Regional hydrology	1:1 000 000-1:50 000	1:3 000 000 or larger
		Soils classification	1:1 000 000-1:50 000	1:3 000 000 or larger
		Topography	1:1 000 000-1:50 000	1:1 000 000 or larger
		Vegetation	1:1 000 000-1:50 000	1:3 000 000 or larger

Figure A-3 (continued)

NATURAL HAZARD INFORMATION FOR THE PRELIMINARY MISSION [a]

SUBJECT	INFORMATION TYPE	DESCRIPTION	PREFERRED MAP SCALE	SCALE RANGE
Earthquake and Tsunami	Maps	Event epicenters	1:2 000 000-1:250 000	1:10 000 000 or larger
		Plate tectonics/faults	1:1 000 000-1:50 000	1:10 000 000 or larger
		Regional geology	1:1 000 000-1:50 000	1:10 000 000 or larger
		Seismic risk/microzonation	1:100 000	1:10 000 000-1:100 000
		Seismicity		1:10 000 000-1:5 000 000
	Studies	Earthquake catalogues		(as provided by the study)
		Event histories		(as provided by the study)
		Tsunamic event history		(as provided by the study)
Landslide	Maps	Slide inventory	1:250 000 - 1:50 000	1:2 000 000 or larger
		Hazard zonation	1:250 000 - 1:50 000	1:2 000 000 or larger
	Studies	Event histories		(as provided by the study)
Volcano	Maps	Ash fall event		1:3 000 000 or larger
		Plate tectonics/faults	1:1 000 000	1:10 000 000 or larger
		Regional geology	1:1 000 000	1:10 000 000 or larger
		Volcanic hazard		1:10 000 000 or larger
	Studies	Catalogue of active volcanoes		(as provided by the study)
		Event histories		(as provided by the study)
Natural Resource Information Related to Geologic Hazards [b]	Maps	Geology	1:1 000 000 - 1:50 000	1: 3 000 000 or larger
		Topography	1:1 000 000 - 1:50 000	1: 3 000 000 or larger

a/ During the Preliminary Mission, only existing information is collected and analyzed. No new information is generated.
b/ Information typically gathered during the Preliminary Mission in any case.

Figure A-4

NATURAL HAZARD INFORMATION FOR PHASE I ACTIVITIES [a]

SUBJECT	INFORMATION TYPE	DESCRIPTION	PREFERRED MAP SCALE [c]	SCALE RANGE
Hurricane	Maps	Bathymetric		1:250 000 - 1:10 000
		Drainage and irrigation		1:250 000 - 1:10 000
		Event-related inundation		1:250 000 - 1:10 000
		Floodplain for design event		1:250 000 - 1:10 000
		Historical events (affected area)		1:500 000 - 1:50 000
		Surge tide for design event		1:50 000 - 1:10 000
	Studies and other information	Aerial photographs		(as provided by the study)
		Coastal infrastructure		(as provided by the study)
		Episodic data		(as provided by the study)
		Event damage		(as provided by the study)
		Flood histories		(as provided by the study)
		Hydrology reports		(as provided by the study)
		Meteorological records		(as provided by the study)
		Satellite imagery	1:100 000 - 1:40 000	1:1000 000 - 1:40 000
		Tide tables		(as provided by the study)
Flood	Maps	Drainage and irrigation		1:250 000 - 1:50 000
		Event-related inundation		1:250 000 - 1:50 000
		Floodplain for design event		1:250 000 - 1:50 000
	Studies and other information	(See "Hurricane" above)		
		Stream flow data		(as provided by the study)
Drought and Desertification	Maps	Aquifer and aquifer recharge areas		1:250 000 - 1:50 000
		Deep water well inventory		1:250 000 - 1:50 000
		Land use change		1:250 000 - 1:50 000
	Studies and other information	Aerial photographs		1:250 000 - 1:40 000
		Aquifer recharge and reports on ground water withdrawn		(as provided by the study)
		Episodic data		(as provided by the study)
		Event damage assessments		(as provided by the study)
		Human and animal population density		(as provided by the study)
		Meteorological records		(as provided by the study)
		Satellite imagery	1:500 000 - 1:40 000	1:1000 000 - 1:40 000
		Wind velocity and direction		(as provided by the study)

Figure A-4 (continued)

NATURAL HAZARD INFORMATION FOR PHASE I ACTIVITIES [a]

SUBJECT	INFORMATION TYPE	DESCRIPTION	PREFERRED MAP SCALE [c]	SCALE RANGE
Natural Resource Information Related to Hydrologic and Atmospheric Hazards	Maps and accompanying studies	Life zones		1:500 000 - 1:60 000
		Geology		1:500 000 - 1:50 000
		Land use		1:500 000 - 1:50 000
		Land-use capability		1:500 000 - 1:50 000
		Precipitation		1:500 000 - 1:50 000
		Soil classification		1:500 000 - 1:20 000
		Topography		1:500 000 - 1:20 000
		Vegetation		1:500 000 - 1:50 000
Earthquake and Tsunami	Maps	Event epicenters		1:500 000 or larger
		Faults		1:500 000 or larger
		Historical events (including tsunami-affected area)		1:500 000 or larger
		Isoseismic		1:500 000 or larger
		Maximum observed intensity		1:500 000 or larger
		Seismic risk/macrozonation		1:500 000 or larger
		Seismotectonic		1:500 000 or larger
	Studies and other information	Engineering design reports on major infrastructure projects		(as provided by the study)
		Event damage assessment		(as provided by the study)
		Interpretative soils reports to identify formations susceptible to liquefaction and slope failure		(as provided by the study)
		Satellite imagery	1:500 000 - 1:40 000	1:1000 000 - 1:40 000
		Strong ground motion investigations		(as provided by the study)
Volcano	Maps	Ash fall event		1:500 000 or larger
		Faults		1:500 000 or larger
		Seismotectonic		1:500 000 or larger
		Volcano inventory		1:500 000 or larger
	Studies and other information	Event damage assessment		(as provided by the study)
		Distribution of recent and historic deposits of lava and ash		(as provided by the study)
		Satellite imagery	1:250 000 - 1:40 000	1:000 000 - 1:40 000
		Volcanic activity monitoring investigations		(as provided by the study)

Figure A-4 (continued)

NATURAL HAZARD INFORMATION FOR PHASE I ACTIVITIES [a/]

SUBJECT	INFORMATION TYPE	DESCRIPTION	PREFERRED MAP SCALE [c/]	SCALE RANGE
Landslide	Maps	Simple hazard zonation map	1:50 000	1:250 000 - 1:25 000
		Landslide inventory	1:50 000	1:250 000 - 1:25 000
	Studies and other information	Event histories and damage reports		(as provided by the study)
Natural Resource Information Related to Geologic Hazards [b/]	Maps and accompanying studies	Aspect		1:250 000 - 1:25 000
		Geology		1:500 000 - 1:25 000
		Geomorphology		1:500 000 - 1:50 000
		Land use		1:500 000 - 1:50 000
		Land capability		1:500 000 - 1:50 000
		Slope		1:250 000 - 1:25 000
		Soil classification		1:500 000 - 1:50 000
		Topography		1:500 000 - 1:50 000
		Vegetation		1:500 000 - 1:50 000

a/ Information to be prepared and analyzed as completely as possible, depending on the previously established presence of the hazard.
b/ Information to be prepared, if not already available, as required by the specific study.
c/ Unless otherwise indicated, according to size of study area.

Figure A-5

NATURAL HAZARD INFORMATION FOR PHASE II ACTIVITIES [a]

SUBJECT	INFORMATION TYPE	DESCRIPTION	PREFERRED MAP SCALE [c]	SCALE RANGE
Hurricane	Maps	Bathymetric		1: 50 000 - 1:10 000
		Drainage irrigation		1:100 000 - 1:10 000
		Event-related inundation		1:100 000 - 1:10 000
		Floodplain for design event		1:100 000 - 1:10 000
		Historical events (affected area)		1:100 000 - 1: 2 500
		Structural damage assessment		1: 50 000 - 1: 2 500
		Surge tide for design event		1: 50 000 - 1: 2 500
	Studies and other information	(see "Hurricane" in Figure A-4)		
Flood	Maps	Drainage and irrigation		1:100 000 - 1: 2 500
		Event-related inundation		1:100 000 - 1: 2 500
		Floodplain for design event		1:100 000 - 1: 2 500
	Studies and other information	(see "Hurricane" in Figure A-4)		
Drought and Desertification	Maps	Aquifer and aquifer recharge area		1:100 000 - 1:10 000
		Deep water well inventory		1:100 000 - 1:10 000
		Land use change		1:100 000 - 1:10 000
Natural Resource Information Related to Hydrologic and Atmospheric Hazards [b]	Maps	(see "Natural Resource Information Related to Hydrologic and Atmospheric Hazards" in Figure A-4)		

Figure A-5 (continued)

NATURAL HAZARD INFORMATION FOR PHASE II ACTIVITIES [a]

SUBJECT	INFORMATION TYPE	DESCRIPTION	PREFERRED MAP SCALE [c]	SCALE RANGE
Earthquake and Tsunami	Maps	Event epicenters		1:100 000 - 1:10 000
		Faults		1:100 000 - 1:10 000
		Historical events (including tsunami-affected area)		1:100 000 - 1:10 000
		Liquefaction and slope failure		1:100 000 - 1:10 000
		Seismic risk/microzonation		1: 50 000 - 1:10 000
		Structural damage assessment		1: 50 000 - 1:10 000
	Studies and other information	(see "Earthquake and Tsunami" in Figure A-4)		
Landslide	Maps	Intermediate or detailed hazard zonation map		1:25 000 - 1:2 000
		Landslide inventory		1:25 000 - 1:2 000
	Studies and other information	Event histories and damage reports		(as provided by the study)
Volcano	Maps	Ash fall event		1:100 000 - 1:10 000
		Faults		1:100 000 - 1:10 000
		Lava flow event		1: 50 000 - 1:10 000
		Volcano inventory		1:100 000 - 1:10 000
	Studies and other information	(see "Volcano" in Figure A-4)		
Natural Resource Information Related to Geologic Hazards [b]	Maps	(see "Natural Resource Information Related to Geologic Hazards" in Figure A-4)		

a/ Information to be prepared, if not already available, as completely as possible and analyzed. This will depend on the previously defined highest potential areas for development, location of selected development projects, and the presence of hazards.
b/ Information to be prepared, if not already available, as required by the specific study.
c/ Unless otherwise indicated, according to size of project area.

Figure A-6

NATURAL HAZARD INFORMATION FOR VULNERABILITY AND RISK ASSESSMENTS

INFORMATION TYPE	DESCRIPTION	PLANNING PROCESS STAGE	SCALE RANGE
Maps and accompanying studies	Basic Information	Preliminary Mission Phases I and II	1:3 000 000 or larger 1:500 000 - 1:25 000
	Urban and rural settlements	Phases I and II	1:500 000 - 1:10 000
	Basin infrastructure	Phases I and II	
	Service infrastructure Lifeline network	Phases I and II	
	Land use	Preliminary Mission Phases I and II	1:3 000 000 or larger 1:500 000 - 1:10 000
	Agriculture cropping patterns	Phases I and II	1:250 000 - 1:50 000
	Water storage, drainage and irrigation	Phases I and II	1:250 000 - 1:10 000
	Structural damage assessment	Phases I and II	1:50 000 - 1:10 000
Studies and other information	Animal carrying capacity and present density	Phases I and II	(as provided by the study)
	Human population density	Phases I and II	(as provided by the study)
	Development project identification	Phase I	1:500 000 - 1:50 000
	Specific development project description	Phase II	1:100 000 - 1:10 000
	Building codes and specifications	Phase II	(as provided by the study)
	Vulnerability assessment	Phase II	(as provided by the study)
	Risk assessment	Phase II	(as provided by the study)

THE ORGANIZATION OF AMERICAN STATES

The purposes of the Organization of American States (OAS) are to strengthen the peace and security of the Hemisphere; to prevent possible causes of difficulties and to ensure the pacific settlement of disputes that may arise among the member states; to provide for common action on the part of those states in the event of aggression; to seek the solution of political, juridical, and economic problems that may arise among them; and to promote, by cooperative action, their economic, social, and cultural development.

To achieve these objectives, the OAS acts through the General Assembly; the Meeting of Consultation of Ministers of Foreign Affairs; the three Councils (the Permanent Council, the Inter-American Economic and Social Council, and the Inter-American Council for Education, Science, and Culture); the Inter-American Juridical Committee; the Inter-American Commission on Human Rights; the General Secretariat; the Specialized Conferences; and the Specialized Organizations.

The General Assembly holds regular sessions once a year and special sessions when circumstances warrant. The Meeting of Consultation is convened to consider urgent matters of common interest and to serve as Organ of Consultation in the application of the Inter-American Treaty of Reciprocal Assistance (known as the Rio Treaty), which is the main instrument for joint action in the event of aggression. The Permanent Council takes cognizance of matters referred to it by the General Assembly or the Meeting of Consultation and carries out the decisions of both when their implementation has not been assigned to any other body; monitors the maintenance of friendly relations among the member states and the observance of the standards governing General Secretariat operations; and, in certain instances specified in the Charter of the Organization, acts provisionally as Organ of Consultation under the Rio Treaty. The other two Councils, each of which has a Permanent Executive Committee, organize inter-American action in their areas and hold regular meetings once a year. The General Secretariat is the central, permanent organ of the OAS. The headquarters of both the Permanent Council and the General Secretariat is in Washington, D.C.

The Organization of American States is the oldest regional society of nations in the world, dating back to the First International Conference of American States, held in Washington, D.C., which on April 14, 1890, established the International Union of American Republics. When the United Nations was established, the OAS joined it as a regional organization. The Charter governing the OAS was signed in Bogotá in 1948 and amended by the Protocol of Buenos Aires, which entered into force in February 1970. Today the OAS is made up of thirty-five member states.

MEMBER STATES: **Antigua and Barbuda, Argentina, The Bahamas** *(Commonwealth of)*, **Barbados, Belize, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Cuba, Dominica** *(Commonwealth of)*, **Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, St. Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, United States, Uruguay, Venezuela.**

ISBN 0-8270-3008-8

$65.00