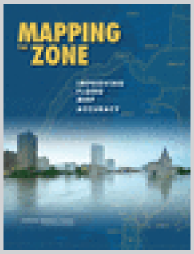


Mapping the Zone: Improving Flood Map Accuracy

ISBN
978-0-309-13057-8

136 pages
8 1/2 x 11
PAPERBACK (2009)

Committee on FEMA Flood Maps; Board on Earth Sciences and Resources/Mapping Science Committee; National Research Council

MAPPING THE ZONE

IMPROVING FLOOD MAP ACCURACY

Committee on FEMA Flood Maps

Board on Earth Sciences and Resources/Mapping Science Committee

Water Science and Technology Board

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by the Federal Emergency Management Agency under Award No. HSFE03-06-C-0030 and by the National Oceanic and Atmospheric Administration under Award No. DG133R07SE2691. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for this project.

International Standard Book Number-13: 978-0-309-13057-8 (Book)
International Standard Book Number-10: 0-309-13057-3 (Book)
International Standard Book Number-13: 978-0-309-13058-5 (PDF)
International Standard Book Number-10: 0-309-13058-1 (PDF)
Library of Congress Control Number: 2009924737

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Cover: June 2008 flooding in Cedar Rapids, Iowa (foreground), and a portion of the FEMA Flood Insurance Rate Map in the same region (background). This part of the downtown is within the Special Flood Hazard Area (zone A), which is subject to a 1 percent or greater chance of flooding in any given year. Photograph courtesy of Stephen Mally. Used with permission. Map extract from FEMA's Map Service Center. Cover design by Van Nguyen.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON FEMA FLOOD MAPS

DAVID R. MAIDMENT, *Chair*, University of Texas, Austin
DAVID S. BROOKSHIRE, University of New Mexico, Albuquerque
J. WILLIAM BROWN, City of Greenville, South Carolina
JOHN DORMAN, State of North Carolina, Raleigh
GERALD E. GALLOWAY, University of Maryland, College Park
BISHER IMAM, University of California, Irvine
WENDY LATHROP, Cadastral Consulting, LLC, Bala Cynwyd, Pennsylvania
DAVID MAUNE, Dewberry, Fairfax, Virginia
BURRELL E. MONTZ, Binghamton University, New York
SPENCER ROGERS, North Carolina Sea Grant, Wilmington
KAREN L. SCHUCKMAN, Pennsylvania State University, University Park
Y. PETER SHENG, University of Florida, Gainesville
JUAN B. VALDES, University of Arizona, Tucson

National Academies Staff

ANNE M. LINN, Study Director, Board on Earth Sciences and Resources
LAUREN E. ALEXANDER, Senior Program Officer, Water Science and Technology Board, and Director, Disasters Roundtable
JARED P. ENO, Research Associate, Board on Earth Sciences and Resources
TONYA E. FONG YEE, Senior Program Assistant, Board on Earth Sciences and Resources

MAPPING SCIENCE COMMITTEE

KEITH C. CLARKE, *Chair*, University of California, Santa Barbara
ROBERT P. DENARO, NAVTEQ Corporation, Chicago, Illinois
GEORGE F. HEPNER, University of Utah, Salt Lake City
JOHN R. JENSEN, University of South Carolina, Columbia
NINA S.-N. LAM, Louisiana State University, Baton Rouge
LEWIS A. LAPINE, South Carolina Geodetic Survey, Columbia
MARY L. LARSGAARD, University of California, Santa Barbara
XAVIER R. LOPEZ, Oracle Corporation, Nashua, New Hampshire
ROBERT B. McMASTER, University of Minnesota, Minneapolis
SHASHI SHEKHAR, University of Minnesota, Minneapolis
EUGENE TROBIA, Arizona State Land Department, Phoenix

National Academies Staff

ANNE M. LINN, Senior Program Officer
JARED P. ENO, Research Associate

BOARD ON EARTH SCIENCES AND RESOURCES

GEORGE M. HORNBERGER, *Chair*, Vanderbilt University, Nashville
GREGORY B. BAECHER, University of Maryland, College Park
KEITH C. CLARKE, University of California, Santa Barbara
DAVID J. COWEN, University of South Carolina, Columbia
WILLIAM E. DIETRICH, University of California, Berkeley
ROGER M. DOWNS, The Pennsylvania State University, University Park
JEFF DOZIER, University of California, Santa Barbara
KATHERINE H. FREEMAN, The Pennsylvania State University, University Park
RUSSELL J. HEMLEY, Carnegie Institution of Washington, Washington, D.C.
MURRAY W. HITZMAN, Colorado School of Mines, Golden
LOUISE H. KELLOGG, University of California, Davis
CLAUDIA INÉS MORA, Los Alamos National Laboratory, New Mexico
BRIJ M. MOUDGIL, University of Florida, Gainesville
V. RAMA MURTHY, University of Minnesota (retired), Minneapolis
CLAYTON R. NICHOLS, Idaho National Engineering and Environmental Laboratory (retired), Sandpoint
RAYMOND A. PRICE, Queen's University, Kingston, Ontario, Canada
BARBARA A. ROMANOWICZ, University of California, Berkeley
JOAQUIN RUIZ, University of Arizona, Tucson
WILLIAM W. SHILTS, Illinois State Geological Survey, Champaign
RUSSELL STANDS-OVER-BULL, Anadarko Petroleum Corporation, Billings, Montana
TERRY C. WALLACE, JR., Los Alamos National Laboratory, New Mexico
HERMAN B. ZIMMERMAN, National Science Foundation (retired), Portland, Oregon

National Research Council Staff

ANTHONY R. DE SOUZA, Director
ELIZABETH A. EIDE, Senior Program Officer
DAVID A. FEARY, Senior Program Officer
ANNE M. LINN, Senior Program Officer
SAMMANTHA L. MAGSINO, Program Officer
CAETLIN M. OFIESH, Associate Program Officer
JENNIFER T. ESTEP, Financial and Administrative Associate
JARED P. ENO, Research Associate
NICHOLAS D. ROGERS, Research Associate
COURTNEY R. GIBBS, Program Associate
TONYA E. FONG YEE, Senior Program Assistant
ERIC J. EDKIN, Program Asssistant

WATER SCIENCE AND TECHNOLOGY BOARD

CLAIRE WELTY, *Chair*, University of Maryland, Baltimore County
JOAN G. EHRENFELD, Rutgers University, New Brunswick, New Jersey
GERALD E. GALLOWAY, University of Maryland, College Park
SIMON GONZALEZ, National Autonomous University of Mexico
CHARLES N. HAAS, Drexel University, Philadelphia, Pennsylvania
KENNETH R. HERD, Southwest Florida Water Management District, Brooksville
JAMES M. HUGHES, Emory University, Atlanta, Georgia
THEODORE L. HULLAR, Private Consultant, Tucson, Arizona
KIMBERLY L. JONES, Howard University, Washington, DC
G. TRACY MEHAN III, The Cadmus Group, Inc., Arlington, Virginia
DAVID H. MOREAU, University of North Carolina, Chapel Hill
THOMAS D. O'ROURKE, Cornell University, Ithaca, New York
DONALD I. SIEGEL, Syracuse University, New York
SOROOSH SOROOSHIAN, University of California, Irvine
HAME M. WATT, Independent Consultant, Washington, DC
JAMES L. WESCOAT, JR., University of Illinois, Urbana-Champaign

National Research Council Staff

STEPHEN D. PARKER, Director
JEFFREY W. JACOBS, Scholar
LAURA J. EHLERS, Senior Staff Officer
STEPHANIE E. JOHNSON, Senior Staff Officer
LAURA E. HELSABECK, Associate Staff Officer
M. JEANNE AQUILINO, Financial and Administrative Associate
ELLEN A. DE GUZMAN, Research Associate
ANITA A. HALL, Senior Program Associate
MICHAEL J. STOEVER, Senior Program Assistant
STEPHEN T. RUSSELL, Project Assistant

Copyright © National Academy of Sciences. All rights reserved.

Preface

Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps portray flood hazard areas, and they form the basis for setting flood insurance premiums and regulating development in the floodplain. As such, they are an important tool for individuals, businesses, communities, and government agencies to understand and deal with flood hazard and flood risk. Improving map accuracy is therefore not an academic question—better maps help everyone.

This study was requested by managers of FEMA's Risk Analysis Division and the National Oceanic and Atmospheric Administration's (NOAA's) Coastal Services Center, supported by NOAA's National Weather Service, National Geodetic Survey, and Coast Survey Development Laboratory. The Committee on FEMA Flood Maps was established to examine the factors that affect flood map accuracy, assess the economic benefits of more accurate flood maps, and identify ways to improve flood mapping, communication, and management of flood-related data. Committee members included academics and practitioners who collectively possessed expertise covering inland and coastal flood modeling and mapping, geospatial data management, flood hazard assessment, and economic and policy implications of flood map accuracy. Information on these topics was gathered from the literature, the Association of State Floodplain Managers, discussions with colleagues, and briefings at five committee meetings held between June 2007 and April 2008. In addition to these traditional means of gathering information, the committee conducted original analyses of variables that influence flood map accuracy, such as elevation and flood flow.

The committee would like to thank the individuals who briefed the committee or provided data, figures, or other input: Ken Ashe, Glenn Austin, Jerad Bales, Julio Cañon, Andy Carter, Tim Cohn, Todd Davison, David Divoky, Mary Erickson, Dean Gesch, Mike Godesky, Susan Greenlee, Ruth Haberman, Eric Halpin, Victor Hom, Marti Ikehara, Doo Sun Kang, Larry Larson, Kevin Long, Doug Marcy, Kate Marney, Robert Mason, Gordon McClung, Sally McConkey, Venkatesh Merwade, Mike Moya, Jim Nelson, Rick Neuherz, Edward Pasterick, Kernell Ries, Dan Roman, Paul Rooney, Rick Sacbibit, Brett Sanders, Eric Tate, Ronnie Taylor, Patty Templeton-Jones, Gary Thompson, D. Phil Turnipseed, Gordon Wells, Bruce Worstell, and Dave Zilkoski. Special thanks go to Thomas Langan, Stephanie Dunham, and Jerry Sparks, who carried out extensive hydrologic and economic case studies for the committee. Their efforts greatly expanded the pool of data from which to draw conclusions about improving the accuracy of flood maps. The committee also thanks the National Academies staff who worked on this report: Lauren Alexander Augustine, Tonya Fong Yee, Jared Eno, and particularly Anne Linn, the study director, who expertly guided the committee's activities and contributed significantly to synthesizing our results.

David R. Maidment
Chair

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Gregory Baecher, University of Maryland, College Park
Richard Bernknopf, United States Geological Survey, Menlo Park, California
Christopher Jones, Christopher Jones and Associates, Durham, North Carolina
William Kirby, United States Geological Survey, retired, Reston, Virginia
Richard Luettich, University of North Carolina, Chapel Hill
William Nechamen, New York State Department of Environmental Conservation, Albany
James Plasker, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland
Kerry Smith, Arizona State University, Tempe
Jery Stedinger, University of Cornell, Ithaca, New York

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Michael Goodchild, University of California, Santa Barbara, and Robert Dalrymple, Johns Hopkins University, Baltimore, Maryland. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Summary

Floods are the leading cause of natural disaster losses in the United States, costing approximately $50 billion in property damage in the 1990s alone. To manage flood risk and minimize future disaster relief costs, the nation invests significant resources in mapping flood hazard areas and providing federal flood insurance to residents in communities that regulate future floodplain development. The Federal Emergency Management Agency's (FEMA's) Flood Insurance Rate Maps (FIRMs, hereafter referred to as flood maps) are used for setting flood insurance rates, regulating floodplain development, and communicating the 1 percent annual chance flood hazard to those who live in floodplains.

Making and maintaining an accurate flood map is neither simple nor inexpensive. FEMA's Map Modernization Program, funded for fiscal years 2003 to 2008, will result in flood maps in digital format for 92 percent of the continental U.S. population. Taking flood maps into the digital world was a great step forward because digital maps are more versatile for floodplain management and other uses and they are easier to update. Yet even after an investment of more than $1 billion, only 21 percent of the population has maps that meet or exceed national flood hazard data quality thresholds (Figure S.1). Even when floodplains are mapped with high accuracy, land development and natural changes to the landscape or hydrologic systems create the need for continuous map maintenance and updates.

FEMA and the National Oceanic and Atmospheric Administration (NOAA) sponsored this study to examine the factors that affect flood map accuracy, assess the benefits and costs of more accurate flood maps, and recommend ways to improve flood mapping, communication, and management of flood-related data. The charge to the committee is given in Box S.1.

The committee based its findings and recommendations on information gathered from presentations, publications, and case studies carried out by the committee and the North Carolina Floodplain Mapping Program, which has high-accuracy data and maps for nearly the entire state, enabling comparison of new and traditional data and techniques. The case studies focused on (1) uncertainties in hydrologic, hydraulic, and topographic data in and near selected streams in Florida and North Carolina, and (2) the economic costs and benefits of creating new digital flood maps in North Carolina. The North Carolina analyses were carried out in three physiographically distinct areas: mountains (city of Asheville), rolling hills (Mecklenburg County), and coastal plain (Pasquotank and Hertford Counties). For the economic analysis, two benefits were considered, based in part on the availability of geospatial data required to carry out the analysis: (1) avoiding flood losses to new buildings and avoiding repairs to infrastructure through accurate floodplain delineation, and (2) setting flood insurance premiums to better match estimates of actual risk.

FACTORS THAT AFFECT FLOOD MAP ACCURACY

The components of FEMA flood maps that are most relevant to the issues of accuracy discussed in this

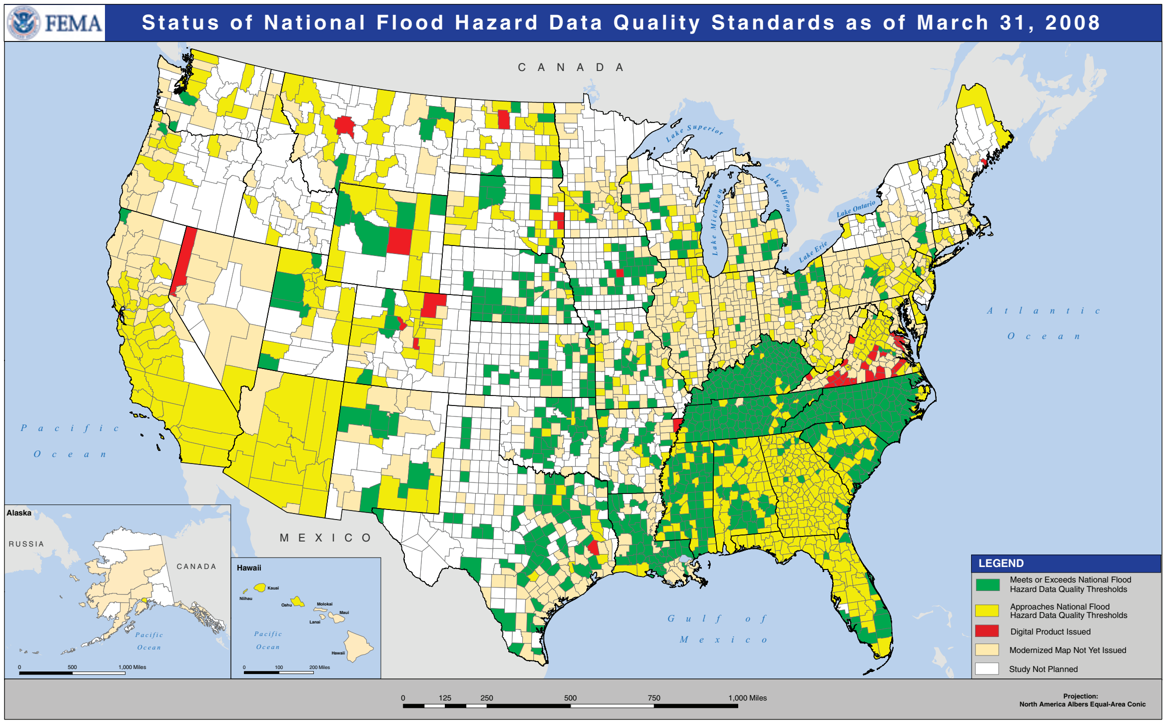


FIGURE S.1 Data quality standards achieved by individual counties as of March 31, 2008. Green counties meet or exceed national flood hazard data quality thresholds. Yellow counties meet some standards. In red counties, the maps have been updated digitally and a digital product has been issued. Compliance with data quality standards was not required for such digital conversions, although a limited FEMA audit suggests that some portions of these counties meet the standards. In beige counties, modernized maps have not yet been issued because the first phase of map production has not been completed or quality data do not exist. No study is planned in white counties. SOURCE: Paul Rooney, FEMA.

report are the floodplain boundaries and base flood elevations. Floodplains are low-lying, relatively flat areas adjoining inland and coastal waters. The most common floodplains mapped are those created by the 1 percent annual chance flood (also known as the 100-year flood) and the 0.2 percent annual chance flood (also known as the 500-year flood). The base flood elevation is the computed elevation to which floodwater is expected to rise or that it is expected to exceed during a 1 percent annual chance flood, and it forms the basis for setting flood insurance premiums and structure elevation regulations.

The extent of potential flood inundation must be predicted from statistical analyses and models. For riverine flooding, statistical estimates of flood discharges at U.S. Geological Survey (USGS) stream gages and digital representations of the land surface topography provide data for hydrologic and hydraulic models. The output is used in geographic information systems to delineate the predicted floodplain area. The process is similar for coastal flood mapping, except the existing repository of observational data (hurricane winds, topography, and bathymetry) is smaller and extreme events are more difficult to capture. As a result, coastal flood maps rely more heavily on modeling of wave and erosion processes and storm surge (water that is pushed toward the shore by the force of winds swirling around a storm) to predict coastal flood elevations. All of the inputs have uncertainties that affect the accuracy of the resulting flood map.

OVERARCHING FINDINGS

Finding 1. Topographic data are the most important factor in determining water surface elevations, base flood elevation, and the extent of flooding and, thus, the accuracy of flood maps in riverine areas.

BOX S.1 Committee Charge

The committee will

1. Examine the current methods of constructing FEMA flood maps and the relationship between the methods used to conduct a flood map study (detailed study, limited detailed study, automated approximate analysis, or redelineation of existing hazard information), the accuracy of the predicted flood elevations, and the accuracy of predicted flood inundation boundaries.
2. Examine the economic impacts of inaccuracies in the flood elevations and floodplain delineations in relation to the risk class of the area being mapped (based on the value of development and number of inhabitants in the risk zone).
3. Investigate the impact that various study components (i.e., variables) have on the mapping of flood inundation boundaries:
    a. Riverine flooding
        - The accuracy of digital terrain information
        - Hydrologic uncertainties in determining the flood discharge
        - Hydraulic uncertainties in converting the discharge into a floodwater surface elevation
    b. Coastal flooding
        - The accuracy of the digital terrain information
        - Uncertainties in the analysis of the coastal flood elevations
    c. Interconnected ponds (e.g., Florida)
        - The accuracy of the digital terrain information
        - Uncertainties in the analysis of flood elevations
4. Provide recommendations for cost-effective improvements to FEMA's flood study and mapping methods.
5. Provide recommendations as to how the accuracy of FEMA flood maps can be better quantified and communicated.
6. Provide recommendations on how to better manage the geospatial data produced by FEMA flood map studies and integrate these data with other national hydrologic information systems.

A study of sampling uncertainties in extreme stage heights at USGS stream gages in North Carolina and Florida found that for 30 of 31 gages, the average uncertainty is approximately 1 foot with a range of 0.3 feet to 2.4 feet. Uncertainties do not appear to vary with the size of the drainage basin or its topographic slope. It may thus be inferred that the lower bound on the uncertainty of the base flood elevation is approximately 1 foot. For the river reaches studied in North Carolina, a 1-foot change in flood elevation corresponds to a horizontal uncertainty in the floodplain boundary of 8 feet in the mountains, 10 feet in the rolling hills, and 40 feet in the coastal plain. This uncertainty has a significant impact on the delineation of inundated areas on flood maps.

The constriction of flood flow by bridges and culverts raises the base flood elevation in the three study areas. Such backwater effects are largest just upstream of the constriction and diminish progressively upstream. They are most pronounced in the coastal plain, extending an average of 1.1 miles and raising base flood elevations by up to 2.5 feet (average 0.9 foot). They are least pronounced in mountainous areas, raising the base flood elevation an average of 0.2 foot, which is not significant, given the sampling uncertainty noted above.

The largest effect by far on the accuracy of the base flood elevation is the accuracy of the topographic data. The USGS National Elevation Dataset (NED), developed from airborne and land surveys, is commonly used in flood map production, even though the elevation uncertainties of the NED are about 10 times greater than those defined by FEMA as acceptable for floodplain mapping. Data collected using high-resolution remote sensing methods such as lidar (light detection and ranging) can have absolute errors on the order of centimeters, consistent with FEMA requirements, but they are not available nationwide. A comparison of lidar data and the NED around three North Carolina streams revealed random and sometimes systematic differences in ground elevation of about 12 feet, which significantly affects predictions of the extent of flooding (e.g., Figure S.2). These large differences exceed FEMA's stated error tolerances for terrain data by an

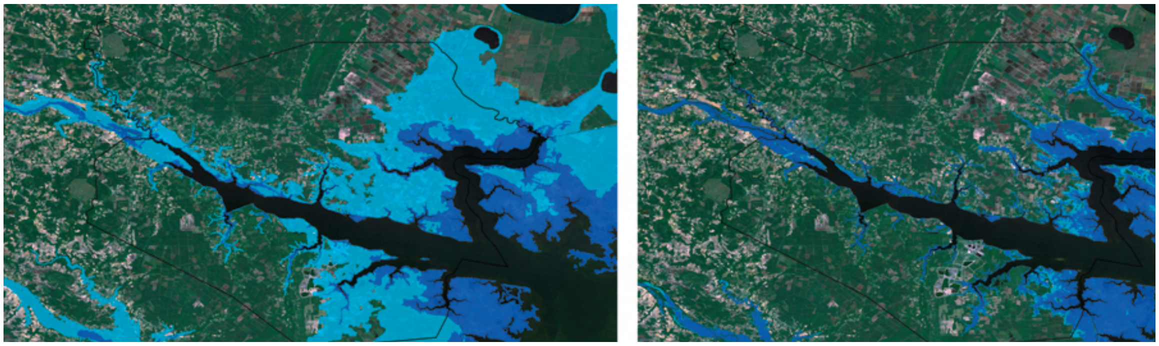


FIGURE S.2 Inundation maps of the area where the Tar-Pamlico River empties into Pamlico Sound of North Carolina. The figure on the left is based on a digital elevation model (DEM) with 30-meter post spacing created from the USGS NED. The figure on the right is based on a DEM with 3-meter post spacing created from North Carolina Floodplain Mapping Program lidar data. The dark blue tint represents land that would become inundated with 1 foot of storm surge or sea level rise. The light blue area represents uncertainty in the extent of inundation at the 95 percent confidence level. SOURCE: Gesch (2009).

order of magnitude and support the need for new topographic surveys, as called for in a National Research Council (NRC, 2007) report *Elevation Data for Floodplain Mapping*. In two of the study areas, random errors in topographic data produce inaccuracies in floodplain boundaries, but do not significantly alter the total area of the floodplain. In the other study area, in addition to random errors, there is a large systematic difference between the lidar and NED data that results from a misalignment of the stream location between the base map planimetric information and the topographic data. As a result, the total areas of the floodplains defined from lidar and from the NED differ by 20 percent. Because imagery is improving faster than elevation, the misalignment problem is growing more acute.

Finding 2. Coastal flood maps can be improved significantly through use of coupled two-dimensional storm surge and wave models and improved process models, which would yield more accurate base flood elevations.

The science of riverine flooding is reasonably well understood, and improvements to inland flood maps can focus on harnessing available technology. In contrast, advancing understanding of the complex dynamics of the coastal inundation process is necessary for improving the accuracy of coastal flood maps. Coastal flood models are evolving rapidly, but published results suggest that replacing FEMA's one-dimensional model for calculating wave heights (Wave Height Analysis for Flood Insurance Studies [WHAFIS]), which was introduced in the late 1970s, with a two-dimensional wave model would improve the accuracy of calculated base flood elevations. Coupled two-dimensional surge and wave models, as well as models that account for erosion processes, the effects of structures, and variations in topography, offer the potential for further improvements of coastal flood map accuracy. A comparison of available models, conducted by an independent external advisory group, would help quantify uncertainties and indicate which models should be incorporated into mapping practice.

Finding 3. Flood maps with base flood elevations yield greater net benefits than flood maps without.

Benefit-cost analyses have shown that the greatest benefits of more accurate flood maps are avoided flood losses to planned new buildings and avoided repairs to infrastructure through more accurate base flood elevations and depiction of floodplain boundaries. Producing a more accurate base flood elevation yields the greatest increment of benefits because it enables insurance premiums and building restrictions to be set commensurate with a more realistic profile of the horizontal and vertical extent of flooding. Only the more expensive of FEMA's flood study methods—detailed studies and most limited detailed studies—yield a base flood elevation. A comparison of study methods in the three case study areas by the North Carolina Floodplain Mapping Program showed that the use of detailed studies and limited detailed studies that generate base flood elevations results in net benefits to the state. In contrast, the use of approximate study methods, which do not yield base flood elevations, results in net costs. This is significant because detailed and limited detailed studies in North Carolina rely on lidar data, and even though lidar surveys are expensive, the costs to map the three study areas are outweighed by the benefits of more accurate maps.

Finding 4. The most appropriate flood study method to be used for a particular map depends on the accuracy of the topographic data and the overall flood risk, including flood probability, defined vulnerabilities, and consequences.

The North Carolina benefit-cost analysis showed that a combination of different study methods produces the greatest economic benefits to the state as a whole. The best study method depends on the characteristics of the area being mapped, such as the present and future potential of flooding, the potential for population growth, the availability of land for development, and the likely economic value of structures to be built. The quality of the topographic data is also important. Where accurate topographic data are available, an accurate base flood elevation can be calculated, a more accurate map can be produced, and thus better decisions can be made about appropriate use of the floodplain.

Finding 5. FEMA's transition to digital flood mapping during the Map Modernization Program creates opportunities for significant improvements in the communication of flood hazards and flood risks through maps and web-based products.

FEMA is moving from simply portraying flood hazard and flood insurance rate zones on maps to communicating and assessing risk, an ambitious goal that leverages the digital flood-related information and maps produced during the Map Modernization Program as well as FEMA tools for estimating flood damage and loss (i.e., Hazards U.S. Multi-Hazards software). To communicate risk, the maps and products must show not only where flood hazard areas are located, but also the likely consequences of flooding (e.g., damage to houses, coastal erosion). Inundation and risk maps beginning to be produced by U.S. federal and state government agencies and by other countries have attributes that merit FEMA's attention.

Maps that show only floodplain boundaries have the disadvantage of implying that every building in a designated flood zone may flood and that every building outside the zone is safe. Providing floodplain residents with the elevation of structures relative to the expected height of a number of floods offers a better way to define graduated risk (from low risk to high risk). Where the necessary data are available (e.g., structure elevation, base flood elevations, flood protection structure performance), a geographic information system could be used to personalize flood risk to individual addresses.

RECOMMENDATIONS

The body of the report contains focused recommendations on how to improve specific aspects of FEMA's flood data, models, and mapping. The following overarching recommendations address Tasks 4 through 6 and are based on the analysis of information presented throughout the report.

Cost-Effective Improvements to FEMA's Flood Study and Mapping Methods

Recommendation 1. FEMA should increase collaboration with federal (e.g., USGS, NOAA, U.S. Army Corps of Engineers), state, and local government agencies to acquire high-resolution, high-accuracy topographic and bathymetric data throughout the nation.

Riverine mapping methods are well established, although improvements could be made in calibrating rainfall-runoff models, updating regression equations (many of which are more than 10 years old) more frequently, and increasing the use of two-dimensional models developed by the research community. The greatest improvement, however, would come from use of high-accuracy, high-resolution topographic data. Improved measurements of channel, lake, estuarine, and near coastal bathymetry would augment the improved measurement of land surface topography enabled by lidar technology. As noted above, the use of lidar data to calculate more accurate base flood elevations and floodplain boundaries reduces future flood losses and produces net benefits to the State of North Carolina. Reducing future flood losses also benefits taxpayers throughout the nation. FEMA has recently begun to support collection of lidar data along the Gulf coast, but lidar data coverage over most inland areas is still sparse.

Recommendation 2. FEMA should work toward a capability to use coupled surge-wave-structure models to calculate base flood elevations, starting with incorporating coupled two-dimensional surge and wave models into mapping practice.

A significant improvement to coastal flood mapping can be made by improving the models. Currently, base flood elevations are calculated by combining storm surge models with wave models, and using the result in models that calculate erosion and wave effects. However, modeling has greatly advanced, and it is now possible to use coupled models that account for storm surge, waves, erosion, and topographic features simultaneously.

Recommendation 3. FEMA should commission a scientific review of the hydrology and hydraulics needed to produce guidelines for flood mapping in ponded landscapes.

Methods to map landscapes in which water tends to flow from one ponded area to the next (shallow flooding) are still being developed. The primary hurdle to progress is the lack of scientific studies and models on the interactions between ponds, the volume of water temporarily stored in the depressions, and the rate at which it percolates out. Commissioning a study would not be costly and is a necessary step toward improving shallow flood mapping.

Quantifying and Communicating the Accuracy of FEMA Flood Maps

Recommendation 4. FEMA should require that every flood study be accompanied by detailed metadata identifying how each stream and coastline reach was studied and what methods were used to identify the magnitude and extent of the flood hazard and to produce the map.

One of the most important ways to quantify and communicate flood map accuracy is to document the data and methods used to study each segment of stream or coastline. FEMA's current metadata reporting requirements do not include all the information needed to assess the quality and reliability of the data underlying the maps. For each stream or coastline mile studied, metadata should describe what input data, mapping, and modeling methods were used; the date of mapping; the contractor; and the starting and ending points.

Managing Geospatial Data

Recommendation 5. FEMA should reference all stream and coastal studies within its Mapping Information Platform to the USGS National Hydrography Dataset.

FEMA Map Modernization has produced a large amount of geospatial data and flood hydraulic models for the nation's streams and coastlines. The result is the most comprehensive digital description of the nation's streams and rivers that has ever been undertaken. These data are stored in the Mapping Information Platform (MIP) on a county-by-county basis. There is no requirement that map information such as stream centerlines be consistent from one county to the next. The USGS National Hydrography Dataset is a seamless, connected map of the nation's streams, rivers, and coastlines. Using a technique called linear referencing, it is feasible to link the FEMA stream and coastline data with the corresponding information in the National Hydrography Dataset. If this were done, FEMA flood data could become an integral part of the nation's hydrologic information infrastructure rather than existing as a separate database.

1

Introduction

Flooding is the nation's leading cause of disaster, contributing to nearly two-thirds of all federal disasters[1] and causing approximately $50 billion in property damage in the 1990s (Downton et al., 2005). Much of the damage occurs in floodplains—the low, relatively flat areas adjoining inland and coastal waters, including areas subject to a 1 percent or greater chance of flooding in any given year.[2] A house in the 1 percent annual chance (100-year) floodplain has a 26 percent chance of being damaged by flooding during a 30-year mortgage, compared to a 9 percent chance of being damaged by fire.[3] Insurance companies generally consider residential flooding too costly to insure because floods can be widespread and cause catastrophic losses (Figure 1.1). The National Flood Insurance Program (NFIP) was established in 1968 to slow increasing flood disaster relief costs by offering federal flood insurance to owners of property in floodplains, provided their communities regulate new development in these areas (FEMA, 2002). The premium that property owners pay is related to their risk of flooding, which is determined by the location of their property on Flood Insurance Rate Maps (FIRMs; hereafter called flood maps) produced by the Federal Emergency Management Agency (FEMA). The accuracy of floodplain boundaries drawn on these maps directly determines how well communities and individuals understand and are insured against their true flood risk (e.g., Box 1.1).

COMMITTEE CHARGE AND APPROACH

This report is the second undertaken by the National Academies to examine FEMA map modernization. The first study, *Elevation Data for Floodplain Mapping* (NRC, 2007), assessed the data needed to map floodplains. It concluded that the existing National Elevation Dataset (NED) is not sufficiently accurate to support accurate floodplain mapping and recommended that a program be established to collect high-accuracy, high-resolution digital terrain data nationwide. This second report broadens the analysis to other factors that affect flood map accuracy, assesses the benefits and costs of more accurate flood maps, and suggests ways to improve flood mapping, risk communication, and management of flood-related data (Box 1.2).

This study was initially requested by managers of FEMA's Risk Analysis Division, and managers from the National Oceanic and Atmospheric Administration's (NOAA's) Coastal Services Center later added their support. Of particular interest to NOAA are the accuracy of geodetic data, which are relied on for all types of flood studies; the accuracy of bathymetric data, which are needed for storm surge modeling; and the usefulness of integrating NOAA inundation map libraries into a national map system.

The committee addressed Tasks 1, 2, and 3 by gathering information from the literature and presentations

---

[1] Of the 1,720 federal disasters declared from 1953 to 2007, flooding contributed to 1,100 disasters, severe storms to 984 disasters, and fire to 845 disasters. See <http://www.fema.gov/news/disasters.fema>.

[2] Presidential Executive Order 11988.

[3] See <http://www.floodsmart.gov/floodsmart/pages/flood_facts.jsp>.

FIGURE 1.1 Flooding in downtown Cedar Rapids, Iowa, June 13, 2008. Floodwaters inundated about 100 city blocks, including May's Island, where City Hall and the courthouse sit. SOURCE: Stephen Mally. Used with permission.

BOX 1.1 Flooding in Conklin, New York, June 28, 2006

Improving the accuracy of maps can change the floodplain boundary and, thus, which properties are designated within the floodplain. Landowners often seek to avoid this designation,[a] which can have the effect of increasing insurance premiums, reducing property values, restricting development, and/or requiring costly mitigation efforts, such as raising the elevation of structures. At the same time, home and business owners have a strong financial interest in having their structures properly insured against flood damage. Residents of communities that are not in mapped 100-year floodplains often have no idea they are vulnerable to property losses until they are inundated. Yet one-third of flood insurance claims are for areas beyond the 100-year floodplain.[b] For example, the largest flood recorded in the Binghamton, New York, area extended beyond the 100-year floodplain to areas where flood insurance is not required, catching residents of the Conklin community off guard. As reported in the *Press & Sun-Bulletin*:[c]

> When Abby Mack moved into her home on Grandview Avenue in Conklin four years ago, her bank told her she didn't need flood insurance. A check of information-based flood maps—which officials rely on to predict the frequency and impact of floods—shows her home is above the flood plain. But as the Susquehanna River continued to rise through the twilight hours of June 28, it became clear that her home and others on her street were threatened. Police evacuated bewildered residents shortly before the river began creeping up their tidy lawns and driveways and pouring into basements. . . . The Mack residence, which lost a hot water heater, other major appliances and carpeting, fared relatively well. The damage was much more extensive just down the street and in other places in Conklin that, according to the maps, shouldn't have been touched by the flood. . . . "The whole flood plain has to be studied and re-evaluated," said Debbie Preston, supervisor of the Town of Conklin, where the recent flood ruined hundreds of properties and forced the evacuation of the entire town.

---

[a] Presentation to the committee by Patty Templeton Jones, Flood Committee of the Institute for Business and Home Safety, on November 8, 2007.

[b] See <http://www.floodsmart.gov/floodsmart/pages/flood_facts.jsp>.

[c] T. Wilber, 2006, Floods 2006—Are Tier flood maps wrong? *Press & Sun-Bulletin,* July 9.

BOX 1.2 Committee Charge

The committee will

1. Examine the current methods of constructing FEMA flood maps and the relationship between the methods used to conduct a flood map study (detailed study, limited detailed study, automated approximate analysis, or redelineation of existing hazard information), the accuracy of the predicted flood elevations, and the accuracy of predicted flood inundation boundaries.
2. Examine the economic impacts of inaccuracies in the flood elevations and floodplain delineations in relation to the risk class of the area being mapped (based on the value of development and number of inhabitants in the risk zone).
3. Investigate the impact that various study components (i.e., variables) have on the mapping of flood inundation boundaries:
   a. Riverine flooding
      - The accuracy of digital terrain information
      - Hydrologic uncertainties in determining the flood discharge
      - Hydraulic uncertainties in converting the discharge into a floodwater surface elevation
   b. Coastal flooding
      - The accuracy of the digital terrain information
      - Uncertainties in the analysis of the coastal flood elevations
   c. Interconnected ponds (e.g., Florida)
      - The accuracy of the digital terrain information
      - Uncertainties in the analysis of flood elevations
4. Provide recommendations for cost-effective improvements to FEMA's flood study and mapping methods.
5. Provide recommendations as to how the accuracy of FEMA flood maps can be better quantified and communicated.
6. Provide recommendations on how to better manage the geospatial data produced by FEMA flood map studies and integrate these data with other national hydrologic information systems.

to the committee and by conducting case studies in North Carolina and Florida (see "Case Studies" below). The results of the first three tasks formed the basis for the recommendations in Tasks 4, 5, and 6.

CASE STUDIES

Case studies were carried out to examine factors that affect riverine flood map accuracy and to assess the costs and benefits of more accurate flood maps. Most of the hydrologic, hydraulic, elevation, and economic analyses were carried out in collaboration with the North Carolina Floodplain Mapping Program. North Carolina was selected because flood maps developed using high-accuracy lidar data were available for nearly the entire state, enabling comparison of traditional and new data and techniques. The North Carolina studies focused on three physiographic regions, including the mountainous city of Asheville (Buncombe County), the rolling hills of Mecklenburg County, and the flat coastal plain of Pasquotank and Hertford Counties (Figure 1.2). Two coastal plain counties were analyzed because the most comprehensive development and insurance information needed for the benefit-cost analysis was available in Pasquotank County, but more comprehensive hydraulic information was available in Hertford County.

The committee used benefit-cost analyses to assess the economic impacts of inaccuracies in floodplain boundaries and flood elevations (Task 2). Such methods, which are used by FEMA for determining the benefits and costs of different mapping approaches, are based on measuring economic impacts, favorable and unfavorable, in monetary terms.[4] The committee's assessment relied on FEMA reports as well as a case study in Mecklenburg and Pasquotank Counties and the City of Asheville. The case study compared the costs of creating new digital flood maps with two result-

---

[4] Benefit-cost analysis differs from economic impact analysis, which traces direct and indirect spending effects through the economy. For example, an economic impact analysis might trace the results of a prediction of a particular type of flood to the amount of damage. A direct effect of flooding is damage to the house, and indirect effects include fewer pizzas but more plywood purchased.

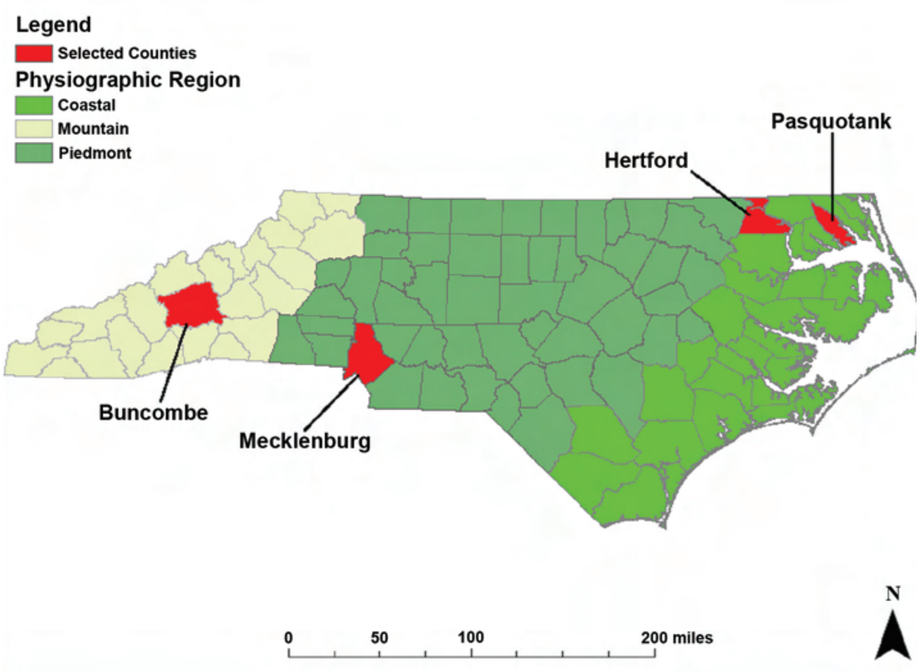


FIGURE 1.2 Physiographic provinces and location of counties studied in North Carolina. Hydrologic, hydraulic, and elevation data were analyzed in Buncombe, Mecklenburg, and Hertford Counties; benefits and costs were assessed in Buncombe, Mecklenburg, and Pasquotank Counties. SOURCE: North Carolina Floodplain Mapping Program. Used with permission.

ing benefits: avoided flood losses for new buildings and avoided repairs to infrastructure through accurate floodplain delineation and setting flood insurance premiums to better match estimates of actual risk. The assumption was that if the benefit-cost ratio was greater than 1, even when only a subset of benefits was considered, society would gain by improving map accuracy. The analysis was based on a comparison of buildings designated as either in or out of the floodplain under different mapping approaches.

The importance of accurate elevation data (Task 3) was evaluated by comparing maps made using the U.S. Geological Survey (USGS) National Elevation Dataset and lidar. For the hydrology and hydraulics analysis (Task 3), the committee followed the National Research Council (NRC, 2000) report by distinguishing two sources of uncertainty: natural variability and knowledge uncertainty. The inherent variability of nature leads to uncertainty that can never be eliminated. For example, the magnitude of future floods cannot be forecast precisely, no matter how much time, effort, or money is invested in flood modeling and mapping. In contrast, knowledge uncertainties arise from either incomplete understanding of events and processes or a lack of data, and they can be reduced with additional information. Knowledge uncertainty associated with riverine flooding (Task 3a) was examined through flood modeling and mapping case studies in Mecklenburg and Hertford Counties and the City of Asheville. Natural variability was quantified through the analysis of flood frequency from recorded annual maximum flood flows and stages at 21 USGS stream gages in the case study areas and other portions of the coastal plain of North Carolina. The NRC (2000) report examined uncertainties in discharge, water surface elevation, and economic damage, and concluded that mathematical flaws in the formal uncertainty analysis method preclude determining the precision of the uncertainty estimates. Consequently, the committee did not attempt a formal uncertainty analysis, in which uncertainties from various sources are combined mathematically to determine the total uncertainty in flood map variables.

Shallow flood frequency (Task 3c) was analyzed using data from 10 USGS stream gages in southwest Florida, an area subject to shallow flooding associated with interconnected ponds. However, comprehensive case studies to quantify factors that affect the accuracy of coastal and interconnected pond maps (Tasks 3b and 3c) were not practical because capabilities to model coastal and shallow flood processes are rapidly evolving. In contrast, methods for riverine flood mapping are more mature and well established. Consequently, the committee simply outlined the accuracy and uncertainty associated with coastal flooding and interconnected ponds.

ORGANIZATION OF THE REPORT

This report examines FEMA's mapping methods and recommends ways to improve flood map accuracy and to communicate and manage flood-related information. Chapter 2 describes how FEMA Flood Insurance Rate Maps are created, maintained, and used for insurance, regulatory, and other purposes. Chapter 3 examines the importance of elevation data in flood map accuracy and describes how land and water surfaces are defined relative to geodetic datums. Chapters 4 and 5 analyze factors that affect the accuracy of flood mapping of inland and coastal regions. Chapter 6 assesses the economic benefits of more accurate flood maps. Chapter 7 discusses ways to communicate flood hazard and risk. Methods used to estimate base flood elevations are summarized in Appendix A. Biographical sketches of committee members (Appendix B), a glossary of commonly used terms (Appendix C), and a list of acronyms and abbreviations (Appendix D) appear at the end of the report.

2

Flood Mapping and Flood Insurance

People have always settled near rivers and coasts, but population growth and the commensurate expansion of the built environment have increased their risk of losses to flooding over time. From the mid 1930s to the late 1960s, the federal government dealt with flood hazard primarily by building flood control structures, such as dams and levees. Flood insurance was not available because (1) the people most likely to buy it were those most prone to flooding, which meant that private companies could not profitably provide coverage at an affordable rate,[1] and (2) existing data about flood extent were insufficient to accurately assess flood risk.

Escalating flood losses and disaster relief costs, particularly the widespread damage caused by Hurricane Betsy, led to the creation of the National Flood Insurance Program (NFIP) in 1968. The objectives of the NFIP, which is administered by the Federal Emergency Management Agency (FEMA), are to identify and map floodprone communities and to make flood insurance available in communities that adopt and enforce floodplain management regulations (e.g., zoning, building requirements, special-purpose floodplain ordinances). More than 20,400 communities currently participate in the NFIP.[2] Although created for insurance and floodplain management purposes, FEMA's Flood Insurance Rate Maps (FIRMs) are now used for many other purposes, including disaster mitigation, land use planning, and emergency response. This chapter describes how FIRMs are created and maintained and how information technology is used to update and share flood-related data.

FLOOD INSURANCE RATE MAPS

Flood Insurance Rate Maps delineate flood hazard areas, identify flood insurance rate zones within these areas, and may show elevation and other data related to flooding. The information that appears on individual maps (and the accuracy of those data) depends on the type of flood hazard (e.g., riverine, coastal) and the way the flood hazard was studied. The primary information portrayed on FIRMs is discussed below.

Flood Hazard Areas

Three types of flood hazard areas are shown on FIRMs:

1. Special Flood Hazard Areas (SFHAs) subject to a 1 percent or greater chance of flooding in any given year (44 CFR 59.1). The 1 percent annual chance flood, also known as the base flood or 100-year flood, is the NFIP standard for regulating new development in the floodplain and determining where mandatory flood insurance coverage is required.

2. Moderate flood hazard areas, including areas subject to a 0.2 percent annual chance (500-year)

---

[1] The private sector stopped covering flood losses in 1929 after a series of devastating floods, including a 1927 flood of the Mississippi River, which inundated 13 million acres and killed several hundred people. See American Institutes for Research, 2002, *A Chronology of Major Events Affecting the National Flood Insurance Program*, 78 pp., available at <http://www.fema.gov/library/viewRecord.do?id=2601>.

[2] See <http://www.floodsmart.gov/floodsmart/pages/about/community_preparedness_ratings.jsp>.

flood (44 CFR 64.3) and SFHAs that are either small (drainage areas of less than 1 square mile), expected to flood less than 1 foot, or protected by levees from the 1 percent annual chance flood. Flood insurance is voluntary, although lenders may require flood insurance for structures. In addition, communities may choose to regulate land use and siting of critical services and emergency response facilities in these areas.

3. Areas in which flood hazards are minimal (e.g., less than a 0.2 percent annual chance of flooding) or undetermined, but still possible. These areas are not subject to federal regulations on insurance or land use, although communities and lenders may impose such requirements.

Each of these areas is divided into flood insurance rate zones, which designate the level and type of flood hazard (Box 2.1). The majority of SFHAs are either riverine and lacustrine (area along the shore of a lake or closed water basin) A zones (subject to a 1 percent annual chance flood) or coastal A zones and V zones (subject to storm surge where wave heights for the 1 percent annual chance flood are 3 feet or greater). Moderate flood areas are designated as shaded Zone X, and areas of minimal flood hazard include unshaded Zone X and zones for which flood hazard has not been determined. Example portions of FIRMs showing some of these zones in a riverine area and a coastal area are shown in Figures 2.1 and 2.2.

FEMA's Map Modernization Program was intended to produce digital FIRMs for all of the nation's 1 percent annual chance floodplains, but a midcourse adjustment gave priority to densely populated areas, where more lives and property are at risk (FEMA, 2006a). Risk-related priorities were based on total population, rate of population growth, number of housing units, number of flood insurance policies and claims, number of repetitive loss properties and claims, and number of declared flood disasters. This decision shifted emphasis from the risk of occurrence of a 1 percent annual chance flood to the risk of more significant flood damage.

BOX 2.1 Definitions of the Most Common Flood Insurance Rate Zones

Zone A: Special Flood Hazard Area (SFHA), defined as land subject to a 1 percent annual chance of flooding. The zone is divided into several subtypes, including

- **A (or unnumbered or approximate A)**: SFHA in which detailed analyses were not carried out and the base flood elevation is not shown.
- **AE, A1 through A30**: SFHA in which the water surface elevation has been determined and is shown on the map.

Zone V: Coastal SFHA subject to high velocity wave action from storms or seismic sources. The zone is divided into several subtypes, including

- **V (or unnumbered V)**: Coastal SFHA for which water surface elevations are not shown.
- **V1 through V30, VE**: Coastal SFHA with velocity hazard and water surface elevation determined and shown on the map. The VE designation is replacing the earlier numbered V designations.

Shaded Zone X, Zone B: Area of moderate flood hazard or future conditions flood hazard, generally defined as the 0.2 percent annual chance flood.

Unshaded Zone X, Zone C: Area of minimal flood hazard, commonly understood to have a lower probability of flooding than the moderate hazard area.

The numbers for zones A1 through A30 were determined by computing the difference between the 1 percent annual chance and 10 percent annual chance flood elevation, multiplying by 10, then applying a conversion factor (FEMA, 1983). The process was similar for numbered V zones, although different multiplication and conversion factors were used. Modernized maps have replaced the A1 through A30 designations with an AE designation, and the B and C designations with an X designation.

SOURCE: 44 CFR 59.1 and 44 CFR 64.3.

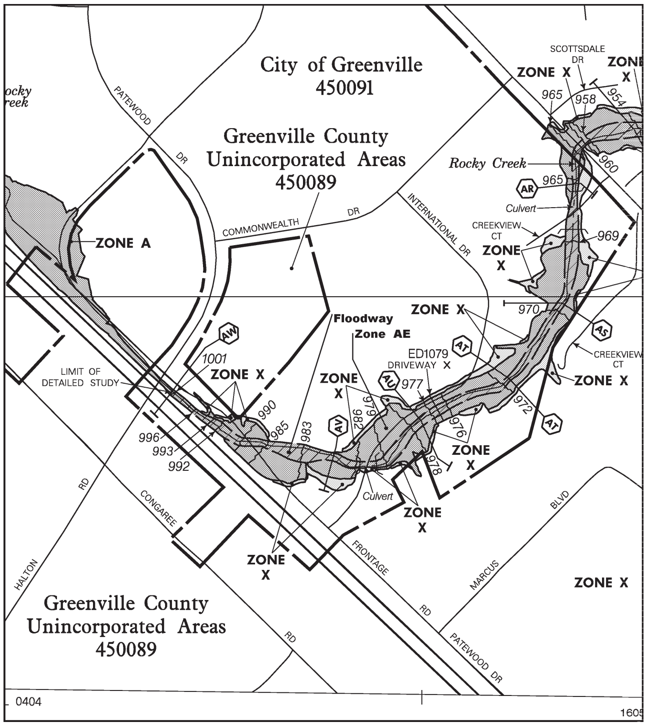


FIGURE 2.1 Extracted image from a paper map (FIRMette) for a riverine area in Greenville, South Carolina. The left side shows an approximate A zone (SFHA, shaded dark gray), where no elevation or floodway information is provided. The right side of the image shows an AE zone (SFHA, shaded dark gray) with lettered cross sections, base flood elevations (wavy lines with elevation), and floodway (hatched area bounded by heavy dashed lines), and a shaded Zone X (moderate flood hazard area, shaded light gray). The other areas are classified as unshaded Zone X (minimal flood hazard). SOURCE: FEMA's Map Service Center, <http://msc.fema.gov/>.

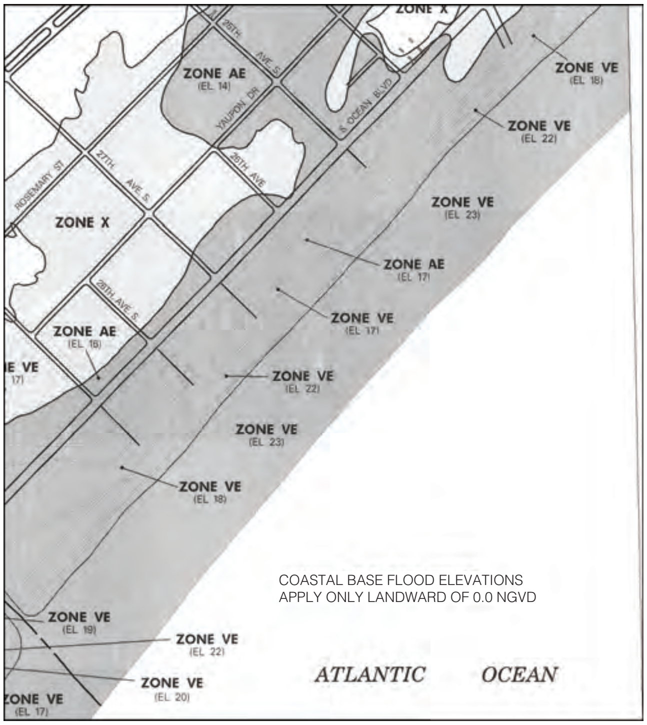


FIGURE 2.2 Example of a FIRMette for a coastal area near Myrtle Beach, South Carolina. The figure shows VE zones (SFHAs subject to coastal wave action) and associated elevations at the point on the ground to which the wave runs up during the 1 percent annual chance flood. Landward, the flood zones transition to Zone AE with their associated base flood elevations. SOURCE: FEMA's Map Service Center, <http://msc.fema.gov/>.

Base Flood Elevations

The base flood elevation (BFE) is the computed elevation of a flood having a 1 percent chance of being equaled or exceeded in a given year (base flood). It accounts for the volume and velocity of water moving through the watershed and reflects the cumulative effects of topography, soils, vegetation, surface permeability, and other factors. The BFE is the regulatory standard for the elevation or floodproofing of structures, and the relationship between the BFE and the elevation of a structure also determines the flood insurance premium. In general, the higher the first floor elevation, the lower the insurance premium. Consequently, the accuracy of BFEs on the flood maps is important for both regulating and insuring properties commensurate with the true risk of flooding.

Despite the importance of accurate BFEs in Special Flood Hazard Areas, in unnumbered A and V zones they are generally only estimated using approximate methods (see "Types of Flood Studies" below), which estimate key variables such as water volume. The determination of flood risk is less certain in these areas, so local communities may require a safety factor (known as freeboard) above the estimated BFE for additional financial protection. However, even where BFEs are established with more certainty, communities may impose freeboard to help protect against damage resulting from multiple 1 percent annual chance floods in a given year or higher than expected flood waters.

Future Hydrologic Conditions

Flood hazard information presented on FIRMs is typically based on conditions in the floodplain and watershed that existed when the map was made. In recent years, however, some growing communities have become interested in projecting how future land use and development in the watershed will affect the extent of the floodplain, and using those projections to regulate floodplain development. In response, FEMA issued a final rule in November 2001 that allows communities the option of showing future conditions floodplains based on land use change on the FIRM, along with the required existing conditions floodplain. The decision about how to use information on future conditions for regulatory decisions is left to the community. FEMA continues to use data on existing conditions for flood insurance purposes and has yet to consider the effects of climate change, long-term erosion of coastal areas, or long-term trends in hydrologic records on the determination of future conditions. By mid-century, the absolute flood elevations on structures along the Gulf Coast will be higher than at the time of their construction because of sea level rise and subsidence. The U.S. Army Corps of Engineers is including location-dependent adjustments in the design of structures to compensate for the expected rise.

FLOOD MAP PRODUCTION

The process for producing flood maps involves three main phases (Figure 2.3):

1. Scoping, including identifying flood risk, assessing immediate and future needs (e.g., development of floodprone areas), and determining what type of flood study is feasible with available resources. This step is carried out by FEMA in conjunction with state and local officials.

2. Development, including collecting technical data, modeling, creating a preliminary map, and performing quality control and quality assurance. Modeling and map production are carried out by a FEMA mapping partner (e.g., contractor, state or local government employee). Once the technical work has been completed, it is reviewed by a FEMA contractor, then preliminary maps are prepared and released to the relevant communities for review.

3. Adoption, including periods for public comment and appeal. FEMA, contractors, and state and local government agencies involved in the process must respond to comments made within the appeal period. Once the protest and appeal process is completed and any outstanding issues are resolved, the maps are finalized and FEMA issues a Letter of Final Determination. The local community then has up to six months to adopt the new map and update its floodplain management ordinances, if necessary, before the map becomes effective (i.e., the most current legal map for regulatory and insurance purposes).

Data for Digital FIRMs

Digital Flood Insurance Rate Maps (DFIRMs) are built from three layers of information (Figure 2.4).

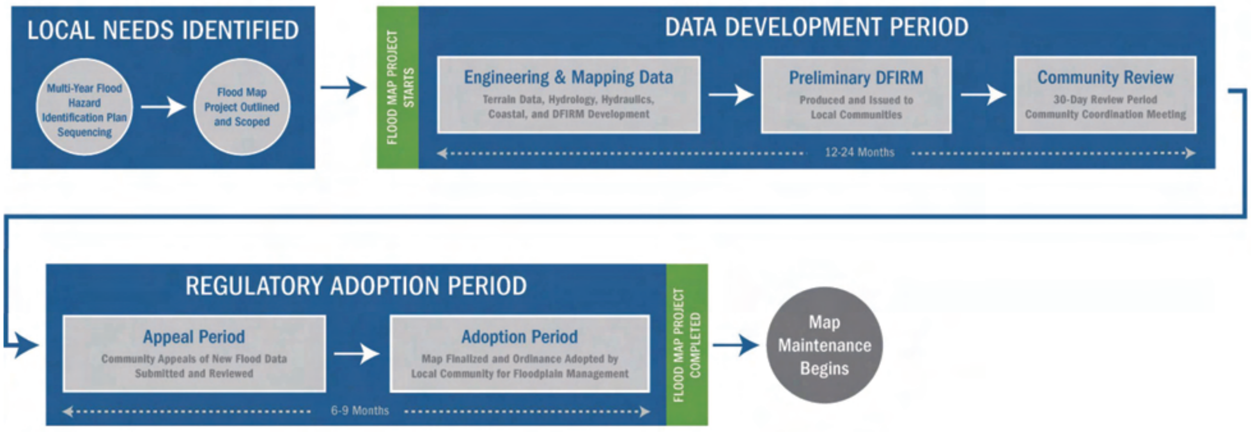


FIGURE 2.3 Flood map production process. SOURCE: Courtesy of Michael Godesky, FEMA.

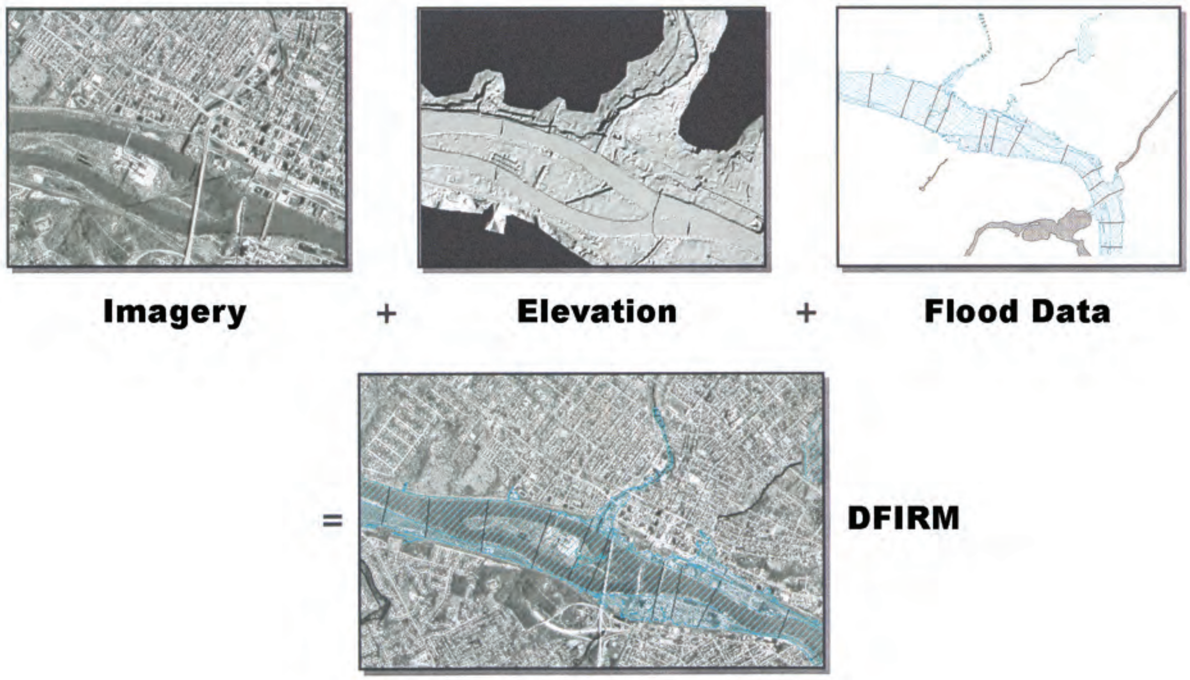


FIGURE 2.4 Major components of DFIRMs. SOURCE: Modified from Maune (2007). Reprinted with permission from the American Society for Photogrammetry and Remote Sensing.

The base map imagery (orthophoto or vector) shows planimetric features such as roads, rivers, and buildings. Digital elevation data are overlain to give each feature in the base map image a vertical position. Finally, flood hazard data, collected and modeled by surveyors and engineers, are overlain to produce the DFIRM.

Methods for Mapping Flood Hazard

FEMA's methods for mapping the most common flood hazards are summarized below and discussed in more detail in Chapters 4 and 5.

Riverine Flooding. Overbank flooding, the most common type of flooding in our nation, occurs when downstream channels receive more water than they can accommodate due to rain, snowmelt, blockage of channels by ice or debris, or dam or levee failure. Mapping riverine flood hazards requires hydrologic and hydraulic studies to determine ground elevations, the depth of floodwaters, the width of floodplains, the amount of water that will be carried by watercourses during flood events, and obstructions to water flow (FEMA, 2003, V. 1 and Appendix C). Cross sections, based on topographic data collected in the field or scaled from U.S. Geological Survey topographic quadrangle maps, are taken to define the floodplain. The locations of these cross sections are chosen to capture variations in topography and possible obstructions to flow.

Coastal Flooding. The coasts of the Great Lakes and the oceans are subject to severe flooding from storm surge, the result of high winds and air pressure changes that push water toward the shore. Coastal flood studies assess the effects of storm surge and wave action and determine base flood elevations (FEMA, 2003, V. 1 and Appendix D). The study process is similar to that for riverine flooding, except that instead of cross sections, transects are surveyed perpendicular to the coastline, yielding onshore and offshore ground elevations. The elevations are then used to compute the expected height of wave crests and wave runup that are added to the storm surge as it approaches the shoreline.

Shallow Flooding. Even a minimal rise in water level can lead to extensive inundation in relatively flat areas

TABLE 2.1 Types of Flood Study Methods

	Detailed (Riverine)	**Detailed (Coastal)**	**Limited Detailed**	**Approximate**	**Redelineation**
Base map[a]	Orthophotography or vector	Orthophotography or vector	Orthophotography or vector	Orthophotography or vector	Orthophotography or vector
Hydrology (flows)	Regression equations, stream gage data, or rainfall-runoff models	Historical water marks and tide gage data	Regression equations or stream gage data	Analysis not technically reviewed	Uses previously published flow information
Hydraulics (flood elevations)	Modeled (steady state or dynamic) with detailed structure survey data	Modeled storm surge, waves, erosion, and wave runup	Modeled (steady state) without survey information on bridge or culvert structures	Analysis not technically reviewed	Uses previously determined elevations
Mapping presentation	Typical zone representations include AE with floodway	Typical zone representations include AE and VE	Zone representation limited to AE	Typical zone representations include A and V	New floodplain boundaries matching new base map information; Letters of Map Change (LOMCs)
Study report	Provides flow estimates, floodway data tables, and flood elevation profiles	Provides shoreline profiles and stillwater data tables	Provides flood elevation and profile information	Not applicable	Republishes flood study
Cost per mile[b]	\$10,000-\$25,000 (typically \$13,500)	Approximately \$9300	\$1500-\$5000 (typically \$3000)	\$250-\$2000 (typically \$900)	

[a] All flood study methods use best available base map at the time of production; the current FEMA minimum standard is digital orthoquarter quadrangles.
[b] SOURCE: Paul Rooney, FEMA.

such as Florida. The low relief and absence of channels in these areas can cause water to flow in sheets across the land surface, often in unpredictable directions. Drainage ditches and stormwater management facilities may be overloaded by storms more severe than the 10 percent annual chance floods for which they are usually designed. Ponding of rainfall in depressions often creates local floods, which may be alleviated by infiltration, evaporation, or mechanical pumping. Shallow flood studies yield a uniform depth of flooding, which is either added to the ground elevation or used to determine a single base flood elevation for a large area (FEMA, 2003, V. 1 and Appendix E). When adequate topographic data are not available, cross sections may be taken to determine storage volume for areas subject to ponding and average flood depths for areas subject to sheet flow.

Types of Flood Studies

The four main approaches used to study riverine flood hazard are (1) detailed studies, (2) limited detailed studies, (3) approximate studies, and (4) redelineation. Each approach yields different information, and the decision about which to use depends on the type of flood hazard, the resources available, and the risk of flood damage. Coastal flood mapping is currently done using the equivalent of detailed studies. Table 2.1 compares the information used and presented in the four study types.

Detailed studies are most expensive and provide the most information about flood hazards, establishing base flood elevations, special and moderate flood hazard areas, and where appropriate, floodways.[3] Limited detailed studies provide a reasonable representation of the floodplain limits and often a base flood elevation. Structures such as bridges or culverts are represented in the models, but their dimensions and elevations are not verified in the field. Approximate studies yield

---

[3] A floodway is the river channel and adjacent land areas required to discharge the base flood without significantly increasing flood heights. Coastal high hazard areas and tidal rivers, which experience regular fluctuations in water surface elevations, do not have designated floodways.

an approximate outline of the floodplain, but no base flood elevations, floodways, moderate hazard areas, or other details. Although comparison of the floodplain boundaries to a topographic map provides an estimate of the base flood elevation, this estimate is inadequate for regulatory purposes. FEMA provides written guidance (FEMA, 1995) and a computer program for calculating approximate water surface elevations on open channels based on specified field measurements (see Appendix A for a list of methods used to estimate BFEs in approximate studies).

Redelineation studies are aimed at producing digital representations of flood maps as part of a national digital flood layer. Redelineation uses existing flood elevation information and redraws the flood boundaries on new or updated topographic maps. All approved changes to the flood maps (see "Map Maintenance" below) are incorporated, resulting in an updated map that reflects the most current effective flood elevation and hazard information. In contrast, the digital conversion method simply scans the flood boundaries shown on paper maps and transfers them to a new digital map. Fifty-four percent of the stream miles mapped until 2007 were the result of the digital conversion process.[4] This approach was discontinued for new studies following FEMA's midcourse adjustment (FEMA, 2006a) and prior to issuance of a new floodplain boundary standard (see below).

FEMA'S MAP MODERNIZATION PROGRAM

The nation has floodplains along approximately 3.5 million miles of rivers and coasts (FEMA, 2006a). Prior to 2003, only 1 million miles had been mapped, often at a lower quality than meets NFIP needs, and most flood maps and related products were outdated and available only in paper form. FEMA's Map Modernization Program was established to collect new flood data in unmapped areas, to update or validate existing flood data, and to create digital flood maps. The federal government invested about $1 billion in this 2003-2008 mapping effort, and considerable matching funds were provided by FEMA's state government and local community partners. This investment in more accurate maps was intended to benefit communities that use the maps to establish zoning and building standards; insurance companies, lenders, real estate agencies, and property owners who use the maps to determine whether flood insurance is required; and government officials who use the maps to support infrastructure, transportation, and other planning and to prepare for and respond to flooding.

Mapping costs and map accuracy are directly related, and funding for the Map Modernization Program was insufficient to produce high-quality maps of the entire nation (GAO, 2004). Moreover, the Government Accountability Office, Congress, and stakeholders were concerned about the accuracy of the mapped floodplain boundaries that were to be digitized (FEMA, 2006a). In response, FEMA made a midcourse adjustment to the Map Modernization Program. Two criteria were used to quantify map and engineering accuracy: (1) a floodplain boundary standard and (2) validation guidelines for flood data and engineering analyses used to delineate floodplains. The floodplain boundary standard is a statistical measure of the vertical discrepancy between the water surface elevation at the boundary of the floodplain and the land surface elevation at that location (FEMA, 2007c). The measure is computed at a sequence of points along the floodplain boundary and a specified percentage of these points must lie within defined error ranges that are more strict for maps produced from detailed studies than for maps produced from approximate studies. The standard is aimed at ensuring that the flood maps match the topographic data used, although adherence to the standard does not itself validate the topographic data. The validation guidelines for flood data and engineering analyses are a set of rules which define whether a flood study done in the past is adequate for current use or whether physical, hydrologic, or methodological changes since the time of the original study are sufficiently great to warrant an updated study (FEMA, 2007b). The intention of these changes was to improve the percentage of studies meeting these criteria while relaxing the original program goal of complete digital flood map coverage of the nation. Doing so is consistent with stakeholders' comments on the midcourse adjustment that "The goal of digitization of the nation's flood maps . . . should not outweigh the goal of achieving accuracy on the newly updated maps" (FEMA, 2008c, p. 22). A map of the data quality standards achieved for U.S. counties by March 2008 is shown in Figure 2.5.

---

[4] Presentation to the committee by Patrick Sacbibit, FEMA, on November 8, 2007.

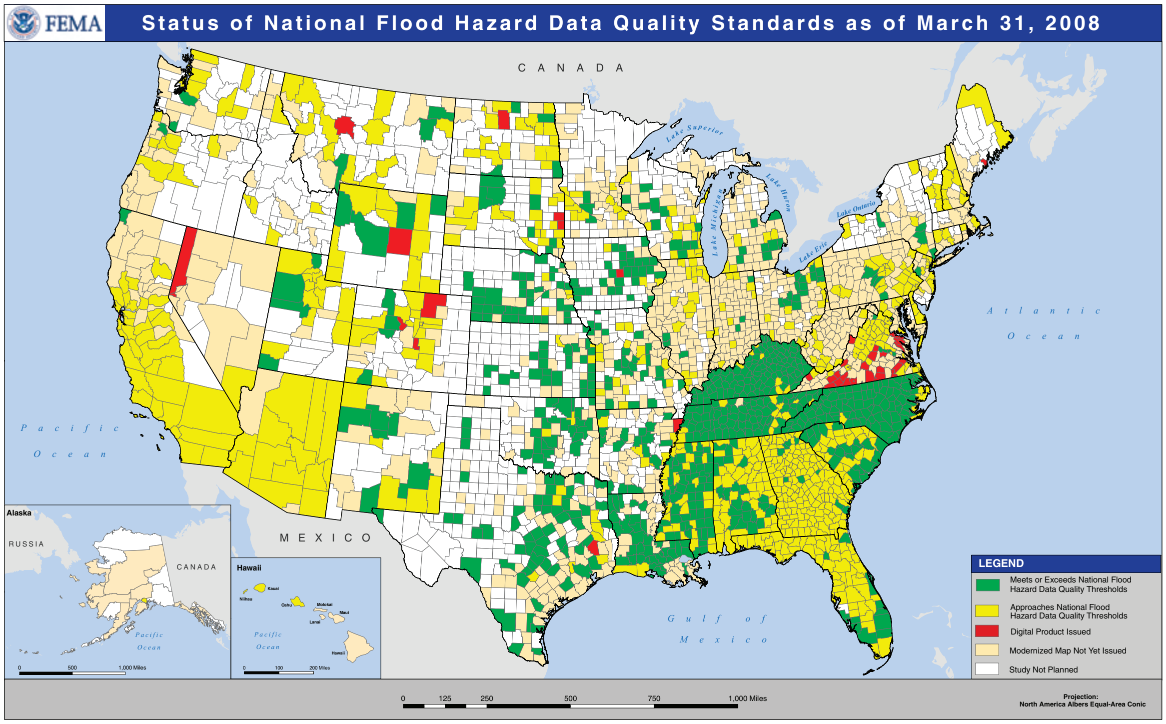


FIGURE 2.5 Data quality standards achieved by individual counties as of March 31, 2008. Green counties (21 percent of the population) meet or exceed the floodplain boundary standard and the engineering analysis standard. Yellow counties (47 percent of the population) meet either the floodplain boundary standard or the engineering analysis standard or part of either standard but below thresholds. In red counties (1 percent of the population), the maps have been updated digitally and a digital product has been issued. Compliance with data quality standards was not required for such digital conversions, although a limited FEMA audit suggests that some portions of these counties meet the standards. In beige counties (26 percent of the population), modernized maps have not yet been issued because the first phase of map production (scoping) has not been completed or quality data do not exist. No study is planned in white counties (5 percent of the population). SOURCE: Paul Rooney, FEMA.

The adjusted goal is to have 65 percent of the U.S. continental land area and 92 percent of the U.S. population covered by digital flood maps (Table 2.2; FEMA, 2006a). For 30 percent of the mapped stream and coastal miles covering 40 percent of the population, the maps should meet the engineering analysis standard. For 75 percent of the mapped stream and coastal miles covering 80 percent of the population, the maps should meet the floodplain boundary standard. These figures illustrate the challenges of increasing flood map accuracy: even if the goals articulated in the midcourse adjustment are achieved, 70 percent of the mapped stream miles will not have validated engineering analyses supporting the flood map, and 25 percent will not meet the floodplain boundary standard. In addition, this standard ensures that the maps match existing topographic data within defined error tolerances, but it does not ensure the accuracy of the topographic data.

MAP MAINTENANCE

A map records the conditions that existed when the data for its compilation were gathered. By the time the data are gathered and analyzed and the map is published, it may already be outdated. Corporate boundaries and other non-flood-related features can change, affecting regulation of floodplain development. Ground elevations in the floodplain can change—for example, when fill is placed in the floodplain to raise building sites or when a new flood control project introduces levees, reservoirs, or stream channel modifications—affecting the spread of floodwater. Small projects, such as clearing channels or building retention basins in new subdivisions, commonly do not have a measurable effect on the base flood and thus do not warrant a map change on their own. Cumulative effects of small projects, however, may be significant.

TABLE 2.2 Adjusted Targets for FEMA's Map Modernization Program

Performance Measure	Original Target (%)	Adjusted Target (%)
Percentage of continental U.S. land area covered by digital flood maps	100	65
Percentage of U.S. population covered by digital flood maps	100	92
Percentage of mapped stream and coastal miles with new, updated, or validated engineering analysis	22	30
Percentage of population covered by maps with new, updated, or validated engineering analysis	15	40
Percentage of mapped stream and coastal miles that meet the 2005 floodplain boundary standard	57	75
Percentage of population covered by maps that meet the 2005 floodplain boundary standard	32	80

SOURCE: FEMA (2006a).

Finally, better topographic data, models, or statistical data on hazard events may become available, potentially improving the depiction of the flood hazard.

FEMA has four approaches to changing flood maps:

1. Restudy, in which a new Flood Insurance Study is carried out to establish new flood profiles, data tables, and flood boundaries when development has substantially changed stormwater runoff conditions or when growth is occurring in a floodprone area that lacks base flood elevations. Restudies can be completely new work or new analysis of existing data using different models, and they result in addition of or adjustment to the BFEs, addition of the 0.2 percent annual chance floodplain, and/or changes in the horizontal extent of the SFHA.

2. Limited map maintenance projects, which are restudies that are limited in size and cost. They are frequently used to increase detail in approximate studies in unnumbered A zones.

3. Revisions, which are made after a flood map is published to reflect changes in the horizontal or vertical extent of the floodplain. Revisions may add or adjust the BFE; add, remove, expand, or contract the mapped floodplain; and/or add or remove a defined floodway.

4. Amendments, which are made to correct mapping inaccuracies, including non-flood-related map elements (e.g., north arrows, graphic scale) and inadvertent inclusion of higher areas in the mapped floodplain. Inadvertent inclusions are commonly found through more accurate or detailed topographic study; when they are too small to depict graphically, they are only correctable in Letters of Map Amendment.

Amendments and revisions generally result in the issuance of a Letter of Map Change (LOMC), and revisions may also result in a physical map revision. Letters of Map Change originated when the production of FIRMs was an expensive photographic-based process, and it was less expensive to issue a letter than to publish a new version of an affected map panel. Applications for LOMCs are approved if computer models and ground surveys technically demonstrate that the ground surface (and the lowest floor elevation, depending on the type of LOMC) is a tenth of a foot above the established BFE, even though current mapping methodologies are not that accurate. Approved LOMCs are used with the associated FIRMs for floodplain regulation and insurance purposes.

Despite ongoing changes in the floodplain, FEMA flood maps are not updated on a regular schedule. Requests for changes are made irregularly and physical map revisions are infrequent due to funding constraints. Priorities must be set, and FEMA developed the Mapping Needs Assessment Process and the Map Needs Update Support System (MNUSS) to document and rank map update needs nationally. However, even high-priority updates (e.g., areas with known unmapped flood hazards, communities that are undergoing rapid growth or that can contribute to the map update) may not be made. Moreover, the time lag between approving and publishing LOMCs and physical map revisions lengthened when FEMA directed funds from map maintenance to digital conversion of paper maps during the Map Modernization Program. As a result, some parcels and structures may not be regulated or insured properly, even though the change in risk is known.

FLOOD MAP INFORMATION TECHNOLOGY

In the early days of the NFIP, data were published and revised in the form of paper maps, Flood Insurance Study reports, and Letters of Map Change—a costly,[5] inefficient, and time-consuming process. Initial steps toward a less paper intensive process led to the creation of FEMA's Map Service Center website in the late 1990s and the development of new mapping products. Through this website, users can extract images from a full-sized paper map to create FIRMettes (e.g., Figure 2.1) that are legally equivalent to the original paper product. The recent availability of LOMCs and Flood Insurance Study reports online has made data even more accessible. Yet although more products are available and distribution has improved, digital updating processes have lagged.

FEMA created the Mapping Information Platform (MIP)[6] on a secure website to allow its mapping partners (e.g., communities, engineers, surveyors, flood control districts, Cooperating Technical Partners) to submit data for review and share work responsibilities. With this system, map information (e.g., flood study data, LOMCs) is being shared, rather than the maps themselves. This system of information sharing shows what might be possible for map updates, which are often slow to be integrated with other map information.

Recommendation. FEMA should ensure that new flood information, revisions, and Letters of Map Change are incorporated into the digital Flood Insurance Rate Maps as soon as they become effective.

The digital environment could also facilitate communication of metadata—information about how flood data were generated. A variety of study methods are often used along a stream reach or coastline. For example, different segments of the same stream flowing through two adjacent communities may have been studied using different techniques and in different years. This distinction was commonly lost when the information was consolidated in the Map Modernization Program. Documenting how each mile was studied—including what input data, mapping, and modeling methods were used, the date of mapping, the contractor, and the starting and ending points of each study segment—would help users better understand the reliability and accuracy of the data. Many of these metadata are not currently included in Flood Insurance Study reports, particularly to this level of detail. However, metadata can easily be linked with digital flood map information, enabling users to examine data age, gathering, and analysis techniques to decide whether the flood data are suitable for the intended use. This is especially important, given that FEMA flood data are increasingly being used for land use planning, emergency response, and risk assessment, in addition to the insurance and regulatory purposes for which they were collected.

Recommendation. FEMA should require that every flood study be accompanied by detailed metadata identifying how each stream and coastline reach was studied and what methods were used to identify the magnitude and extent of the flood hazard and to produce the map.

FLOOD DATA AND A NATIONAL HYDROLOGIC INFORMATION SYSTEM

The FEMA Map Modernization Program is by far the largest investment that the nation has made in hydrologic information in recent years. It is also the largest effort that the nation has ever made to digitally describe the morphology of its streams and rivers. This investment could have many benefits beyond flood mapping. The flood models could be used for flood management and planning studies or for building real-time flood inundation mapping systems. The digital terrain and stream channel information could be used for water quality studies of contaminant transport in streams. FEMA is one of several federal agencies generating spatial hydrologic information and it is reasonable to ask how the data and models compiled during the Map Modernization Program could be made part of a National Hydrologic Information System.

Each of FEMA's flood studies covers a geographic region, often a county. Within that region, each stream reach is considered a separate entity with its own flood

---

[5] FEMA distributes more than 1 million paper maps each year, and the average cost of producing maps for a typical county is $250,000 to $500,000. Presentation to the committee by Paul Rooney, FEMA, on August 20, 2007.

[6] See <https://hazards.fema.gov/femaportal/wps/portal>.

discharge estimate, stream cross sections, and BFE. The floodplain boundaries of individual reaches are merged to delineate the Special Flood Hazard Area on a map panel. The digital information describing a single flood study is stored in hundreds or even thousands of files, which must be compiled for each county mapped in the nation. A key purpose of FEMA's MIP is to store these files so that they will be available for later retrieval. Two types of files are involved: the files that comprise the flood map (DFIRMs) and files of raw field data analyzed in engineering studies to define the BFE (Data Capture Standard database; FEMA, 2003, Appendix L).

Walker and Maidment (2006) examined the design of a geodatabase model to store flood map information. They showed that the most critical parts of the data capture standards are the stream centerlines and cross sections used in the flood hydraulics model. If accurate geographic information system (GIS) files of these are maintained along with the flood hydraulics model, the model could be georeferenced and used in subsequent applications. This involves preserving data defining the connection between two coordinate systems: the Cartesian (x, y, z) coordinate system used to record the meandering of the channel through the landscape and the (s, n, z) coordinate system used in the river hydraulics model, in which s represents stationing distance along the river and n represents the distance across a particular cross section in the river. In effect, the hydraulic model "straightens" the channel by ignoring the bends and considering only how far along and transverse to the stream centerline the water flows. Unless both sets of coordinates are stored in the archived map and model information, it will be difficult or impossible at a later date to place a hydraulic model cross section at the correct map location along the stream.

One limitation of FEMA studies is that they are done county by county and there is no requirement that the underlying streamlines match across county boundaries. This difficulty can be overcome if FEMA streamline data are matched with those of the U.S. Geological Survey (USGS) National Hydrography Dataset (NHD).[7] The NHD is a seamless, digital representation of streams and water bodies at map scales of 1:24,000 and 1:100,000 in the continental United States.[8] Walker and Maidment (2006) showed that for Fayette County, Texas, the 1:24,000 NHD streamlines cover all the streams mapped in the Map Modernization Program, and that each FEMA-mapped stream segment could be located in a corresponding position on the NHD. Thus, the flood study data collected by FEMA could be linked to and become a part of the nation's larger repository of hydrologic information, enabling it to be used for much more than flood mapping.

Recommendation. FEMA should reference all stream and coastal studies within its Mapping Information Platform to the USGS National Hydrography Dataset.

---

[7] Presentation to the committee by Sally McConkey, Association of State Floodplain Managers, on November 8, 2007.

[8] See <http://nhd.usgs.gov/>.

3

Elevation and Height Data

A flood map is the final outcome of a multitude of measurement, engineering, and data analysis tasks. The purpose of a flood study is to predict the height of water and the extent to which it will inundate the landscape in a modeled flood event. The elevations of the land, water, and hydraulic structures (e.g., bridges) are key elements in a flood study, and the accuracy to which these elements are determined is a critical factor in the accuracy of the final flood map. The Federal Emergency Management Agency's (FEMA's) accuracy standards for land surface elevations are summarized in Box 3.1. This chapter explains how elevation is measured and examines the impact of elevation uncertainties in flood studies.

The data components of a flood study that involve a measurement of height or elevation can be grouped into four general categories:

1. *Elevation reference surface*. Before elevation can be measured or the data used in engineering analysis, a measurement system must be established. The location of "zero" and a physical reference for elevation zero (in other words, a vertical datum) must be established on the Earth, where it can be used for all types of height measurements.
2. *Base surface elevation*. Two types of base surfaces are important to flood studies: land surface elevation (topography) and its underwater equivalent (bathymetry). Topography is expressed as the height of a location above the geodetic datum and is in most cases a positive value. Bathymetry is expressed as the depth of the land surface below rivers, lakes, and oceans; positive depth is equivalent to negative elevation.
3. *Water surface elevation*. The depth of water in rivers, lakes, and streams and the point at which water overtops their banks and spreads across the landscape are the subjects of riverine flood studies. The depth of water in the ocean and the impact of extreme events such as hurricane-induced storm surge or earthquake-induced tsunamis are the subjects of coastal flood studies. The height of water surfaces is measured with stream and tide gages. The location and elevation of the gages themselves must be determined accurately in order to correctly relate water surface measurements to other elevations.
4. *Structure elevation*. The vulnerability of buildings and infrastructure to flood damage is directly related to their location with respect to the floodplain and the elevation and orientation of critical structural components with respect to the height of potential floodwaters. In addition, structures within the floodway (such as bridges, dams, levees, and culverts) influence the conveyance of water in a stream channel during a flood event, affecting flood heights.

These categories are described in more detail below.

ESTABLISHING A REFERENCE SURFACE

To measure something with a ruler, we place the zero mark at the end of the object and measure length or distance relative to that mark. The term datum refers to a reference surface against which position measurements are made; it defines the location of zero on the measurement scale. Three fundamentally differ-

BOX 3.1 FEMA Land Surface Elevation Accuracy Standards

FEMA has established two land surface elevation accuracy standards, depending on whether the terrain is flat or rolling to hilly (FEMA, 2003, Appendix A):

1. Two-foot contour interval equivalent for flat terrain (vertical accuracy = 1.2 feet at the 95 percent confidence level). This means that 95 percent of the elevations in the dataset will have an error with respect to true ground elevation that is equal to or smaller than 1.2 feet.
2. Four-foot contour interval equivalent for rolling to hilly terrain (vertical accuracy = 2.4 feet at the 95 percent confidence level.)

These standards provide a benchmark for determining the importance of variations in the way elevation is measured and defined in the flood mapping process.

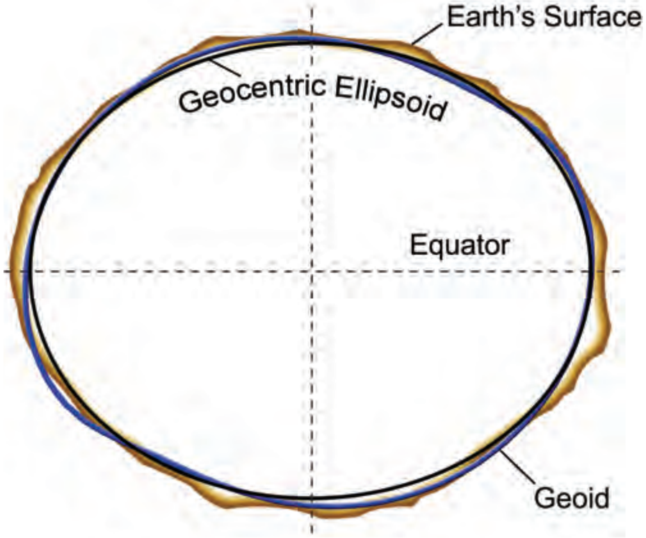


FIGURE 3.1 Relationship of the Earth's surface, the geoid, and a geocentric ellipsoid. The height difference between the geoid and the ellipsoid is the geoid separation. SOURCE: Kevin McMaster, URS Corporation. Used with permission.

ent types of vertical datums—ellipsoidal, orthometric, and tidal—are relevant to flood studies. In the United States, establishing and maintaining vertical datums is the responsibility of the National Oceanic and Atmospheric Administration's (NOAA's) National Geodetic Survey (NGS).

Ellipsoidal Datums

The Global Positioning System (GPS) provides the most accurate and efficient means for establishing fundamental reference marks (also called monuments) on the Earth's surface, and it forms the basis for most land and aerial surveys performed today. Land surveys are performed using handheld and tripod-mounted GPS equipment; airborne photogrammetric or remote sensing surveys employ GPS and inertial measurement systems to track the position of the sensor and project the data into accurate ground coordinates. GPS satellite systems measure distances to the Earth's surface relative to a mathematically idealized (smooth) ellipsoid that closely approximates the shape of the Earth (Figure 3.1). Heights computed with respect to this surface are referred to as ellipsoid heights. However, neither the Earth's surface nor its gravity field, as delineated by the undulating geoid surface, matches this idealized ellipsoid.

Orthometric Height Datums

Modeling the flow of water across the Earth's surface requires a reference surface defined by constant gravitational potential; this surface is referred to as the geoid. Heights measured with respect to an equipotential gravity surface are called orthometric heights, and the difference between the ellipsoid and the geoid at any particular location on the Earth is called the geoid height, or geoid separation (Figure 3.1). Geoid models developed and maintained by the NGS are used to convert ellipsoid heights to orthometric heights.

The orthometric height datum for surveying and mapping the North American continent is the North American Vertical Datum of 1988 (NAVD 88). NAVD 88 supersedes the National Geodetic Vertical Datum of 1929 (NGVD 29), which was used in many early flood maps and provided the basis for many engineering flood studies still in use today.[1] The height differences between NGVD 29 and NAVD 88 can be large (Figure 3.2), ranging from –49 cm (–1.6 feet) in Florida to +158 cm (+5.2 feet) in Colorado. Elevation differences between NGVD 29 and NAVD 88 are immaterial to flood mapping as long as elevations are referenced to the same datum. A potential problem arises when old

---

[1] See <http://geodesy.noaa.gov/faq.shtml> and Maune (2007) for a description of the differences between the two datums.

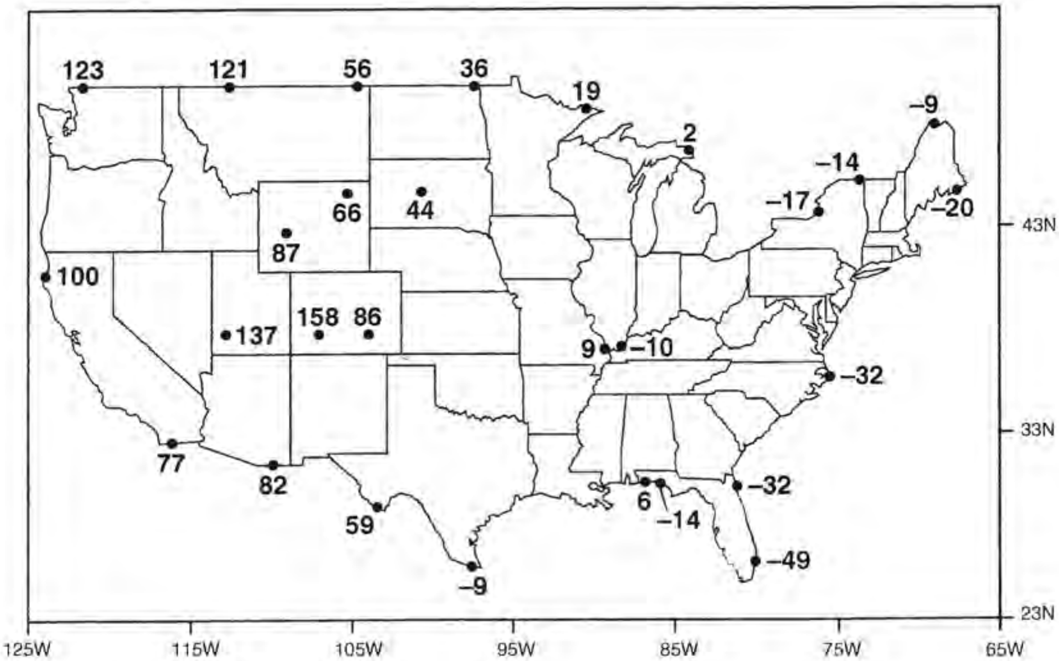


FIGURE 3.2 Differences in heights (NAVD 88 minus NGVD 29) in units of centimeters. In the eastern United States, NGVD 29 is generally higher than NAVD 88, with differences of 30 cm along the Carolina coasts and nearly half a meter in some parts of Florida. In the western United States, NAVD 88 is higher than NGVD 29 and height differences are greater than in the east, more than a meter in many locations. SOURCE: Maune (2007). Reprinted with the permission of the American Society for Photogrammetry and Remote Sensing.

engineering analyses, based on NGVD 29, are used for new studies, based otherwise on NAVD 88. Although conversion programs are available, the old surveys and methods used to establish NGVD 29 elevations are not a robust substitute for new measurements made with modern surveying technology and tied to well-founded, well-maintained NAVD 88 control monuments. Furthermore, the NGVD 29 elevations for benchmarks in areas of active subsidence frequently were not adjusted to account for movement of the terrain.

Finding. FEMA is justified in requiring that all survey data be referenced to the NAVD 88 datum.

Establishing an orthometric height datum that can provide centimeter-level height accuracy requires the use of either geodetic survey leveling observations or GPS measurements and a high-accuracy geoid model. The current version of NAVD 88 does not apply to islands, which cannot be reached with leveling measurements from the continental United States. Therefore, uniform national standards for FEMA flood maps cannot be met until an improved orthometric height datum and geoid model exist. The NGS is engaged in this task through geodetic leveling in U.S. territorial islands and implementation of the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project, which is estimated to be completed in 2017 (NOAA, 2007). If local island vertical datums are established, efforts should be made to ensure that the observations conform to national geodetic standards and that the data are archived and easily available for later adjustments.

The NGS Height Modernization Program includes the development of a high-accuracy geoid model and tools to assist with datum transformations. Height modernization has been implemented in only a few states (Figure 3.3). Yet it is essential for ongoing maintenance and expansion of NAVD 88 to support FEMA's standards and requirements for flood studies and floodplain mapping. The control monumenta-

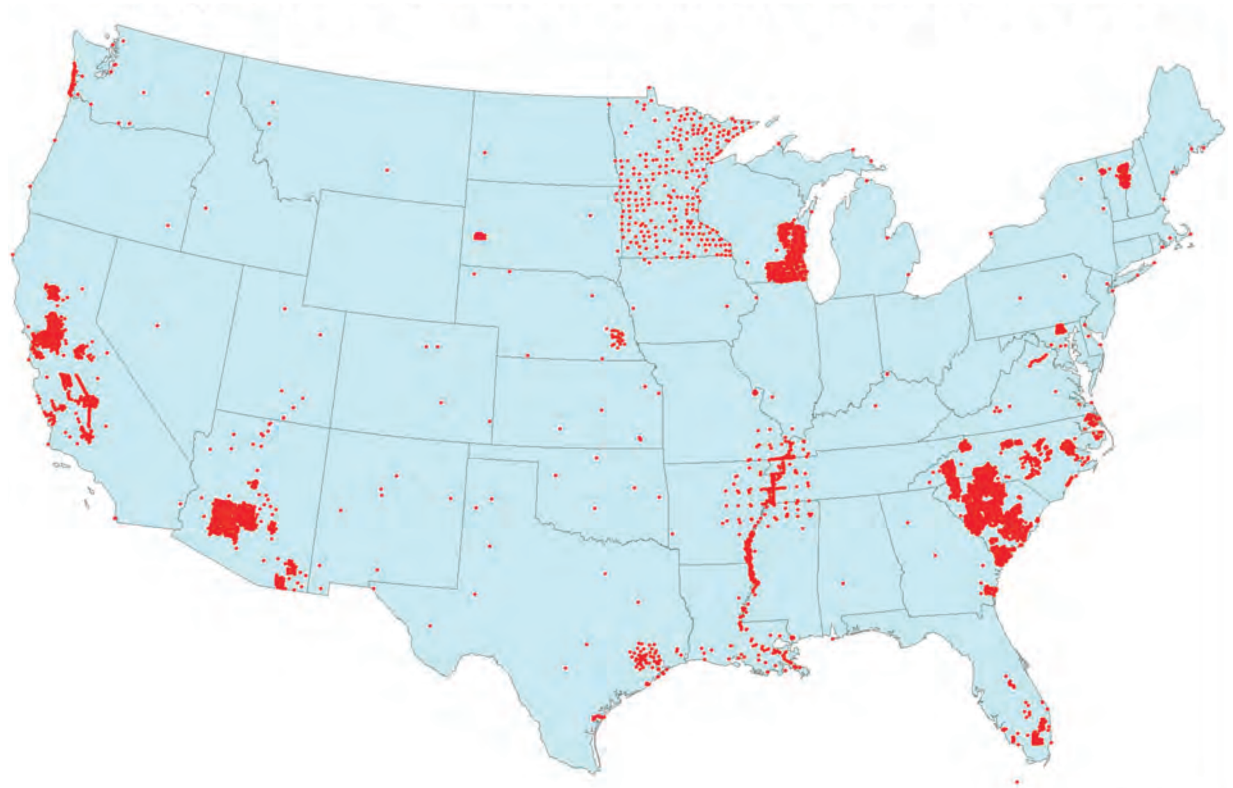


FIGURE 3.3 Location of NGS height modernization stations as of March 2007. SOURCE: Courtesy of D. Zilkoski, NOAA.

tion established by the program can be used as a basis for remote sensing surveys of topographic surfaces and hydrographic surveys of bathymetric surfaces. Establishing additional high-accuracy control points throughout the nation would make it possible to tie local structure surveys, including those performed for Elevation Certificates, to the common vertical reference system, ensuring a precise comparison to computed base flood elevations and accurate evaluation of flood risk.

Tidal Datums

There are numerous tidal datums (e.g., mean sea level), each defined by a certain phase of the tide and targeted to a particular application. The principal tidal datums in the United States are measured at tide gage stations over 19-year periods.[2] Tide gages measure local water levels; therefore, tidal datums are location specific and cannot be extended to areas with different oceanographic characteristics without substantiating measurements. Importantly for floodplain mapping, mean sea level at two different locations will not be on the same equipotential gravity surface. Thus, when performing engineering studies or making maps over large coastal areas, water surface elevations referenced to any tidal datum must be converted to the orthometric height datum used to reference the topographic surface. The relationship between tidal and orthometric height datums is shown in Figure 3.4.

The choice of an appropriate vertical datum depends on a number of factors, including whether the primary interest is the height of land or the depth of water. Regardless, it is essential to have access to well-maintained control monuments whose elevation with respect to the desired datum(s) is known with very high accuracy so they can be used as reference points for further elevation measurements.

---

[2] Further information is available at <http://tidesandcurrents.noaa.gov/datum_options.html>.

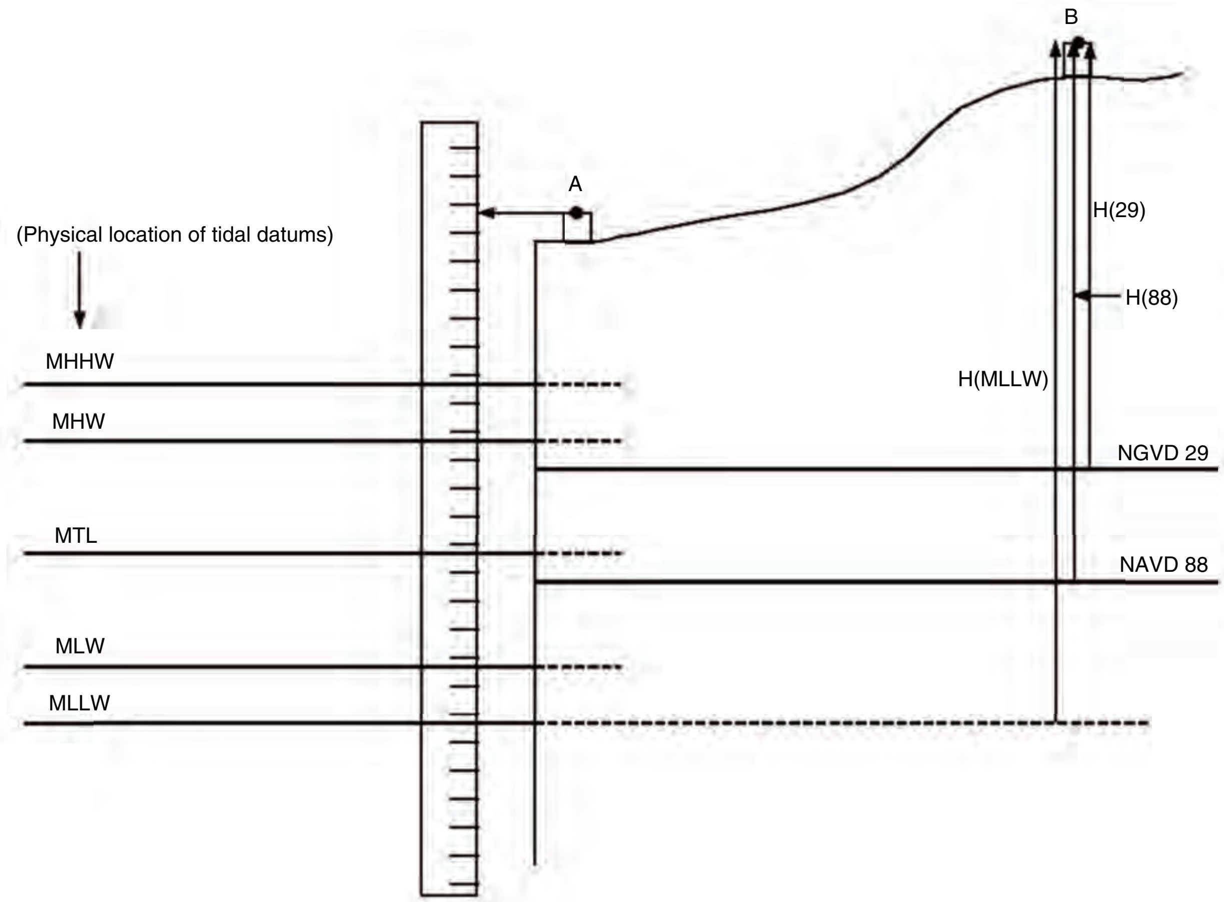


FIGURE 3.4 Where is zero on this scale? Height differences between tidal datums such as mean lower low water (MLLW) and geodetic datums are derived by leveling from a tidal benchmark (A), to which tidal datums are referenced, to a geodetic benchmark (B), and comparing heights. NOTE: MHHW = mean higher high water, MHW = mean high water, MLW = mean low water, MTL = mean tide level. SOURCE: Courtesy of D. Zilkoski, NOAA.

ESTABLISHING BASE SURFACES

Topographic Surfaces

The goal of topographic mapping is to develop a detailed and accurate three-dimensional model of the bare Earth, without vegetation or man-made structures, to be used as a base map surface. Topography can be mapped directly using traditional surveying instruments such as theodolites and levels or remotely using photogrammetry (aerial surveying). Photogrammetry was used to produce the majority of elevation contours shown on U.S. Geological Survey (USGS) 1:24,000-scale topographic maps (Figure 3.5). Digital elevation models (DEMs) were historically derived from these contours or from photogrammetric data compiled from the aerial photographic sources used to create the topographic maps. However, these methods are being superseded by new remote sensing technologies, particularly lidar (light detection and ranging) and IFSAR (interferometric synthetic aperture radar), which can quickly produce highly accurate surface models over large areas.

Although land surface elevation is stable in many areas, natural processes and human activities can cause elevation changes on the order of inches per year. Continual monitoring of subsidence and updating of elevation databases every few years may be required in these areas (e.g., coastal Louisiana, Texas, and Mississippi; central valley of California). In geologically stable areas, topographic changes caused by construction and development can be tracked locally and fed into a national database.

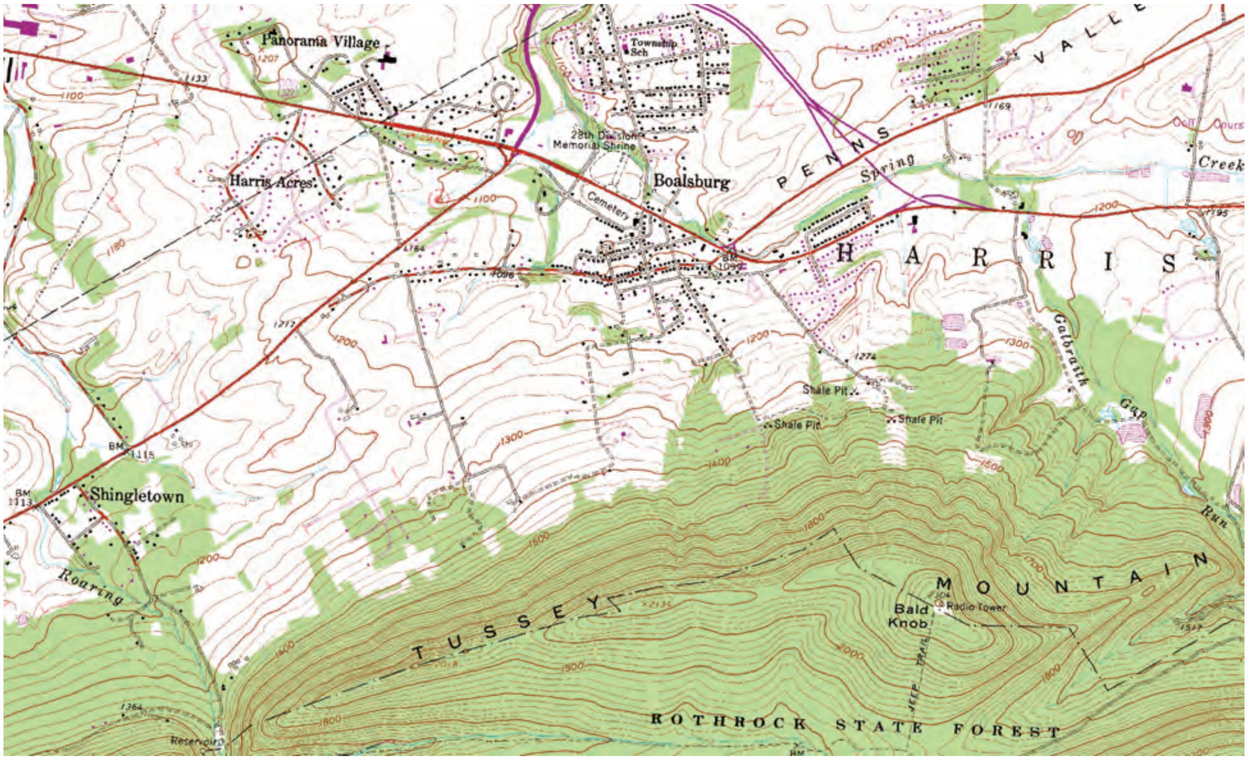


FIGURE 3.5 Portion of a USGS topographic map in Centre County, Pennsylvania, depicting elevation contours derived photogrammetrically from stereo aerial photography.

The National Elevation Dataset (NED), which is maintained by the USGS, is composed largely of USGS digital elevation models at 30-meter and 10-meter post spacing, but also includes some high-resolution, more accurate datasets acquired by the USGS and state and local governments. A shaded relief map created from the NED is shown in Figure 3.6. Independent tests have shown that the overall vertical accuracy of elevation data in the NED is 14.9 feet at the 95 percent confidence level (NRC, 2007). Although local NED accuracy may meet FEMA accuracy requirements in limited areas of the country, the overall value falls far short of these requirements, which are 1.2 feet in flat terrain and 2.4 feet in hilly terrain at the 95 percent confidence level (Box 3.1).

Finding. The National Elevation Dataset and the tagged vector contour data from 1:24,000 topographic maps used to create it have an elevation uncertainty that is about 10 times larger than that defined by FEMA as acceptable for floodplain mapping.

Bathymetric Surfaces

The bottom surface of rivers, lakes, and oceans is keenly important to hydraulic and storm surge modeling. However, no technology exists for obtaining accurate and detailed measurements of the entire bottom surface for all types of rivers, lakes, and coastal areas of interest in a flood study. Hydrographic surveys can be performed from boats, using sounding devices to produce profiles and samples of the bottom surface. Bathymetric lidar can be used to the extent that the blue-green laser light can penetrate the water. It is quite useful in clear water (e.g., around Hawaiian coral reefs), somewhat useful in shallow areas (e.g., along barrier islands of the southeastern United States), but ineffective in turbid rivers, lakes, streams, and oceans.

River bathymetry is defined using field-surveyed cross sections (e.g., Figure 3.7) immediately upstream and downstream of bridges and culverts. Traditional survey instruments (e.g., levels, total stations) or GPS are typically used to determine water surface elevations

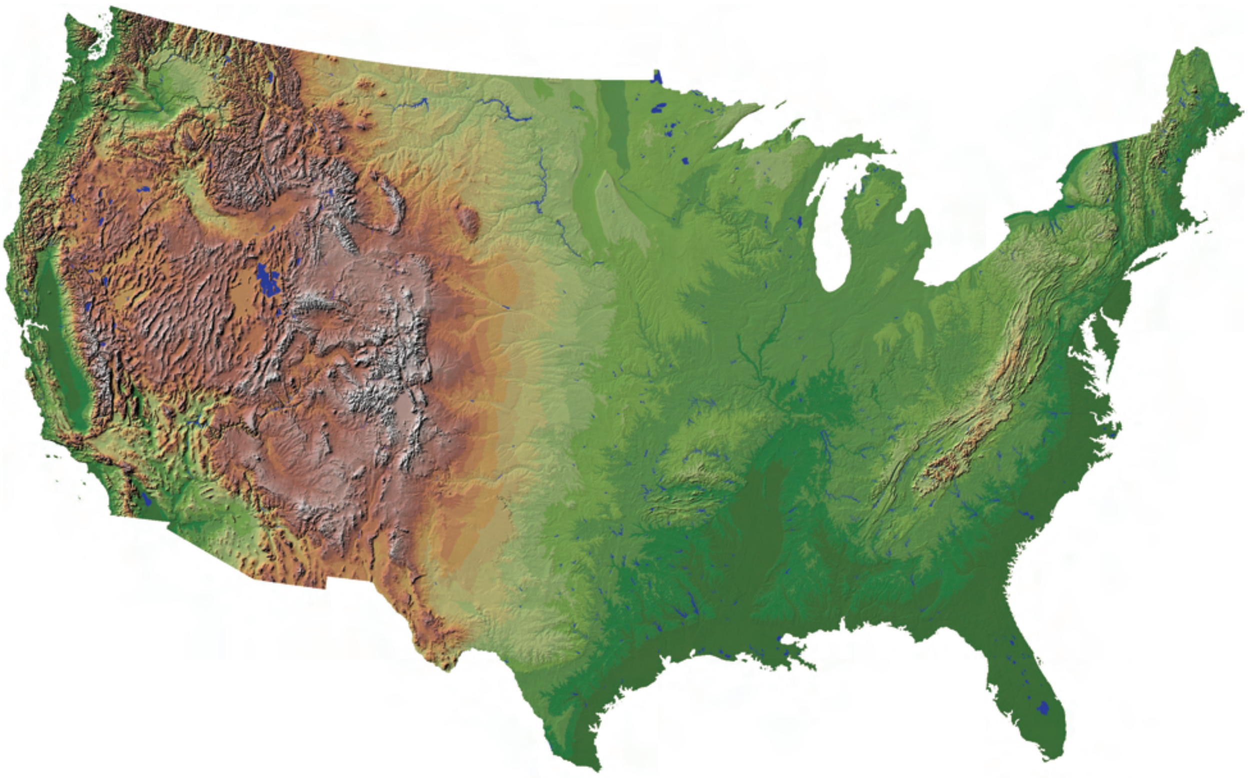


FIGURE 3.6 A shaded relief representation of the conterminous Unites States created from the National Elevation Dataset. Elevation is shown as a range of colors, from dark green for low elevations to white for high elevations. SOURCE: USGS, <http://erg.usgs.gov/isb/pubs/factsheets/fs10602.html>.

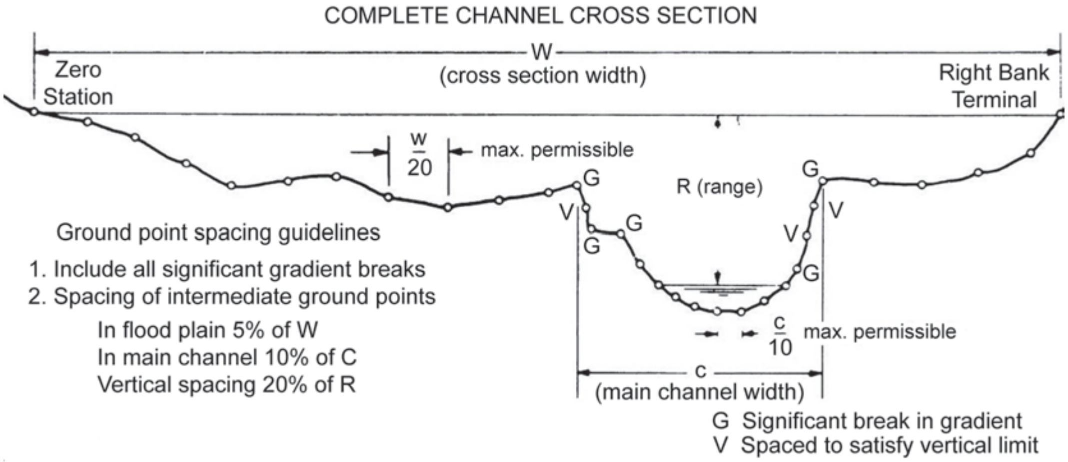


FIGURE 3.7 Example of a riverine cross-section survey. Elevations are measured at all significant breaks in gradient and at intermediate points depending on the width and depth of the river. SOURCE: FEMA (2003).

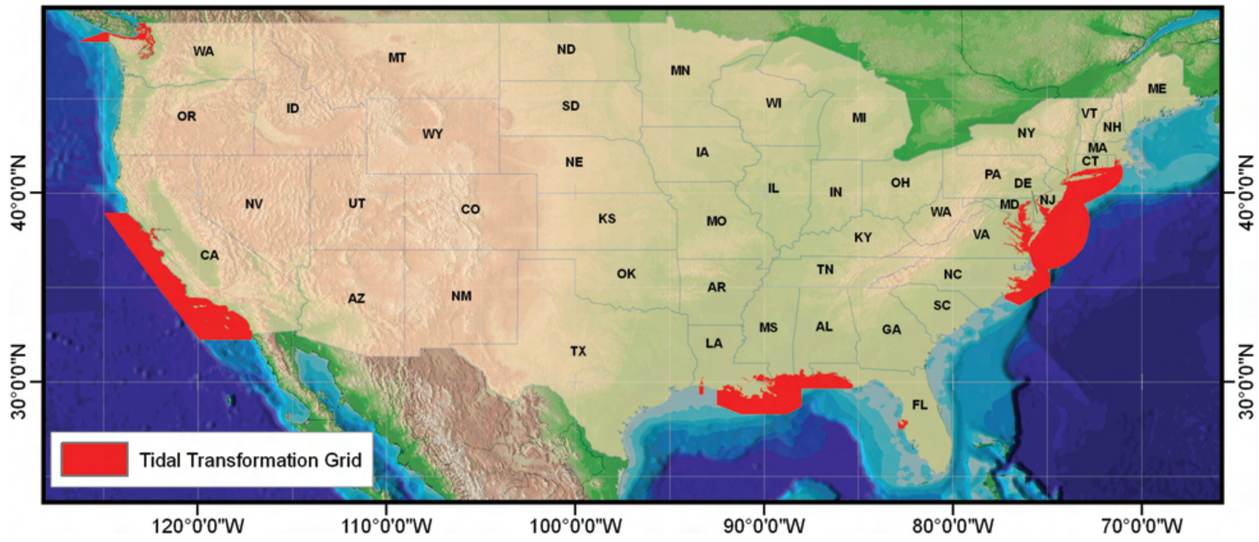


FIGURE 3.8 Areas where VDatum is currently available to transform coastal measurements to a common vertical datum. SOURCE: Bang Le, NOAA.

along the water edge. FEMA guidelines require cross-section surveys to include an elevation at the deepest part of the channel (FEMA, 2003). Cross-section surveys derive elevation from nearby geodetic control monuments, applying observed height differences between these known points and the newly surveyed points to establish their elevation with respect to the vertical datum.

NOAA's National Ocean Service (NOS) is responsible for mapping bathymetry in coastal areas, and the U.S. Army Corps of Engineers is responsible for mapping the bathymetry of navigable inland waterways. Because bathymetric charts are used for marine navigation, they display depth below a tidal datum. To produce coastal flood hazard maps, bathymetric data must be converted to NAVD 88. A NOAA software tool (VDatum) enables coastal water surface elevation measurements, which are made relative to a tidal datum, to be related to the orthometric height datum used as the reference surface for FEMA maps and studies. This makes it possible to merge topographic and bathymetric surfaces to create the seamless elevation surface needed to support storm surge modeling, coastal flood studies, and coastal floodplain mapping. Recent hurricanes along the Gulf Coast and the subsequent imperative to update storm surge models and coastal flood hazard maps demand continuation of this work, but funding shortfalls have slowed its completion until 2013.[3] Areas where sufficient input data (hydrodynamic models and sea surface topographic grids) exist to use the tool are shown in Figure 3.8.

MEASURING AND MONITORING WATER SURFACE ELEVATIONS

Water surfaces are dynamic by nature, changing over a wide range of time scales as a result of variations in the amount of rainfall, the influence of diurnal tides, the dynamics of ocean circulation, and changes in global sea level. Measurements of water surface elevations must be monitored continuously over long periods of time to identify trends and cycles.

Riverine Water Surfaces

Stream gages are the most common way to monitor riverine water surfaces. Stream gages measure stream stage, or height of the water relative to the gage. Discharge, which is the volume of water passing the gage location in a given interval of time, can be calculated from stream stage height using a rating curve based on historical measurements of flow and stage at the gage

---

[3] See <http://vdatum.noaa.gov>.

location. The USGS operates a network of more than 7,000 stream gages nationwide and provides real-time data, recorded at 15- to 60-minute intervals.[4] A typical USGS stream gage is shown in Figure 3.9. Stream gages usually survive flood events and provide much needed information about riverine water surface elevations used to calibrate flood models and determine flood frequencies.

Lidar offers another way to monitor water surface elevations. Figure 3.10 shows an inundation map of part of the Iowa River made using lidar data during flooding in the summer of 2008. Such real-time, high-accuracy measurements of water surface elevation could also be used to evaluate the relative accuracies of different types of flood studies (e.g., detailed, approximate). Currently, high-water marks of historical floods are used for this purpose, but they are sparse and no systematic efforts are made to archive them in a national repository of flood data.

Coastal Water Surfaces

Tide gages measure water heights relative to the gage. To determine water level with respect to any tidal or orthometric height datum, the height of the gage must be known with respect to that datum. Since tidal datums change over time and since tide gage measurements are used to develop tidal datums, it is prudent to maintain the height of the tide gage with respect to a more solidly fixed orthometric height datum.

The NOS maintains tide gages as part of the National Water Level Observation Network (NWLON). The network includes approximately 200 long-term, continuously operating water level stations throughout the United States—including islands, territories, and the Great Lakes—vertically referenced to nearby geodetic control monuments. NWLON stations provide the reference for tide prediction products, serve as controls for determining tidal datums for short-term water level stations, and are a key component of NOAA's tsunami and storm surge warning systems. The data continuity, vertical stability, and careful referencing of NWLON stations also enable the data to be used to estimate relative sea level trends, such as those shown in Figure 3.11.

FIGURE 3.9 Typical USGS stream gage. The box on top of the metal pipe contains a data logger that has a pulley with a metal wire holding a float at one end. As the water in the stream moves up and down, the float moves, turning the pulley and changing the gage-height reading. The data are transmitted to computers via satellite radio. SOURCE: USGS.

Finding. There are significant long-term linear trends in sea levels around the U.S. coastline; in most cases, sea levels are rising with respect to the land surface. The rate of change of sea level is significant when compared to flood map accuracy standards.

Measuring the extreme water elevations caused by storm surge has been a challenge. Gages are often destroyed by the surge and waves, so water surface elevations are usually estimated by surveying high water marks left on buildings and other elevated objects that survive the storm. Such surveys require deployment of numerous technicians during the height of rescue and recovery activities because data must be collected before they are altered or destroyed by cleanup efforts. A pre-storm deployed network of temporary gages designed to survive extreme events was established by the USGS after the 2005 hurricane season to begin building a record of the timing, extent, and magnitude of storm surge.

---

[4] Stream gage data are available through the National Water Information System, <http://waterdata.usgs.gov/nwis/rt>.

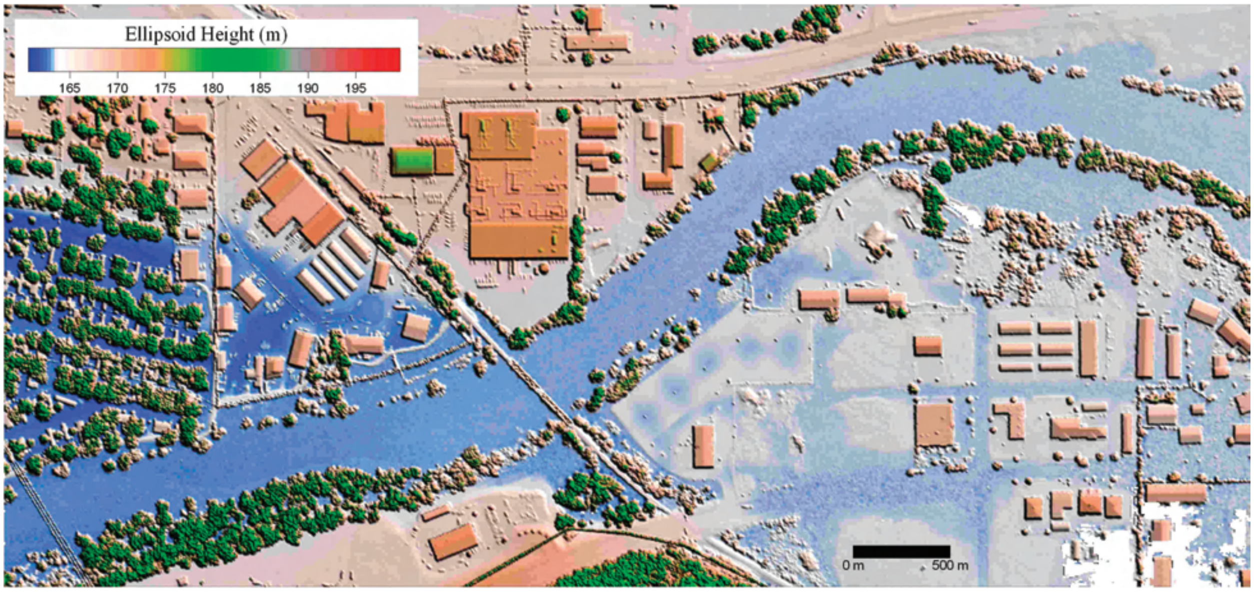


FIGURE 3.10 Color-coded image map of floodwater surface elevation above the ellipsoid using lidar in Iowa City, Iowa. Areas in the darkest blue (160 meters) have the lowest ellipsoid heights. The lighter blue areas indicate higher water surface elevations (163 meters). Water is flowing from right to left so the flooded regions on the left side of the picture are "downslope" from the flooded areas on the right side of the picture. The lidar data were collected by the National Science Foundation's National Center for Airborne Laser Mapping in June 2008 for IIHR-Hydroscience and Engineering at the University of Iowa. SOURCE: Courtesy of Ramesh Shrestha, University of Florida, and Witold Krajewski, IIHR-Hydroscience and Engineering. Used with permission.

SURVEYING STRUCTURE ELEVATIONS

Hydraulic Structures

For detailed studies, FEMA guidelines specify that the dimensions and elevations of all hydraulic structures and underwater sections adjacent to the structures must be obtained from available sources or by field survey where necessary (FEMA, 2003). Aerial surveys are not permitted. Data required for detailed studies of hydraulic structures are summarized in Table 3.1.

For limited detailed studies, bridges and hydraulic structures are typically modeled using field measurements or as-built records, rather than precise survey measurements.[5] For approximate studies, bridge, culvert, dam, and weir data may be estimated from photographs, orthophotos, or existing topographic mapping without performing field surveys (FEMA, 2003). Oblique aerial digital imagery, now available in some communities, can also provide good estimates of hydraulic structure dimensions.

Buildings

Elevation Certificates provide elevation information necessary to document compliance with community floodplain management ordinances, to determine the proper insurance premium rate, and to support requests for map amendment or revision. Surveys for Elevation Certificates have traditionally been made using differential levels and total stations, with differential elevations relative to the nearest available (not necessarily the most accurate) benchmark to minimize survey costs. In recent years these methods have been supplemented with GPS surveys and GPS-derived elevations relative to the most accurate control monument in the community. GPS-derived structural elevation data on Elevation Certificates are estimated to be accurate to ±0.5 foot at the 95 percent confidence level (FEMA, 2005b).

Data from Elevation Certificates are rarely available in digital format for all buildings in a community.

---

[5] Presentation to the committee by Paul Rooney, FEMA, on August 20, 2007.

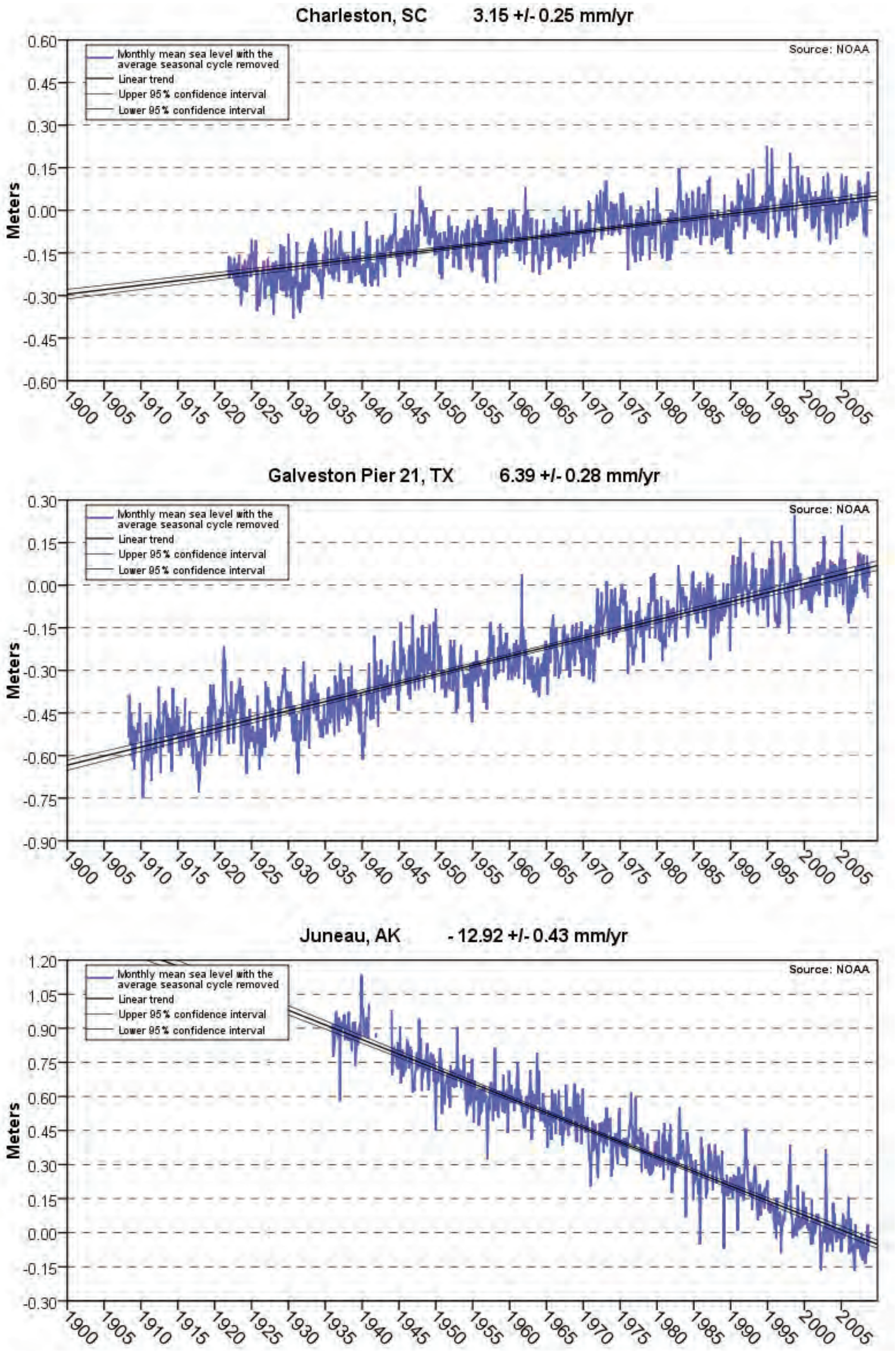


FIGURE 3.11 Sea level trends throughout the twentieth century determined from continuously operating water level stations. Sea level is increasing at Charleston, South Carolina, and Galveston, Texas. It is decreasing at Juneau, Alaska, indicating that the land level is rising faster through postglacial rebound than the sea level. SOURCE: NOAA, <http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml>.

TABLE 3.1 Data Requirements for Detailed Studies of Hydraulic Structures

Bridges	Culverts	Dams and Weirs
• Size and shape of openings • Upstream and downstream channel invert elevations • Entrance conditions (e.g., wingwalls, vertical abutments) • Bridge deck thickness, low-steel elevation, and bridge parapet type (i.e., solid railing, open railing) • Roadway embankment side-slope rate • Type and width of roadway pavement • Top-of-road section of sufficient length for weir-flow calculations	• Size and shape of openings • Upstream and downstream channel invert elevations • Entrance conditions (i.e., headwall, wingwalls, mitered to slope, projecting) • Height of road surface above culvert invert and vertical dimensions of guardrails • Roadway embankment side-slope rate • Type and width of roadway pavement • Top-of-road section of sufficient length for weir-flow calculations	• Top-of-dam elevation • Normal pool elevation • Principal spillway type, inlet and outlet elevations, and dimensions • Emergency spillway type (if applicable), elevation, and dimensions

A FEMA (2005b) report examined whether it is technically feasible to mass-produce Elevation Certificates inexpensively using aerial remote sensing. If so, an elevation registry could be populated with elevation data for all structures in a community for electronic rating of flood insurance policies and for geographic information system (GIS) analysis of flood risks. Although the study found that lowest adjacent grade elevations of reasonable accuracy could be produced from aerial surveys, other elevation data (e.g., elevation of basement floors) cannot be determined without on-site land surveys. Therefore, there are no current plans to establish an elevation registry of all structures in or near floodplains.

IMPACT OF ELEVATION UNCERTAINTIES IN A FLOOD STUDY

The base flood elevation (BFE) is the critical piece of water surface elevation data portrayed on a flood map. The accuracy of the BFE depends on the accuracy of other elevation components described above.

Vertical and Horizontal Uncertainties

The BFE is expressed as a height above NAVD 88. There are three sources of uncertainty implicit in this elevation: (1) geodetic uncertainty in defining the true elevation of the datum itself, (2) terrain uncertainty in measuring the height of the ground surface above the datum, and (3) hydraulic uncertainty in calculating the floodwater depth above the stream channel and floodplain surface. Once the BFE has been determined, it is mapped on the terrain surface to determine the horizontal extent of flooding across the landscape. The point at which the water surface intersects the terrain becomes the floodplain boundary. Elevation errors in the terrain surface can therefore affect the horizontal location of the floodplain boundary.

USGS Digital Elevation Models and Floodplain Mapping

The accuracy of the terrain surface is a function of the accuracy of the survey methods used to produce it. Land or airborne surveys determine elevations at a limited number of points on the ground, and a continuous terrain surface is created by interpolating between the points. The density and spacing of the measurements depend on the survey technology used and have a significant effect on cost. Therefore, it is important to establish the optimum point spacing and density to represent the terrain surface: too few points, and key features may be left out or smoothed over; too many points, and cost and data management may become burdensome.

Throughout the history of the FEMA floodplain mapping program, a mixture of data has been used to define topography. In detailed studies of high-flood-risk areas, data of accuracy equivalent to 4-foot contours or better have generally been used, at least for the main rivers and streams. In approximate studies of lower-flood-risk areas, USGS digital elevation data are more commonly used, either as tagged vector contour data or as digital elevation models derived from such data. However, the USGS DEM has three shortcomings for floodplain mapping (NRC, 2007):

1. On average, USGS DEM data contained in the NED are more than 35 years old, while FEMA flood mapping standards call for data measured within the last 7 years.

2. The standard gridded digital elevation model in the NED has 30-meter point spacing, but many land features (e.g., levees, berms, small streams, drains) are less than 30 meters wide and may be missing from the terrain surface generated from the DEMs.

3. The original surveys were performed from high-altitude photography, and the absolute elevation error is on the order of meters.

Lidar is capable of taking dense measurements (i.e., one or more points for every square meter on the ground), and absolute errors in elevations are measurable in centimeters, rather than meters, which is in accordance with current FEMA requirements (FEMA, 2003). To quantify the differences between NED and lidar data, the committee requested the North Carolina Floodplain Mapping Program (NCFMP) to produce flood maps made using each type of data in the North Carolina case study areas. Figure 3.12 and Table 3.2 show the elevation differences around streams in flat Hereford County, hilly Mecklenburg County, and mountainous Buncombe County.

Ground truthing proves that the lidar data meet FEMA requirements for floodplain mapping (NCFMP, 2008) and supports the NRC (2007) recommendation for nationwide collection of high-resolution, high-accuracy topographic data.

Finding. At Ahoskie Creek and the Swannanoa River, the stream and topographic data are well aligned for both lidar data and the NED, so while there are random differences between then, the average difference is small. At Long Creek, the stream and topographic data are aligned for the lidar data but not for the NED, so there is a large systematic difference between lidar and NED at this location.

The elevation differences have important implications for predicting the extent of expected flooding. Figure 3.13 depicts the difference in predicted flood inundation in Pamlico Sound using a USGS digital elevation model and the NCFMP lidar data. Uncertainties in the amount of land inundated are much

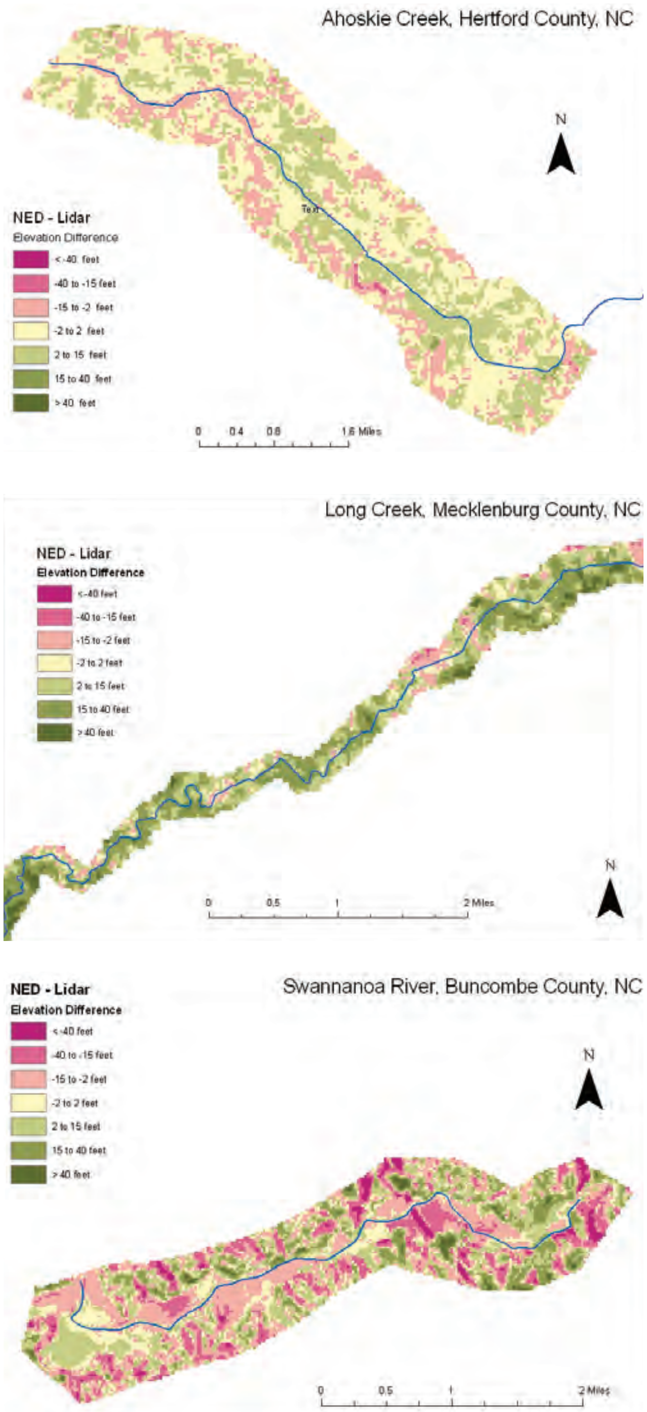


FIGURE 3.12 Elevation differences between the USGS NED and the North Carolina Floodplain Mapping Program lidar along rivers in three counties in North Carolina. Areas in red and pink are lower than appear on FEMA flood maps and suggest that the floodplain extends further than expected. *Top:* Eastern coastal plain (Ahoskie Creek, elevation ranging from 1 foot to 74 feet). *Middle:* Central piedmont (Long Creek, elevation ranging from 566 to 767 feet). *Bottom:* Western mountains (Swannanoa River, elevation ranging from 1,966 to 2,202 feet). SOURCE: Courtesy of T. Langan, North Carolina Floodplain Mapping Program. Used with permission.

TABLE 3.2 Elevation Difference Statistics, NED Minus Lidar

Stream	Mean (ft)	Standard Deviation (ft)	Minimum (ft)	Maximum (ft)
Ahoskie Creek	0.5	3.9	34.8	−25.3
Long Creek	14.7	15.6	81.5	−46.0
Swannanoa River	−2.0	17.5	89.7	−139.3

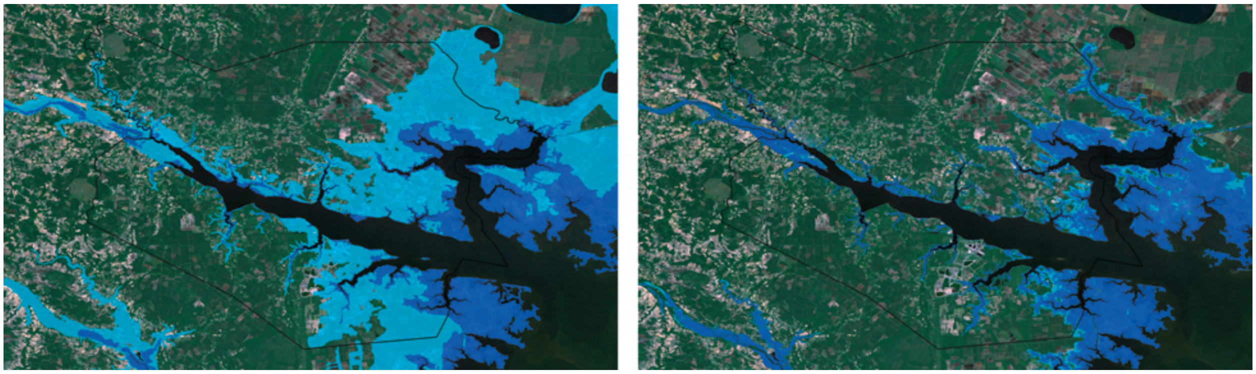


FIGURE 3.13 Inundation maps of Beaufort County, North Carolina, where the Tar-Pamlico River empties into Pamlico Sound. The figure on the left is based on a 30-meter DEM created from the USGS NED. The figure on the right is based on a 3-meter DEM created from NCFMP lidar data. The dark blue tint represents land that would become inundated with 1 foot of storm surge or sea level rise. The light blue area represents uncertainty in the extent of inundation at the 95 percent confidence level. SOURCE: Gesch (2009).

greater with the DEM. The large differences represent potential error in determination of the flood boundary and, thus, the flood risk.

CONCLUSIONS

It is neither trivial nor inexpensive to accurately measure and monitor the elevation of land, water, and structures across a vast geographic area. However, the committee's analysis shows that the accuracy of elevation data has an enormous impact on the accuracy of flood maps. Ensuring that future flood studies are based on the most accurate and consistent foundation possible requires (1) continuation of a suite of agency elevation programs and (2) acquisition of accurate, high-resolution elevation data. Key elements of this foundation include the National Height Modernization program, VDatum, and improved measurement of terrain and of streamflow and storm surge during flood events. Major efforts include the following:

- *Elevation for the Nation*. The North Carolina case study demonstrates the sensitivity of flood studies and floodplain boundary determinations to the resolution and accuracy of topographic data. Clearly, the standard practice of using the best available elevation data does not meet the needs of FEMA's floodplain mapping program. As concluded by the National Research Council (NRC, 2007), a seamless, high-resolution, high-accuracy topographic dataset is needed nationwide to support floodplain mapping. The governance and implementation of Elevation for the Nation is currently being considered (along with similar initiatives for nationwide imagery, transportation, and parcel data) by the National Geospatial Advisory Committee. Elevation for the Nation would rely on nationwide availability of high-accuracy control monumentation provided by national height modernization.

Recommendation. FEMA should increase collaboration with the USGS and state and local government

agencies to acquire high-resolution, high-accuracy topographic data throughout the nation.

- *National Water Information System*. Stream gage data, available through the USGS National Water Information System, provide the necessary riverine discharge information required for flood studies. Flood maps can be produced with much greater accuracy when a long and consistent history of stream gage information, and therefore discharges during flooding, is available.
- *USGS Storm Surge Network*. The USGS currently deploys short-duration storm surge gages prior to expected landfall of hurricanes. These gages are a considerable improvement over post-storm watermark surveys, which are subject to significant errors and uncertainties in the peak storm surge and wave conditions. Accurate storm surge measurements are critical for verifying coastal storm surge models using selected historical storms (see Chapter 5).
- *National Water Level Observation Network*. Flood risk is increasing rapidly in coastal areas due to a combination of land subsidence, sea level rise, population growth, and development. Coastal water elevations, measured and monitored through NOAA's NWLON program, provide essential information for FEMA's coastal flood maps. The information provided by NWLON tide gages is also critical to the development of VDatum, which in turn is needed to develop seamless topographic-bathymetric surfaces for coastal flood studies.

Elevation and height data are analogous to the foundation of a skyscraper; even if the engineering design and construction are flawless, the entire building is at risk of failure if the foundation is inadequate. It would be wise to lay a strong foundation before investing additional time, effort, and money in further construction of a building. Yet we have not taken such an approach to elevation data as they pertain to floodplain mapping. The technology and knowledge to build and maintain a comprehensive and accurate elevation measurement system have been available for 15 to 20 years. The main hurdle to implementing such a system nationwide has been cost. The relative costs and benefits of investing substantially in elevation data to produce more accurate flood maps are discussed in Chapter 6.

4

Inland Flooding

FEMA has studied nearly 1 million miles of rivers and streams,[1] so considerable experience has been gained in mapping riverine flood hazard, and mapping methods are well established. In contrast, approaches to mapping unconfined flows over broad, low-relief areas and the ponding of floodwaters in depressions (shallow flooding) are only emerging. This chapter addresses floodplain mapping associated with riverine flooding and flooding in ponded landscapes.

Riverine flood mapping is typically carried out for river and stream reaches with drainage areas exceeding 1 square mile. Each river reach is considered as a separate entity, and a collection of reaches is studied in a planning region such as a county. For each reach, the design flood discharge for the 100-year storm event is estimated using U.S. Geological Survey (USGS) regression equations, rainfall-runoff modeling, or statistical analysis of peak discharges measured at stream gages. The river channel shape and longitudinal profile are described by a stream centerline, and a set of cross sections is measured transverse to the centerline. Data for the cross sections may be obtained from an approximate data source, such as the National Elevation Dataset, and/or by land surveying or aerial mapping. The base flood elevation is computed at each cross section using the design discharge and a channel roughness factor by applying a hydraulic model such as HEC-RAS (Hydrologic Engineering Center-River Analysis System). The points of intersection of the water surface and land surface for each cross section are mapped on the landscape and joined by a smooth line to define the floodplain boundary for the Special Flood Hazard Area. This process is repeated for a 500-year storm to define the floodplain boundary for the shaded Zone X, which indicates the outer limits of moderate flood hazard.

There is no national repository of maps of historical flood inundation that can be used to determine actual floodplain boundaries. Rather, floodplain boundaries must be estimated by indirect means and thus flood maps contain various kinds of uncertainties. Most of these uncertainties arise from the interaction of water and land. In any storm, floodwaters flow across the land as the shape of the land surface and forces of gravity dictate. The water surface is smooth in all directions—indeed the assumption in one-dimensional models of riverine flooding is that the water surface is horizontal along a cross-section line perpendicular to the direction of flow. In contrast, the land surface is uneven, so the uncertainty in mapping the base flood elevation (BFE) is influenced by both the uncertainty in mapping land surface elevation and the uncertainty in the depth and extent of flood inundation of the landscape. There are three main sources of uncertainty in riverine flood mapping:

1. Hydrologic uncertainty about the magnitude of the base flood discharge;
2. Hydraulic uncertainty about the water surface elevation; and
3. Mapping uncertainty about the delineation of the floodplain boundary.

---

[1] Presentation to the committee by Michael Godesky, FEMA, on November 8, 2007.

Uncertainties in the base flood discharge create uncertainties in the calculated base flood elevation and in the delineation of the floodplain boundary. For a given base flood discharge, uncertainties in hydraulic modeling and parameters create uncertainty in the BFE. For a given BFE, uncertainties in terrain elevation and boundary delineation methods create uncertainties in the location of the floodplain boundary. Although the discharge, elevation, and extent of inundation are interrelated, uncertainty increases with each step of the mapping process. The purpose of this chapter is to define the magnitude of these uncertainties in relation to the nature of the data and methods used in flood mapping.

UNCERTAINTY OF THE BASE FLOOD ELEVATION AT STREAM GAGES

A large number of factors have an effect on flood map uncertainty. It is helpful to have a benchmark measure of uncertainty to determine with some level of objectivity what is or is not significant. The BFE is a useful benchmark because it separates the hydrology and hydraulics analysis from the mapping step.

USGS stream gage sites are the principal places in the country where flood elevations have been measured precisely and consistently over many years. Each year of streamflow record includes the stage height (water height relative to a gage datum elevation) recorded every 15 minutes as well as the maximum stage height and corresponding maximum discharge for the year. The USGS publishes these peak stage heights and discharges for more than 27,000 stream gages as part of its National Water Information System.[2] This includes data from the approximately 7,000 USGS gages presently operational, as well as approximately 20,000 gage sites that were operational for some period in the past but are now closed. Frequency analysis of peak discharges is the standard approach for defining extreme flow magnitudes. Peak stage heights can also be subjected to flood frequency analysis using the same approach. Although this approach is unconventional, the uncertainty in the peak stage revealed by frequency analysis forms a lower bound on the uncertainties inherent in BFE estimation by normal means.

It is true that frequency analysis of stage height is not the same thing as frequency analysis of base flood elevation because the BFE is defined relative to an orthometric datum, the North American Vertical Datum of 1988 (NAVD 88; see Chapter 3), and the stage height is defined relative to an arbitrary gage elevation datum. However, it is not necessary to reconcile these datums because what we are seeking is not the elevation itself, but rather the uncertainty of the elevation. The difference between the stage height and the flood elevation is the fixed datum height that is the same for all measurements and thus does not affect their variations from year to year. It should be understood that the purpose of this exercise is to gain insight into the sampling variation of extreme water surface elevations around a statistically determined expected value, not to statistically determine the base flood elevation. Indeed, because the BFE depends on the land surface elevation, which is different at each gaging station on a river, and on drainage area and other factors that vary from one location to another, it is not possible to regionalize the computation of the BFE as it is to regionalize the corresponding base flood discharge. However, as the following analysis demonstrates, there is a great deal of commonality among the sampling uncertainties around statistically estimated extreme stage heights. It is this commonality that lends insight into the corresponding uncertainties in the BFE estimated at the same locations. The sampling uncertainties of extreme stage heights are a lower bound on the corresponding and larger uncertainties in the base flood elevation.

The committee analyzed peak flow records in three physiographic regions in North Carolina to determine whether the uncertainty in the BFE is influenced by topography. The stations evaluated included six gages around mountainous Asheville in Buncombe County, seven gages in the rolling hills near Charlotte in Mecklenburg County, and eight gages distributed along the flat coastal plain (Figure 4.1). The average land surface slope, computed from the National Elevation Dataset, is 26.7 percent in Buncombe County, 6.1 percent in Mecklenburg County, and 0.304 percent in Pasquotank County in the coastal plain. On average, a 1-foot rise in land elevation in Buncombe County corresponds to a horizontal run of 3.7 feet, while in Pasquotank County a 1-foot rise corresponds

---

[2] See <http://nwis.waterdata.usgs.gov/usa/nwis/peak>.

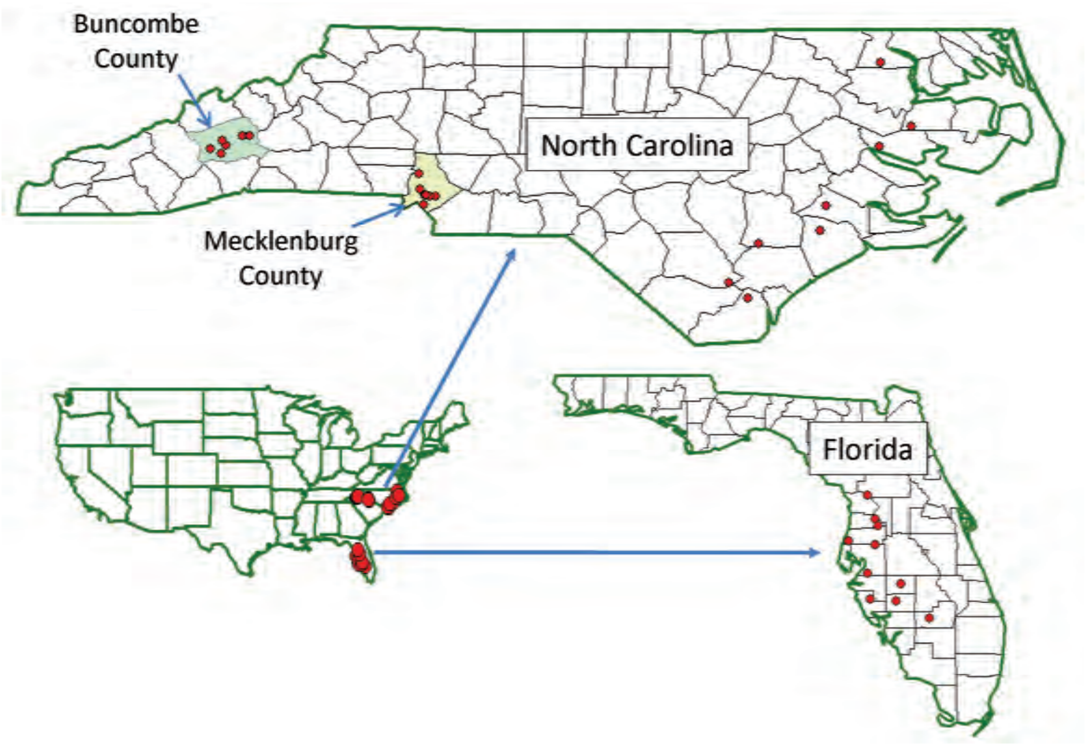


FIGURE 4.1 Map of stream gages analyzed in this report.

to a horizontal run of 329 feet. In the mountains, flood discharges for a given drainage area are large, but the floodwaters are confined within narrow valley floodplains. In the coastal plain, lower terrain slope leads to less flood discharge for a given drainage area, but once the banks overflow, floodwaters spread over a broader floodplain. The relationship between the terrain slope and the river slope is discussed below (see "Channel Slope").

Peak stage data were also studied from 10 gages in southwest Florida (Table 4.1), which has a pitted landscape with many sinkholes where water ponds in depressions and flows from one pond to another until it reaches a stream or river. These stage height data were analyzed to determine whether BFE uncertainties were different in pitted landscapes compared to landscapes with dendritic drainage patterns. Altogether, 31 stream gage records were examined from North Carolina and Florida. The gages have an average length of record of 54 years and an average drainage area of 458 square miles. Although the spatial distribution of USGS stream gages is biased toward larger streams and rivers, the drainage area of the gages examined varied by three orders of magnitude—from approximately 5 square miles to approximately 5,000 square miles—which is a reasonable representation of the range of drainage areas for stream reaches used in floodplain mapping.

At each stream gage site, the historical record of both flood discharges and flood stage was analyzed using the U.S. Army Corps of Engineers (USACE) Statistical Software Package HEC-SSP.[3] Although some stream gage records include estimates of "historical" floods before the period of gaged record, these were not included in the present study. In some gage records, there are notes that the flood flows were affected by factors such as urbanization or releases from upstream reservoirs. The committee did not separate out these records in the belief that riverine environments must be mapped, regardless of whether such events occurred. In a few of the coastal gages, the times of occurrence of the maximum flood stage and maximum flood discharge differ slightly, and in those cases, the largest value was used. For each gage, the log-Pearson III distribution was applied to both discharges and stage heights, as

---

[3] <http://www.hec.usace.army.mil/software/hec-ssp/>.

TABLE 4.1 Stream Gages Used for Flood Frequency Analysis

USGS Site	**Site Name**	**Drainage Area (square miles)**	**Years of Record**
Buncombe County			
03448000	French Broad River at Bent Creek, N.C.	676	54
03448500	Hominy Creek at Candler, N.C.	79.8	37
03451000[a]	*Swannanoa River at Biltmore, N.C.*	*130*	*78*
03451500	French Broad River at Asheville, N.C.	945	85
03450000	Beetree Creek near Swannanoa, N.C.	5.46	72
03449000	North Fork Swannanoa River near Black Mountain, N.C.	23.8	32
Mecklenburg County			
02142900[a]	*Long Creek near Paw Creek, N.C.*	*16.4*	*41*
02146750	McAlpine Creek below McMullen Creek near Pineville, N.C.	92.4	31
02146600	McAlpine Creek at Sardis Road near Charlotte, N.C.	39.6	45
02146700	McMullen Creek at Sharon View Road near Charlotte, N.C.	6.95	44
02146507	Little Sugar Creek at Archdale Drive at Charlotte, N.C.	42.6	29
02146500	Little Sugar Creek near Charlotte, N.C.	41	52
02146300	Irwin Creek near Charlotte, N.C.	30.7	44
North Carolina Coastal Plain			
02092500	Trent River near Trenton, N.C.	168	51
02093000	New River near Gum Branch, N.C.	94	44
02105900	Hood Creek near Leland, N.C.	21.6	34
02105769	Cape Fear River at Lock #1 near Kelly, N.C.	5,255	37
02108500	Rockfish Creek near Wallace, N.C.	69.3	26
02053500[a]	*Ahoskie Creek at Ahoskie, N.C.*	*63.3*	*57*
02084500	Herring Run near Washington, N.C.	9.59	31
02084557	Van Swamp near Hoke, N.C.	23	27
Southwest Florida			
02256500	Fisheating Creek at Palmdale, Fla.	311	75
02295637	Peace River at Zolfo Springs, Fla.	826	74
02296750	Peace River at Arcadia, Fla.	1,367	77
02298830	Myakka River near Sarasota, Fla.	229	70
02300500	Little Manatee River near Wimauma, Fla.	149	68
02303000	Hillsborough River near Zephyrhills, Fla.	220	67
02310000	Anclote River near Elfers, Fla.	72.5	62
02312000	Withlacoochee River near Trilby, Fla.	570	76
02312500	Withlacoochee River near Croom, Fla.	810	67
02313000	Withlacoochee River near Holder, Fla.	1,825	75

[a] Locations of detailed flood hydrology and hydraulic studies.

illustrated in Figure 4.2 for the 78 years of record on the Swannanoa River at Biltmore.

It is evident in Figure 4.2 that both the flood discharges and the stage heights have a similar frequency pattern. The base flood discharge is the value for the computed curve (red line) at exceedance probability 0.01 (20,672 cubic feet per second [cfs]), and the corresponding base flood stage height is 22.65 feet above gage datum. The uncertainty of the base flood is quantified by the dashed confidence limits in the graphs, a range from 16,024 to 28,514 cfs for the flow and 19.54 to 27.30 feet for the stage height.

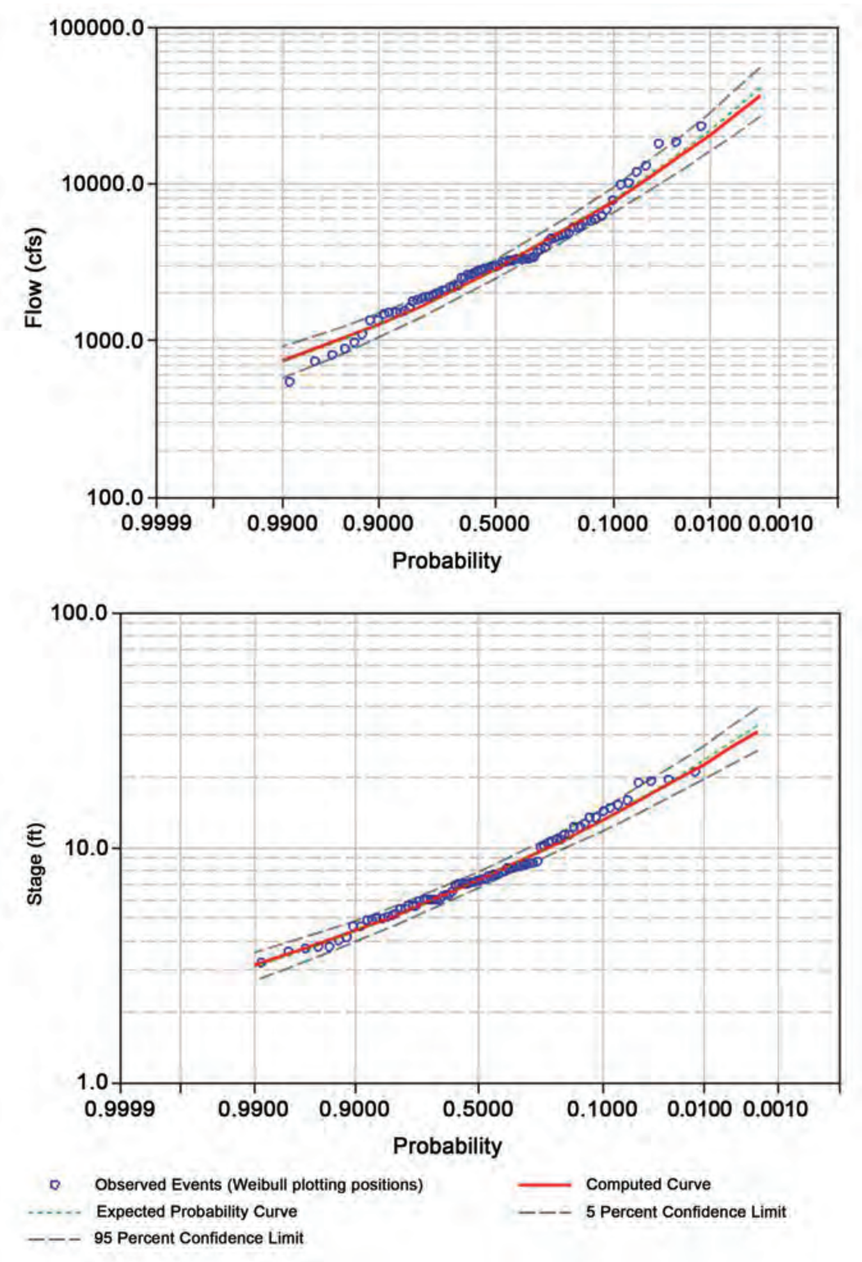


FIGURE 4.2 Frequency analysis of flood discharge and stage height for gage 03451000, the Swannanoa River at Biltmore, North Carolina, computed using USGS peak flow data and the HEC-SSP program.

These confidence limits were computed using the noncentral *t*-distribution as defined in Bulletin 17-B (IACWD, 1982).[4] This range represents approximately 1.645 standard errors above and below the estimate of the mean, so a good measure of the sampling error in the base flood elevation can be derived from the range in the confidence limits. This estimate of the sampling error provides a sense of how much inherent uncertainty exists in BFEs derived from measured annual flood elevations at gages with long flood records.

Figure 4.3 plots the estimated sampling error of the

---

[4] Bulletin 17B does not include regional skew information for peak stage analysis. Thus, the confidence limits calculated by this method provide only an approximate estimate of the sampling error of the peak stage data. This is sufficient and appropriate for the purpose that these limits are used in this study.

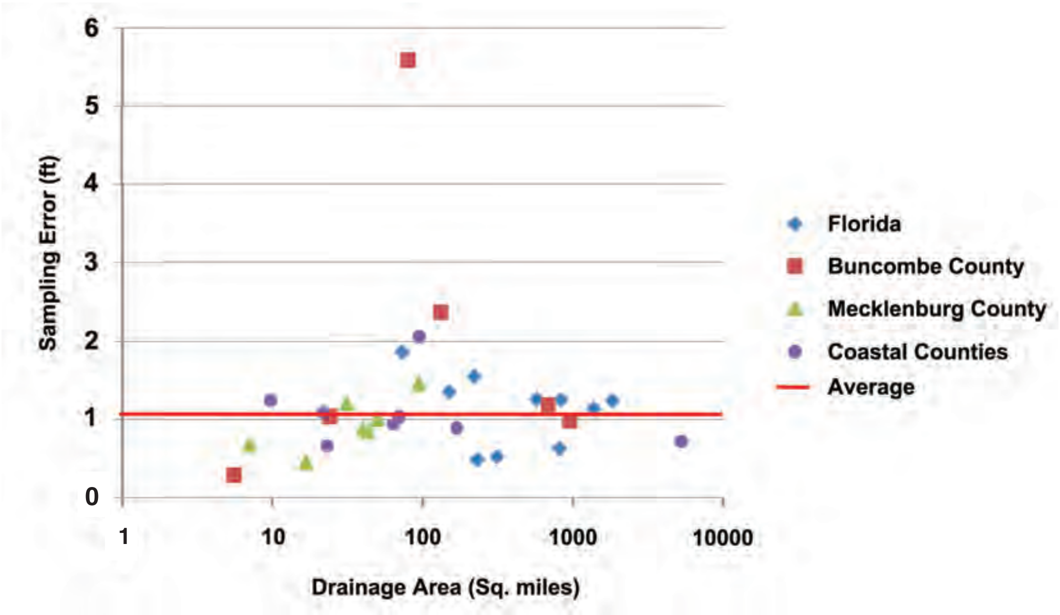


FIGURE 4.3 Sampling error of the 100-year stage height at 31 Florida and North Carolina stream gage sites.

computed 100-year stage heights against drainage area at all 31 stream gages. This graph displays a surprising result: there is no correlation of the sampling error with drainage area or topography across the three regions of North Carolina, nor is there any significant difference in the results from the Florida gages compared with those from North Carolina. One large outlier in the sampling error (5.6 feet) occurs at Hominy Creek in Candler, North Carolina, and was caused by a couple of unusually large floods that significantly skewed the stage frequency curve at that stream gage site. If this value is omitted, the average value of the remaining standard errors is 1.06 feet, with a range of 0.3 foot to 2.4 feet.

This frequency analysis of stage heights has a number of limitations: no regional skew estimates were included (none exist for stage height data), the number of stream gages was relatively small (31 gages of 27,000 for which the USGS has peak gage records), and only a small region of the nation was examined. This analysis should be considered as indicative but not definitive of what a more comprehensive study of such data across the nation might reveal. Despite these limitations, a reasonable statistical interpretation of the result is that a null hypothesis cannot be rejected, namely that the sampling error of the 100-year stage height, or equivalently the 100-year BFE, does not vary with drainage area or geographic location over the gages studied. Moreover, the average sampling error was 1 foot with a range from 0.3 foot to 2.4 feet for 30 of the 31 sites. In other words, even at locations with long records of measured peak floods, the BFE cannot be estimated more accurately than approximately 1 foot, no matter what mapping or modeling approach is used. This value provides a benchmark against which the effects of variations in methods can be evaluated—a variation that produces a change in BFE of more than 1 foot may be significant. At ungaged sites, uncertainties in the BFE are necessarily higher.

Finding. The sampling error of the base flood elevation estimated using flood frequency analysis of annual maximum stage heights measured at 30 long-record USGS stream gage sites in North Carolina and Florida does not vary with drainage area, topography, or landscape type and has an average value of approximately 1 foot.

DETERMINING THE FLOOD DISCHARGE

Riverine flood studies involve a combination of statistical, hydrologic (rainfall-runoff), and hydraulic models. Determining the BFE involves first determining the base flood discharge. This can be done three ways:

1. A hydrologic model is used to predict the peak discharge associated with a design storm (hypothetical event of a desired frequency),

2. The peak discharge that has a 1 percent chance of occurring in a given year is observed directly (by frequency analysis at a gage site), or

3. The peak discharge is inferred using regional regression equations.

In all cases, a hydraulic model is subsequently used to compute the BFE, and geographic information system (GIS) mapping methods are required to overlay the computed flood elevation on the surrounding topography to determine the extent of the floodplain. Figure 4.4 illustrates the hydrologic and hydraulic modeling processes and input involved in riverine floodplain mapping.

Three hydrologic methods are used in flood mapping studies:

1. Flood frequency analysis—statistical estimation of flood discharges as illustrated above for the gage studies in North Carolina and Florida;

2. Rainfall-runoff models—hydrologic simulation models that convert storm rainfall to stream discharge applied using standardized design storms; and

3. USGS regional regression equations—simple methods for estimating the flood discharge as a function of drainage area and sometimes other parameters.

In a flood mapping study, each river reach between significant tributaries is treated as a separate entity and a corresponding flood discharge must be defined for it. Approximate studies use USGS regional regression equations, and limited detailed studies use regression equations or gage data (Table 2.1). In detailed studies, a mixture of methods is used—rainfall-runoff models in about half of the studies and flood frequency analysis or regression equations in the others (Table 4.2).

Flood Frequency Analysis

About 30 percent of detailed mapping studies use flood frequency analysis to establish the peak flow for the 100-year flood event (Table 4.2). The log-Pearson III is the U.S. standard of practice for flood frequency analysis for gaged sites (IACWD, 1982). Three statistical quantities (mean, standard deviation, and skewness coefficient) are required to estimate the parameters of the probability distribution. The Interagency Advisory Committee on Water Data (IACWD, 1982) guidelines identify procedures for the use of regional estimates of

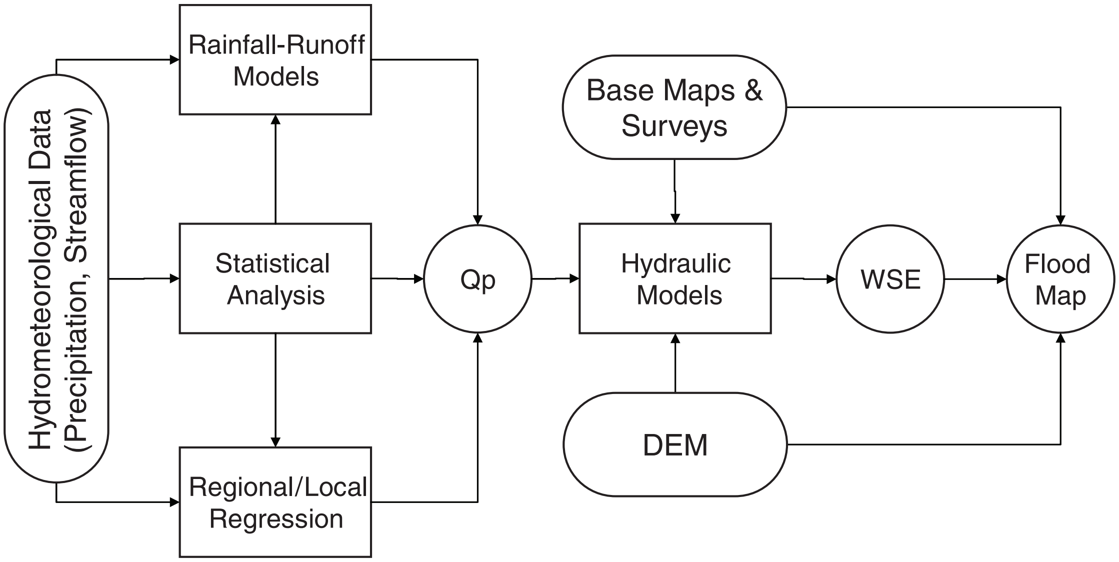


FIGURE 4.4 Schematic of an idealized flood mapping study showing the type of input, models, and output used. The outputs from each step are used as inputs to the next step. Digital elevation models (DEMs) and surveys are used first to configure and provide input to the hydraulic model in the form of cross sections, structures, and roughness coefficients, and later as input to flood map creation. NOTE: Q_p = flood peak flow; WSE = water surface elevation.

TABLE 4.2 Methods Used to Compute the Peak Discharge in Detailed Flood Mapping Studies

Method	Percentage Used
USGS regional regression equations	22
Rainfall-runoff models	48
Flood frequency analyses	30

SOURCE: Presentation to the committee by Michael Godesky, FEMA, on November 8, 2007.

the skewness coefficient when the data record is not sufficiently long and for the treatment of outliers and other data anomalies. Even when all the guidelines are followed however, sampling uncertainty remains and is characterized by the confidence intervals of the peak flood estimates, as shown above for flood flows and stage heights.

A National Research Council (NRC, 2000) report distinguished between two kinds of uncertainty:

1. *Natural variability* deals with inherent variability in the physical world; by assumption, this “randomness” is irreducible. In the water resources context, uncertainties related to natural variability include things such as streamflow, assumed to be a random process in time, or soil properties, assumed to be random in space. Natural variability is also sometimes referred to as aleatory, external, objective, random, or stochastic uncertainty.
2. *Knowledge uncertainty* deals with a lack of understanding of events and processes or with a lack of data from which to draw inferences; by assumption, such lack of knowledge is reducible with further information. Knowledge uncertainty is also sometimes referred to as epistemic, functional, internal, or subjective uncertainty.

Estimation of flood peaks at return periods of interest for determining 100-year and 500-year (1 and 0.2 percent annual chance) floods illustrates the concepts of natural variability and knowledge uncertainty. Figure 4.5 shows the same kind of flood frequency curves illustrated in Figure 4.2 except that the confidence limits computed by the HEC-SSP program for specific flood probabilities are highlighted. These data are for the French Broad River at the Asheville, N.C. gage site (gage 3451500) in Buncombe County, which has 85 years of peak discharge record, the longest flow record in this study. As in Figure 4.2, natural variability is represented by the central red line and expresses the relation between the magnitude of the flood discharge and its return period or likelihood of occurrence. Knowledge uncertainty is expressed by the spread of the confidence limits around this estimated line. As more data are used in a frequency analysis, the confidence band around the flood frequency curve becomes narrower.

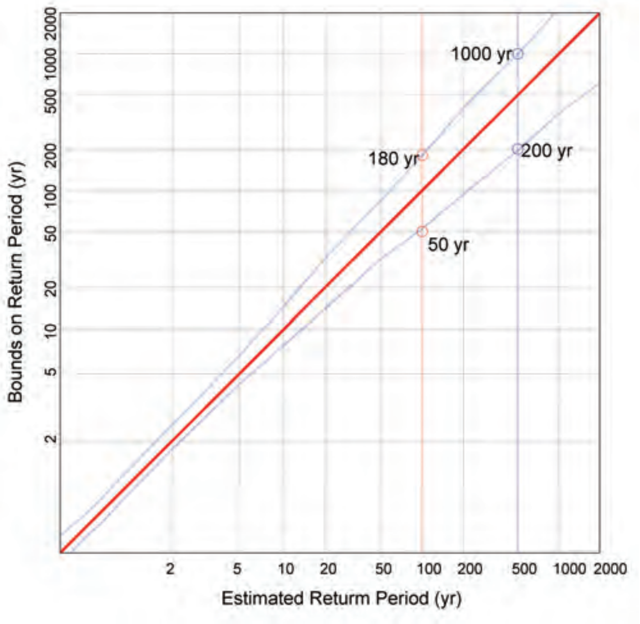


FIGURE 4.5 Return periods for flood discharge at the French Broad River at Ashville, N.C., for the expected flood discharge and its upper and lower confidence limits (dotted lines).

For this gage, reading up from the horizontal axis value of 100 years return period for flood discharge and across to the vertical axis yields an equivalent return period of 50 years for the lower confidence interval discharge and 180 years for the upper confidence interval discharge. The corresponding values for the 500-year flood range from a 200-year to a 1,000-year return period. Similar results were obtained for confidence limits on the 100-year flood stage. This means that knowledge uncertainty is significant even when frequency analysis is performed on long gage records.

Rainfall-Runoff Models

Rainfall-runoff models are mathematical representations of the natural system’s complex transformation of rainfall into runoff. To compute the flow discharge at the watershed's outlet, hydrologic models include basic flow routing techniques and one-dimensional representations of overland flow and channel hydraulics. These approximations permit several subbasins to be nested into a single model, allowing better accounting for spatial variability and computation of the flow hydrograph (time record of discharge) within the watershed. Hydrologic models can be event-based or continuous, depending on whether the initial conditions of model parameters such as soil moisture are assumed or updated using information gathered between storms. The Federal Emergency Management Agency (FEMA) accepts 13 event-based and 3 continuous hydrologic modeling software programs for determining flow hydrographs.[5]

The natural variability of quantities such as precipitation, soil moisture, and soil physical and hydraulic properties is typically described using probabilistic models (Merz and Thieken, 2005). Knowledge uncertainty is associated with the structure of the model and its ability to capture the behavior of the studied system in part or as a whole, the model parameters used to quantify the relationships between the various components of the system, and model input and output.

Model calibration and parameter estimation are perhaps the most important aspects of hydrologic modeling and are a major contribution to knowledge uncertainty. FEMA (2003) guidelines allow models to be calibrated using (1) historical rainfall observations, which can improve model performance under different rainfall conditions, or (2) a design storm, such as those defined in the National Oceanic and Atmospheric Administration's (NOAA's) Atlas 14,[6] against the corresponding peak flow of the same return period (frequency). The typical procedure is to estimate the return period of the peak flow of a historical flood, use the design storm for that return period, and then calibrate the hydrologic model so it reproduces the observed flood flow. The optimized parameters are then used to calculate the 100-year peak flow. However, using a single peak flow calibration may prove to be inadequate, given the demonstrated importance of long records with a sufficiently large number of events (storm hydrographs) to estimate parameters (e.g., Sorooshian and Gupta, 1983; Sorooshian et al., 1983; Yapo et al., 1996, 1998).

Recommendation. FEMA should calibrate hydrologic models using actual storm rainfall data from multiple historical events, not just flood design storms.

Hydrologic modeling uncertainty is often described in the form of a probability distribution of model output (e.g., peak discharge for the required return period). By changing the distribution of model parameters, it is possible to identify both the impact of uncertainty in model parameters on hydrologic predictions and the effects of uncertainties in model input and model structure on predictive uncertainty. Figure 4.6 demonstrates that addressing only parameter uncertainty can lead to biased and, in some cases, incorrect assessment of total uncertainty.

USGS REGIONAL REGRESSION EQUATIONS

USGS regional regression equations are used to compute flood discharges in nearly all approximate mapping studies and in about 20 percent of detailed studies. A state is divided into regions, each with a set of USGS regression equations that allow flood map practitioners to compute flood discharges for the required recurrence intervals. When the USGS develops these equations, peak discharges at ungaged sites are regionalized by developing empirical relationships between the peak discharge and basin characteristics using statistical analyses of annual maximum flows at gaged sites. Regionalization was originally accomplished through nonlinear regression analysis. With this procedure, records from gaged sites were used to define a set of empirical relations between selected recurrence interval discharges and a set of exogenous or independent variables, always including drainage area. These relations were then used to estimate discharges at selected recurrence intervals for ungaged sites. A more recent approach to regionalization is the region of influence generalized least squares method, in which an interactive procedure is used to estimate recurrence interval discharges (Tasker and Stedinger, 1989). For each ungaged site, a subset of gaged sites with similar basin characteristics

---

[5] <http://www.fema.gov/plan/prevent/fhm/en_hydro.shtm>.

[6] <http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_docs.html>.

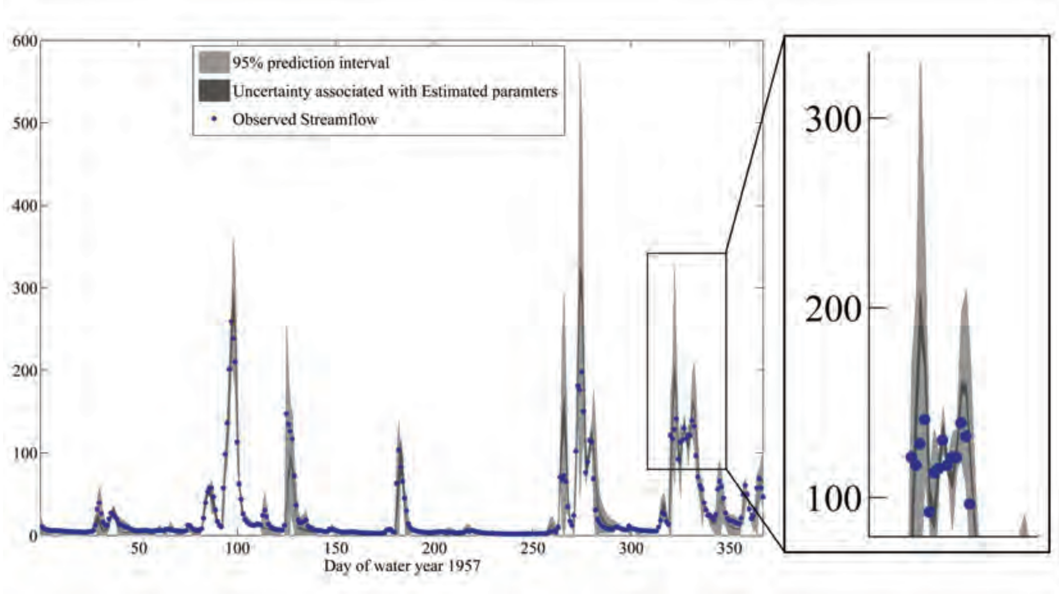


FIGURE 4.6 Streamflow hydrograph prediction uncertainty associated with estimated parameters (dark gray) for the Sacramento Soil Moisture Accounting (SAC-SMA) model and 95 percent confidence interval for prediction of observed flow (light gray) for water year 1957 at the Leaf River basin's outlet (USGS Station 02472000 Leaf River, near Collins, Mississippi). The last few peaks are enlarged to better show the uncertainty distributions. The 95 percent confidence interval represents the total likely uncertainty arising from model, parameter, and input uncertainties. It is noteworthy that the 95 percent confidence interval in model prediction is very large at or near peak flow events. SAC-SMA is the core hydrologic model in the National Weather Service River Forecasting System. SOURCE: After Ajami et al. (2007). Copyright 2007 American Geophysical Union. Reproduced by permission of AGU.

is selected and regression techniques are used to determine the relation between flood discharge and basin characteristics at gaged sites. This relation is then used to estimate flood discharges at ungaged sites. Tests of this approach in Texas (Tasker and Slade, 1994) and Arkansas (Hodge and Tasker, 1995) yielded estimates with lower prediction errors than those produced using traditional regional regression techniques. The region of influence method was used for the North Carolina regional regression equations (Pope et al., 2001) discussed in this chapter.

Regression methods have evolved from ordinary least squares to weighted least squares to generalized least squares. Because of the different climate, physiographic, and hydrologic conditions across the country, more than 200 explanatory variables are used at one location or another. The equations are developed by state-level studies, so problems can arise at state boundaries if different equations are used for the same variable on either side of the boundary. Table 4.3 summarizes the methods currently used to derive flood discharge equations.

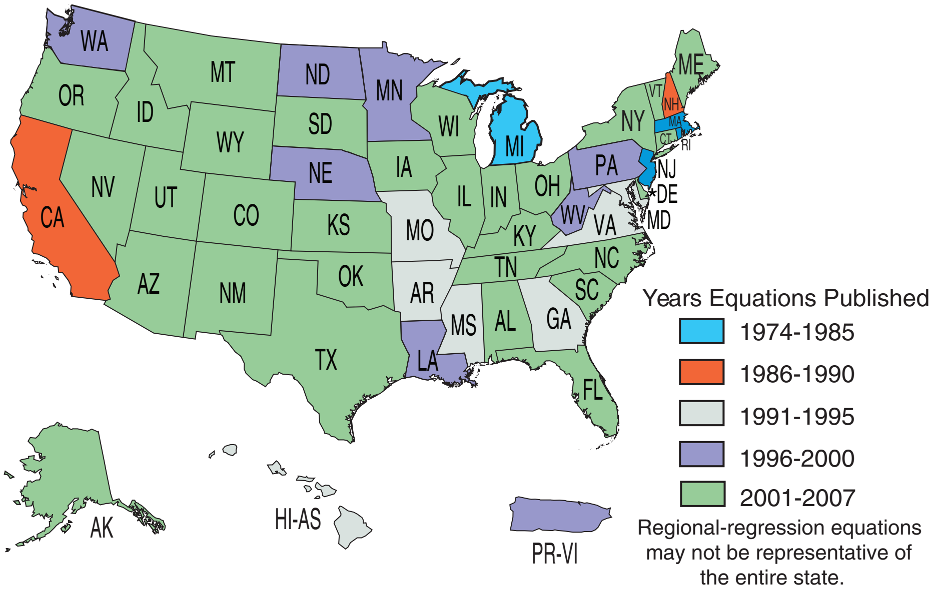
Figure 4.7 shows the age of the regression equations used at the state level for rural basins. Most states have updated their regional regression equations since 1996. However, basins that cross state boundaries may be analyzed using regression equations of different ages and different regression methodologies, creating inconsistent results across the basin.

Regression equations in North Carolina generally take the form $Q_T = \alpha A^\beta$, where Q_T is the T-year flood

TABLE 4.3 Methods Used to Derive Empirical Flood Equations

Regression Method	Number of States or Regions	Percentage of Total
Ordinary least squares	7	13
Weighted least squares	4	4
Generalized least squares	43	81
Multiple linear regression	1	2

NOTE: These numbers do not include USGS Water Science Centers that use region of influence analyses in addition to one of these regression methods.
SOURCE: USGS.



Regional-regression equations may not be representative of the entire state.

FIGURE 4.7 Summary of rural peak flow regression equations by date of completion. SOURCE: USGS.

peak, *A* is the catchment area, and α and β are regression coefficients. Catchment area, or the area draining to a defined point on the stream system, is the single most important independent variable. In effect, all the other variables that might influence the peak discharge are bound up in the coefficients α and β of the regression equation, which are assumed constant within a particular region. In North Carolina, regression equations are defined for three regions—the Blue Ridge-piedmont region, the sand hills area, and the coastal plains. The discharges calculated using the equations are shown in Figure 4.8. For a 100-square-mile drainage area, the 100-year flood discharge estimate is 13,250 cfs in the Blue Ridge-piedmont area, 6,340 cfs in the coastal plain, and 3,400 cfs in the sand hills area. Hence, flood discharge in the flat coastal plain is about one-half of the discharge in the Blue Ridge-piedmont area. The low discharge in the sand hills area may reflect the presence of more absorbent soils.

Although the USGS regression equations are the same for the Blue Ridge and piedmont regions, these regions are physiographically distinct from one another (as the committee has treated in the flood study in North Carolina). When the equations were being derived, there were insufficient stream gages in the Blue Ridge Mountains to distinguish it statistically from the piedmont region. The USGS is currently revising the regression equations for the Blue Ridge region using additional stream gages from adjacent states with similar topography.

Finding. The variation in peak flow predictions between regions illustrates the importance of developing regression equations at the river basin level, independent of state boundaries. States with significantly outdated regression equations that should be updated include Michigan, Massachusetts, New Jersey, California, and New Hampshire.

North Carolina Case Study of Flood Discharge Estimation

At the request of the committee, the North Carolina Floodplain Management Program (NCFMP) conducted case studies of flood hydrology, hydraulics, and mapping in three study reaches in North Carolina. These included Swannanoa River in Buncombe County (mountains), Long Creek in Mecklenburg County (piedmont), and Ahoskie Creek in Hertford County (coastal plain; Figure 4.9). Lidar (light detection and ranging) topographic data and detailed studies yielding BFEs and floodplain boundaries were available for all three study

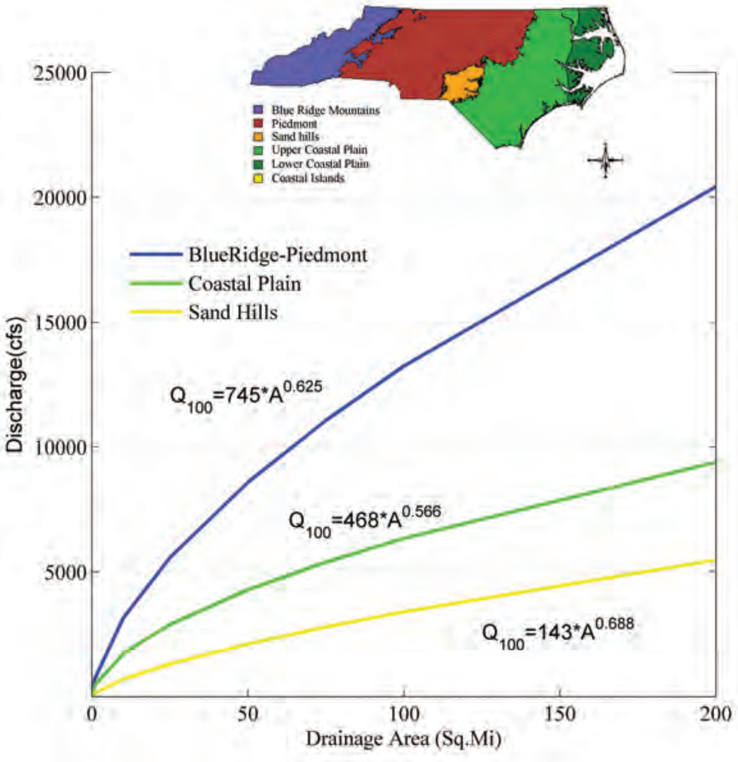


FIGURE 4.8 100-year flood peak discharges estimated from regression equations in three physiographic regions of North Carolina.

reaches. Some characteristics of the study reaches are summarized in Table 4.4. The reaches have similar lengths, in the range of 5 to 7 miles, but significantly different upstream drainage areas, ranging from 8 to 108 square miles.

In all cases, the effect of variations in flood methods is compared to a base case of hydrology using a rainfall-runoff model (if available), hydraulics using HEC-RAS with survey of structures in the floodplain, and terrain mapped by lidar. Four variants of hydrologic methods for determining the flood peak discharge were examined:

1. *Rainfall runoff model (RR).* Both HEC-1 and HEC-Hydrologic Modeling System were used and calibrated using historical peak flows recorded at stream gages. The calibrated models were then used to calculate the 100-year flood peak flow.

2. *Regional regression (REG).* USGS regional regression equations for rural watersheds in North Carolina were used to obtain the 100-year peak flow.

3. *95 percent lower and upper confidence limits (REGLOW and REGUP).* The limits of the 95 percent confidence interval around the regional regression value (plus or minus 42 to 47 percent of the base flood discharge) were used to estimate the 100-year peak flow.

4. *Adjusted regional regression (ADJREG).* The peak discharges from the rural regional regression equations were adjusted at and near the gages to match estimates from flood frequency analysis of stream gage data.

A typical result for the effect of these variations in flood discharge on the BFE is shown in Figure 4.10. The water surface profiles for the rainfall-runoff, rural regression, and adjusted regression methods are virtually identical, within a sampling error of 1 foot. Use of the lower and upper limits of the regression equation confidence limits (upper and lower lines in Figure 4.10) changes the water surface elevation profile by an average of about 2 feet along Long Creek. However, the standard practice is to use flow values at the fitted regression line. Choosing flows at the range of the

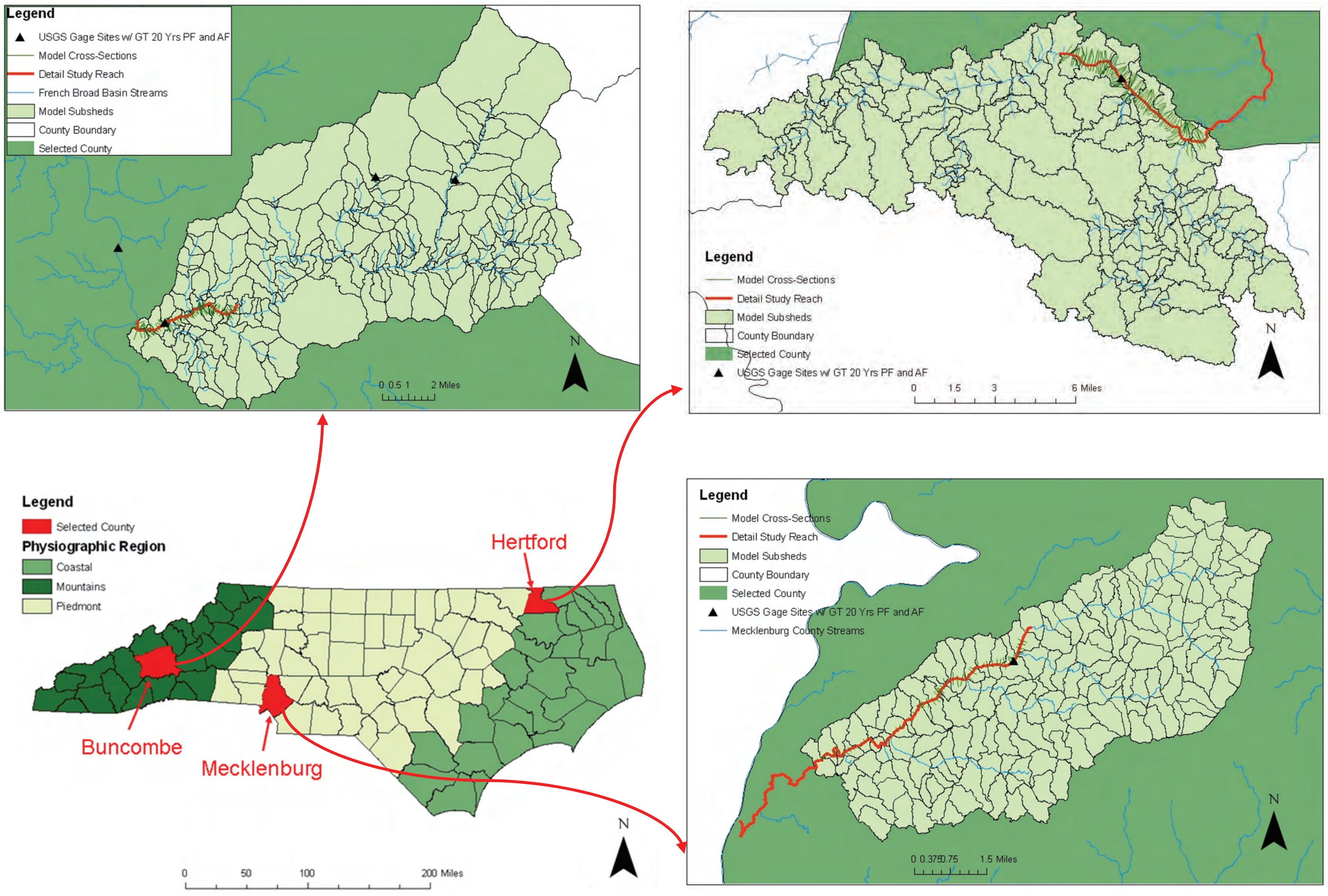


FIGURE 4.9 Location of the study reaches. Source NCFMP (2008). Used with permission.

TABLE 4.4 Characteristics of the Study Reaches

River	Drainage Area at Upstream End (square miles)	Drainage Area at Downstream End (square miles)	Length of Reach (miles)
Swannanoa River	108	133	4.8
Long Creek	8	32	5.7
Ahoskie Creek	60	136	7.1

upper and lower confidence limits on the regression equation illustrates the effect of an extreme variation in the design discharge above and below the value that would be used in a flood study.

It seems surprising at first that there is so little difference between the results from rainfall-runoff, flood frequency analysis, and regional regression equations because the regional regression equations are simple empirical expressions that do not involve the precision of rainfall-runoff modeling or flood frequency analysis. However, the results from all these methods are driven by their calibration to the flood frequency curves developed at the stream gages, and each of the three study reaches has a USGS stream gage with long-term records. For methods where the regression equation flood estimate is adjusted to match the results of flood frequency analysis (rainfall-runoff model approach and adjusted regression method), the flood frequency analysis at the stream gage dominates the results. However, regional regression equations, which are not adjusted to gages, do not produce flows that are sufficiently different from the other methods to create significant changes in water surface elevation at any of the study sites. The standard deviations of the differences in base flood elevations at corresponding cross sections between the rainfall-runoff model and the regression equations at Long Creek and the Swannanoa River are 0.04 foot and 0.67 foot, respectively. This means that for these study reaches, the USGS regional regression equation method is estimating flood discharges with sufficient precision to support FEMA flood mapping efforts.

The average error of prediction for a 100-year flood in the USGS regional regression equations differs by physiographic region in North Carolina: 47 percent in the mountain-piedmont area, 42 percent in the coastal plains, and 57 percent in the sand hills area. Table 4.5 shows the effect on the BFE of flood discharges set at the upper and lower limits of this prediction error. The values shown are the average effects for all cross sections in a study reach. On average, when the flood discharge is at its upper prediction error (REGUP), the

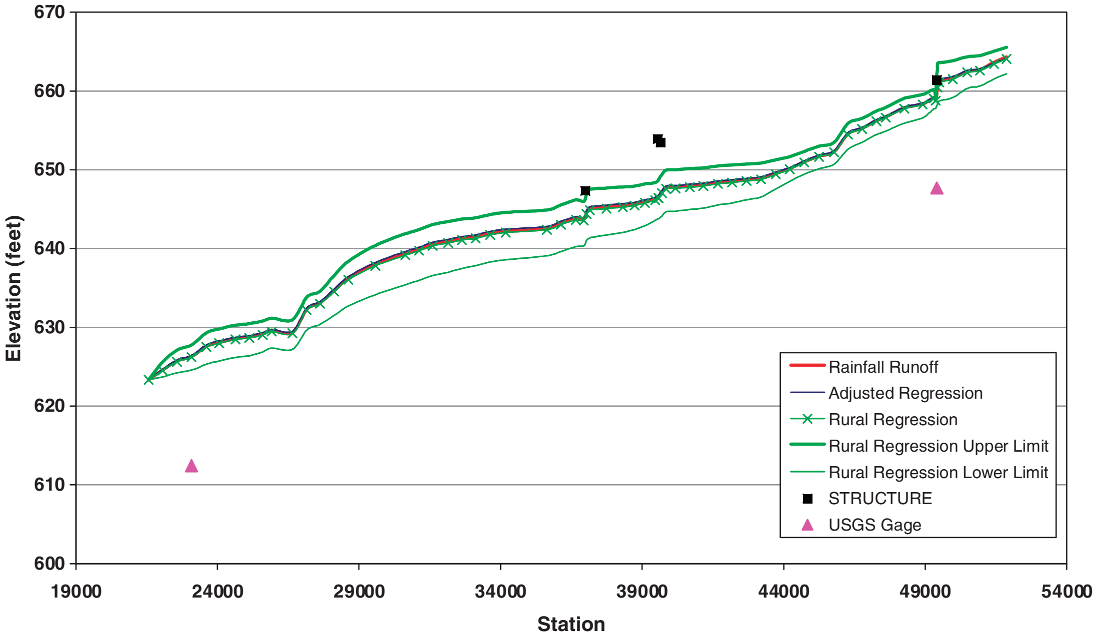


FIGURE 4.10 Effect of variations in hydrologic methods on the base flood elevation on Long Creek, North Carolina. SOURCE: NCFMP (2008). Used with permission.

TABLE 4.5 Effect on Base Flood Elevation of Regression Equation Discharges at the Limits of Their Prediction Error

Equation	Ahoskie Creek (ft)	Long Creek (ft)	Swannanoa River (ft)	Average (ft)
REGUP	0.71	1.93	0.65	1.10
REGLOW	−2.53	−2.66	−4.96	−3.38

BFE is increased by 1.1 feet, and when it is at its lower prediction error (REGLOW), the BFE is reduced by 3.38 feet.

Finding. Flood frequency analysis of stream gage records is the most reliable method of defining peak flood discharges. Discharges calculated from rainfall-runoff models or from regional regression equations adjusted for flood frequency analysis results at a nearby gage produce similar BFE profiles. The USGS regional regression equations also produce similar BFE profiles in the three reaches examined in this study. The only hydrologic method that significantly affects the BFE profile is to change the flood discharge to the limits of the prediction error of the regression equations—this raises or lowers the BFE profiles by an average of 1 to 3 feet in the three study reaches.

HYDRAULIC MODELS

Inaccuracies in hydraulic modeling add to inaccuracies associated with the base flood discharge and decrease the accuracy of the BFE. Figure 4.11 illustrates the potential sources of inaccuracy in open-channel hydraulic modeling. Each model has its own sources of uncertainties, and the magnitude of errors in the model results depends on input, parameters, model structure, and local conditions. Because model uncertainties vary significantly between models, only uncertainties associated with parameters and boundary conditions are discussed below.

The physics of fluid flow is well understood and is generally captured by mathematical formulations that conserve mass, energy, and momentum. In open-channel flow, both the density and the viscosity of water can be assumed constant in nearly all practical situa-

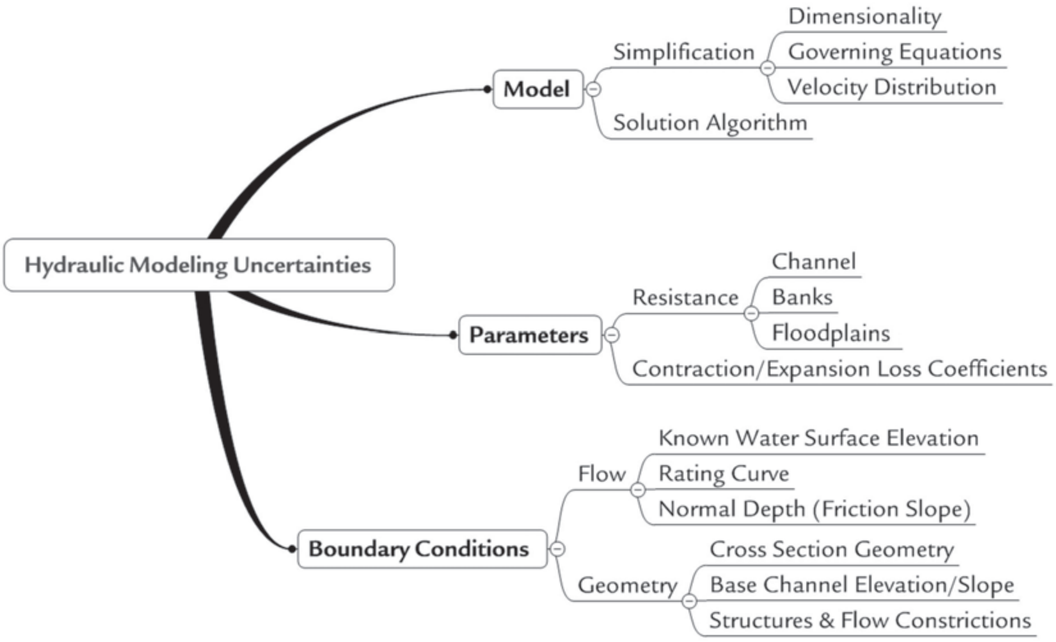


FIGURE 4.11 Possible sources of inaccuracies in hydraulic modeling for floodplain delineation.

tions, which greatly simplifies the equations required to model the motion of water and to compute the surface water elevation within the channel. However, equations are still needed to account for (1) changes in the water surface profile caused by the irregular shapes of natural channels, which create flow resistance, and (2) structures and flow impediments, which increase the height of the water surface upstream and create a backwater effect.

In practical open-channel hydraulics, the depth-averaged velocity is a good representation of the flow velocity. As a result, the flow can be approximated using one- or two-dimensional models. In one-dimensional approximations, the flow velocity is assumed to vary only in the direction of the longitudinal channel slope. The flow velocity is averaged over both the depth and the width of the flow at each cross section. A single water surface elevation value is computed, and the depth of water over all points in the cross section is determined by extending a horizontal water surface elevation line across the channel. The floodplain boundary is delineated at the location where the water surface elevation line intersects the topographic surface of land surface elevation.

Most one-dimensional hydraulic models require significant input data (Figure 4.12). The study domain

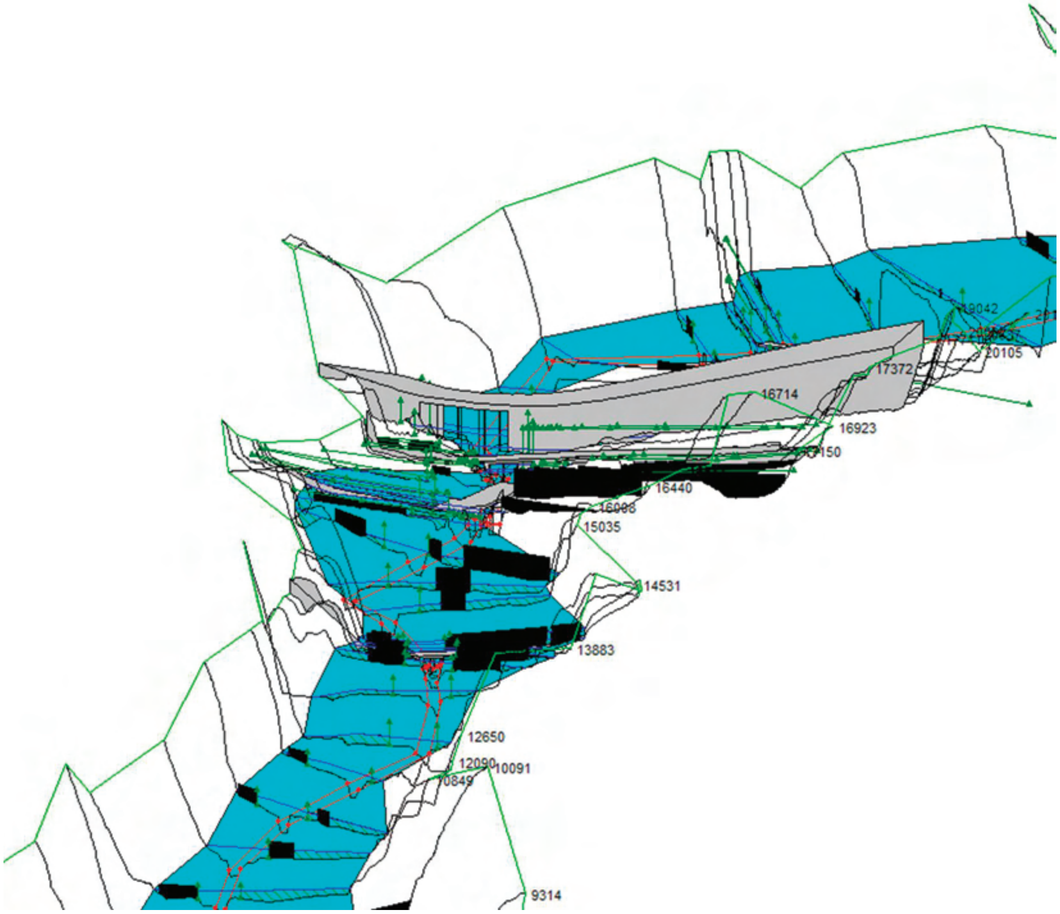


FIGURE 4.12 A typical three-dimensional representation of a one-dimensional model of a detailed flood study along a segment of a study reach on the Swannanoa River, North Carolina, showing the information required for the U.S. Army Corps of Engineers' one-dimensional HEC-RAS model. The vertical scale is exaggerated to highlight cross-sectional features. Solid black lines represent the channel cross section. Blue areas represent the water surface computed for given discharge. Gray areas are structures that extend across the channel and for a reasonable distance along the channel. Black areas are structures that can be represented by a vertical plane as flow impediments. Dashed areas indicate where water can pond. Numbers at the right side of some cross sections refer to the distance (here in feet) from the downstream end of the reach. Data from the North Carolina Floodplain Mapping Program.

is generally extended beyond the upstream and downstream boundaries of the targeted reach to ensure that backwater effects are taken into account and that numerical errors in the computed surface water profile are minimized. A stream centerline is then defined, and the cross-section geometry is determined at regular intervals along the centerline and at structures, river bends, and major points of change in channel slope and/or cross-section geometry. Accurate representation of structures and river bends is important for identifying flow constrictions and areas where water can pond, such as at bridges and roadway embankments. Finally, information about surface roughness (i.e., flow resistance) must be gathered for each cross section. Several equations that relate surface roughness to flow characteristics are available, but the most popular in open-channel flow computation is the Manning equation. Modelers generally determine the Manning roughness coefficient at several points across the channel and floodplain by visual examination and use of standardized tables and photographs of channels of known roughness.

One-dimensional models are computationally efficient and are considered by many engineers to produce reasonably accurate surface water profiles (Büchele et al., 2006), although the accuracy must be checked at river junctions, loops, branches, and significant lateral inflows. Because the output of one-dimensional models must be superimposed on digital elevation data to produce a Flood Insurance Rate Map, the final mapping product is sensitive to variations in surface elevation that were not captured in the cross sections. This may cause inconsistent model results, particularly in urban areas where roads, walls, and other structures can create preferential flow paths. Since the flood map is drawn on a topographic surface and the water surface elevation is determined by a hydraulic model using cross sections, it is important for the topographic surface and cross sections to be consistent with one another. This may not be the case if the cross sections are defined by land surveying and the topographic surface is defined by aerial photogrammetry (Tate et al., 2002). Careful adjustment and reconciliation of topographic and cross-section data sources are needed for detailed mapping studies.

In two-dimensional models, the velocity is averaged over only the flow depth, and velocity components are computed in directions both parallel and perpendicular to the longitudinal channel slope. The resultant velocity is then quantified in magnitude and direction. These models solve the complex flow equations using numerical algorithms that iteratively advance the solution in space and time over computational quadrilateral or triangular meshes. The size and shape of the mesh grids depend on factors such as the numerical solution method, available terrain data, level of required detail, and available computational resources.

Two-dimensional models are computationally demanding and require considerable expertise to prepare and execute. However, FEMA flood studies require only a single discharge value for the peak flow of the 100-year event, so flood mapping analyses are performed assuming steady flow. In steady flow the water surface elevation is constant over time; in unsteady flow the water surface elevation is computed for each cross section or grid point location as a function of time. The steady flow assumption simplifies the data requirements, particularly with respect to boundary conditions, and greatly reduces the computational demand.

Two-dimensional models offer many advantages over one-dimensional models, including more accurate resolution of the actual surface water elevation and direct determination of floodplain extent. A study comparing the two types of models found that two-dimensional models have significantly greater ability to determine flow velocity and direction than one-dimensional models (TRB, 2006). Computing velocity is an important element of flood damage calculations, particularly in urban areas where measurable damage to buildings and other properties can result from fast flow. The Transportation Research Board (TRB, 2006) study found that the difference between one-dimensional and two-dimensional models is smallest within the confines of the main channel (green), increases across the channel and floodplain, and is largest near the smaller branch of the river (Figure 4.13). This divergence across the channel and floodplain results from the inability of the one-dimensional model to capture complex features, such as braided streams, multiple openings, and bridge crossings near channel bends. Consequently, the choice of model can significantly affect determination of floodplain elevations and the vertical extent of the channel.

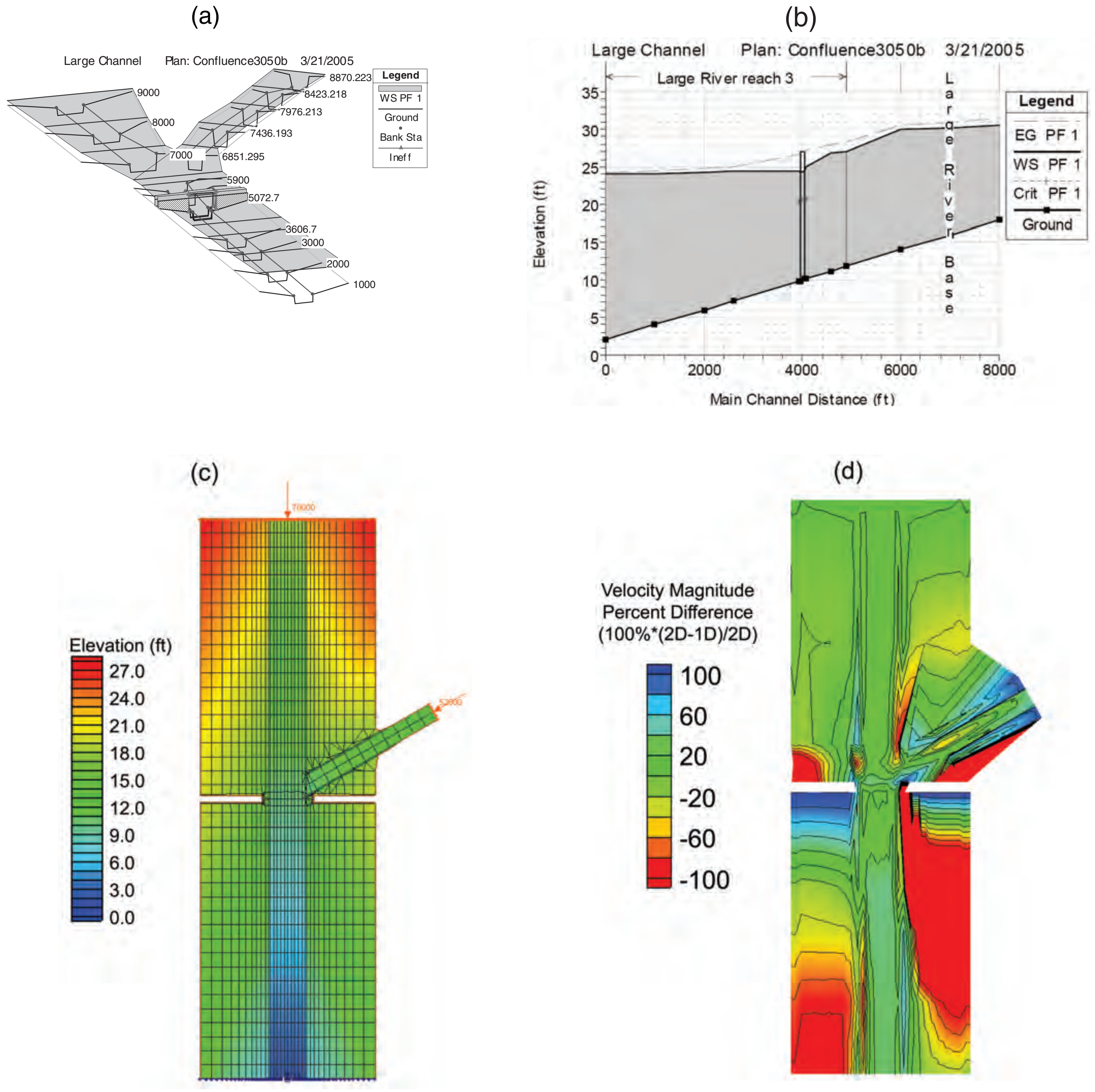


FIGURE 4.13 Differences between one-dimensional and two-dimensional models for an idealized channel with a single opening bridge downstream of a river confluence. (a) One-dimensional model setup information, (b) surface water elevation at main channel centerline produced by the one-dimensional model, (c) two-dimensional model setup with computational mesh, and (d) relative difference in the magnitude of flow velocity. Positive numbers in d indicate that the two-dimensional model produced higher velocity values, and negative numbers indicate that the one-dimensional model produced higher flow velocity values. SOURCE: TRB (2006).

This conclusion highlights a potential source of uncertainty in mapping floodplains using one-dimensional models. Models acceptable under current FEMA guidelines include 11 one-dimensional steady flow models, 10 one-dimensional unsteady flow models, and 4 two-dimensional steady-unsteady flow models.[7] The guidelines note the limitations of each model and recommend validation and calibration in most cases, but do little to help mapping partners determine which type of models are most appropriate for a given community. Furthermore, the guidelines require the mapping partner to check velocities at river bends to determine potential erosion. For meandering rivers, the TRB (2006) report suggests that such determinations are better made through two-dimensional models. Partnerships with academic institutions and individuals often facilitate the transition of research models into practical applications. For example, the National Weather Service has led two extensive distributed hydrologic model intercomparison projects (Smith et al., 2004, 2008), in part to establish links with researchers developing the next generation of hydrologic models.

Recommendation. FEMA should work toward greater use of two-dimensional flood hydraulic models where warranted by the floodplain geometry, including preferential flood pathways and existing and planned structures.

NORTH CAROLINA FLOOD MAPPING CASE STUDY

Riverine Flooding

The NCFMP (2008) study considered different combinations of three parameters: (1) hydrologic study type, (2) hydraulic study type, and (3) source of terrain information. The effects of variations in hydrologic methods have been described above. The effects of variations in hydraulic and terrain data are now discussed. Five approaches were examined:

1. *Detailed Study (DS)*. Lidar data were used for topography, field surveys for channel cross sections and for bridge and culvert openings; ineffective flow areas and channel obstructions were defined; and Manning's *n* could vary along the channel.
2. *Limited Detailed Study North Carolina (LDSNC)*. Same as a detailed study except that field surveying of channel structures was estimated or limited.
3. *Limited Detailed Study National (LDSNAT)*. Same as for LDSNC except no channel structures or obstructions were included and ineffective flow areas were removed near structures.[8]
4. *Approximate (APPROX)*. Same as for LDSNC except that Manning's *n* was uniform along the channel profile (it can have separate values for the channel and the left and right overbank areas).
5. *Approximate-NED (APPROX-NED)*. Same as APPROX but the National Elevation Dataset (NED), rather than lidar, was used for terrain representation.

Figure 4.14 shows the differences among these five methods in representing a channel cross section on the Swannanoa River.

Figure 4.15 illustrates the differences between water surface elevation computed using the five different hydraulic study methods on Long Creek. As long as lidar terrain data are used, the effect of variations in the hydraulic methods (DS, LDSNC, LDSNAT, APPROX) is quite small. The cascading appearance of the water surface profile for the APPROX-NED model is due to a horizontal misalignment between the base map planimetric information and the elevation information. In other words, detailed mapping of the stream network within Mecklenburg County shows the correct location of the stream centerline, and when lidar data are used to define elevation, the topographic and base map imagery are correctly aligned. However, when the National Elevation Dataset is used to define topography, the stream centerline and the topography are not correctly aligned and the stream appears to flow over small ridges and gullies rather than down a stream channel. The NED is on average 14.7 feet above the lidar on Long Creek (Table 3.2), hence the elevated water surface profile.

The BFE profiles for Ahoskie Creek and the Swannanoa River are plotted in Figure 4.16 for the five

---

[7] See <http://www.fema.gov/plan/prevent/fhm/en_hydra.shtm>.

[8] The LDSNAT variant is specific to the NCFMP (2008) case study and does not imply that FEMA limited detailed studies omit description of structures.

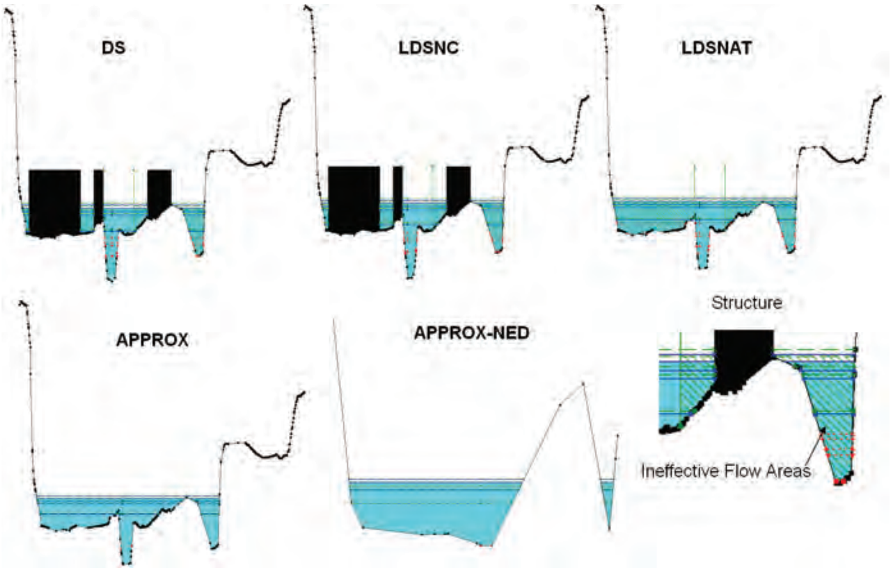


FIGURE 4.14 Differences in the channel cross section and structure geometry among the five different hydraulic study types for station 16008 of the Swannanoa River reach. Structures are shaded black, and water is shaded blue. The lower-right figure illustrates areas that are isolated from the main channel by a structure. Such areas of ineffective flow can store water but do not convey it. SOURCE: North Carolina Floodplain Mapping Program. Used with permission.

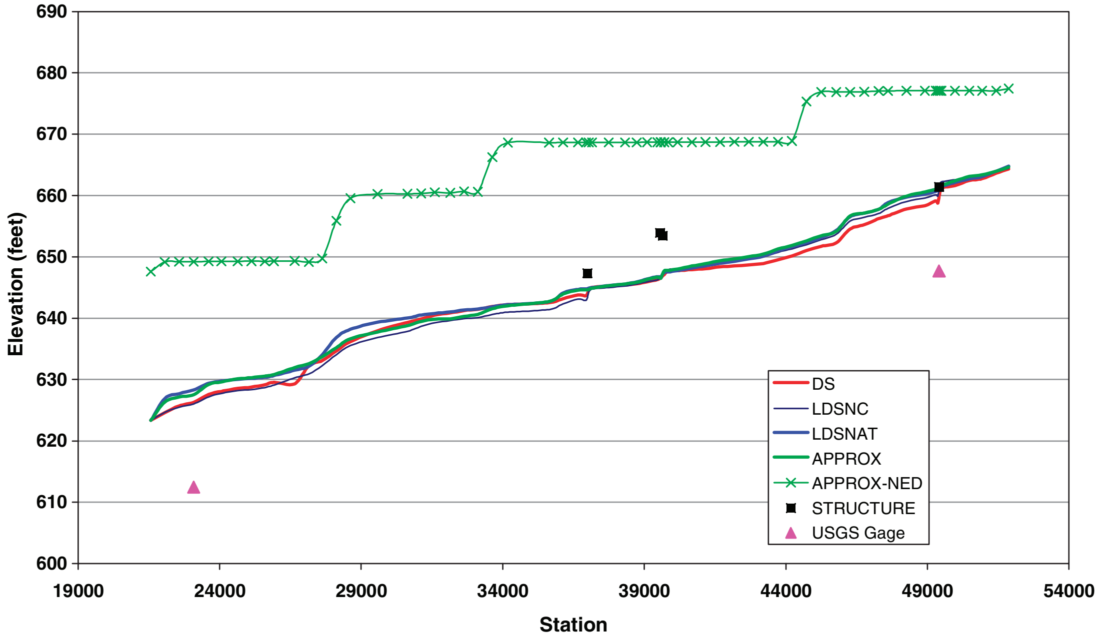


FIGURE 4.15 Base flood elevation profiles for different hydraulic study types on Long Creek. SOURCE: NCFMP (2008). Used with permission.

hydraulic and mapping study types. In these streams, the profiles reveal a great deal of random variation in the APPROX-NED BFE profile—sometimes it is above the other profiles and sometimes below, and the magnitude of the variations is significantly greater than the magnitude of variations in other hydraulic methods. This result countered expectations that map accuracy is affected at least as much by the accuracy

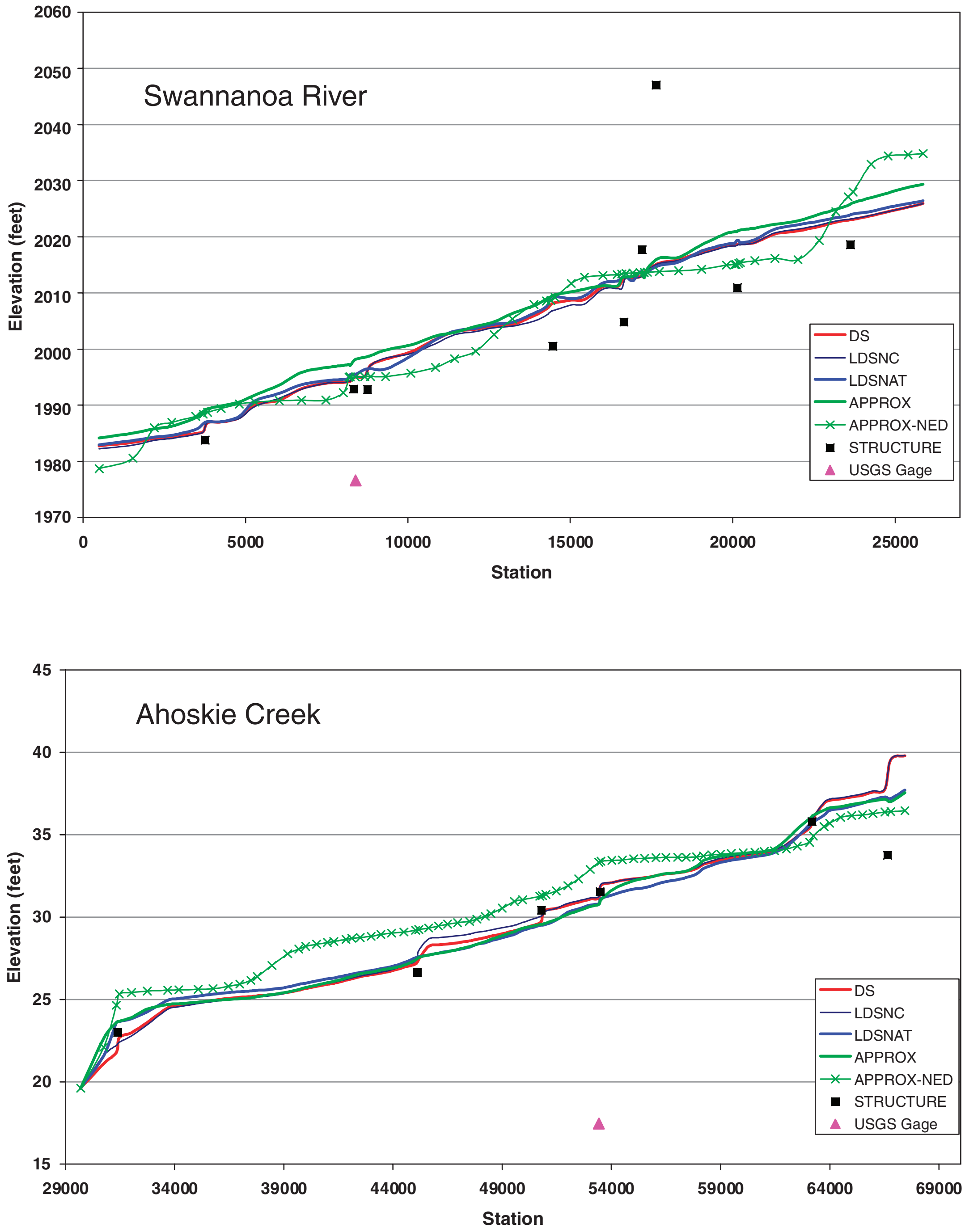


FIGURE 4.16 Water surface elevation profiles for different hydraulic study types on the Swannanoa River and Ahoskie Creek. SOURCE: NCFMP (2008). Used with permission.

of the hydraulic model and hydraulic parameters as by the accuracy of the topographic data. The case studies, which had the advantage of using precise topographic (lidar) data for analysis, clearly show that topographic data is the most important factor in the accuracy of flood maps in riverine areas.

Table 4.6 quantifies the differences between the flood elevation profiles in Figure 4.16 for detailed

TABLE 4.6 Base Flood Elevation Differences Between Detailed and Approximate-NED Studies

Stream	Mean (ft)	Standard Deviation (ft)	Minimum (ft)	Maximum (ft)
Ahoskie Creek	0.95	1.30	−3.34	2.87
Long Creek	20.89	3.07	13.11	26.45
Swannanoa River	0.18	3.61	−5.12	9.91

studies using lidar terrain data and approximate studies using NED terrain data. The differences are striking, particularly for Long Creek, where on average the BFE is more than 20 feet higher if calculated using the NED rather than lidar. In the other two study reaches, the NED BFE is, on average, fairly close to the lidar BFE, but at particular cross sections the two elevations may differ by up to 10 feet.

Finding. The base flood elevation profile is significantly more influenced by whether the National Elevation Dataset or lidar terrain data are used to define land surface elevation than by any variation of methods for calculating channel hydraulics.

Backwater Effects of Structures

One of the key reasons for doing detailed surveys of structures in stream channels is to estimate their backwater effects. The structures are shown as black squares in Figure 4.16, and it can be seen that the flood profiles jump upward at some of these locations. Bridges and culverts constrain the movement of floodwaters during very large discharges, and the water elevation upstream of a structure increases to create the energy needed to force the water to flow through the structure. Intuitively, these backwater effects should propagate further upstream in flat terrain than in steep terrain, but by how much? The impact of backwater on the surface water profile was the highest in Ahoskie Creek on the coastal plain, where six structures caused backwater effects and all of them extended to the next structure upstream (Table 4.7). On Long Creek, all four structures had backwater effects and three reached the next structure. On the Swannanoa River, six of nine structures had backwater effects, including five that reached the next structure. The average distance that a backwater effect propagated upstream was 1.12 miles on Ahoskie Creek, 0.5 mile on Long Creek, and 0.30 mile on the Swannanoa River. As expected, these results demonstrate that backwater effects from structures increase base flood elevations and that the distance these effects extend upstream is longest at Ahoskie Creek in the coastal plain and shortest on the Swannanoa River in the mountains of western North Carolina.

Finding. Backwater effects of structures influence the base flood elevation profile on all three study reaches and are most pronounced in the coastal plain.

Channel Slope

The three study areas were chosen in mountains, rolling hills, and coastal plains to examine the extent to which differences in terrain affect flood properties. Table 4.8 shows various measures of the slope in these study areas: the longitudinal and lateral slope values were derived from the HEC-RAS models for flood flow. The lateral slope is the value along the stream cross sections at the edge of the floodplain, averaged for the left and right banks of the cross section and over all cross sections in the reach. The terrain slope was derived from the NED over the whole county. As one would expect, the longitudinal slopes of the stream channels are much lower than the lateral slopes; that is, the land slopes much more steeply away from the channel than along it. Even though the terrain slope for the Swannanoa River (26.7 percent) is nearly 100 times that for Ahoskie Creek (0.3 percent), the longitudinal channel slopes of those two reaches differ by only a factor of 3.5 (0.18 percent versus 0.05 percent). In other words, despite the large differences in topography between the mountains of western North Carolina and the flat coastal plain, the creeks and rivers in those regions are much more similar to one another than to the surrounding terrain. The longitudinal slopes of the rivers are much flatter than the average slope terrains through which they flow. This may help to explain why there are no pronounced regional differences in

TABLE 4.7 Effect of Backwater Upstream of Structures

Stream	Number of Structures	Extended to Next Structure[a]	Average Elevation (ft)[b]	Maximum Elevation (ft)[b]	Distance Upstream (miles)[c]
Ahoskie Creek	6	6	0.89	2.54	1.12
Long Creek	4	3	0.34	0.73	0.50
Swannanoa River	9	5	0.20	2.02	0.30

[a] An elevated backwater effect extended from one structure to the next one upstream.
[b] Refers to the difference between the two elevation profiles with and without structures.
[c] Average distance upstream from a structure from which backwater effects propagate.

TABLE 4.8 Channel and Terrain Slopes

Stream	Terrain Slope[a] (%)	Longitudinal Slope (%)	Lateral Slope (%)	Lateral Run/Rise (ft/ft)
Ahoskie Creek	0.3	0.05	2.4	42
Long Creek	6.1	0.13	9.8	10
Swannanoa River	26.7	0.18	12.9	8

[a] Terrain slope is the average for the NED over the county where the reach is located, except for Ahoskie Creek, which is located in Hertford County but the terrain slope is for an adjacent county (Pasquotank), where relevant data were available.

the sampling error of the 100-year BFE estimates at stream gages. This is heartening for floodplain mapping because it suggests that there is a good deal more similarity in stream flood processes across broad regions than might be expected.

Finding. The river channels in the three study reaches have longitudinal slopes that are much flatter and more similar than are the average terrain slopes of the landscapes through which the rivers flow.

Delineating Special Flood Hazard Areas

Once the BFE profile is determined, the next step in the flood mapping process is to delineate the Special Flood Hazard Areas (SFHAs). This involves transforming vertical elevation profiles into horizontal area polygons drawn around the stream reach. The data on rise-run in Table 4.8 give an idea of the sensitivity of the lateral spreading of water to variations in the flood elevation. At Ahoskie Creek, a 1-foot change in vertical elevation changes the horizontal location of the floodplain boundary by 1/0.024 = 42 feet. A 1-foot rise in flood elevation will change the floodplain boundary on average by 10 feet at Long Creek and 8 feet on the Swannanoa River. Since there is no inherent difference in the sampling uncertainty in BFE by region (Figure 4.3), it follows that floodplain boundary delineation is more uncertain in the coastal plain than in the piedmont or mountains—in fact, about four to five times more uncertain, in proportion to the rise-run data. This shows that having very accurate topographic data for floodplain mapping is especially critical in regions with low relief.

The dominant effect of terrain data (lidar versus NED) has been illustrated for the base flood elevation (Figures 4.15 and 4.16). Figure 4.17 compares floodplain delineations based on lidar and the NED. The top map in red shows the SFHA defined by the lidar-detailed study approach; the dark green overlay in the middle map shows the BFE profile from the lidar-detailed study approach plotted on NED terrain information, and the light green overlay in the bottom map shows the approximate study approach with all computations done using the NED as the terrain base. There are significant discrepancies in the floodplain boundaries among these different approaches. An evaluation of the economic impact of the location of floodplain boundaries is presented in Chapter 6.

A simple way to compare floodplain maps is to count the number of acres in the floodplain, as summarized in Table 4.9. The values correspond to the top and bottom maps in Figure 4.17. At Ahoskie Creek, the SFHA is 1,756 acres for the lidar-detailed study

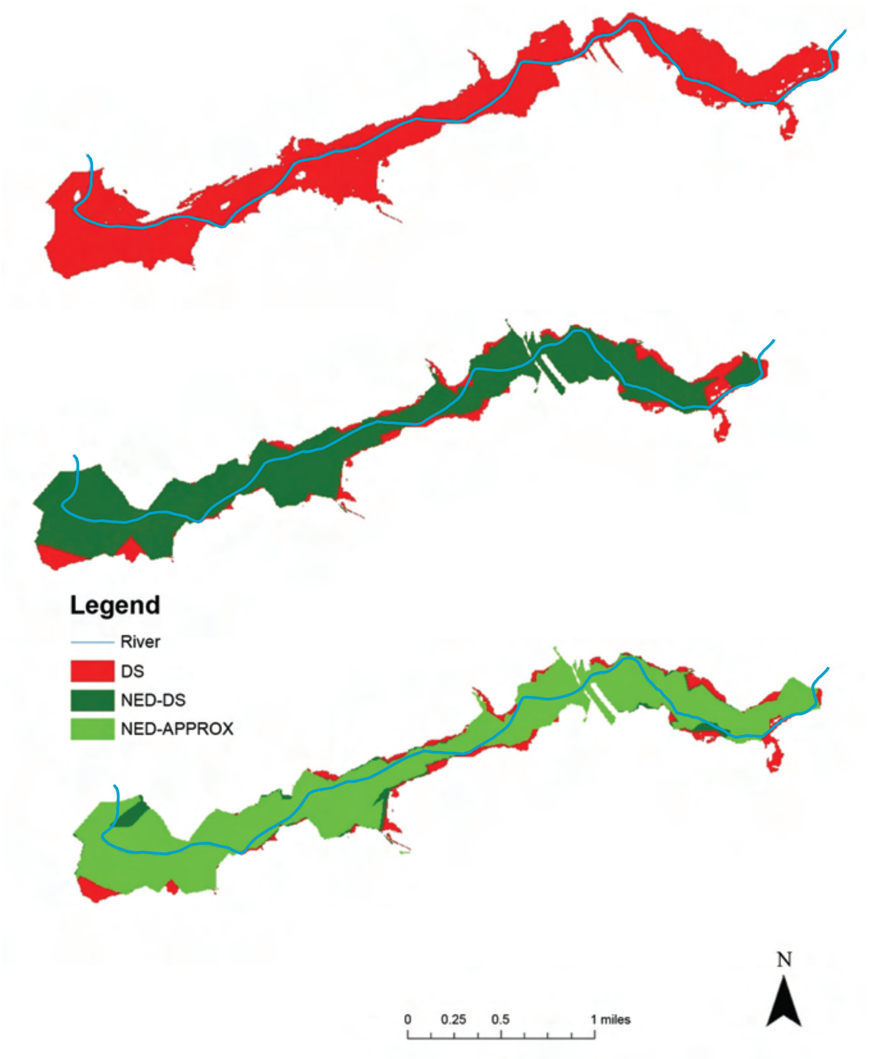


FIGURE 4.17 Inundated areas in Swannanoa River using different hydraulic study types. SOURCE: North Carolina Floodplain Mapping Program. Used with permission.

TABLE 4.9 Differences in Inundated Area for Various Hydraulic Study Types

	Ahoskie Creek		Swannanoa River		Long Creek	
Topographic Source	Area (acre)	Percent Difference	Area (acre)	Percent Difference	Area (acre)	Percent Difference
Lidar-DS	1,756	NA	485	NA	325	NA
NED-APPROX	1,744	−0.7	490	0.9	390	20.1

NOTE: NA = not applicable.

and 1,744 acres for the approximate-NED study, a 0.7 percent difference. On the Swannanoa River, the two areas are 485 and 490 acres, a 0.9 percent difference. On Long Creek, the areas are 325 and 390 acres, a difference of 20.1 percent, which reflects the larger errors in the NED at Long Creek than at Ahoskie Creek and the Swannanoa River.

Finding. In the three reaches examined, approximate study methods yield a good estimate of the number

of acres in the Special Flood Hazard Area, provided the stream location and topographic information are properly aligned.

SHALLOW FLOODING

In some regions, drainage is dominated by water flow from one ponded area to the next. Rivers still exist in such landscapes, but the mechanisms by which water reaches them are different than in the normal dendritic stream and channel systems that carry flow downstream. Ponding landscapes are common in Florida, where surficial sedimentary deposits overlie limestone formations. Dissolution within the limestone causes pitting, subsidence, and in some cases, collapse of the surface to form sinkholes.

The land surface terrain in these landscapes has low slope, so watershed delineation becomes an exercise in determining the drainage area surrounding each depression (Figure 4.18), rather than the drainage area of a point on a stream network. During severe storms, water accumulates in each land surface depression until it reaches the lowest elevation on its drainage divide with a neighboring depression and flows into the next downstream pond. This process continues until a developed stream or river is reached, at which point the flow dynamics become similar to those in dendritic drainage landscapes.

The committee's frequency analysis of stage heights included 10 stream gages with long-term flow records in southwest Florida (Figure 4.3). No significant differences in the sampling uncertainty of the 100-year flood stage were found for the Florida gages compared to the 21 gages that were studied in North Carolina.

Finding. Despite the difference in landscape flow processes between the dendritic stream river systems of North Carolina and the ponding landscapes in Florida, the resulting river base flood elevations determined at USGS gage sites have a similar sampling uncertainty.

FEMA guidelines do not specify procedures for dealing with the hydrology and hydraulics of ponded landscapes. The Southwest Florida Water Management District (SWFWMD) has developed some sophisticated tools for delineating drainage areas in pitted landscapes. The InterConnected Pond Routing model (ICPR) uses broad-crested weir equations to compute the hydraulics of flow between ponds. These equations determine the flow over a berm between one pond and the next as a function of the elevation of water above the berm. The interaction of one pond with the next is treated like upstream and downstream flow through a culvert—if the water elevation in the downstream pond is high enough, it can affect the discharge from the upstream pond. Other factors that are important include the volume of the water temporarily stored in the depressions, the duration of the critical design storm, and the rate of percolation of floodwaters through the base of the ponds or pits. Surface sediments can absorb significant quantities of water during a long design storm, but hydrologic methods that account for percolation have not yet been incorporated into FEMA flood mapping guidelines. Significant work remains to lay the scientific foundation for flood modeling of

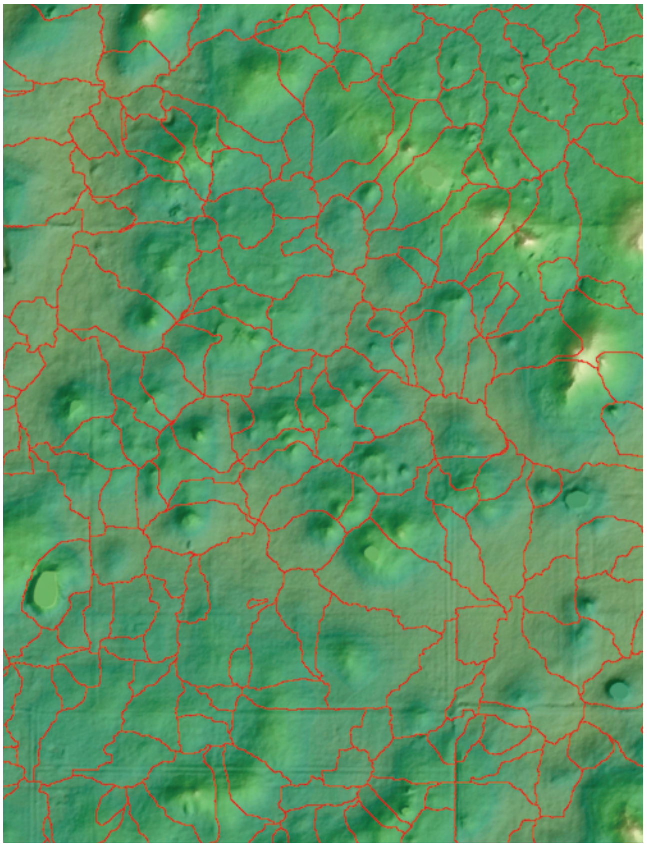


FIGURE 4.18 Drainage areas (red lines) of a ponded landscape in Florida. SOURCE: Southwest Florida Water Management District. Used with permission.

these landscapes. Such analysis is beyond the resources of this committee.

Recommendation. FEMA should commission a scientific review of the hydrology and hydraulics needed to produce guidelines for flood mapping in ponded landscapes.

CONCLUSIONS

The main insights arising from case studies of elevation uncertainty at stream gages and flood mapping uncertainty are the following:

- The sampling uncertainty of the base flood elevation at 31 USGS stream gages in North Carolina and Florida is 1 foot with a range of 0.3 foot to 2.4 feet, as inferred from frequency analysis of long records of annual maximum stage heights. This uncertainty does not show any systematic pattern of variation with drainage area or geographic location at these sites. Thus, there is a lower bound of approximately 1 foot on the uncertainty of the BFE as normally determined in floodplain mapping, since indirect methods of computing BFEs at ungaged sites will have uncertainty at least as great as uncertainties observed at stream gages.
- On three stream reaches in North Carolina, the lateral slope at the boundary of the floodplain is such that a 1-foot change in flood elevation has a corresponding horizontal uncertainty in the floodplain boundary of 8 feet in the mountains, 10 feet in the rolling hills, and 40 feet in the coastal plain.
- Observed flood discharges at stream gages are the most critical component for estimating the base flood discharge in the three study reaches because all hydrologic methods are calibrated using these data and each stream reach contained a stream gage. BFEs computed from the peak discharge estimated from the various hydrologic methods do not differ much, so the choice of hydrologic method does not introduce much uncertainty in the BFE beyond the lower bound uncertainty (1 foot) estimated by frequency analysis of USGS stage records. The most significant effect of hydrologic variations on BFEs is produced by introducing the average error of prediction into the regression flow estimates (from 42 to 47 percent), which changes the BFE by an average of 1 to 3 feet at the three study sites.
- Structures in the channel induce backwater in all three study reaches, with backwater effects extending over the entire length of the reach in the coastal plain but less far in the rolling hills and mountains. The maximum backwater elevation increase found was 2.5 feet in the coastal plain reach, and the backwater effect extended an average of 1.1 miles upstream. In the mountains, the backwater effect extended an average of 0.3 mile upstream.
- The greatest effect by far of any variant on the BFE is from the input data for land surface elevation: lidar or the National Elevation Dataset. At Long Creek, the BFE computed on the NED is 21 feet higher than on lidar because of a misalignment of the stream location on the NED. At the other two study sites, the average elevation of the BFEs for the two terrain data sources is about the same, but differs at particular locations by 3 to 10 feet. This result overturns the conventional view that map accuracy is affected at least as much by the accuracy of the hydraulic model and hydraulic parameters as by the accuracy of the topographic data.
- The floodplain boundaries produced using lidar and the NED differ from one another, but at two of the three study sites the number of acres enclosed within the Special Flood Hazard Area is about the same for a detailed study using lidar data and an approximate study using the NED. At the third site (Long Creek), the difference in the number of acres within these areas is about 20 percent. This suggests that while floodplain boundary locations are more uncertain in approximate studies than in detailed studies, the total areas they encompass can be reasonably similar, provided the stream and topographic data are properly aligned.

These conclusions were based on limited studies in small areas of North Carolina and Florida, which were carried out to examine the uncertainty of riverine flood mapping quantitatively rather than qualitatively. They are indicative but not definitive of what more comprehensive analyses of a similar character done nationwide might reveal. The importance of the results lies not in the specific numbers but rather in the insights they provide about the relative effect of variations in hydrologic, hydraulic, and terrain methods on flood map accuracy.

5

Coastal Flooding

A primary objective of coastal flood studies is to predict the extent and force of floodwaters over land. Because of sparse empirical records and the statistical rarity of extreme coastal events, coastal flood prediction relies on complex numerical models that approximate the processes and phenomena that lead to coastal floods. The predictions yield base flood elevations (BFEs) and spatial areas of flood hazard, which are presented on the Federal Emergency Management Agency's (FEMA's) coastal flood maps. This chapter reviews the methodology of coastal flood mapping. The focus is on hurricane-induced flooding, which is responsible for all the major aspects of coastal flooding, including storm surge, heavy rain, and overflowing rivers.

The committee did not undertake a set of detailed case studies of coastal flood mapping, nor is it possible to obtain lower bound estimates of flood map accuracy by analysis of stage height records as was done for riverine flooding (Chapter 4). Coastal flood mapping differs from inland flood mapping in several ways. First, there is much greater dependence on simulation models in coastal mapping along with less ability to make inferences from historical gage records as for inland mapping. In riverine flooding, the floodwaters flow down the river system past a succession of stream gages so the maximum discharge and water surface elevation are recorded at many locations. In coastal flooding, the storm comes onshore in a direction transverse to the line of tide gages along the coast. Indeed, no tide gage may be located at the point of maximum effect of a coastal storm. Second, the methodology for coastal flood mapping evolved significantly following hurricanes Katrina and Rita in 2005, and during the Map Modernization Program FEMA was expanding and significantly modifying its guidance documents on coastal flood mapping. The end result is that coastal flood mapping is much more complex and uncertain than riverine flood mapping, and its accuracy is less able to be characterized quantitatively. Accordingly, this chapter presents a survey of coastal flood mapping methodologies and the committee's assessment of the effectiveness of alternative approaches.

FLOOD HAZARDS IN COASTAL SYSTEMS

Coastal flood hazards arise from wave and surge dynamics that originate in the ocean and subsequently interact with bathymetric and topographic features on the ocean bottom and land surface (Figure 5.1), respectively. Coastal flood models must account for these features throughout the coastal zone as well as processes associated with the storm surge and waves that create the flood hazard (FEMA, 2006b). Bathymetry and topography change constantly as a result of storms and erosion, and also vary geographically. These geographic differences affect BFEs and result in different coastal flooding responses and flood hazard areas. For example, the Pacific coast is characterized by steep bathymetry and narrow coastal shelves, and flooding is dominated by waves rushing up the shore (wave runup). In contrast, the Atlantic and Gulf coasts are characterized by wide, shallow coastal shelves, and flooding is dominated by storm surge and breaking waves. Erosion continually

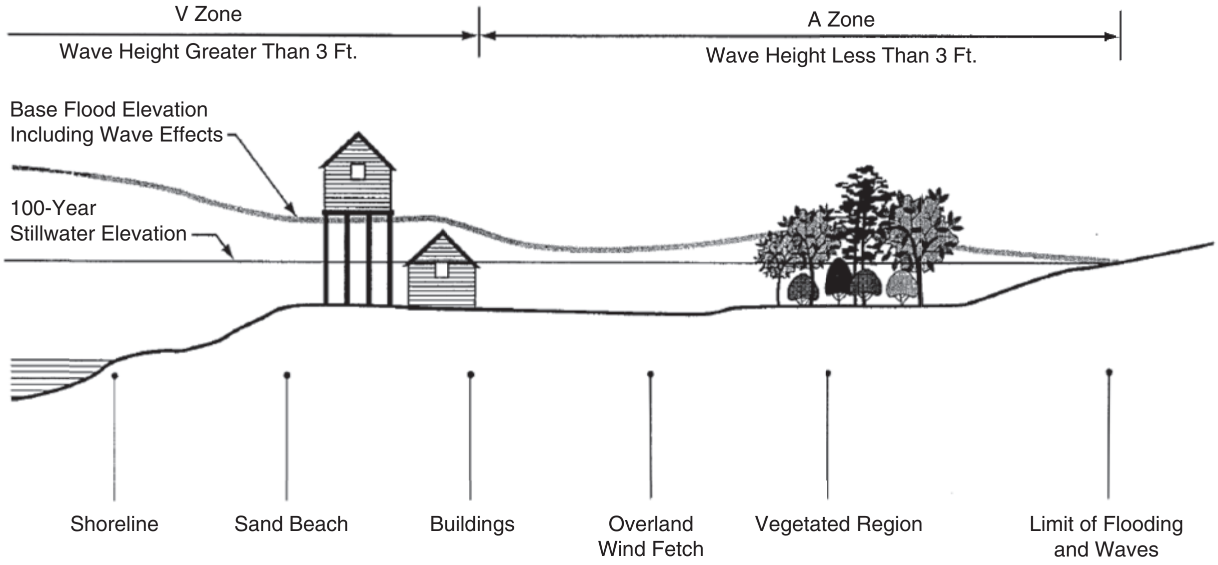


FIGURE 5.1 Onshore features that affect the propagation of waves, flood insurance rate zones (V and A zones), and base flood elevations. The 100-year stillwater elevation is the water level with a 1 percent annual chance of being exceeded in a given year. SOURCE: FEMA (2003).

or episodically changes the ground surface and complicates flood hazard mapping, especially along the Atlantic coast, which has dunes that are reshaped by storms, and, to a lesser degree, the Gulf coast.

Storm surge, tides, and waves are the greatest contributors to coastal flooding. Storm surge is the pulse of water that washes onto shore during a storm, measured as the difference between the height of the storm tide and the predicted astronomical tide. It is driven by wind and the inverse barometric effect of low atmospheric pressure, and is influenced by tides and by uneven bathymetric and topographic surfaces. Faster wind speeds and larger storms create a greater storm surge potential. Storm surge alters topographic features that might otherwise dampen the effects of surge and wave forces. For example, sand dunes that normally prevent storm water progress onto a barrier island may be reshaped or even removed during a severe storm.

Water surface elevations at the shoreline are a combination of the average water level determined by wind setup (due to the direct action of wind stresses at the air-sea interface) and wave setup (due to breaking waves, Figure 5.2) and a fluctuating water level caused by wave runup (the maximum extent of high-velocity uprush of individual waves above the average water level). All of these factors are included in coastal flood models to estimate the BFE.

FEMA COASTAL FLOOD MODELING METHODOLOGY

The Basic Structure of Current Coastal Flood Models

Coastal flood models estimate BFEs using empirical and probabilistic input data and two modeling steps (Figure 5.3 and Table 5.1):

1. Storm surge models are often loosely coupled with wave models to calculate the 1 percent annual chance stillwater elevation (SWEL) and the wave dynamics associated with a coastal flooding event. Recent flood studies in Mississippi and Louisiana used loosely coupled two-dimensional (2-D) surge and wave models to calculate the SWEL and wave setup.
2. The SWEL value (with or without wave setup) from the wave and surge models is used to calculate wave crest values using erosion and wave calculations through the Coastal Hazards Analysis and Modeling Program (CHAMP) and the Wave Height Analysis

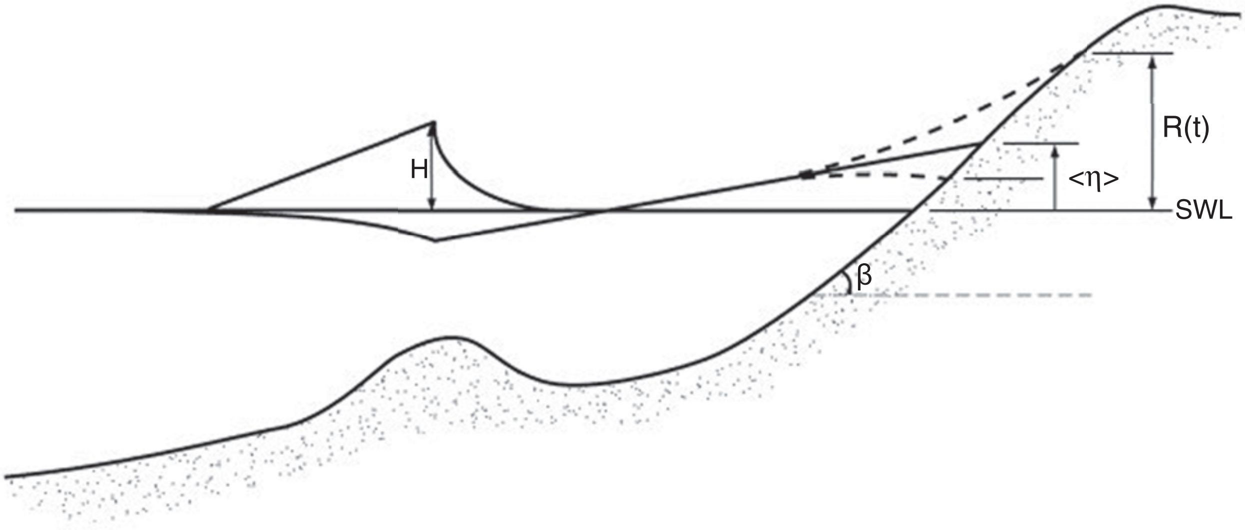


FIGURE 5.2 Schematic of wave setup (η; rise in the water surface caused by breaking waves of height *H*) and wave runup (*R*(*t*); the rush of wave water up a slope or structure). Wave setup and wave runup raise water elevations above the stillwater level (SWL).
SOURCE: U.S. Geological Survey, <http://coastal.er.usgs.gov/hurricanes/impact-scale/water-level.html#runup>.

for Flood Insurance Studies (WHAFIS) program. The recent Mississippi study used the SWEL and wave setup calculated by the Advanced Circulation (ADCIRC) and Simulating WAves Nearshore (SWAN) models to calculate the wave crest in CHAMP. The wave crest is combined with the SWEL and wave setup to yield the BFE. Depending on the region, wave runup and overtopping may have to be calculated and added to the wave crest.

Evolution of Coastal Flood Models and Mapping

Prior to 1975, coastal BFEs for Flood Insurance Rate Maps (FIRMs) were calculated using limited historical records and an early storm surge model, but without consideration of waves. In the late 1970s, FEMA supported the development of a 2-D storm surge model (FEMASURGE) for calculating the SWEL caused by storm surge, again without consideration of wave effects on the storm surge or BFEs. These early models used simplified assumptions, coarse grid resolutions, and a simple parametric hurricane model to minimize computational effort.

In 1977, FEMA asked the National Research Council (NRC) to determine how to incorporate calculations of wave height and runup in flood map projects for Atlantic and Gulf coast communities. The NRC (1977) concluded that wave height predictions should be included in coastal flood mapping and provided a methodology to account for varying fetch lengths (length of water over which a given wind has blown), barriers to wave transmission, and regeneration of waves likely to occur over flooded land areas. Based on the NRC (1977) recommendations, FEMA developed WHAFIS to provide wave heights for the BFEs.

FEMA has also made many incremental improvements in probabilistic methods for selecting an ensemble of hurricane and storm parameters and return periods; storm surge modeling; and calculation of wave setup, wave runup, wave crest, erosion, and the effects of structures on surge and waves. For example, the Joint Probability Method (JPM), introduced in 1981, was used to determine the hurricane ensemble and return period in coastal regions based on available hurricane data and statistical properties of hurricane wind parameters at landfall. The catastrophic flooding in Louisiana and Mississippi during Hurricane Katrina in 2005 triggered new interest in developing more advanced models. JPM has been improved, and the Interagency Performance Evaluation Task Force

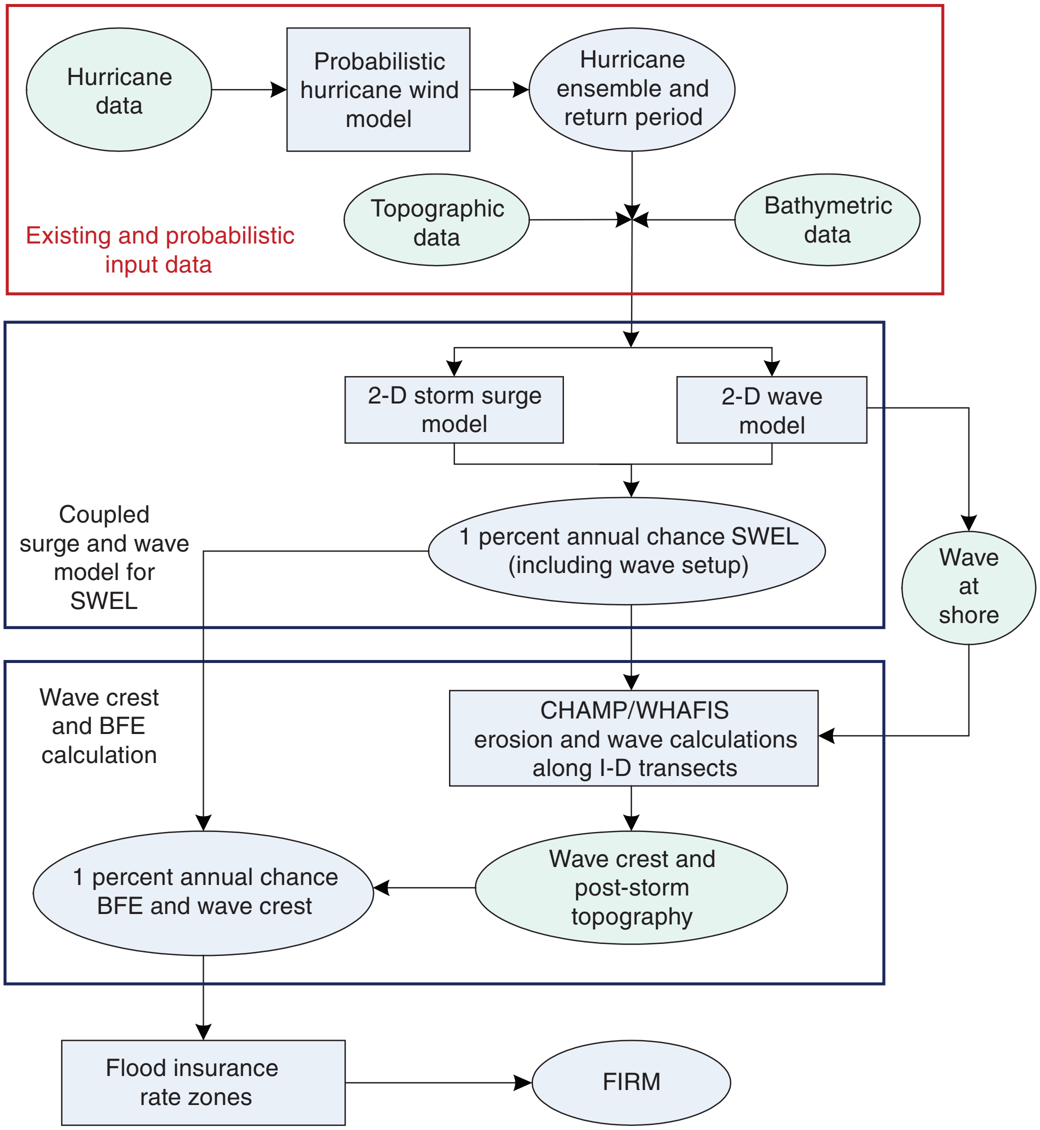


FIGURE 5.3 Current FEMA coastal mapping procedures used in Mississippi and Louisiana. In these studies, two-dimensional surge (ADCIRC) and wave (SWAN for Mississippi and STeady State spectral wave [STWAVE] for Louisiana) models are used to calculate the 1 percent annual chance stillwater elevation, and CHAMP/WHAFIS is used to calculate overland wave crest and post-storm topography. The 1 percent annual chance SWEL and the wave crest are then combined to calculate the BFE. NOTE: FIRM = Flood Insurance Rate Map.

TABLE 5.1 Elements of FEMA's Current Coastal Flood Mapping Process

Empirical and Probabilistic Input Data	Coupled Surge and Wave Models for SWEL Calculation	Wave Crest and BFE Calculation
• Hurricane data • Probabilistic hurricane wind model data • Hurricane ensemble and return period data • Bathymetric data • Pre- and post-storm topographic data	• 2-D storm surge model • 2-D wave model	• CHAMP/WHAFIS erosion and wave calculations along one-dimensional (1-D) transects • Post-storm topographic data to verify CHAMP/WHAFIS results

(IPET, 2008) developed the JPM-OS (Optimal Sampling) method to reduce the number of hurricanes in the hurricane ensemble. The Empirical Simulation Technique (EST), was developed to reduce the computational burden by considering only the combinations of storm characteristics that have been observed in the historical record. A comparison of the JPM and EST methods appears in Divoky and Resio (2008). A new generation of storm surge and wave models is now being used for flood mapping in Mississippi, Louisiana, Texas, and North Carolina and will be used in other states in the future.

FEMA's guidelines for coastal flood mapping have also evolved.[1] Policies and procedures were established for storm surge modeling by 1985 and for wave and V zone modeling by 1995. Updates in coastal modeling guidance accelerated in 2002. Separate guidance has been developed for the Atlantic and Gulf coasts, the Pacific coast, and sheltered coastlines. Yet even with these updates, the recent switch to coupled storm surge-wave modeling for flood map production is still "beyond the scope of these guidelines" (FEMA, 2007a), and mapping contractors are referred to the specific user's manual for each model. FEMA is currently working with individual mapping contractors to implement the models in flood map production.

Wave Height Analysis for Flood Insurance Studies (WHAFIS)

WHAFIS analyzes wave effects along one-dimensional (1-D) transects normal to the shore (Figure 5.4) to determine the wave height. The relatively simple 1-D method was originally recommended because wave transformation processes in shallow water were not well understood, and robust 2-D wave models and the computational power to run them did not exist (NRC, 1977). Patches added to the original WHAFIS program since 1989 include methods to calculate wave height elevations above the storm surge elevation and wave setup along 1-D transects. The improved WHAFIS was combined with patches for calculating wave runup and storm-induced dune erosion along 1-D transects into a new software package, CHAMP. The results are then interpolated to produce the wave crest over a 2-D onshore environment.

Wave crests calculated by CHAMP/WHAFIS have not been sufficiently validated, creating potentially significant uncertainties in BFE estimates. Factors that contribute to the uncertainty of WHAFIS wave crest calculations include the following (Sheng and Alymov, 2002):

- Wave transformation is a 2-D process that cannot be represented in a 1-D model.
- WHAFIS wave crests and BFEs are not 1 percent annual chance values (i.e., probabilistic wave conditions are not incorporated in the WHAFIS calculations).
- Surge and wave are completely decoupled, which may lead to over- or underestimates of the BFE.
- The 540-square-foot rule for dune erosion (i.e., a dune exceeding a cross-sectional area of 540 square feet will not be breached in a 1 percent annual chance storm) has not been validated.
- The approach for wave dissipation by vegetation, buildings, and levees has not been validated.
- One-dimensional transects do not reflect 2-D terrain.
- Manual interpolation of 1-D results to two dimensions is subjective.

Despite these known limitations, WHAFIS has been the wave analysis method recommended by FEMA since 1989. A number of 2-D models have been developed, and studies demonstrate that coupled 2-D models are at least as accurate as WHAFIS and in most cases are better at representing the fullness of wind wave crest and storm surge dynamics in coastal flood zones (e.g., Sheng and Alymov, 2002). The current 2-D coupled surge and wave models use probabilistic methods, whereas WHAFIS determines wave crest elevation on top of the SWEL along 1-D transects. Which modeling approach yields more uncertainty in the BFE value has not been studied.

FEMA Coastal Flood Modeling in the Post-Katrina Era

Since Hurricane Katrina in 2005, FEMA has encouraged rapid advancements in coastal flood modeling and mapping. Improvements currently under way

---

[1] See description and references at <http://www.fema.gov/plan/prevent/fhm/dl_vzn.shtm#1>.

FIGURE 5.4 Aerial photograph of the coast near Biloxi, Mississippi, showing the layout of one-dimensional WHAFIS transects (red lines). SOURCE: Courtesy of David Divoky, HSMM/AECOM. Used with permission.

include development of better hurricane ensemble parameters, more accurate estimates of the return period of storms in several coastal regions, more accurate simulations of storms surge and estimations of SWEL in Louisiana and Mississippi, and increased use of very fine, unstructured grids (100 meters or less) to resolve complex coastal terrains and enable the use of high-resolution lidar (light detection and ranging) data.

FEMA (2006b) recommended merging developments in hydrodynamic and statistical methods with established methods for wave analysis, erosion assessment, and flood hazard mapping. However, coupled 2-D surge and wave models are not yet fully integrated into mapping practice because 2-D wave models “do not incorporate bottom friction and obstruction effects of the sort considered by WHAFIS” and FEMA has not developed guidelines for 2-D overland wave modeling (FEMA, 2008b). Recent applications of coupled 2-D surge and wave models have demonstrated their ability to calculate wave setup and wave crest (Sheng and Alymov, 2002; IPET, 2008).

In Louisiana, Mississippi, and North Carolina, novel approaches to coastal flood mapping are either under way or have recently been completed. These new coastal mapping studies are the first to replace FEMASURGE with the ADCIRC model and could be used as part of a more comprehensive assessment of methods for enhancing mapping—for example, by gathering more data for verifying wind, storm surge, and wave models (see below).

FROM MODELS TO MAPS: DEVELOPING THE NEXT GENERATION OF COASTAL FLOOD MODELS

Coastal flood models—and by extension, coastal flood maps—will continue to be improved in the coming decades, driven by the increased availability of high-resolution topographic data and more sophisticated models. This section identifies opportunities to improve the accuracy of coastal flood models and recommends ways to guide the development of the next generation of coastal flood models and maps.

Decreasing Uncertainty in Coastal Flood Models

The BFE is a key variable used to define flood hazard areas on coastal FIRMs. However, it is the final output of the models and reflects uncertainties in the input data and every stage of the modeling process. Major sources of uncertainty include calculation of the SWEL using a 2-D surge model and the nonprobabilistic wave crest using a 1-D WHAFIS model, use of coarse grid resolution and small model domain, use of simple and empirical procedures or models to represent the effect of topographic features on surge and waves, quantification of hurricane return period and ensemble, exaggerated wind conditions (e.g., 80 miles per hour blowing perpendicular to shore), unrealistic wave boundary conditions at the shore, and topographic and bathymetric data. Sources of uncertainty in storm surge and wave models are shown in Figure 5.5. The impact of uncertainties in these factors on the accuracy of calculated storm surge and coastal inundation has not been examined, but may need to be quantified to make significant improvements in coastal models and maps. The sensitivity and uncertainty of simulated storm surge and inundation to these factors is beginning to be examined in regional test beds, such as the one described in Box 5.1.

Considerable differences exist among the available storm surge models in terms of model dimensionality, grid resolution, efficiency, and processes modeled. Increasing model grid resolution in the coastal region improves the model's ability to resolve local and geometric features and increases the accuracy of simulated surge. Increasing the size of the coastal domain enables modelers to simulate hurricane effects further from shore, reducing uncertainty in surge and wave water levels. However, both the increased resolution and the increased domain size add to the computational time of the simulations. Added computational resources enabled recent coastal flood studies in Mississippi and Louisiana to use much higher resolution and larger coastal domains than have traditionally been used for these types of studies (e.g., IPET, 2008). More efficient surge and wave models would reduce computation costs.

The accuracy of simulated storm surge and waves is sensitive to the way wave-current interaction is parameterized in the model, including the wave-enhanced drag coefficient, radiation stress, and wave-current bottom friction.

Recommendation. FEMA should work with other federal agencies and academic institutions to develop a test bed to assess and compare the various models used for coastal flood mapping. As a start, FEMA should compare the flood maps for the New Orleans region produced by IPET using coupled 2-D surge and wave models with those produced by FEMA using a 2-D surge model and a 1-D wave model.

More Robust 2-D and 3-D Models

Storm surge has been simulated using 1-D, 2-D, and three-dimensional (3-D) models, although 1-D models have known shortcomings. After Hurricane Katrina, FEMA accelerated the improvement of coastal modeling methodology by adopting the more advanced 2-D surge model ADCIRC and the 2-D wave model SWAN. Although FEMA has not fully embraced the use of coupled 2-D surge and wave models to calculate BFEs and wave crests, the successful use of this method by the Interagency Performance Evaluation Task Force increases the likelihood that 2-D methods will eventually replace the current 2-D (wave and surge models) plus 1-D (WHAFIS/CHAMP) method.

Recommendation. FEMA should use coupled 2-D surge and wave models to reduce uncertainties associated with the use of a 2-D surge model and the 1-D WHAFIS model. Before choosing which models to incorporate into mapping practice, an analysis of the impact of various uncertainties on the models should be undertaken.

Sometimes even 2-D models cannot represent the full range of physical processes involved. For example, marshes, barrier islands, buildings, dunes, and levees resist storm surge and waves, and hence can significantly affect the surge, wave heights, and inundation. These 3-D processes are not adequately resolved in FEMA-approved 2-D storm surge models and may require 3-D modeling. Another example concerns flow-structure interaction, which has a significant effect on flooding in some regions. Even when the SWEL is below the height of a coastal barrier (e.g., a levee or large dune), the topographic feature may be overtopped and/or eroded. If these processes are not included in the models, flooding and waves in the land

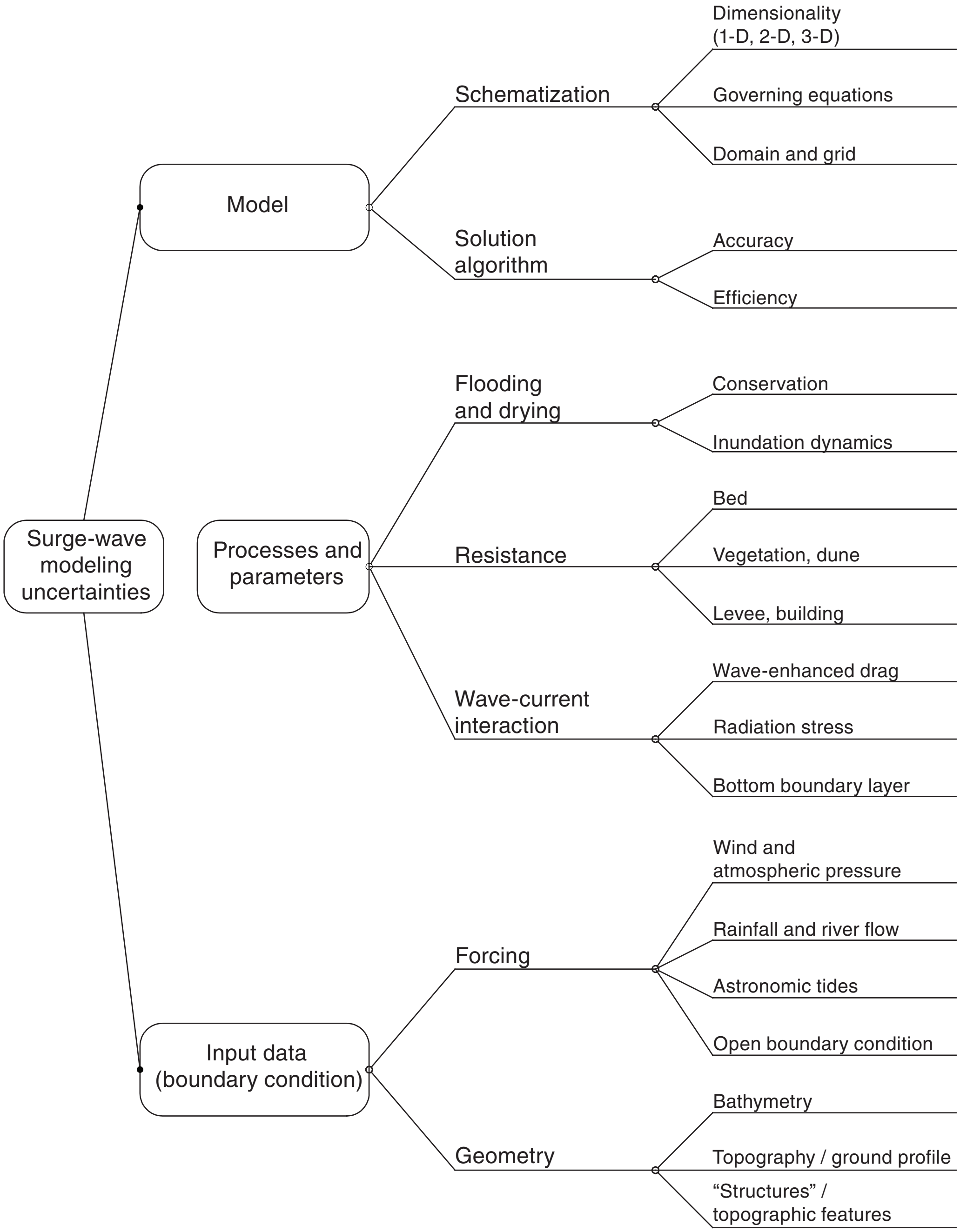


FIGURE 5.5 Sources of uncertainties associated with storm surge and wave modeling. Although every item in this figure contributes to the overall uncertainty of the simulated storm surge and waves and the calculated 1 percent annual chance flood elevation, their relative contributions are not well understood because a systematic uncertainty analysis has not been done.

area and bays behind the topographic features could be underestimated. Hence, it is important to incorporate the effect of topographic features on coastal flooding in 2-D or 3-D storm surge and wave models, as appropriate.

In addition to developing new capabilities, the next generation of coastal flood models can take better advantage of the capabilities of existing 2-D and 3-D models. For example, 2-D wave models already in use with storm surge models represent a significant

BOX 5.1 Coastal Mapping Test Bed

Over the last few years, flood mapping along the Atlantic and Gulf coasts has shifted from locally applied storm surge models to the regionally applied ADCIRC model coupled with the SWAN wave model as maps are updated. FEMA has also authorized the use of other storm surge models. These models were typically developed independently from university research efforts. Each model has its own strengths, weaknesses, and data needs. However, there have been little direct comparisons of the models and limited testing to optimize computational efficiency and data needs.

An effective way to compare the accuracy and/or efficiency of different models and to optimize the data requirements is to develop a model test bed. One such test bed is being developed under a grant from the National Oceanic and Atmospheric Administration's (NOAA's) Integrated Ocean Observing System Program through the Southeast Coastal Ocean Observing Regional Association. The test bed consists of four modeling groups, including the University of Florida (CH3D-SSMS modeling system), the University of North Carolina (ADCIRC model), the University of South Florida (FVCOM), and North Carolina State University (CEMAS based on POM), plus participants from NOAA, FEMA, the U.S. Army Corps of Engineers (USACE), the U.S. Geological Survey, the Florida Department of Emergency Management, the North Carolina Division of Emergency Management, the Northeast Florida Regional Planning Council, Broward County, Florida, and URS Corporation. High-resolution topographic and bathymetric data along the southeastern coasts as well as historical storm data will be collected and analyzed for verification of the four academic models and the NOAA SLOSH model. After verification, the models will be used to determine how different model features or attributes will affect model accuracy and efficiency, and how model parameters and options such as grid density and time steps can be varied to optimize modeling accuracy and efficiency. The different models will be used to produce storm surge atlases (similar to the SLOSH maps) and prototype FIRMs, and these products will be compared to determine how sensitive they are to different model features and attributes. The test bed will be complete by the end of 2010.

SOURCE: <http://ioos.coastal.ufl.edu/>, <http://ioos.noaa.gov/>.

improvement over WHAFIS. These changes, illustrated in Figure 5.6, would significantly advance FEMA's coastal models by yielding more accurate estimates of the SWEL, wave crest, and BFE.

Recommendation. FEMA should work toward a capability to use coupled surge-wave-structure models to calculate base flood elevations, starting with incorporating coupled two-dimensional surge and wave models into mapping practice.

Post-storm Topographic Data

Topographic data following a 1 percent annual chance or more severe storm is becoming increasingly available in some coastal areas. Post-hurricane Katrina and Rita topographic data were used in Louisiana and Mississippi to validate the existing levee overtopping-erosion model (IPET, 2008). These data could also be used to develop and validate more robust storm surge and wave models in the future. Precedence for collecting post-storm topography during most of the recent storms has been set and should become the new standard practice.

Recommendation. FEMA should expand collection of high-resolution topographic data to all coastal counties and require collection of post-storm topographic data to validate storm surge and wave models and improve their accuracy.

Bathymetric Data

Accurate bathymetry is a prerequisite for accurate simulation of storm surge, waves, and coastal flooding. Since storm surge and waves propagate over a long distance before landfall, it is necessary to have accurate bathymetry for both the offshore (greater than 20-meter depth) and the nearshore (less than 20-meter depth) regions. Currently available bathymetric data are often outdated, particularly far from shore where the data may be decades old. However, updating bathymetric data is costly. Given limited funding, priority should be given to bathymetric surveys in the nearshore region where high surge and waves develop and affect coastal communities. Nonlinear wave models have shown that infragravity waves (waves with a period of 20 to 300 seconds) are created by wave-bathymetry interactions at depths of 15 to 20 meters

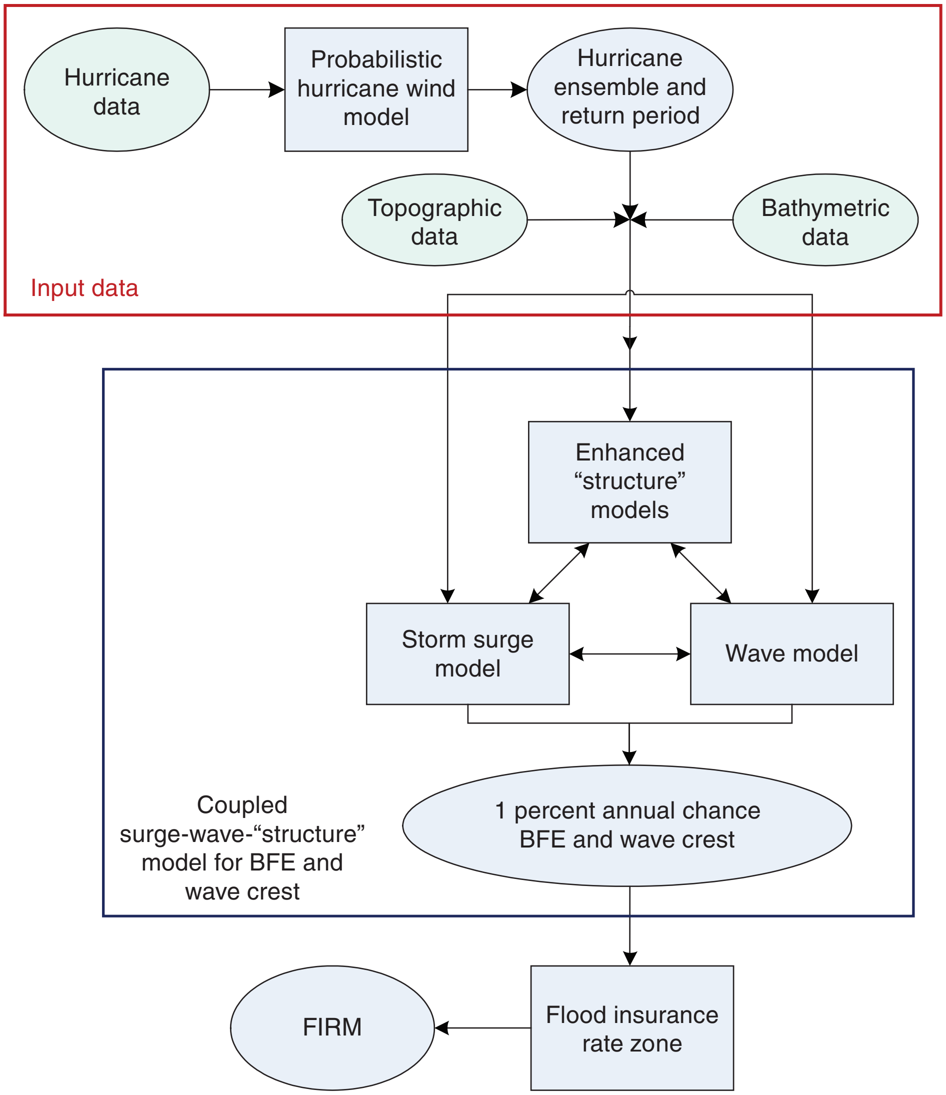


FIGURE 5.6 Recommended coastal flood modeling and mapping procedures for FEMA. Coupled surge-wave-structure models allow calculation of 1 percent annual chance SWEL, wave setup, wave crest, and BFE simultaneously. Enhanced "structure" models account for surface roughness, erosion, and overtopping or failure of topographic features. In the interim, the committee recommends using post-storm topography and new data to develop or validate the "structure" models and to validate the CHAMP/WHAFIS erosion-wave calculations and using fully coupled surge-wave models for SWEL and wave crest calculations.

and shallower. The extent to which perturbations in the bathymetry affect storm surges or waves modeled using FEMA's flood mapping methods is unknown, although preliminary tests suggest that surge and waves are more sensitive to nearshore bathymetry than to offshore bathymetry.

Recommendation. FEMA should work with NOAA and the USACE to acquire high-accuracy bathymetric data in coastal, estuarine, and riverine areas.

A Comprehensive Coastal Flood Mapping Uncertainty Study

FEMA has overseen many incremental improvements to the basic CHAMP/WHAFIS model structure. Some of the patches contain simplifying assumptions that could increase uncertainty in the calculated BFE. The uncertainties associated with these patches, however, have never been assessed quantitatively. Similarly, the research community has been creating increasingly sophisticated 2-D and 3-D models for surge, waves, and other coastal phenomena (e.g., Sheng and Alymov, 2002; IPET, 2008). Whether any of these new models would improve FEMA's modeling process is just beginning to be assessed in test beds. For example, the test bed led by the University of Florida is comparing four research storm surge and inundation models as well as the flood maps produced using the models.[2] A comprehensive uncertainty study could help identify opportunities to increase the accuracy of coastal flood studies and priorities for improving FEMA's coastal flood modeling and mapping methods.

Recommendation. FEMA should commission an external advisory group to conduct an independent, comprehensive assessment of coastal flood models to identify ways to reduce uncertainties in the models and to improve the accuracy of BFEs.

Such an assessment could consider factors such as

- Performance metrics and standards for storm surge models and wind fields,
- The necessary size of the coastal domain for storm surge simulation,
- The effectiveness of patches applied to the WHAFIS/CHAMP model, and
- The level of uncertainty associated with current 2-D and 3-D models, probabilistic methods, and WHAFIS.

CONCLUSIONS

Coastal flood studies rely on models of atmospheric and ocean phenomena that originate far from shore and that change in the nearshore and onshore environment. Considerable progress has been made in modeling these phenomena and mapping coastal flood hazard over the last 30 years. The modeling changes were usually incorporated in the form of patches. Modeling methodology is now poised for a major step forward, enabled by the availability of more advanced models and increased computing power, and sped by the need to better understand and represent coastal flood processes in the wake of Hurricane Katrina.

The key to improving coastal flood maps lies in improving the coastal flood models that are used to calculate the BFE, improving estimates of hurricane return period, and gathering more accurate pre- and post-storm topographic data. Published studies comparing WHAFIS with 2-D surge and wave models suggest that coupled 2-D surge and wave models yield more accurate BFEs, and the committee endorses their use. Other models emerging from the research community offer new or enhanced capabilities—such as those for calculating the effect of waves on storm surge and the effect of levees, marshes, or dunes on storm surge and waves—but they have not been compared to one another or to FEMA models to determine whether incorporating them into mapping practice would significantly improve the accuracy of coastal flood maps. A comprehensive model intercomparison study would help focus effort on which models should be further developed and adopted into FEMA methodology. The ultimate goal would be to use coupled models of storm surge, waves, and the effects of surface roughness, erosion, and overtopping or failure of topographic features to calculate the 1 percent annual chance stillwater elevation, wave setup, wave crest, and base flood elevation simultaneously. Similarly, cost comparisons of recent coastal mapping studies in Louisiana, Mississippi, and North Carolina—which were not available at the time of writing of this report—with older studies would help FEMA choose which new models are most cost-effective to pursue.

---

[2] See <http://ioos.coastal.ufl.edu>.

6

Benefits and Costs of Accurate Flood Mapping

All societies have more needs and desires than resources to fulfill them. Benefit-cost analysis provides a framework to understand and balance the various requirements of society against available resources. If the benefits are greater than the costs, the project contributes positively to society. Benefit-cost analysis of maps and their underlying data suggests that increasing the accuracy of maps or portraying additional information yields positive net benefits (Bernknopf et al., 1988, 1990, 1993, 1997; Mileti et al., 1992; Olson and Olson, 2001; Halsing et al., 2004; NRC, 2006). These "value of information" studies show that the information itself has value, which increases with greater accuracy or comprehensiveness.

Few studies have evaluated the net benefits of improved flood map accuracy. The most comprehensive assessment was undertaken by the Federal Emergency Management Agency (FEMA) in 1997 and updated in 2000. This chapter describes the benefits and costs of more accurate flood maps and summarizes the results of benefit-cost analyses carried out by FEMA and the State of North Carolina. The benefit-cost analyses focused on mapping, not related topics such as flood hazard mitigation.

BENEFITS AND COSTS

Most of the costs and some of the benefits of more accurate flood maps can be quantified, drawing on studies of floods and other kinds of hazards (e.g., Bernknopf et al., 1993; NRC, 2006). Direct costs (e.g., collection of elevation data) and indirect costs (e.g., implementation of required mitigation measures) are generally measurable using observed expenditures. Direct benefits (e.g., use of the data to estimate flood risk more accurately) are easier to measure than benefits that are non-market or temporal in nature.[1] Improvements in models, data collection, or mapping methods generally yield incremental benefits (e.g., improved land use regulation).

For flood map creation and accuracy improvement, most of the direct costs and some of the direct benefits are borne by the public sector; other costs and benefits are spread across society (Table 6.1). The direct costs to FEMA are a function of the level of effort required to carry out flood studies, evaluate the results, update and maintain the maps, and produce and distribute paper and digital products. The direct costs to users include the time and effort required to use the maps and request updates, as well as the monetary costs of complying with insurance and land use regulations.

The benefits of more accurate flood maps accrue to individuals, communities, and society as a whole. Flood-related information is a public good—that is, a product or service that can be shared by many users simultaneously without detracting from its value to any one of them. Flood maps are used an estimated 30 million times each year by government agencies, FEMA contractors, lenders, insurance agents, land developers, realtors, community planners, property owners, and

---

[1] Where market prices do not exist because the commodity (flood information) is not "traded," non-market valuation is sometimes used to estimate benefits.

TABLE 6.1 Benefits and Costs of Improved Map Accuracy

Category	Impact	Benefits	Costs
Land use: floodplain regulations	Reduced loss of life	• Able to target higher-risk areas • Able to identify evacuation needs	
	Reduced loss of property	• Able to target higher-risk areas • Lower-risk areas less restricted • Building restrictions match risk • Less time and money spent on contesting maps • Eventual payback on freeboard costs • Wise floodplain investment, including infrastructure	• Increased construction costs • Loss of land to development • Need to update regulations and inform the public of changes
	Reduced loss of business	• Fewer business interruptions • Fewer public service interruptions	• Increased construction costs
	Preservation of natural functions of floodplains	• Natural storm water management • Improved water quality • Increased ecological diversity	• Loss of land to development
Insurance	Rates	• Structures insured at appropriate levels • More consistent insurance ratings through better information about risk	• Rates may increase for some
	Coverage	• More insurance purchased because of improved understanding of risk	
Property values		• Lower (or no) devaluations because of better information on risk • Change in practices that have led to devaluations	
Emergency services	Resource deployment	• More efficient allocation in planning and response	

SOURCE: Compiled from FEMA (1997) and NRC (2006).

others for insurance purposes, land management, mitigation, risk assessment, and disaster response.[2] Because these uses are not mutually exclusive, it is appropriate to sum the benefits, as is done in conventional benefit-cost analyses (e.g., NRC, 2006).

Several categories of benefits emerge from benefit-cost analyses of flood maps (FEMA, 1997; NCFMP, 2008) and work on flood and seismic hazards (Bernknopf et al., 1993; Chivers and Flores, 2002; NRC, 2006). Most of these benefit categories arise from improvements in both horizontal accuracy (i.e., proper depiction of the floodplain boundary) and vertical accuracy (i.e., proper assessment of risk), although the nature and level of benefits may differ for each type of accuracy. These benefit categories and their associated costs are summarized in Table 6.1 and described below.

Land Use

More accurate flood maps provide a more reliable measure of risk and enable floodplain managers to better target land use regulations. Owners of properties that were incorrectly designated within the floodplain benefit by having building restrictions lifted or lessened, which will lower future construction costs, eliminate mandatory retrofitting, and enable the land to be used in more ways. Adding building and land use restrictions to properties that should have been designated within the floodplain can lead to measures to protect equipment, inventories, and personal possessions. Although up-front costs are higher, developing and using land commensurate with the true risk will reduce future losses of life, property, and business. A benefit-cost analysis of National Flood Insurance Program (NFIP) building standards in coastal areas found that the benefits of freeboard exceed the construction costs by 3 to 7 percent (Jones et al., 2006).

Another possible benefit of more accurate maps is that fewer individuals will contest floodplain boundaries and levels of risk, saving time and money. Greater trust in the maps could also lead to more, but wiser, investment. Finally, management of floodplains to preserve important natural functions (e.g., slowing storm water runoff, buffering water quality) benefits the entire community. Although some work has been done on valuing

---

[2] Presentation to the committee by Paul Rooney, FEMA, on August 20, 2007.

these beneficial functions (e.g., CDWR, 2005), many are still unquantified.

Insurance

Better estimates of flood risk enable structures to be insured at appropriate levels, which benefits both individuals and the nation. Those for whom flood insurance is not mandatory will not be required to purchase it, while those who need or want it can purchase the right amount (e.g., Box 6.1). Two problems remain. First is the problem of those who need but do not carry flood insurance (e.g., owners of mortgage-free properties in the floodplain). Nationwide about half of the single-family homes in Special Flood Hazard Areas (SFHAs) are insured, although market penetration in the areas hit by the 2008 Midwest flood was less than 10 percent (coastal areas have higher participation) (Maurstad, 2008). Greater accuracy may lead to improved understanding of flood risk and ultimately to more widespread insurance coverage. In addition, insurance rates and coverage will be more accurate and consistent because the risk ratings will be more accurate and consistent. Second is the problem of moral hazard wherein the availability of flood insurance encourages people to build in places they might not otherwise. Accurate pricing of insurance premiums, relative to risk, may reduce this problem.

BOX 6.1 Impact of Improved Flood Maps on Insurance

More accurate flood maps can increase or decrease insurance premiums of individual property owners, as the following examples from two counties in New Jersey illustrate. In Monmouth County, more accurate flood maps created using lidar (light detection and ranging) elevation data resulted in an additional 3,680 structures being redesignated as within the floodplain. The property owners with mortgages are now required to pay for flood insurance, causing financial hardship for some (e.g., people living on a fixed income). Passaic County flood maps were updated to include flood mitigation measures installed along Molly Ann's Brook by the U.S. Army Corp of Engineers. The more accurate maps had the opposite effect of the revised Monmouth County maps, removing 56 homes and 6 commercial buildings from the floodplain designation and relieving many homeowners of the mandatory requirement for flood insurance.

SOURCE: S. Kempf, 2008, Community flood maps: A tale of two NJ cities, *Association of State Floodplain Managers Newsletter,* May.

Property Values

Numerous studies have analyzed the impacts of flooding, coastal storms, and the NFIP on property values (e.g., Montz and Tobin, 1988; Holoway and Burby, 1990; Chivers and Flores, 2002; Bin and Polasky, 2004; Hallstrom and Smith, 2005; Smith et al., 2006), although additional information is needed to connect property values and map accuracy. The impacts of more accurate maps on property values are both location specific and hard to measure. In cases where buildings in the floodplain are devalued relative to buildings in areas with lower flood risk, more accurate floodplain boundaries could either increase or decrease property values. An adverse impact could be lessened because the risk will be better understood and property values could be assessed at appropriate levels. More accurate maps may also be less costly to use because there will be fewer questions about the accuracy or interpretation of the map in mortgage determinations.

Temporal Considerations

The accuracy of flood maps changes with time and so do the benefits and costs. Costs are highest at the outset when flood-related data are being collected, modeled, and analyzed (Bernknopf et al., 1993; FEMA, 1997). The more detailed the flood study method, the greater are the data, modeling, and analysis demands, and the higher are the initial costs (Table 2.1). Costs can decrease significantly when maps exist and require only updates or reanalysis.

Maps created using state-of-the-art techniques and the most current information provide the best possible representation of flood hazard, at least for a short time. These accurate maps provide the immediate benefit of enabling society to better prepare for and respond to future flooding. Thereafter, development and changes in hydrology and hydraulics will degrade map accuracy, while mapping updates and incorporation of knowledge from previous flood events will increase map accuracy. The accumulation of information from flood events has intermediate and long-term benefits. Post-flood inspections yield information needed to improve models and update the maps. For example, inundation maps of the June 2006 floods in New York are being used to update Flood Insurance Rate Maps created in 1985. Knowledge about how the built environment responds to floods and coastal surges leads to improved building design and safer siting and thus to reduced future damage, social losses, and the need for federal disaster assistance. Similarly, experience responding to floods leads to more robust plans for emergency services and thus minimizes future loss of life and property. The information gained also contributes to society's underlying knowledge base across multiple disciplines.

FEMA BENEFIT-COST ANALYSES

In 1997, FEMA analyzed the incremental costs and benefits of modernizing its Flood Hazard Mapping Program (FEMA, 1997). The analysis considered all costs, including costs for flood data updates, map maintenance, new mapping, conversion to new standards, and customer service. It also calculated three benefits that could be quantified with reliable data:

1. Reduced damage to new residential properties,
2. Reduced damage to new non-residential structures, and
3. Reduced costs of map reviews.

The first two were calculated by determining the annual damage that would be prevented by designing new construction using more accurate flood data and subtracting the increased construction costs for complying with NFIP requirements (up to 5 percent). The third was based on estimates of the time saved by using improved maps and digital products for mortgage and permit applications and flood insurance policy ratings. The study found incremental benefits of $1.75 billion and incremental costs of $848 million over a 50-year period, for a benefit-cost ratio of 2.1.

In 2000, FEMA repeated the analysis, modifying the projected number of new structures in SFHAs and factoring in survey responses on flood map inventory needs from all mapped communities (the original analysis considered only 10 percent of mapped communities; FEMA, 2000). The updated analysis yielded incremental benefits of $1.33 billion and incremental costs of $799 million, for a benefit-cost ratio of 1.7. The analysis also estimated how the new construction benefit would change over time. The benefits to new construction are greatest in areas that are unstudied or studied through approximate methods because no flood elevation data are available to site new buildings. As more flood elevation data become available through map modernization, the benefits for new construction decline. FEMA estimated that factoring in this declining benefit decreases the benefit-cost ratio to 1.5.

FEMA's Office of Inspector General audited its cost estimate for the Map Modernization Program in 2000 (OIG, 2000). It found that FEMA's methodology was sound and no major costs were overlooked, but that the estimate could be significantly in error because costs were not always verified or drawn from reliable sources, some assumptions (e.g., cost of flood studies) have a major effect on cost, and cost savings from partnerships and technological innovation (e.g., use of lidar) were not considered. FEMA agreed with most of the findings and outlined steps for improving future cost estimates in the report's appendix. The revised costs have not yet been incorporated in a benefit-cost analysis.

NORTH CAROLINA CASE STUDY

Many benefits and costs are too varied to assess generically—case studies are required to understand them at the local level, where implementation occurs. The North Carolina Floodplain Mapping Program (NCFMP) determined the costs and three benefits of more accurate maps in three different physiographic regions in North Carolina and also examined the costs and benefits of different flood study methods for the entire state (NCFMP, 2008). The communities chosen represent the typical level of development within three physiographic regions: Pasquotank County in the coastal region, Mecklenburg County in the piedmont region, and the city of Asheville in Buncombe County within the mountain region (see Chapter 1, "Case Studies"). Geospatial data necessary to complete the assessment (e.g., parcel boundaries attributed with zoning, building value, and construction date; digital flood hazard information) were available for each of

TABLE 6.2 Profile of Case Study Areas

		Number of Buildings[b]		**Percentage of Buildings**[b]		**Number of Insurance Policies**[b]		**Percentage of Policies**[b]		**Percentage of Buildings Insured**	
Area	**Population**[a]	**Inside the SFHA**	**Outside the SFHA**	**Inside the SFHA**	**Outside the SFHA**	**Inside the SFHA**	**Outside the SFHA**	**Inside the SFHA**	**Outside the SFHA**	**Inside the SFHA**	**Outside the SFHA**
Pasquotank	39,951	5,652	8,309	40	60	979	279	78	22	17.3	3.4
Mecklenburg	827,445	22,091	178,614	11	89	1,765	1,267	58	42	8.0	0.7
Asheville	69,045	1,307	23,711	5	95	269	83	76	24	20.6	0.4

[a] In 2006 for Pasquotank and Mecklenburg Counties; in 2003 for Asheville.

[b] Determined using FIRMs effective prior to creation of the North Carolina Floodplain Mapping Program. Not all the buildings located outside the SFHA are in a delineated floodplain and are in areas covered by the FIRMs.

SOURCE: NCFMP (2008).

the counties or municipality. Building, population, and insurance information for the study areas is summarized in Table 6.2.

The percentages of homes in the SFHA carrying flood insurance are low, given that anyone with a federally backed mortgage is required to carry insurance, but they are generally consistent with national averages for riverine areas, which range from 10 to 25 percent.[3] Both the national and the North Carolina percentages reflect the unwillingness of floodplain residents to obtain insurance, perhaps because of their lack of trust in the maps or their lack of understanding of what the maps portray. More credible maps might encourage individuals to take action to minimize their risk, such as carrying flood insurance or elevating their buildings.

The NCFMP selected three types of benefits for analysis, based on the availability of geospatially referenced map data:

1. Expected annual flood losses avoided to new buildings and infrastructure through accurate identification of flood elevations and/or areal extent of the floodplain.
2. Expected additional annual flood insurance premiums to be collected by the NFIP for properties newly designated within the SFHA on more accurate maps. This is a benefit because Congress intended the NFIP to be funded through collection of premiums.
3. Expected annual flood insurance premium savings to policy holders who, as a result of more accurate maps, are placed in lower-rate zones or removed from the mandatory insurance requirements of the NFIP.

To calculate the incremental benefits of more accurate maps, the NCFMP compared Q3 flood data[4] digitized from Flood Insurance Rate Maps (FIRMs) with data from new digital FIRMs (DFIRMs) produced using detailed study, limited detailed study North Carolina, and redelineation methods (Table 6.3). The limited detailed study method used by North Carolina is different from the limited detailed study method used nationally (see “North Carolina Flood Mapping Case Study” in Chapter 4). The DFIRMs contain better flood hazard information than the old FIRMs, including

1. Identification of new SFHAs or more accurate portrayal of existing SFHAs,
2. Determination of base flood elevations (BFEs) where none existed, and
3. Updates of existing BFEs using revised hydrologic and/or hydraulic analyses.

The areal differences in the SFHAs and other flood insurance rate zones in the old FIRMs were compared with the SFHAs and other zones in the new DFIRMs using a geographic information system (GIS). Then the buildings in each of the zones were counted to determine the number of parcels that changed hazard designation as a result of the remapping. This change

---

[3] Personal communication from Mary Jo Vrem, FEMA, on July 14, 2008.

[4] Q3 data are digital representations of certain flood data on paper FIRMs, such as 1 percent and 0.2 percent annual chance floodplain boundaries and flood insurance zone designations.

TABLE 6.3 Distribution of Flood Study Methods in the Case Study Areas

	Linear Study Miles		
Study Method	**Asheville**	**Mecklenburg**	**Pasquotank**
Limited detailed study North Carolina	27	0	40
Redelineation	56	0	81
Detailed study	27	569	40

SOURCE: NCFMP (2008).

analysis was performed for five different types of buildings: single-family residential, two- to four-family homes, other residential, nonresidential, and mobile homes. For example, some single-family residential parcels identified as outside the SFHA (Zone B, C, or X; see Box 2.1) on old FIRMs were found to be within the SFHA (e.g., Zone AE, AO) on the new DFIRMs. The new DFIRMs provide base flood elevations, while many older FIRMs do not. The losses avoided for each building were calculated as a percentage of the current value of the building. This percentage was based on FEMA assumptions for potential property damage to structures in zones without BFEs (FEMA, 1989). The study calculated the losses avoided to structures that would be built at or above the BFE on vacant parcels zoned for homes or buildings in and outside the SFHA. Depth-damage relationships used in risk assessments (e.g., HAZUS [Hazards US]; see Chapter 7) were not explored.

Changes in flood hazard zones as a result of better mapping affect insurance premiums. To calculate the incremental benefits of flood insurance premiums better matching risk, the NCFMP quantified the difference in annual flood insurance premiums for each property based on its location relative to the SFHA on the old FIRM and the new DFIRM.

Benefit 1. Flood Losses Avoided for New Buildings and Infrastructure

The development of vacant parcels (buildout) that are zoned for building cannot be predicted each year. Therefore, the case study estimated future flood damage avoided to new or improved buildings by assuming that 20 percent, 40 percent, and 60 percent of vacant parcels zoned for building were to have structures constructed in compliance with NFIP floodplain management regulations (i.e., with the lowest floor at or above the new BFEs). Using population growth from U.S. census projections for the state (Census Bureau, 2005) as a proxy for the rate of development, the 20 percent buildout scenario could be realized between 2020 and 2025. For the 20 percent buildout scenario in Pasquotank County, an estimated $354,000 in annual flood losses could be avoided, including

- $284,000 by building the lowest floor at or above the new BFEs,
- $65,000 by more accurately determining BFEs, and
- $5,000 by using updated detailed studies for siting and design of structures.

Annual flood losses and related disaster assistance expenditures avoided for public infrastructure and buildings were estimated based on payouts for flooding and hurricane disasters between 1993 and 2005. The study found that $1.32 of flood losses have occurred to public infrastructure for every $1.00 of flood losses to insured buildings. The NCFMP evaluated average annual disaster-related expenditures to repair or reconstruct public infrastructure (e.g., roads, bridges, wastewater facilities, public buildings, public utilities) compared to average annual flood insurance claims throughout the state. It assumed that the same ratio could be expected for flood losses avoided by implementing minimum NFIP floodplain management regulations based on reliable flood hazard data. In Pasquotank County, the calculated benefit of flood damages avoided for new infrastructure was $465,000. This resulted in the total benefits from structural and infrastructure loss avoidance of $819,000.

These benefits would double and triple with the 40 percent and 60 percent buildout scenarios, respectively. Analyses of Mecklenburg County and Asheville yielded similar results, although the financial benefit

TABLE 6.4 Annual Flood Losses Avoided for Buildings Sited Using Different Study Methods

Percent		Benefits (thousand dollars per year)				
Buildout	**Area**	**Limited Detailed Study North Carolina**	**Redelineation**	**Detailed Study**	**Infrastructure**	**Total**
20	Pasquotank	53	130	171	53	819
	Mecklenburg	NA	NA	21,920	NA	21,920
	Asheville	287	312	220	287	595
40	Pasquotank	106	260	824	106	1,638
	Mecklenburg	NA	NA	43,830	NA	43,830
	Asheville	674	624	440	674	1,190
60	Pasquotank	158	390	1,236	158	2,457
	Mecklenburg	NA	NA	65,750	NA	65,750
	Asheville	861	936	660	861	1,785

NOTE: NA = not applicable.
SOURCE: NCFMP (2008).

of more accurate flood maps is significantly greater in Mecklenburg County (Table 6.4), which has higher population and building values than the other case study areas. Overall, the study found that benefits were greatest in areas that previously had no defined BFEs.

Benefits 2 and 3. Flood Insurance Better Matching Risk

Better mapping enables more accurate determination of the need for flood insurance and the means of rating risk. The new DFIRMs increased the number of buildings designated within Special Flood Hazard Areas by 807 (NCFMP, 2008). The increase in number of property owners who must purchase flood insurance benefits the NFIP, which would collect additional premiums of $935,600 in the three case study areas. The expected annual increase in premiums reflects the actual market penetration for each county or municipality (see Table 6.2), with an expected growth in the number of insurance policies of 4 percent due to increased enforcement of mandatory purchase requirements, public awareness, and/or confidence in the map products. The number of policies in force for North Carolina increased by 4 percent between 2006 and 2007. Of the property newly designated within the SFHA, 491 buildings now have BFE data where none previously existed. The BFE data allow a finer discrimination of flood insurance rate zones, lowering premiums for owners of buildings with BFEs that are lower as a result of updated studies (505 buildings). Properties with new or lowered BFEs would have lower premiums that would result in annual savings for their owners of $498,000.

The NCFMP study estimated that policy holders whose properties are no longer identified as being within the SFHA but continue to carry flood insurance because reduced (preferred) rates are available would save $642,900 in premiums annually in the three study areas. However, property owners who had been paying Zone A insurance premiums but cancel their flood policies as a result of the new information expose themselves to financial risk and the government to emergency payments. Recent studies carried out as part of the five-year evaluation of the NFIP recommend that owners of property located between the 100-year and 500-year floodplains be required to carry flood insurance (Galloway et al., 2006; Wetmore et al., 2006). Under the 20 percent buildout scenario, premiums to the NFIP are estimated to increase by $112,100 and policy holders would save $607,900 annually in the three case study areas (NCFMP, 2008).

Benefits of Different Mapping Approaches

To determine which flood study method yields the greatest net benefits, the NCFMP examined four methods: approximate studies using the National Elevation Dataset (APPROX-NED), limited detailed studies, detailed studies (see Table 2.1), and a combination of methods used by North Carolina. The analysis showed that use of APPROX-NED, the only method

TABLE 6.5 Estimated Benefits and Costs of Flood Study Methods

Study Method[a]	Unit Cost per Mile	Total Discounted Benefits[b] (million dollars)	Total Discounted Costs[b] (million dollars)	Benefit-Cost Ratio
APPROX-NED study	$1,423	$335.42	$391.40	0.86
Limited detailed study, North Carolina method	$1,908	$582.32	$404.59	1.44
Detailed study	$6,539	$922.13	$519.22	1.78
Combination, North Carolina method	$2,419	$933.21	$417.23	2.24

[a] The APPROX-NED study is assumed to have 20% of the flood damage losses avoided by the detailed study, and the limited detailed study North Carolina method to have 60% of the flood damage losses avoided by the detailed study.

[b] A 7% annual discount rate was used to transform gains and losses occurring in different time periods to a common unit of measurement in accordance with OMB (1992).

SOURCE: NCFMP (2008).

that does not yield a base flood elevation, resulted in net costs to the state and that the other methods produced net benefits (Table 6.5; NCFMP, 2008). The net benefit of statewide mapping would have been $173 million using all limited detailed studies and $398 million using all detailed studies. However, when the decision on which method to use was based on factors such as demographics, development plans, quality of existing data, flood history, and the nature of the terrain—the approach followed by the state—the net benefits were $511 million.

Statewide Benefit-Cost Analysis

The NCFMP followed the FEMA (1997) benefit-cost methodology to determine the net benefits of more accurate maps for North Carolina (NCFMP, 2008). Benefits were determined by extrapolating the results of the three case studies to the entire state and calculating additional savings from fewer flood-related business interruptions, reduced costs of map reviews (including mandatory flood insurance purchase determinations by lenders as part of the mortgage lending process, flood insurance policy ratings when a policy is sold, and building permits by local officials), and use of the data by multiple agencies. Engineering and mapping costs and the increased cost of construction for new buildings located in previously unmapped or undermapped areas were quantified and other cost estimates were taken from FEMA (1997). For 2000 through 2050, the NCFMP found a benefit-cost ratio of 2.3. This is comparable to FEMA's (1997) assessment of 2.1 for map modernization.

CONCLUSIONS

The potential benefits (and beneficiaries) of more accurate flood maps are numerous. By far the greatest benefit calculated was avoided losses to planned new buildings (FEMA, 1997; NCFMP, 2008) and avoided repairs to infrastructure (FEMA, 1997) through more accurate identification of flood elevations and the areal extent of the floodplain. Only detailed studies and most limited detailed studies provide base flood elevations.

In North Carolina, detailed and limited detailed studies rely on lidar data, rather than the U.S. Geological Survey's National Elevation Dataset. Lidar surveys cost $27 million for the entire state, yet the benefits of carrying out detailed and limited detailed studies outweigh these costs. This is significant because the analysis in Chapter 3 showed the importance of high-resolution, high-accuracy terrain data such as lidar in the accuracy of flood maps.

The NCFMP (2008) study is the first detailed analysis of the economic benefits of improved flood map accuracy in a digital environment. One of its key contributions is demonstration of a method to realistically assess the value of modernized mapping programs and to choose the type of flood study method. Although the analysis focused on areas subject to riverine flooding, the method would also work for areas subject to coastal flooding.

Both the FEMA (1997) and the NCFMP (2008) studies calculate a benefit-cost ratio of more than 2, but the exact economic benefits are unknown because of uncertainties in the assumptions, variations in costs and benefits across the country, and the difficulty of quantifying some kinds of benefits. Nevertheless, because all of the costs but only some of the benefits were considered, the results are likely the right order of magnitude, suggesting that more accurate maps produce net benefits for the nation.

Finding. Significant flood losses could be avoided by replacing maps that contain inaccurate spatial definitions and that lack base flood elevations with maps that accurately define the spatial extent of the SFHA and provide base flood elevations. The marginal benefits derived from these more accurate maps exceed the marginal costs of their preparation. Determination of base flood elevations produces the greatest increment of benefits.

Finding. No single approach to map preparation is appropriate for all circumstances. The benefits and costs of each method are risk and vulnerability dependent.

Recommendation. The flood study method should be determined based on the accuracy of the topographic data in the county or watershed under study and the current and future risk to those in the mapped area.

7

Mapping and Risk Communication: Moving to the Future

The Federal Emergency Management Agency (FEMA) has announced that in the next phase of its efforts to update and improve national flood hazard mapping it intends to "combine flood hazard mapping, risk assessment tools, and mitigation planning into one seamless program . . . to encourage beneficial partnerships and innovative uses of flood hazard and risk assessment data in order to maximize flood loss reduction."[1] FEMA envisions carrying out this RiskMap strategy by continuing to focus on improving and maintaining flood hazard data and maps while "delivering quality products and services to the right audience, using the right methods, at the right time," and by increasing local mitigation actions to ultimately reduce losses of life and property. The committee believes that FEMA can achieve its objectives by modifying existing programs to improve the accuracy of flood data and maps, as outlined in Chapters 3 through 5, and by making a leap forward in communicating hazard and risk information. This will require FEMA to both improve the quality of existing flood maps and move on a new path of risk assessment and information dissemination. This chapter describes improvements that can be made to FEMA flood maps to improve flood risk communication.

IMPROVING COASTAL FLOODING DESIGNATIONS

Flood insurance rate zones are a primary way to communicate flood hazard because areas known or suspected to be subject to flood damage have higher premiums. Zone designations have evolved over the years as more is learned about how the built environment responds to flooding. For example, V (velocity) zones were added to coastal flood maps beginning in 1976 to account for the probability of damage in areas affected by waves and erosion. A case can be made to further refine coastal flood insurance rate zones, enabling a more accurate representation of coastal flood hazards.

Coastal A Zone

Two flood insurance rate zones apply to coastal areas: (1) V zones along the water's edge, which are subject to damage from both inundation and wave heights greater than 3 feet; and (2) A zones further inland, which are subject to damage from inundation and waves of less than 3 feet (Figure 5.1). At some distance inland, the waves dissipate and damage is caused by inundation alone.

Historically, waves in the A zone have been assumed to be nondamaging. This assumption was challenged by a study of flood insurance claims from Hurricane Opal in 1995, which found that losses in some coastal A zones were more consistent with losses expected in V zones (EQE, 2000; Jones et al., 2001). The threshold for wave damage to buildings used to define the boundary between A and V zones is a 3-foot breaking wave, which was recommended by the U.S. Army Corps of Engineers (USACE) in 1975 (USACE, 1975). However, more recent tests suggest that building damage is likely from lower (1 to 2 feet) breaking waves (e.g.,

---

[1] <http://www.fema.gov/plan/ffmm.shtm#1>.

Tung et al., 2000). A number of reports have since recommended applying V-zone construction standards to the coastal A zone, defined as subject to breaking waves between 1.5 and 3 feet (ASCE, 2005a, 2005b; FEMA, 2005a, 2006c, 2006d; Wetmore et al., 2006).

The insurance losses in the coastal A zone following Hurricane Opal and recommendations to apply V zone construction standards suggest that the current zone boundaries do not adequately capture true coastal flood risk. Possible solutions include the following:

1. Lower the V zone boundary definition to a 1.5-foot breaking wave, which would expand V zone insurance rates and construction standards across the coastal A zone.
2. Retain the breaking wave threshold of 3 feet in the V zone and formally define the coastal A zone as areas subject to breaking waves between 1.5 and 3 feet.

FEMA is exploring both options. The first maps to include the extent of 1.5-foot waves were released in preliminary form for three coastal Mississippi counties in 2007. The boundary, called the "limit of moderate wave action delineation," is not labeled a zone because it has no regulatory or insurance function, but simply provides guidance for reconstruction. Although this approach improves the portrayal of flood hazard in coastal A zones, it would not change construction standards and thus would not lower the risk of damage.

Recommendation. FEMA should redefine the V zone boundary based on a 1.5-foot breaking wave rather than the present 3-foot wave.

Coastal E Zone

The National Flood Insurance Program has the authority to identify erosion (E) zones in coastal and riverine environments but has not acted on it. A 1990 National Research Council (NRC) report recommended mapping coastal E zones to more accurately reflect the hazards of storm-induced and long-term erosion (NRC, 1990). Following debate in the House and Senate in 1994, Congress declined to approve FEMA erosion mapping and directed FEMA to study the coastal erosion problem.[2] In 2000, the Heinz Center recommended that "Congress should instruct the Federal Emergency Management Agency to develop erosion hazard maps that display the location and extent of coastal areas subject to erosion" (Heinz Center, 2000). To date, Congress has taken no action on this recommendation and FEMA has not moved on its own.

A coastal E zone would be a special area within the V zone, and its seaward side would define the area where significant flood-related and long-term beach and dune erosion is expected to occur. This area is partially identified in the course of FEMA's modeling procedures but is not currently drawn on the resulting coastal flood maps. Long-term erosion is measured by state or federal government agencies, but is not factored into flood maps, even when erosion rates are high compared to the lifetime of buildings. For example, the average rate of oceanfront erosion in North Carolina has been about 2 to 3 feet per year over the last 50 years.[3]

Flood-related and long-term erosion increases wave heights, so buildings in erosion zones need deeper and higher foundations than buildings outside erosion zones. However, current standards call for foundations to extend to a minimum depth of –10 feet North American Vertical Datum 1988 (NAVD 88) for the entire V zone (ASCE, 2005b). As a result, foundations may be overdesigned (and more costly than necessary) in areas of low erosion and potentially underdesigned in areas of high erosion. This problem is likely to become more acute with climate change, which is expected to lead to sea level rise and more frequent or intense storms and thus to increase coastal erosion (IPCC, 2007). Similarly, insurance premiums are uniform throughout the V zone, but studies have shown that flood damage is greater in areas subject to both erosion and waves than areas further inland that are subject to waves alone (Rogers, 1990; USACE, 2005). Mapping an E zone could yield more actuarially realistic flood

---

[2] Congressional Record, National Flood Insurance Reform Act of 1994, House of Representatives, May 3, 1994; Congressional Record, Community Development Banking and Financial Institutions Act of 1993, Senate, March 17, 1994.

[3] Based on data from <http://dcm2.enr.state.nc.us/Maps/ER_1998/SB_Factor.htm>.

insurance rates because the hazards are represented more accurately.

Recommendation. FEMA should begin mapping E zones to better serve insurance and floodplain management needs.

MAPPING FLOOD RISK

Risk is defined as the product of the probability of an event and the consequences of its occurrence (Einstein, 1988). For there to be a risk, there must be a hazard consisting of an initiator event, a receptor, and a pathway linking the two. For example, in the event of heavy rainfall (the initiator), floodwater may propagate across the floodplain (the pathway) and inundate housing (the receptor) that may suffer material damage (the consequence). If the consequences of an event can be mitigated by some intervening measure (e.g., presence of a levee, floodwall, or other structure), the probability that the intervening measure will function as designed must be factored into the risk equation.

Hazard and risk maps are essential tools for helping the public understand the challenge it faces by living in a flood hazard area. They can also help communicate the inundation risks associated with global warming and sea level rise. However, although much has been written on risk communication in general, little formal research has been done in the United States on effective ways to use maps to communicate flood risk to those in the floodplain. What studies exist indicate continued problems of low market penetration (Dixon et al., 2006) and communication associated with FEMA's flood hazard maps (e.g., the annual chance terminology is still not commonly used by government officials, the media, or the public; Galloway et al., 2006) and the potential benefits of risk mapping (IPET, 2008).

A hazard map shows the location and probability of a hazard. FEMA's paper and digital Flood Insurance Rate Maps (FIRMs) are hazard maps because they show floodplain boundaries that indicate different flooding probabilities (i.e., 1 percent and 0.2 percent annual chance floods). A risk map not only shows the hazard probability, but also includes the probability that protection systems (e.g., levees, dams) will operate properly and the consequences of failure of the system for a given event. While DFIRMs will be needed for the National Flood Insurance Program for some time, the communication of flood risk to better inform the public and support an effective mitigation program will require FEMA to shift its risk mapping communication focus to a higher and more technical level. Geographic Information System (GIS) and database technologies and the widespread availability of the Internet offer opportunities to leverage the Map Modernization investment to effectively communicate risk through improved maps and websites. Tools such as Hazards U.S. (HAZUS) provide communities, private companies, and others with an understanding of GIS the opportunity to learn more about the risks they face.

Hazard and Risk Maps

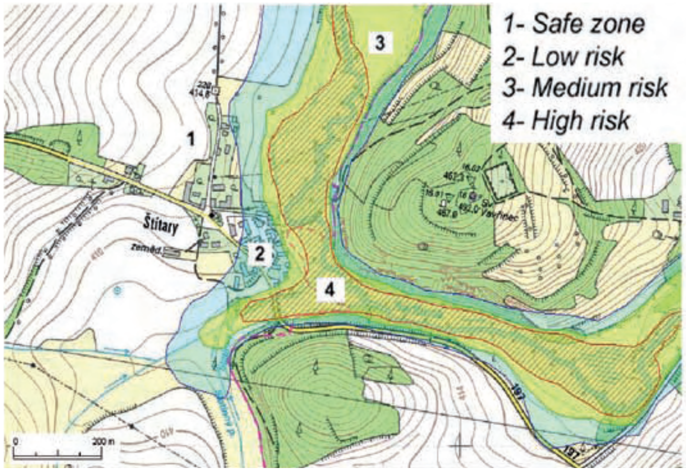
Considerable effort is underway in the United States and abroad to take advantage of new mapping capabilities to portray up-to-date information that floodplain occupants need and will use. Maps can integrate information about the flood hazard with information about the economic, social, or environmental consequences of flooding. In 2008, the European Commission published an atlas of flood maps that provides examples of the best mapping techniques used in 19 European countries, the United States, and Japan.[4] The atlas contains examples of maps designed to support risk communication, land use planning, emergency notification and response, insurance rating, and historical analysis. The maps reflect involvement at the national, regional, and local levels and public-private partnerships.

The Czech government, in cooperation with Swiss Re, an international insurance company, and MMC, a European GIS company, has developed the Flood Risk Assessment Tool, an interactive system that identifies up to six different risk zones within the floodplain. The tool is similar to FloodSmart prepared under FEMA's Map Modernization Program, but has a higher level of discrimination. Users are able to enter a database and extract information about an area of interest. Figure 7.1 illustrates a map with four risk zones.

The German state of Rheinland-Pfalz has developed maps for the Mosel River Basin that portray

---

[4] <http://ec.europa.eu/environment/water/flood_risk/flood_atlas/index.htm>.



Description of the zones:
Zone 1 – out of probable max. flood
Zone 2 – up to possible max. flood
Zone 3 – up to average 50 years flood
Zone 4 – up to average 20 years flood

FIGURE 7.1 Czech flood insurance rate map, in the area of Roudna. Four zones are designated to communicate risk, from safe zones (white), which are outside areas of probable maximum flooding, to high-risk zones (green hatched), which are subject to inundation from an average 20-year flood (a flood that has a 5 percent chance of occurring in any given year). SOURCE: Swiss Re. All rights reserved. Used with permission. See also, <http://ec.europa.eu/environment/water/flood_risk/flood_atlas/index.htm>.

possible danger zones. The degree of hazard is expressed by the "intensity" of a flood event, as measured by the relationship between water depth and flow velocity. In Figure 7.2, red represents substantial hazard to persons, animals, and property; orange represents moderate hazard; and yellow represents minor hazard.

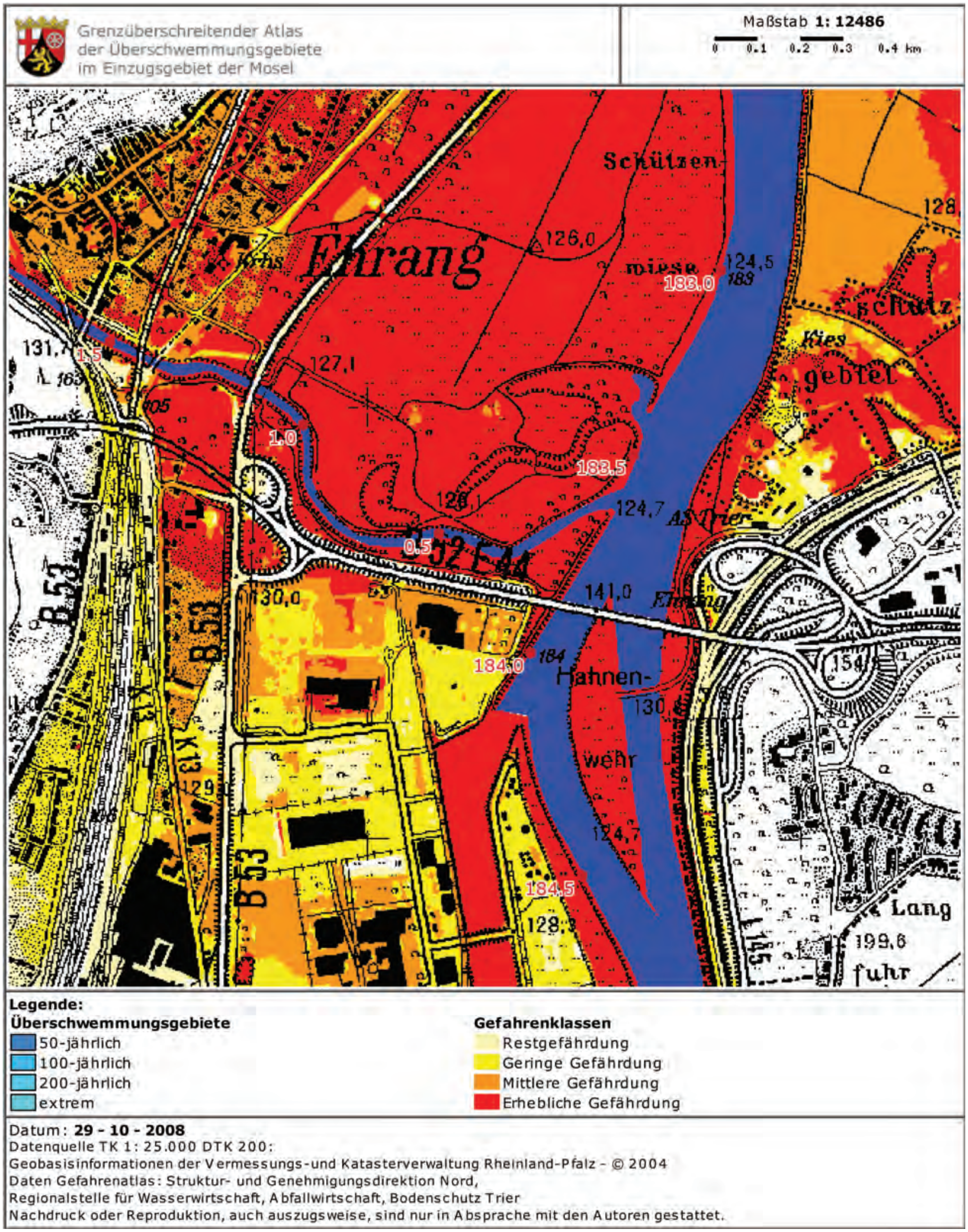
Flood maps may be used to illustrate the impact of flooding on future land development. For example, the European Space Agency shows the relationship between flooding and land use descriptively by overlaying the extent of historical flooding on planned urban development (Figure 7.3).

Work on improving flood risk communication through maps has also been taking place in the United States. The National Oceanic and Atmospheric Administration's (NOAA's) Advanced Hydrologic Prediction Service has developed prototype maps of the observed and/or forecast water level and depths of inundation at or near a stream gage, using National Weather Service forecasts, models and map inundation libraries produced by states, and U.S. Geological Survey (USGS) stream gages. The maps display anticipated water levels extending from flood stage through record or major flooding, whichever is greater. Modeling and accuracy constraints (e.g., in floodwater elevation, terrain data) limit coverage to river reaches within a mile and a half of an existing stream gage.

Where developed, the flood inundation maps can be used by local emergency managers and other decision makers to plan for disasters and guide actions during floods. An interactive website enables users to choose which features to show on the inundation map, including water depth, FEMA 100-year and 500-year floodplain boundaries and floodways, and roads. Potential impacts are identified for different depths of inundation. For example, at a flood stage of 23 feet (moderate to major flooding) in the Goldsboro, North Carolina, area, the strobe lights beyond the end of the runway at Seymour Johnson Air Force Base are flooded (Figure 7.4).

As part of the examination of post-Hurricane Katrina hazards, the USACE has recently published risk maps showing the depths of inundation for different flood scenarios in the New Orleans area (Figure 7.5). Because the maps were developed incorporating the probability of a flood event, the probability that the flood protection system (e.g., levees, floodwalls) will perform as designed, the probabilities of overtopping or failure of the structures, and the consequences of the flood event (inundation), these products are true risk maps rather than hazard maps. Other USACE risk maps have been prepared displaying economic consequences and loss of life.

Flood maps may also be used to portray changing situations. For example, the government of France



Datum: **29 - 10 - 2008**
Datenquelle TK 1: 25.000 DTK 200:
Geobasisinformationen der Vermessungs-und Katasterverwaltung Rheinland-Pfalz - © 2004
Daten Gefahrenatlas: Struktur- und Genehmigungsdirektion Nord,
Regionalstelle für Wasserwirtschaft, Abfallwirtschaft, Bodenschutz Trier
Nachdruck oder Reproduktion, auch auszugsweise, sind nur in Absprache mit den Autoren gestattet.

FIGURE 7.2 Danger zones along the Mosel River, Germany, showing substantial flood hazard (red), moderate hazard (orange), and minor hazard (yellow). SOURCE: <http://www.gefahrenatlas-mosel.de/>, EXCIMAP Atlas of Flood Maps. Used with permission.

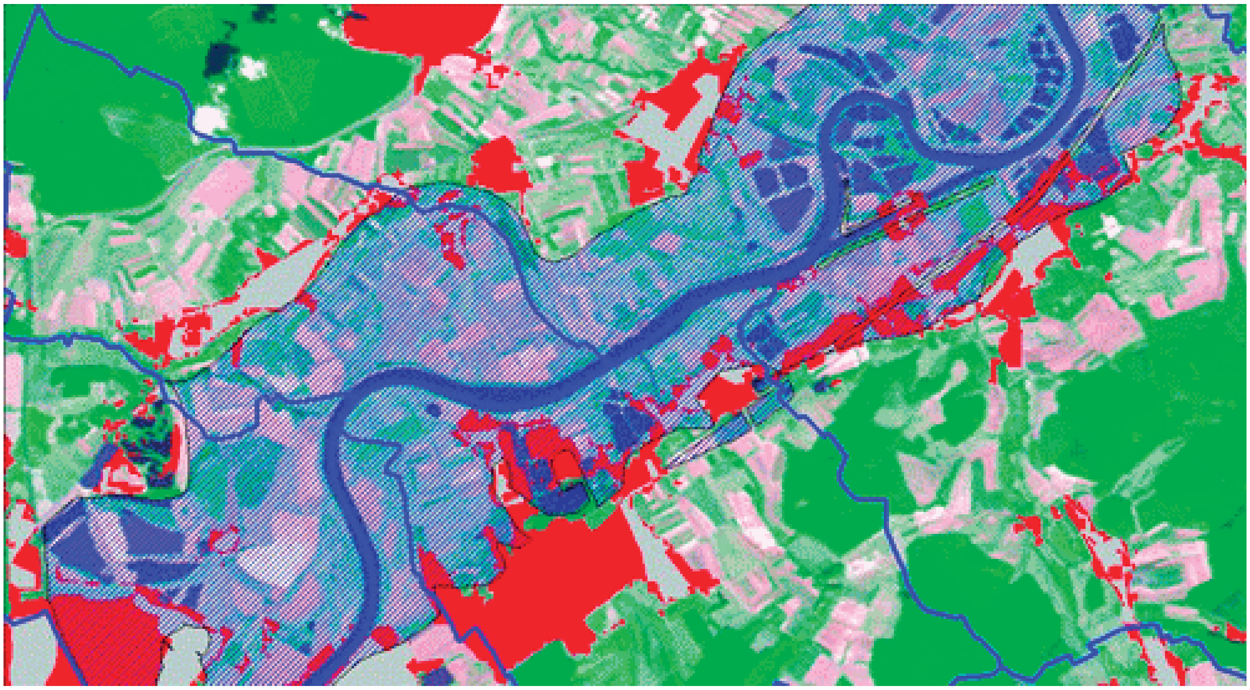


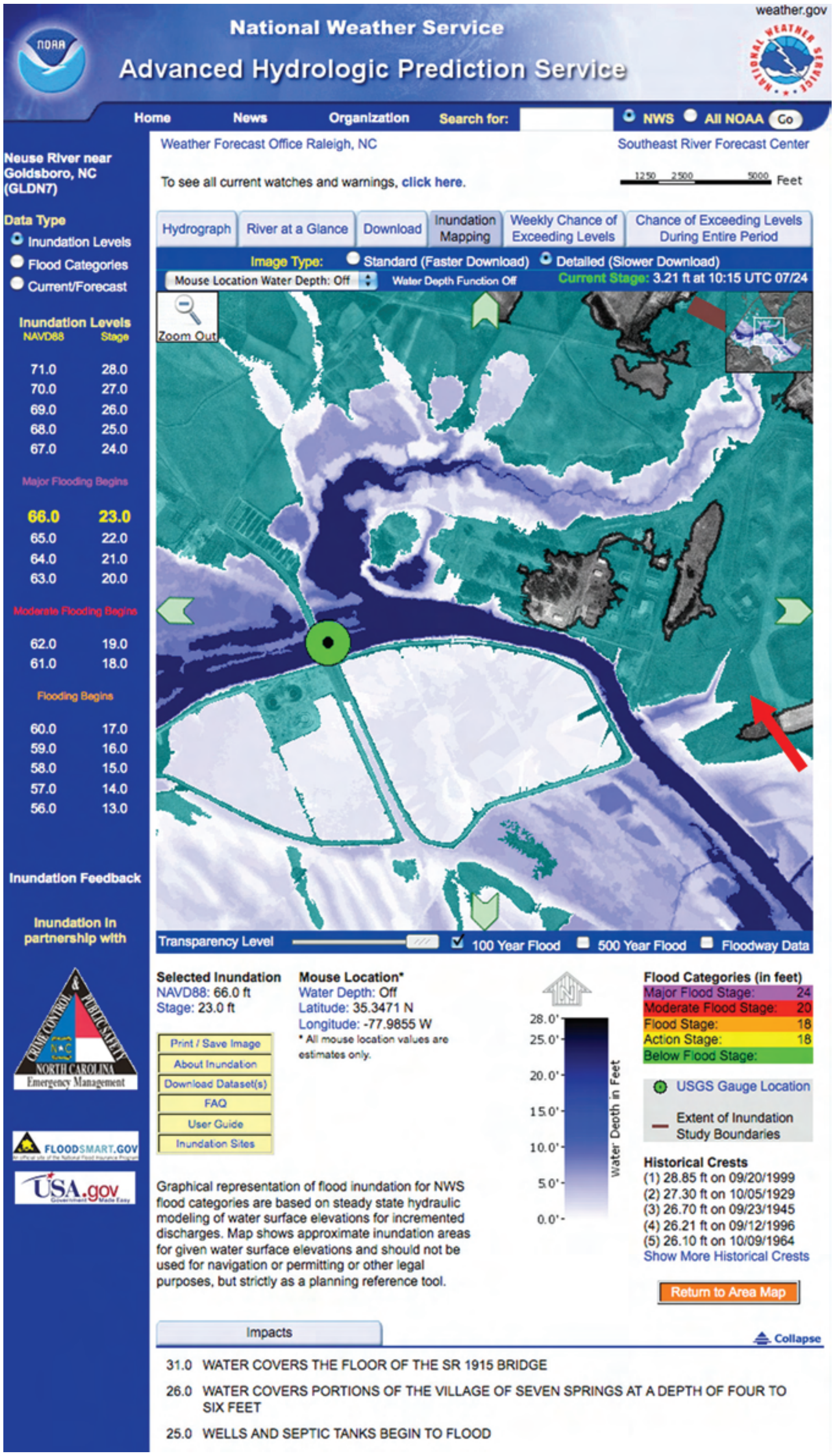
FIGURE 7.3 Flood risk map of a section of the Moselle River, near the village of Cattenom, France. Hatched blue indicates areas that are historically floodprone. The gray shows the extent of the urban area in the 1960s, and red shows subsequent urban and industrial development. The map is superimposed on a false-color composite SPOT image, showing vegetation (green) and bare soil (pink). Maps such as this make it easier to decide where to build structures or flood control measures. SOURCE: Processed by SERTIT, <http://www.eomd.esa.int/booklets/booklet172.asp>. Used with permission.

has taken steps to make maps with real-time weather information available to the public. Using a new flood warning system (Adaptation of Geographical Information for Flood Warning [AIGA]), Cemagref and Météo France monitor real-time flows and streamflow changes on selected rivers in the Mediterranean region of France, and provide maps of the risk connected with rainfall and runoff. The level of risk is portrayed by colors, with red indicating "a disaster event that is likely to isolate and endanger a large number of homes," orange indicating that a large number of roads are going to be cut off and movement by road will be difficult and dangerous, and yellow indicating that "property damage is likely and that the highest level of caution is recommended" (Figure 7.6). AIGA can also provide information on hydrologic risk, such as the nature of the flows.

The above maps illustrate the wide variety of exciting products that offer significant improvements in the ability to communicate risk to those in the floodplain. In the United States, FEMA's paper and digital FIRMs represent the only near nationwide coverage, albeit limited, of flooding and, given the significant federal investment in the flood map program, provide a logical base for extensions into new areas. Still to be resolved is how to incorporate uncertainty into mapping products. Work on visualizing uncertainty of geospatial data is beginning to be done (e.g., MacEachren et al., 2005), but a consensus does not yet exist.

Finding. FEMA's transition to digital flood mapping during the Map Modernization Program creates opportunities to develop a variety of hazard and risk maps.

Finding. Combining the appropriate attributes of FEMA DFIRMs with attributes of NOAA inundation maps, USACE risk maps, and the innovative mapping techniques developed by state and local entities and other countries would significantly enhance the communication of flood risk information to those who live in floodplains or manage floodplain development.



Neuse River near Goldsboro, NC (GLDN7)

To see all current watches and warnings, click here.

Data Type
● Inundation Levels
○ Flood Categories
○ Current/Forecast

Image Type: ○ Standard (Faster Download) ● Detailed (Slower Download)

Mouse Location Water Depth: Off
Water Depth Function Off
Current Stage: 3.21 ft at 10:15 UTC 07/24

Inundation Levels

NAVD88	Stage
71.0	28.0
70.0	27.0
69.0	26.0
68.0	25.0
67.0	24.0
Major Flooding Begins	
66.0	**23.0**
65.0	22.0
64.0	21.0
63.0	20.0
Moderate Flooding Begins	
62.0	19.0
61.0	18.0
Flooding Begins	
60.0	17.0
59.0	16.0
58.0	15.0
57.0	14.0
56.0	13.0

Transparency Level ☑ 100 Year Flood ☐ 500 Year Flood ☐ Floodway Data

Selected Inundation
NAVD88: 66.0 ft
Stage: 23.0 ft

Mouse Location*
Water Depth: Off
Latitude: 35.3471 N
Longitude: -77.9855 W
* All mouse location values are estimates only.

Flood Categories (in feet)

Major Flood Stage:	24
Moderate Flood Stage:	20
Flood Stage:	18
Action Stage:	18
Below Flood Stage:	

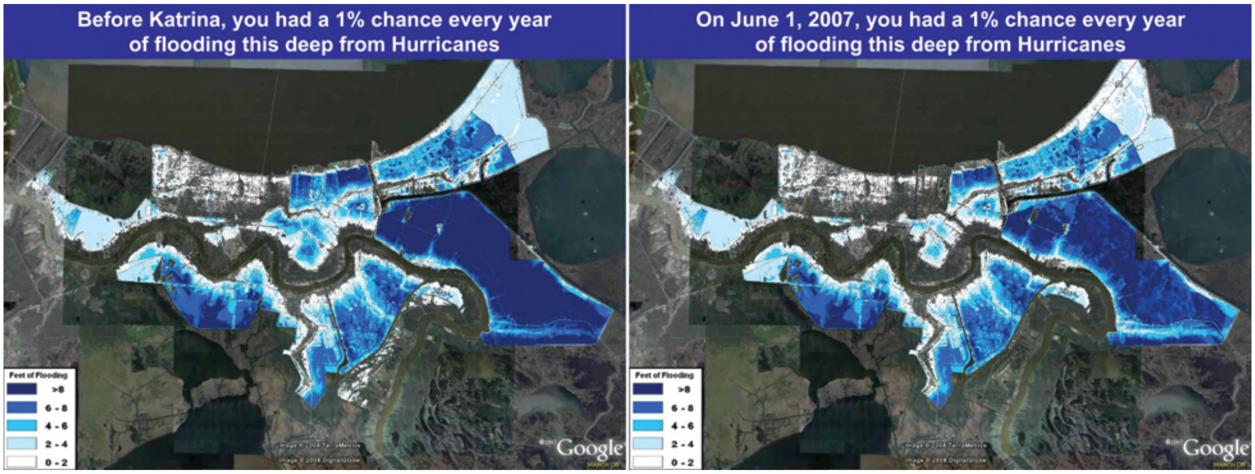
● USGS Gauge Location
— Extent of Inundation Study Boundaries

Graphical representation of flood inundation for NWS flood categories are based on steady state hydraulic modeling of water surface elevations for incremented discharges. Map shows approximate inundation areas for given water surface elevations and should not be used for navigation or permitting or other legal purposes, but strictly as a planning reference tool.

Historical Crests
(1) 28.85 ft on 09/20/1999
(2) 27.30 ft on 10/05/1929
(3) 26.70 ft on 09/23/1945
(4) 26.21 ft on 09/12/1996
(5) 26.10 ft on 10/09/1964
Show More Historical Crests

31.0	WATER COVERS THE FLOOR OF THE SR 1915 BRIDGE
26.0	WATER COVERS PORTIONS OF THE VILLAGE OF SEVEN SPRINGS AT A DEPTH OF FOUR TO SIX FEET
25.0	WELLS AND SEPTIC TANKS BEGIN TO FLOOD

FIGURE 7.4 NOAA flood inundation map of a segment of the Neuse River near Goldsboro, N.C., showing the extent of flooding when water levels are forecast to rise to a stage of 23 feet (blue) and the location of the 1 percent annual chance floodplain (blue green) from a FEMA map. The darker the blue, the greater is the depth of inundation. The water depth is 0 to 2 feet near the edge of the Seymour Johnson Air Force Base runway (red arrow). The green circle shows the USGS stream gage where the National Weather Service provides the river forecast. The topographic data, digital elevation models, and hydraulic models underlying the map were produced by the USGS office in Raleigh and the North Carolina Floodplain Mapping Program. SOURCE: <http://www.weather.gov/ahps/inundation.php>.



Before Katrina, you had a 1% chance every year of flooding this deep from Hurricanes

On June 1, 2007, you had a 1% chance every year of flooding this deep from Hurricanes

FIGURE 7.5 Flood risk maps for New Orleans. Water surface elevations are mean values, with a sensitivity of ±2 feet. The maps assume 50 percent pumping capacity. SOURCE: USACE, New Orleans District, <http://www.mvn.usace.army.mil/hps2/hps_risk_depth_map.asp>.

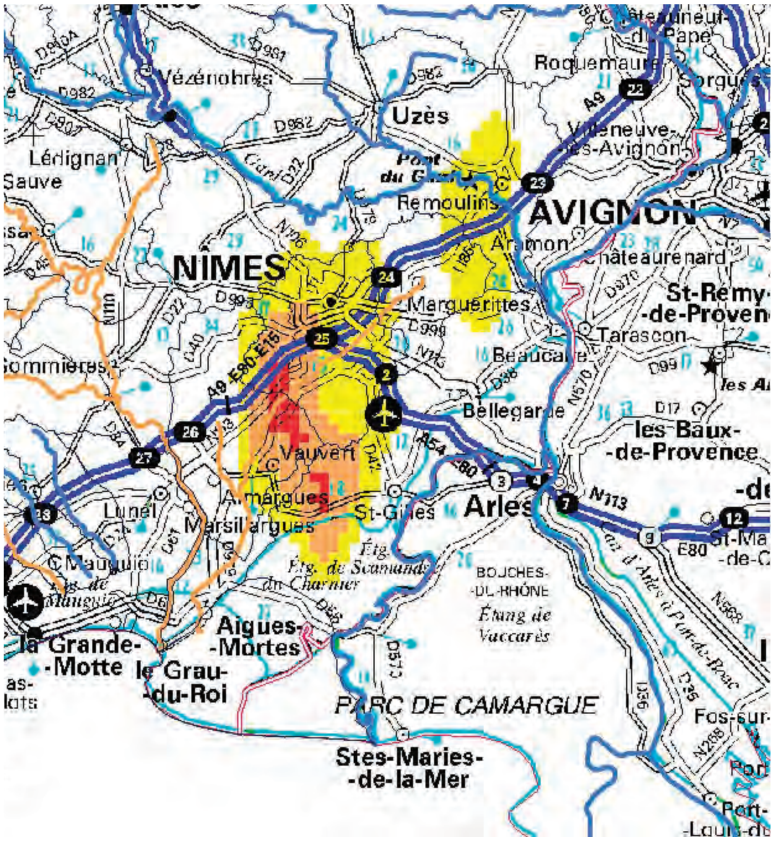


FIGURE 7.6 EOS-AIGA map of flood risk around Nimes, France. SOURCE: Météo France, Institut Géographique National. Used with permission.

Elevation and Risk

On many flood maps, the likelihood of flooding is based on location relative to the horizontal extent of the floodplain. However, using floodplain boundaries suggests that every building inside the Special Flood Hazard Area (SFHA) may flood and that every building outside is safe. In fact, there is no magic boundary that separates those subject to flooding from those not at risk; one-third of flood insurance claims are for areas outside the SFHA.[5] Moreover, risk within the floodplain is not uniform because of variations in the elevation of land and structures. At its FloodSmart.gov website, FEMA provides a tool that enables individuals to type in an address and see whether the property is at low, moderate, or high risk of flooding. The assessment is based on the location of the property relative to the 1 percent and 0.2 percent annual chance floodplain boundaries on digital FIRMs.[6]

The elevation of structures relative to the expected height of floodwaters offers a finer discrimination of risk. Some countries are beginning to use elevation to communicate risk. For example, a website in the Netherlands enables users to identify ground level relative to mean sea level by entering a postal code.[7] The elevation difference provides a sense of potential flood risk in the event of a dike failure. In the United States, building elevation information tied to latitude, longitude, and street addresses is available from Elevation Certificates, although these are not yet electronically accessible (see Chapter 3, "Surveying Structure Elevations") and Elevation Certificates are not available for every structure in and near the floodplain. Similarly, base flood elevations and system performance information are not available for all floodplains. However, the GIS technology needed to provide an individualized risk assessment based on system performance and the difference between the lowest floor elevation and the base flood elevation does exist. If complete risk information were available, individuals would be able to enter an address on the web, click on "flood risk," and see something like: "The building at 123 Main Street has a 26 percent chance of being flooded to a depth of 2.3 feet or more during the next 30 years." For this to work, elevation information for individual structures, base flood elevations for the floodplain area, and information about the probability that any protection structures will perform as designed must be kept up to date and accessible via the web. The probability of system failure would also be computed, and a personalized, quantified risk of flooding could then be provided to individuals.

HAZUS

A critical component of the risk equation is determination of the consequences of flooding, including which buildings are likely to be damaged by floods of different magnitudes and the extent of the damage. To standardize estimates of potential losses from natural hazards including floods, FEMA developed and is continuously improving the Hazards U.S. Multi-Hazards (HAZUS-MH) software. The GIS software facilitates loss estimation from floods by integrating spatial analysis, database management tools, and a suite of hazard, damage, and loss estimation modules (Figure 7.7). The flood module addresses both coastal and riverine flooding and can be operated at three different levels of increasing complexity and detail (Table 7.1). In addition

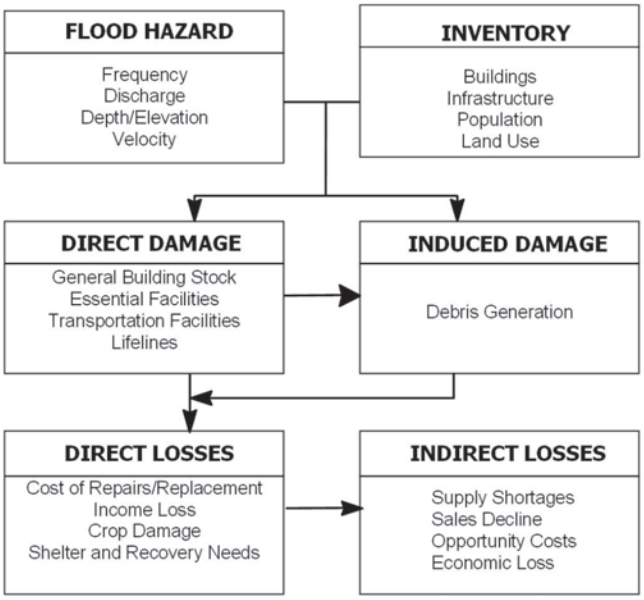


FIGURE 7.7 Components of FEMA's HAZUS-MH flood module.
SOURCE: FEMA E13 Basic HAZUS course material, 2008.

---

[5] <http://www.floodsmart.gov/floodsmart/pages/flood_facts.jsp>.

[6] <http://www.floodsmart.gov/>.

[7] <www.ahn.nl/hoogtetool>.

TABLE 7.1 Flood Hazard Module Use Levels in FEMA's HAZUS-MH

		Estimates of Flood Hazard			**Loss Estimates**	
		Inland		**Coastal**		
HAZUS Level	**Base Elevation**	**Hydrology**	**Hydraulics**	**Wave Model**	**Inventory**	**Damage Function**
1. Default databases	Any available NED	USGS regression	Default resistance equation	Default 1-D wave model	Census track data	Default damage curves
2. User-modified data	User supplied	User-supplied Q_p at river reach	Default resistance equation	Default 1-D wave model	Modify inventory	Modify parameters
3. Expert-supplied data	User supplied	Hydrologic model output at reaches	Hydraulic model output (predefined BFE surface grid)	Modify wave parameters	Detailed building or facility types	Community-based damage functions

NOTES: 1-D = one-dimensional; NED = National Elevation Dataset.

to simple hydrologic, hydraulic, and wave models, which are suitable only for preliminary analyses, HAZUS-MH allows the user to supply model output, building inventory data, and localized building and facility level damage curves. The higher levels of HAZUS require disciplinary expertise, as well as significant expertise in database management and operations.

HAZUS is used by federal, state, and local governments to estimate potential flood damage. For example, it formed the basis for damage information developed as part of the risk and reliability sections of the recently completed Interagency Performance Evaluation Task Force (IPET, 2008) report on risks in the New Orleans area following Hurricane Katrina. The availability of HAZUS, combined with information already gathered as part of floodplain mapping, places FEMA's floodplain mapping program in a position to develop effective hazard-consequence flood maps.

Finding. The mapped location of buildings inside or outside an SFHA does not adequately convey a sense of flood hazard. Flood risk can be assessed and communicated more effectively in terms of the relative elevations of the structures and facilities in the flood hazard area.

CONCLUSIONS

The principal product created by FEMA's Map Modernization Program is digital flood maps to replace paper flood maps. In some cases, this conversion was made using updated or new hydraulic, hydrologic, and topographic data. These maps represent an improvement in the quality of flood hazard information provided to the public. Where paper maps have merely been converted to digital representations, the value added has been minimal, and these maps will have to be updated to communicate flood hazard more accurately. This task must be accomplished to fully meet the objectives of the FEMA Map Modernization Program.

New technologies offer FEMA the opportunity to vastly improve the accuracy and thus the utility of digital maps. Current procedures for producing riverine and coastal maps can be improved, and these improvements are economically and socially justified. Improving the accuracy of flood maps by using higher-quality topographic data as well as updated hydrology and hydraulics enables communities to more accurately portray flood hazard and mitigate the risk to existing structures. Coastal flood mapping has revealed hazards beyond simply inundation—buildings can be damaged by wave action and by erosion of their foundations. Refining current coastal flood zone definitions to correspond more closely to actual flood damage during coastal flood events could lead to more accurate and consistent insurance ratings and thus to a better sense of flood hazard.

FEMA's RiskMap goals open the door to the possibility of significantly improving the communication of risk to those in the most hazardous areas as well as those responsible for mitigating the risk. New technologies will enable FEMA to portray information about the flood hazard and flood risk through multiple means and to tailor the information to meet the specific needs of government, business, and the public at large. The variety of map products that can be generated and the availability of web tools to provide personalized information to floodplain occupants will enable them to make decisions that ultimately will reduce national risk in the floodplain.

Recommendation. FEMA should commission a study on technology and metrics to analyze and communicate flood risk.

References

Ajami, N.K., Q.Y. Duan, and S. Sorooshian, 2007, An integrated hydrologic Bayesian multimodel combination framework: Confronting input, parameter, and model structural uncertainty in hydrologic prediction, *Water Resources Research*, **43**, W01403, doi: 10.1029/2005WR004745.

ASCE (American Society of Civil Engineers), 2005a, *Minimum Design Loads for Buildings and Other Structures*, ASCE/SEI Standard 7-05, American Society of Civil Engineers, Reston, Va., available on CD-ROM.

ASCE, 2005b, *Flood Resistant Design and Construction*, ASCE Standard 24-05, American Society of Civil Engineers, Reston, Va., 80 pp.

Bernknopf, R.L., R. Campbell, and C. Shapiro, 1988, An economic and geographic appraisal of a spatial natural hazard risk: A study of landslide mitigation rules, *Environment and Planning A*, **20**, 621-631.

Bernknopf, R.L., D.S. Brookshire, and M. Thayer, 1990, Earthquake and volcano notices: An economic evaluation of changes in risk perception, *Journal of Environmental Economics and Management*, **18**, 35-49.

Bernknopf, R.L., D.S. Brookshire, D.R. Soller, M.J. McKee, J.F. Sutter, J.C. Matti, and R.H. Campbell, 1993, *Societal Value of Geologic Maps*, U.S. Geological Survey Circular 1111, Denver, Colo., 53 pp.

Bernknopf, R.L., D.S. Brookshire, M. McKee, and D.R. Soller, 1997, Estimating the social value of geologic map information: A regulatory application, *Journal of Environmental Economics and Management*, **32**, 204-218.

Bin, O., and S. Polasky, 2004, Effects of flood hazards on property values. Evidence before and after Hurricane Floyd, *Land Economics*, **80**, 490-500.

Büchele, B., H. Kreibich, A. Kron, A. Thieken, J. Ihringer, P. Oberle, B. Merz, and F. Nestmann, 2006, Flood-risk mapping: Contributions towards an enhanced assessment of extreme events and associated risks, *Natural Hazards and Earth System Sciences*, **6**, 485-503.

CDWR (California Department of Water Resources), 2005, *Multi-objective Approaches to Floodplain Management on a Watershed Basis: Natural Floodplain Functions and Societal Values*; available online at <http://www.economics.water.ca.gov/downloads/EPA/Floodplain%20Functions%20Values_May%2005.doc>.

Census Bureau, 2005, Table A1: Interim projection of the total population of the United States and states: April 1, 2000 to July 1, 2030, Population Division, Interim State Population Projections; available online at <http://www.2010census.biz/population/projections/SummaryTabA1.pdf>.

Chivers, J., and N.E. Flores, 2002, Market failure in information: The National Flood Insurance Program, *Land Economics*, **78**, 515-521.

Divoky, D., and D.T. Resio, 2008, Performance of the JPM and EST methods in storm surge studies, 13 pp.; available online at <http://www.waveworkshop.org/10thWaves/Papers/divokyResioJPMESTpaperFinal.pdf>.

Dixon, L., N. Clancy, S.A. Seabury, and A. Overton, 2006, *The National Flood Insurance Program's Market Penetration Rate: Estimates and Policy Implications*, RAND Corporation, Santa Monica, Calif., 116 pp.; available online at <http://www.fema.gov/library/viewRecord.do?id=2599>.

Downton, M.W., J.Z. Barnard Miller, and R.A. Pielke Jr., 2005, Reanalysis of U.S. National Weather Service flood loss database, *Natural Hazards Review*, **February**, 13-22.

Einstein, H.H., 1988, Landslide risk assessment procedure, in *Proceedings of the Fifth International Symposium on Landslides*, Lausanne, Switzerland, A.A. Balkema, Rotterdam, pp. 1075-1090.

EQE International, 2000, *HAZUS Preview Model Methods and Data—Final Technical Report*, Report to the National Institute of Building Sciences, Washington, D.C., 200 pp.

FEMA (Federal Emergency Management Agency), 1983, *Flood Insurance Study: Guidelines and Specifications for Study Contractors*, FEMA 37; available online at <http://www.fema.gov/pdf/fhm/frm_gstc02.pdf>.

FEMA, 1989, *Analysis of the Costs and Benefits of Providing Technical Assistance to and Monitoring Compliance by NFIP Participating Communities: Working Draft*, 39 pp.

FEMA, 1995, *Managing Floodplain Development in Approximate Zone A Areas: A Guide for Obtaining and Developing Base (100-Year) Flood Elevations*, FEMA 265; available online at <http://www.fema.gov/plan/prevent/fhm/dl_zonea.shtm>.

FEMA, 1997, *Modernizing FEMA's Flood Hazard Mapping Program: An Assessment of Benefits and Costs*, 42 pp.

FEMA, 2000, *Modernizing FEMA's Flood Hazard Mapping Program: An Updated Assessment of the Benefits and Costs*, FEMA internal document, 7 pp.

FEMA, 2001, *What Is a Benefit? Guidance on Benefit-Cost Analysis of Hazard Mitigation Projects*, Revision 2.0, Flood Insurance and Mitigation Administration, Washington, D.C., 82 pp.

FEMA, 2002, National Flood Insurance Program: Program description; available online at <http://www.fema.gov/doc/plan/prevent/floodplain/nfipdescrip.doc>.

FEMA, 2003, *Guidelines and Specifications for Flood Hazard Mapping Partners*; available online at <http://www.fema.gov/library/viewRecord.do?id=2206>.

FEMA, 2004, *Federal Guidelines for Dam Safety: Glossary of Terms*, Interagency Committee on Dam Safety, Washington, D.C., 28 pp.; available online at <http://www.ferc.gov/industries/hydropower/safety/guidelines/fema-148.pdf>.

FEMA, 2005a, *Design and Construction in Coastal A Zones*, Hurricane Katrina Recovery Advisory, 5 pp.; available online at <http://www.fema.gov/pdf/rebuild/mat/coastal_a_zones.pdf>.

FEMA, 2005b, *Evaluation of Alternatives in Obtaining Structural Elevation Data*, prepared by Dewberry & Davis LLC, 136 pp.; available online at <http://www.fema.gov/pdf/nfip/alt_elevations/elevations_final.pdf>.

FEMA, 2006a, *Flood Map Modernization, Mid-course Adjustment*; available online at <http://www.fema.gov/library/viewRecord.do?id=2195>.

FEMA, 2006b, *Guidelines and Specifications for Flood Hazard Mapping Partners, Final Draft*, October 2006, FEMA Region VI, Washington, D.C., 360 pp.

FEMA, 2006c, *Hurricane Katrina in the Gulf Coast*, Mitigation Assessment Team Report, Building Performance Observations, Recommendations, and Technical Guidance, FEMA 549, 584 pp.; available online at <www.fema.gov/library/viewRecord.do?id=1857>.

FEMA, 2006d, *Recommended Residential Construction for the Gulf Coast: Building on Strong and Safe Foundations*, FEMA 550, 261 pp.; available online at <www.fema.gov/library/viewRecord.do?id=1853>.

FEMA, 2007a, *Atlantic Ocean and Gulf of Mexico Coastal Guidelines Update*, 360 pp.; available online at <http://www.fema.gov/library/viewRecord.do?id=2458>.

FEMA, 2007b, *Guidance for Validating Flood Hazard Data: Flood Map Modernization*, issued April 9, 2007, Washington, D.C., 15 pp.

FEMA, 2007c, Revised Procedure Memorandum 38—Implementation of Floodplain Boundary Standard (Section 7 of MHIP V 1.0), issued by Doug Bellomo, Risk Analysis Division, on October 17, 2007.

FEMA, 2008a, *FEMA's Risk MAP Strategy—Integrating Mapping, Assessment, and Mitigation Planning*, Draft Strategy, February 20, 2008; available online at <http://www.fema.gov/plan/ffmm.shtm>.

FEMA, 2008b, *Guidance for Coastal Flood Hazard Analyses and Mapping in Sheltered Waters*, Technical Memorandum, February 2008, 22 pp.

FEMA, 2008c, *Multi-year Flood Hazard Identification Plan*, version 3, 24 pp.; available online at <http://www.fema.gov/library/viewRecord.do?id=3276>.

Galloway, G.E., G.B. Baecher, D. Plasencia, K.G. Coulton, J. Louthain, M. Bagha, and A.R. Levy, 2006, *Assessing the Adequacy of the National Flood Insurance Program's 1 Percent Flood Standard*, Water Policy Collaborative, University of Maryland, College Park, 197 pp.

GAO (Government Accountability Office), 2004, *Flood Map Modernization: Program Strategy Shows Promise, but Challenges Remain*, GAO-04-417, Washington, D.C., 49 pp.

Gesch, D.B., 2009, Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea level rise, *Journal of Coastal Research,* in press.

Hallstrom, D., and V.K. Smith, 2005, Market responses to hurricanes, *Journal of Environmental Economics and Management*, **50**, 541-561.

Halsing, D., K. Theissen, and R. Bernkopf, 2004, *A Cost-Benefit Analysis of the National Map*, U.S. Geological Survey Circular 1271, Reston, Va., 49 pp.

Heinz Center, 2000, *Evaluation of Erosion Hazards*, a Collaborative Project of the H. John Heinz III Center for Science, Economics and the Environment, Prepared for the Federal Emergency Management Agency, 205 pp.; available online at <http://www.heinzcenter.org/publications/PDF/erosnrpt.pdf#pagemode=bookmarks&view=Fit>.

Hodge, S.A., and G.D. Tasker, 1995, *Magnitude and Frequency of Floods in Arkansas*, U.S. Geological Survey Water Resources Investigations Report 95-4224, Denver, Colo., 277 pp.

Holoway, J.M., and R. Burby, 1990, The effects of floodplain development controls on residential land values, *Land Economics*, **66**, 259-270.

IACWD (Interagency Advisory Committee on Water Data), 1982, *Guidelines for Determining Flood Flow Frequency*, Bulletin 17B (revised and corrected), U.S. Geological Survey, Reston, Va., 186 pp.; available online at <http://water.usgs.gov/osw/bulletin17b/dl_flow.pdf>.

IPCC (Intergovernmental Panel on Climate Change), 2007, *Climate Change 2007: Synthesis Report*, Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, R.K. Pachauri, and A. Reisinger, eds., Geneva, Switzerland, 104 pp.

IPET (Interagency Performance Evaluation Task Force), 2008, *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System*, Final Report, 9 volumes; available online at <https://ipet.wes.army.mil/>.

Jones, C., W. Coulbourne, and P. Tertell, 2001, Consideration of a new flood hazard zone: Coastal A zone, in *New Trends in Floodplain Management*, Association of State Floodplain Managers Conference Proceedings, Charlotte, N.C., pp. 21-25.

Jones, C.P., W.L. Coulbourne, J. Marshall, and S.M. Rogers, Jr., 2006, *Evaluation of the National Flood Insurance Program's Building Standards*, Federal Emergency Management Agency; available online at <http://www.fema.gov/business/nfip/nfipeval.shtm>.

MacEachren, A.M., A. Robinson, S. Hopper, S. Gardner, R. Murray, M. Gahegan, and E. Hetzler, 2005, Visualizing geospatial information uncertainty: What we know and what we need to know, *Cartography and Geographic Information Science*, **32**, 139-160.

Maune, D.F., ed., 2007, *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd edition, American Society for Photogrammetry and Remote Sensing, Bethesda, Md., 655 pp.

Maurstad, D., 2008, Levees, risk, and shared responsibility: The federal perspective, Annual Meeting of the National Association of Flood and Stormwater Management Agencies, Napa, Calif., August.

Merz, B., and A.H. Thieken, 2005, Separating natural and epistemic uncertainty in flood frequency analysis, *Journal of Hydrology*, **309**, 114-132.

Mileti, D.S., C. Fitzpatrick, and B.C. Farhar, 1992, Lessons from the Parkfield earthquake prediction, *Environment*, **34**, 16-39.

Montz, B.E., and G.A. Tobin, 1988, The spatial and temporal variability of residential real estate values in response to flooding, *Disasters: The International Journal of Disasters Study and Practice*, **12**, 167-177.

NCFMP (North Carolina Floodplain Mapping Program), 2008, *Accomplishments, Lessons Learned, and Benefits*, Raleigh, N.C., in preparation; available online at <http://www.ncfloodmaps.com/program_review.htm>.

New York Department of Environmental Conservation, 1992, *Reducing the Impacts of Stormwater Runoff from New Developments*, 178 pp.; available online at <http://www.dec.ny.gov/chemical/29080.html>.

NOAA (National Oceanic and Atmospheric Administration), 2007, *The GRAV-D Project: Gravity for the Redefinition of the American Vertical Datum*, 38 pp.; available online at <http://www.ngs.noaa.gov/GRAV-D/GRAV-D_v2007_12_19.pdf/>.

NRC (National Research Council), 1977, *Methodology for Calculating Wave Action Effects Associated with Storm Surges*, National Academy Press, Washington, D.C., 11 pp.

NRC, 1990, *Managing Coastal Erosion*, National Academy Press, Washington, D.C., 204 pp.

NRC, 2000, *Risk Analysis and Uncertainty in Flood Damage Reduction Studies*, National Academy Press, Washington, D.C., 202 pp.

NRC, 2006, *Improved Seismic Monitoring, Improved Decision-Making*, National Academies Press, Washington, D.C., 183 pp.

NRC, 2007, *Elevation Data for Floodplain Mapping*, National Academies Press, Washington, D.C., 152 pp.

OIG (Office of Inspector General), 2000, *Audit of FEMA's Cost Estimate for Implementing the Flood Map Modernization Plan*, FEMA, Audit Report H-09-00, Washington, D.C., 42 pp.

Olson, R.A., and R.S. Olson, 2001, Socioeconomic reverberations of earthquake prediction: Snapshot in time, Peru, 1979-1981, *Natural Hazards Review*, **2**, 124-131.

OMB (Office of Management and Budget), 1992, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*, Circular A-94, October 29, 1992; available online at <http://www.whitehouse.gov/omb/circulars/a094/a094.html>.

Pope, B.F., G.D. Tasker, and J.C. Robbins, 2001, *Estimating the Magnitude and Frequency of Floods in Rural Basins of North Carolina—Revisited*, U.S. Geological Survey Water Resources Investigations Report 01-3207, Raleigh, N.C., 54 pp.

Rogers, S.M. Jr., 1990, Designing for storm surge and wave damage in coastal buildings, in *22nd Coastal Engineering Conference, Proceedings of the International Conference,* July 2-6, 1990, American Society of Civil Engineers, Delft, The Netherlands, pp. 2908-2921.

Sheng, Y.P., and V. Alymov, 2002, *Coastal Flooding Analysis of Pinellas County Using ALSM Data: A Comparison between UF's 2-D Method and Results vs. FEMA's Method and Results*, Final Report for Pinellas County, Florida, Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL, 67 pp.

Smith, M.B., K.P. Georgakakos, and L. Xu, 2004, The distributed model intercomparison project (DMIP), *Journal of Hydrology*, **298**, 1-3.

Smith, M.B., V.I. Koren, S.M. Reed, Z. Zhang, Y. Zhang, F. Moreda, Z. Cui, N. Mizukami, and S. Sheldon, 2008, The distributed model intercomparison project: Phase 2 Motivation and experiment design, *Journal of Hydrology*, in review.

Smith, V.K., J.C. Carbone, J.C. Pone, D. Hallstrom, and M.E. Darden, 2006, Adjusting to natural disasters, *Journal of Risk and Uncertainty*, **33**, 37-54.

Sorooshian, S., and V.K. Gupta, 1983, Automatic calibration of conceptual rainfall-runoff models—The question of parameter observability and uniqueness, *Water Resources Research*, **19**, 260-268.

Sorooshian, S., V.K. Gupta, and J.L. Fulton, 1983, Evaluation of maximum-likelihood parameter-estimation techniques for conceptual rainfall-runoff models—Influence of calibration data variability and length on model credibility, *Water Resources Research*, **19**, 251-259.

Tasker, G.D., and R.M. Slade, Jr., 1994, An interactive regional regression approach to estimating flood quantiles, in D.G. Fontane and H.N. Tuvel, eds., *Water Policy and Management—Solving the Problems*, *Proceedings of the 21st Annual Conference of the Water Resources Planning and Management Division,* May 23-26, 1994, American Society of Civil Engineers, Denver, Colo., pp. 782-785.

Tasker, G.D., and J.R. Stedinger, 1989, An operational GLS model for hydrologic regression, *Journal of Hydrology*, **111**, 361-375.

Tate, E.C., F. Olivera, and D.R. Maidment, 2002, Creating a terrain model for floodplain mapping, *Journal of Hydrologic Engineering*, **7**, 100-108.

TRB (Transportation Research Board), 2006, *Criteria for Selecting Hydraulic Models*, National Cooperative Highway Research Program Web-Only Document 106, 720 pp.; available online at <http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w106.pdf>.

Tung, C.C., B. Kasal, S.M. Rogers, Jr., and S.C. Yeh, 1999, *Behavior of Breakaway Wall Subjected to Wave Forces: Analytical and Experimental Studies*, North Carolina Sea Grant, UNC-SG-99-03, Raleigh, N.C., 49 pp.

USACE (U.S. Army Corps of Engineers), 1975, *Guidelines for Identifying Coastal High Hazard Zones*, Galveston, Tex., 92 pp.

USACE, 2005, *Coastal Storm Damage Relationships Based on Expert Opinion*, Institute for Water Resources, Alexandria, Va., 22 pp.

Walker, S.W., and D.R. Maidment, 2006, *Geodatabase Design for FEMA Flood Hazard Studies*, CRWR Online Report 2006-10, Center for Research in Water Resources, University of Texas, Austin, 186 pp.; available online at <http://www.crwr.utexas.edu/reports/2006/rpt06-10.shtml>.

Wetmore, F., G. Bernstein, D. Conrad, C. DiVincenti, L. Larson, D. Plasencia, and R. Riggs, 2006, *The Evaluation of the National Flood Insurance Program: Final Report*, American Institutes for Research, Washington, D.C., 53 pp.; available online at <http://www.fema.gov/business/nfip/nfipeval.shtm>.

Yapo, P.O., H.V. Gupta, and S. Sorooshian, 1996, Automatic calibration of conceptual rainfall-runoff models: Sensitivity to calibration data, *Journal of Hydrology*, **181**, 23-48.

Yapo, P.O., H.V. Gupta, and S. Sorooshian, 1998, Multi-objective global optimization for hydrologic models, *Journal of Hydrology*, **204**, 83-97.

Appendixes

Appendix A

Methods for Estimating Base Flood Elevations in Approximate Studies

Method	Comments
Base flood profile extrapolation	Data extrapolation is acceptable when a site is within 500 ft upstream of a stream reach for which a 100-year profile has been computed by detailed study methods, and the floodplain and channel bottom slope characteristics are similar to the downstream reaches. However, the area must be free of backwater effects from downstream structures
Point of the boundary method	Determine the ground elevation in the field where the shaded Special Flood Hazard Area (SFHA) is located on both sides of the structure for which the base flood elevation (BFE) is needed. Assuming water seeks its own level, interpolate between these two elevations to the location of the building
Redelineation	Many approximate studies entailed no fieldwork and their floodplains were calculated by “stripping” cross sections from topographic maps to determine the volume of water in a watershed then overlaying the approximate floodplains onto base maps of variable accuracy. Because these floodplains are based on topographic configurations, overlaying a Flood Insurance Rate Map (FIRM) onto a topographic map at the same scale can produce an estimated BFE if the floodplain boundary generally conforms to the contour lines along the flooding source in question
Contour interpolation method	This method is similar to the topographic study approach, but the SFHA crosses contour lines In riverine areas, the difference between the water surface elevations on opposite banks of a flooding source must be within one-half of the map contour interval to meet national map accuracy standards.[a] In these cases, the approximate BFE will be equal to the elevation of the lower of the two bank elevations plus one-half the contour interval. This method should be performed at each structure location In lacustrine areas, the difference between the highest and lowest determined water surface elevations around the flooding source must be within one-half of the map contour interval to be acceptable (FEMA, 1995)
Historical high-water mark plus a factor of safety	Historical high-water marks often signify “worst case scenarios.” Communities may utilize them as BFEs and may also add a safety factor, commonly 1 to 3 ft above historical high-water marks
Water control structures plus freeboard	Communities may determine the elevation at the high end of a water control structure, such as the top of a berm at a detention basin. The high end approximates the worst possible scenario of overbank flooding. Communities may add freeboard to this elevation, typically 1 to 3 ft above the highest point of the water control structure
Stream gage data	Stream gages measure fluctuations in water height. Data recorded during flood events can yield a BFE in the location of the stream gage. Because of varying conditions along a watercourse, gage information from various locations should be utilized to determine the variation of BFE along that watercourse. Gages that were not operational during known flood events should not be relied on to establish BFEs

continued

Method	Comments
Flood study	Agencies other than FEMA may have elevation information that may not appear on the FIRM or the Flood Insurance Study (FIS) report. These include • Federal sources of floodplain studies, technical information, and design manuals (e.g., Army Corps of Engineers, Tennessee Valley Authority, U.S. Geological Survey, National Resources Conservation Service, Federal Highway Administration) • State agencies (e.g., environmental agencies, departments of transportation, state geological surveys, state floodplain management agencies) • Local or regional agencies (e.g., river basin commissions, flood control districts, local and county planning commissions, public works departments, utility companies and agencies, dam commissions)
Preliminary Flood Insurance Study	Communities have discretion in using data from studies and maps that are in progress and have not yet been given final approval or adopted and published. The information from draft or preliminary studies may be the "best-available" data in areas with only approximate A zones
Profiles from a Flood Insurance Study	This involves comparison of the location of the site on the FIRM to cross-section lines, and then utilizing that relationship to read a BFE on the appropriate profile sheet included in the FIS report
Floodway data tables from a Flood Insurance Study	The tables identify the BFE with and without the computed floodway at each cross section for a stream reach. Rather than reading the profiles, the floodway data table provides the BFE at the cross section, eliminating interpolation or profile reading errors
FIRM	While the FIRMs may indicate BFEs, they are graphical depictions of the observations and computations reported in the FIS report and are not as accurate or precise as information within the report. Aside from graphical approximations or errors in transferring information from the report to the map, BFEs on FIRMs are shown to whole feet, while information within the FIS report is shown to one-tenth of a foot, a big difference

[a] National map accuracy standards are available at <http://rockyweb.cr.usgs.gov/nmpstds/nmas.html>. "Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale."

Appendix B

Biographical Sketches of Committee Members

David R. Maidment, *chair*, is the Hussein M. Alharthy Centennial Chair in Civil Engineering and director of the Center for Research in Water Resources at the University of Texas at Austin, where he has been on the faculty since 1981. He received a Ph.D. in civil engineering from the University of Illinois at Urbana-Champaign. Prior to joining the University of Texas, he was a research scientist at the Ministry of Works and Development in New Zealand and at the International Institute for Applied Systems Analysis in Vienna, Austria. He was also a visiting assistant professor at Texas A&M University. Dr. Maidment's research focuses on surface water hydrology, particularly in the application of geographic information systems (GIS) to hydrology, and floodplain mapping. He has chaired or been a member of six National Research Council (NRC) committees and chaired the Committee on Floodplain Mapping Technologies. Dr. Maidment has received many awards, including the U.S. Geological Survey (USGS) Hydrologic Benchmark Award for contributions to the USGS National Water-Use Information Program in 2002 and the Environmental Systems Research Institute (ESRI) Lifetime Achievement Award for his contributions to the application of GIS in water resources in 2003. He is a fellow of the International Water Resources Association and a national associate of the National Academies.

David S. Brookshire is a professor of economics and director of the Science Impact Laboratory for Policy and Economics at the University of New Mexico. He is also on the executive board of the center for Sustainability of Semi-arid Hydrologic and Riparian Areas (SAHRA) at the University of Arizona. Dr. Brookshire received his Ph.D. in economics from the University of New Mexico. He has been a contributor to the development of the contingent valuation method for valuing non-market commodities. He specializes in public policy issues related to natural resources, the environment, and natural hazards. Current research interests include seismic risk, urban hazards, demands of industrial and consumer water users, the value of water in non-market settings, western water market structures, the use of GIS process modeling for exploring alternative institutions, and behavioral characteristics of water leasing markets and urban boundary issues relating to the preservation of open space. He is a former member of the NRC Committee on the Economic Benefits of Improved Seismic Monitoring.

J. William Brown is the assistant city engineer for the City of Greenville, South Carolina, where he heads the Environmental Engineering Bureau. His responsibilities include serving as the National Floodplain Insurance Program administrator for the city as well as the qualified local program administrator for delegation of National Pollutant Discharge Elimination System Authority for the State of South Carolina. Previous experience includes 10 years with DuPage County, Illinois, as a senior project engineer, where he managed the county's floodplain mapping program. His duties included coordinating and negotiating technical issues with state and federal agencies, as well as managing all activities related to the county's Cooperating Technical Partner Agreement with the Federal Emergency Management Agency (FEMA). Mr. Brown received an M.S. in agricultural engineering from Oklahoma State University and pursued graduate work in biosystems and agricultural engineering and water resources at the University of Minnesota. He is the past chair of the Illinois Association for Floodplain and Stormwater Management and served on its executive board for six years. Since 2004 he has co-chaired the Mapping and Engineering Standards Committee for the Association of State Flood Plain Managers (ASFPM).

John Dorman is the director of the Geospatial and Technology Management Office in the North Carolina Division of Emergency Management. He is responsible for the development, implementation, and management of all geospatial data, applications, and information technology infrastructure. Mr. Dorman previously served as the statewide planning administrator for the Office of State Budget, Planning, and Management, where he oversaw statewide programmatic and performance planning and budgeting, the North Carolina Geodetic Survey, the State Data Center, and the North Carolina Center for Geographic Information and Analysis. Following Hurricane Floyd in 1999, North Carolina became the first state in the nation to be designated a cooperating technical state under FEMA's Cooperating Technical Partners program. From this designation, the North Carolina Floodplain Mapping Program (NCFMP) was created and placed under Mr. Dorman's supervision. In 2005, Mr. Dorman was given responsibility for managing all information technology infrastructure and applications in the Division of Emergency Management. Mr. Dorman is a graduate of North Carolina State University with a degree in political science.

Gerald E. Galloway is a Glenn L. Martin Institute Professor of Engineering and an affiliate professor of public policy at the University of Maryland, College Park. His 38-year career in the military included positions such as commander of the Army Corps of Engineers District in Vicksburg, Mississippi, and professor and founding head of the Department of Geography and Environmental Engineering and dean of the Academic Board at the U.S. Military Academy. He was promoted to brigadier general in 1990 and retired from active duty in 1995. Dr. Galloway earned his M.S.E. at Princeton and his Ph.D. in geography (specializing in water resources) from the University of North Carolina at Chapel Hill. A civil engineer, public administrator, and geographer, Dr. Galloway's current research focuses on the development of U.S. national water policy in general and national floodplain management policy in particular. Prior to joining the University of Maryland, he was vice president, Geospatial Strategies, for the ES3 Sector of the Titan Corporation. He is a member of the NRC Water Science and Technology Board and the Committee to Review the Joint Subcommittee on Ocean Science and Technology (JSOST) U.S. Ocean Research Priorities Plan. He is a member of the National Academy of Engineering.

Bisher Imam is an adjunct associate professor in the Department of Civil and Environmental Engineering and a senior researcher at the Center for Hydrometeorology and Remote Sensing at the University of California, Irvine (UCI). He received a Ph.D. in watershed hydrology from the University of Arizona. Dr. Imam's research focuses on (1) use of remote sensing data and GIS to study the impacts of climate variability on water resource availability and hydrologic responses of both urban and natural watersheds, (2) representation of spatial variability of hydrologic properties and processes in hydrologic models, (3) uncertainty analysis in hydrologic models, and (4) bridging the gap between science and applications. Prior to joining UCI, Dr. Imam was the associate director of the Hydrologic Data and Information System at the University of Arizona, where he led efforts to improve online visualization of and access to remote sensing data within a hydrologically relevant framework. Earlier, he contributed to the development, testing, and evaluation of the Water Quality Decision Support System during his work as a researcher at the U.S. Department of Agriculture's Southwest Watershed Research Center in Tucson, Arizona. He has been a consultant to the U.S. Agency for International Development, the United Nations Educational, Scientific and Cultural Organization, and occasionally to private firms on issues related to hydrologic data and modeling.

Wendy Lathrop is president of Cadastral Consulting, LLC; a licensed professional land surveyor in New Jersey, Pennsylvania, Delaware, and Maryland; and a licensed professional planner in New Jersey. She is also a certified floodplain manager through the ASFPM and a certified floodplain surveyor through a joint program between North Carolina, FEMA, and the American Congress on Surveying and Mapping (ACSM). Ms. Lathrop received an M.E.S. in environmental studies from the University of Pennsylvania. Her practical experience with the National Flood Insurance Program began with flood hazard mapping in 1974 when the program was still under the Department of Housing and Urban Development, and continued with years of field and office work relating to Elevation Certificates, applications for Letters of Map Change, and land development and planning. Her firm, Cadastral Consulting, LLC, was formed primarily to provide continuing education for surveyors, but now also includes her consulting practice. Ms. Lathrop served as the ACSM representative to the Technical Mapping Advisory Council to FEMA from 1995 through the council's culmination in 2000, and has served on task forces creating the current and immediately prior versions of the Elevation Certificate.

David F. Maune, colonel, retired, is a senior project manager for Dewberry in Fairfax, Virginia. He has a Ph.D. in geodetic science and photogrammetry from the Ohio State University. Colonel Maune's career in military mapping, charting, and geodesy began in 1963 and included positions such as director of the Defense Mapping School and commander and director of the U.S. Army Topographic Engineering Center. After retirement, Dr. Maune joined the private sector, managing projects for FEMA, USGS, the National Oceanic and Atmospheric Administration (NOAA), and numerous states and counties. He was instrumental in FEMA's transition to the use of Global Positioning System (GPS) and lidar (light detection and ranging) technologies and is recognized as an industry leader in the use of lidar data for floodplain mapping and in the independent quality assurance and quality control (QA/QC) of lidar data. He wrote FEMA's standards for aerial mapping and surveying, which include the use of lidar technology in hydraulic modeling. He was the principal author of *National Height Modernization Study—Report to Congress*, published by the National Geodetic Survey in 1998, and editor and principal author of both the first and the second editions of *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, published by the American Society for Photogrammetry and Remote Sensing (ASPRS) in 2001 and 2007. He is a registered geodetic surveyor, photogrammetric surveyor, and ASPRS-certified photogrammetrist. He is also a certified floodplain manager for the ASFPM.

Burrell E. Montz is a professor, director of graduate studies in the Department of Geography, and associate director of the Center for Integrated Watershed Studies at Binghamton University. She received her Ph.D. from the University of Colorado in Boulder. Dr. Montz has more than 25 years of experience with research in natural hazards, concentrating primarily on flood hazards, floodplain management, and the social science aspects of response and policy development. She has evaluated the effects and effectiveness of various mitigation measures for flooding, including floodplain designation; the flow and use of warning system information by different communities; and the use of GIS to better understand vulnerability to multiple hazards. Dr. Montz served on the NRC Committee to Assess the National Weather Service Advanced Hydrologic Prediction Service Initiative.

Spencer Rogers is an extension specialist with North Carolina Sea Grant, where he specializes in hurricane-resistant construction techniques, shoreline erosion, coastal management, and marine construction. He is also on the faculty of the University of North Carolina at Wilmington's Center for Marine Science and is an adjunct faculty member at North Carolina State University's Department of Civil Engineering. He was previously employed by the Florida Bureau of Beaches and Shores. Mr. Rogers has an M.S. in coastal and oceanographic engineering from the University of Florida. He represents marine science and technology on the North Carolina Coastal Resources Advisory Council, which advises the North Carolina Coastal Resources Commission on coastal management regulations. Mr. Rogers is a member of FEMA's Hurricane Katrina Mitigation Assessment Team, North Carolina's floodplain mapping Cooperating Technical State committee (for which he reviews the coastal maps), and the National Institute of Building Sciences HAZUS (Hazards, U.S.) Flood and Hurricane committees. He is a member of the National Association of Coastal

Engineers, the American Society of Civil Engineers (ASCE), ASFPM, and the American Shore and Beach Preservation Association.

Karen L. Schuckman is an instructor in geography at the Pennsylvania State University, where she teaches remote sensing and geospatial technology in the online GIS programs offered by the John A. Dutton e-Education Institute. She is also a consultant to URS Corporation in Gaithersburg, Maryland, where she provides expert knowledge in remote sensing and photogrammetry—including floodplain mapping, disaster response and preparedness, critical infrastructure, and transportation—to engineering practice groups. As the Geospatial Technology Leader at URS from 2005 to 2006, Ms. Schuckman supported response, recovery, and mitigation projects for FEMA following Hurricanes Katrina, Rita, and Wilma. Prior to that, she spent 10 years at the EarthData Group, where she held several positions including geospatial applications director for EarthData Solutions; senior vice president of EarthData Technologies; and president and general manager of EarthData International of North Carolina. Notable projects led by Ms. Schuckman for EarthData include lidar acquisition for the North Carolina Floodplain Mapping Program, numerous transportation mapping projects for state transportation departments, and technology demonstration projects for NOAA, the National Aeronautics and Space Administration, and the Department of Transportation. Prior to joining the private sector, Ms. Schuckman worked for the USGS National Mapping Division, in Menlo Park, California. She is the immediate past president of the ASPRS, vice chair of the NOAA Advisory Committee on Commercial Remote Sensing, and a member of the NRC Committee on Floodplain Mapping Technologies. Ms. Schuckman has a B.S. in meteorology and a certificate in GIS from the Pennsylvania State University, and is an ASPRS-certified photogrammetrist and a licensed professional land surveyor.

Y. Peter Sheng has been a professor of coastal and oceanographic engineering at the University of Florida since 1986, where he studies coastal hazards and physical and biogeochemical processes in coastal, estuarine, riverine, and lake waters. He received his Ph.D. in engineering and fluid and thermal sciences from Case Western Reserve University. Dr. Sheng's main research interests include storm surges, coastal waves, current-wave interaction, bottom boundary layer dynamics, turbulent transport processes, hurricane wind and land interaction, inundation processes, cyberinfrastructure, and numerical modeling and forecasting. One of the models developed by Dr. Sheng, CH3D (Curvilinear-Grid Hydrodynamics in 3D)-Storm Surge Modeling System (SSMS), can be used to simulate and forecast hurricane-induced storm surge, wave, and coastal inundation and has been applied to simulate and forecast the storm surge and inundation in Florida, Alabama, Mississippi, Louisiana, and the Chesapeake Bay since 2003. From 1998 to 2003, he worked with Pinellas County, Florida, and FEMA to review and update the Flood Insurance Rate Map (FIRM) for the county using this model. Dr. Sheng is a current member of the Southeast Coastal Ocean Observing Regional Association, the Gulf of Mexico Coastal Ocean Observing System, and the NRC Committee on New Orleans Regional Hurricane Protection System.

Juan B. Valdes is a professor and department head of the Department of Civil Engineering and Engineering Mechanics and a professor in the Department of Hydrology and Water Resources at the University of Arizona. He joined the faculty in 1997 after serving on the faculty of Texas A&M University and Simon Bolivar University in Caracas, Venezuela. He is a registered professional engineer in Texas. Dr. Valdes received his Ph.D. in water resources from the Massachusetts Institute of Technology. His research interests include stochastic and deterministic hydrology; flood forecasting; analysis, synthesis, and sampling of hydrologic processes; mathematical modeling of natural resources systems; modeling of space-time precipitation; environmental risk assessment; and stochastic modeling of environmental processes. He is on the executive committee of SAHRA, where he coordinates international research efforts, particularly on drought characterization and forecasting and water resources management in transboundary basins. He is a fellow of the American Geophysical Union (AGU) and ASCE, and serves on the board of directors of the Consortium of Universities for the Advancement of Hydrologic Science, the scientific advisory committee of the Inter American Institute for Global Change Research, and on panels and advisory boards for AGU, NOAA, and NASA.

Appendix C

Glossary

0.2 Percent Annual Chance Flood—A flood that has a 0.2 percent chance of being equaled or exceeded in any given year; also known as a 500-year flood (FEMA, 2003)

1 Percent Annual Chance Flood—A flood that has a 1 percent chance of being equaled or exceeded in any given year; also known as a 100-year flood (FEMA, 2003)

100-Year Flood—See 1 percent annual chance flood (FEMA, 2003)

500-Year Flood—See 0.2 percent annual chance flood (FEMA, 2003)

Accuracy—The degree of correctness attained in a measurement. (FEMA, 2003)

- **Horizontal Accuracy—**The positional accuracy of a dataset with respect to a specified horizontal datum (Maune, 2007)
- **Vertical Accuracy—**The positional accuracy of a dataset with respect to a specified vertical datum (Maune, 2007)

Amendment—A determination by the Federal Emergency Management Agency (FEMA) that a property has inadvertently been included in a Special Flood Hazard Area (SFHA) as shown on an effective Flood Insurance Rate Map (FIRM) and is not subject to inundation by the 1 percent annual chance flood. Generally, the property is located on natural high ground at or above the BFE or on fill placed prior to the effective date of the first NFIP map designating the property as within an SFHA. Limitations of map scale and development of topographic data more accurately reflecting the existing ground elevations at the time the maps were prepared are the two most common bases for amendment requests (FEMA, 2003)

Approved Model—A numerical computer model that has been accepted by FEMA for use in performing new or revised hydrologic or hydraulic analyses for National Flood Insurance Program (NFIP) purposes. All accepted models must meet the requirements set forth in Subparagraph 65.6(a)(6) of the NFIP regulations (FEMA, 2003)

Approximate Study—A flood hazard study that uses topographic data, typically without bathymetry or bridge or culvert opening geometry, to conduct approximate hydrologic and hydraulic analyses. The analysis results in the delineation of floodplain boundaries for the 1 percent annual chance (100-year) flood, but does not include the determination of base flood elevations (BFEs) or base flood depths (FEMA, 2003)

Backwater—Water backed up or retarded in its course compared to its normal or natural condition of flow (FEMA, 2003)

Base Flood—A flood that has a 1 percent chance of being equaled or exceeded in any given year, also referred to as the 100-year flood. The base flood is the national standard used by the NFIP and all federal agencies for the purposes of requiring the purchase of flood insurance and regulating new development (<http://www.fema.gov/NFIPKeywords/>)

Base Flood Elevation (BFE)—The elevation of a flood having a 1 percent chance of being equaled or exceeded in any given year (FEMA, 2003)

Bathymetry—The measurement and study of water depths. Traditionally bathymetry has been expressed with contours and hydrography with spot depths (Maune, 2007)

Benchmark—A permanent monument established by any federal, state, or local agency, whose elevation and description are well documented and referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88) (FEMA, 2003)

Benefits—Positive effects of an action. For FEMA flood hazard mitigation projects, benefits are defined as avoided damages and losses (FEMA, 2001)

Calibration—The process of identifying and correcting for systematic errors in hardware, software, or procedures; determining the systematic errors in a measuring device by comparing its measurements with the markings or measurements of a device that is considered correct (Maune, 2007)

Catchment Area—An area of land that is occupied by a drainage system consisting of a surface stream or a body of impounded surface water, together with all tributary surface streams and bodies of impounded surface water that drains into a single outlet; also called drainage basin or watershed (<http://water.usgs.gov/glossaries.html>)

Coastal Flooding—Flooding that occurs along the Great Lakes, the Atlantic and Pacific Oceans, and the Gulf of Mexico (FEMA, 2003)

Confidence Level—The probability that errors are within a range of given values (Maune, 2007)

Cooperating Technical Partners—Participating NFIP communities, regional agencies, and state agencies that are active participants in the FEMA Flood Hazard Mapping Program (FEMA, 2003)

Cross Section—A line across a floodplain, developed from topographic data, at which a computation of flood flow has been made to establish a potential flood elevation (<http://www.fema.gov/media/fhm/champ/ot_chmp.htm>)

Datum—A common vertical or horizontal elevation reference point (<https://hazards.fema.gov/femaportal/>)

- **Ellipsoidal Datum**—A set of constants specifying the coordinate system used for geodetic control, that is, for calculating coordinates of points on the Earth; also known as geodetic datum (<http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml>)
- **Orthometric Datum**—The reference surface from which orthometric heights are measured (i.e., NAVD 88 or NGVD 29)
- **Tidal Datum**—A surface with a designed elevation from which heights or depths are reckoned, defined by a certain phase of the tide. A tidal datum is local, usually valid only for a restricted area about the tide gage used in defining the datum (Maune, 2007)

Design Storm—A rainfall event of specified size and return frequency that is used to calculate runoff volume. It is assumed that the design storm for a given frequency will produce a simulated runoff peak and volume having the same return frequency. Thus, a 100-year design storm should produce a 100-year runoff and volume (New York Department of Environmental Conservation, 1992)

Detailed Study, Coastal—A coastal flood hazard study that uses transects and offshore bathymetry to conduct detailed erosion, wave height, and wave runup analyses and to prepare floodplain mapping. The analysis results in the determination and publication of BFEs and designation of the coastal high-hazard areas (V zones) (FEMA, 2003)

Detailed Study, Riverine—A riverine flood hazard study that uses topographic data, channel bathymetry, and bridge or culvert opening geometry to conduct detailed hydrologic and hydraulic analyses and floodplain mapping. The analysis results in the delineation of floodplain boundaries for the 1 percent annual chance (100-year) flood, determination of BFEs or flood depths, and normally, a regulatory floodway (FEMA, 2003)

Digital Elevation Model (DEM)—A file with terrain elevations recorded for the intersection of a fine-grained grid and organized by quadrangle as the digital equivalent of the elevation data on a topographic base map (FEMA, 2003)

Digital Flood Insurance Rate Map (DFIRM)—A Flood Insurance Rate Map that has been prepared as a digital product, which may involve converting an existing manually produced FIRM to digital format or creating a product from new digital data sources using a geographic information system (GIS) (FEMA, 2003)

Digital Terrain Model (DTM)—A land surface represented in digital form by an elevation grid or lists of three-dimensional coordinates (FEMA, 2003)

Discharge—The volume of water that passes a given location within a given period of time. Usually expressed in cubic feet per second (<http://water.usgs.gov/glossaries.html>)

Drainage Area—The area upstream of a specific location, measured in a horizontal plane, that has a common outlet at the site for its surface runoff from precipitation that normally drains by gravity into a stream. Drainage areas include all closed basins, or noncontributing areas, within the area unless otherwise specified (<http://water.usgs.gov/glossaries.html>)

Elevation—The distance of a point above the specified surface of constant potential; the distance is the direction of gravity between the point and the surface (<http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml>)

Elevation Certificate—A form on which the lowest floor elevation, lowest adjacent grade, and highest adjacent grade of a building are certified relative to the base flood elevation for the location of the building. Other descriptive information is also provided to help identify the flood risk to the building surveyed (Maune, 2007)

FIRMette—A full-scale section of a Flood Insurance Rate Map created by users online by selecting the desired area from a FIRM image. It also includes the map title block, north arrow, and scale bar (<http://msc.fema.gov/webapp/wcs/stores/servlet/FemaWelcomeView?storeId=10001&catalogId=10001&langId=-1>)

Flood—A general and temporary condition of partial or complete inundation of normally dry land areas from (1) the overflow of inland or tidal waters or (2) the unusual and rapid accumulation or runoff of surface waters from any source (FEMA, 2003)

Flood Hazard Mapping Partner—Community officials; regional agency officials; state agency officials; communities, regional agencies, and state agencies participating in the FEMA Cooperating Technical Partners Program; other federal agencies; FEMA contractors; contractors of communities, regional agencies, and state agencies; community residents and property owners; other program constituents, including the U.S. Congress; insurance lending, real estate, and land development industries; and federal, state, and local disaster and emergency response officials whose combined contribution with FEMA staff obtain and maintain accurate, up-to-date flood hazard information (FEMA, 2003)

Flood Insurance Rate Map (FIRM)—The insurance and floodplain management map produced by FEMA that identifies, based on detailed or approximate analyses, the areas subject to flooding during a 1 percent annual chance (100-year) flood event in a community and flood insurance risk zones. In areas studied by detailed analyses, the FIRM shows BFEs to reflect the elevations of the 1 percent annual chance flood. For many communities, when detailed analyses are performed, the FIRM also may show areas inundated by a 0.2 percent annual chance (500-year) flood and regulatory floodway areas (FEMA, 2003)

Flood Insurance Risk Zones—The areas, also referred to as flood insurance rate zones, shown on a FIRM that are used to determine flood insurance premium rates for properties in the community covered by the FIRM. The flood insurance risk zones include SFHAs (e.g., Zones A, A1-30, AE, V, V1-30, VE, V0) and areas outside SFHAs (e.g., Zone X) (FEMA, 2003)

Flood Insurance Study (FIS)—A compilation and presentation of flood risk data for specific watercourses, lakes, and coastal flood hazard areas within a community. When a flood study is completed for the NFIP, the information and maps are assembled into an FIS. The FIS report contains detailed flood elevation data in flood profiles and data tables (<http://www.fema.gov/plan/prevent/floodplain/nfipkeywords/fis.shtm>)

Flood Insurance Study Report—A document, prepared and issued by FEMA, that presents the results of the detailed flood hazard assessment performed for a community. The primary components of the FIS report are text, data tables, photographs, and flood profiles (FEMA, 2003)

Flood Peak—The highest value of the stage or discharge attained by a flood; thus, peak stage or peak discharge (<http://water.usgs.gov/glossaries.html>)

Flood Profile—A graph of elevation of the water surface of a river in flood, plotted as ordinate, against distance, measured in the downstream direction, plotted as abscissa (<http://water.usgs.gov/glossaries.html>)

Flood Stage—The height of a water surface above an established datum plane (FEMA, 2003)

Floodplain—Any land area that is susceptible to being inundated by water from any source (FEMA, 2003)

Floodplain Management—The operation of a program of corrective and preventative measures for reducing flood damage, including emergency preparedness plans, floodcontrol works, and floodplain management regulations (FEMA, 2003)

Floodplain Management Regulations—The zoning ordinances, subdivision regulations, building codes, health regulations, special-purpose ordinances, and other applications of enforcement used by a community to manage development in its floodplain areas (FEMA, 2003)

Floodway—The regulatory area defined as the channel of a stream plus any adjacent floodplain areas that must be kept free of encroachment so that the base flood discharge can be conveyed without increasing the BFEs more than a specified amount (FEMA, 2003)

Freeboard—A factor of safety usually expressed in feet above a flood level for purposes of floodplain management. Freeboard tends to compensate for the many unknown factors that could contribute to flood heights greater than the height calculated for a selected size flood and floodway conditions, such as wave action, bridge openings, and the hydrological effect of urbanization of the watershed (44 CFR 59.1)

Geographic Information System (GIS)—A system of computer hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modeling, and display of spatially referenced data for solving complex planning and management problems (FEMA, 2003)

Geoid—The equipotential (level) surface of the Earth's gravity field, which on average coincides with mean sea level in the open undisturbed ocean. The geoid undulates up and down with local variations in the mass and density of the Earth (Maune, 2007)

Global Positioning System (GPS)—A satellite-based navigation and positioning system that enables horizontal and vertical positions to be determined (FEMA, 2003)

Height—The distance, measured along a perpendicular, between a point and a reference surface (e.g., height of an airplane above the ground surface). The distance, measured upward along a plumb line (line of force), between a point and a reference surface of constant geopotential. *Elevation* is preferred if the reference surface is the geoid (Maune, 2007)

- **Ellipsoid Height**—The height above or below the reference ellipsoid (i.e., the distance between a point on the Earth's surface and the ellipsoidal surface, as measured along the normal [perpendicular] to the ellipsoid at the point and taken positive upward from the ellipsoid) (Maune, 2007)

- **Orthometric Height (Elevation)—**The height above the geoid as measured along the plumbline between the geoid and a point on the Earth's surface, taken positive upward from the geoid (Maune, 2007)

Hydraulic Analysis—An engineering analysis of a flooding source carried out to provide estimates of the elevations of floods of selected recurrence intervals (FEMA, 2003)

Hydraulic Model—A computer program that uses flood discharge values and floodplain characteristic data to simulate flow conditions and determine flood elevations (FEMA, 2003)

Hydrograph—A graph showing stage, flow, velocity, or other water properties with respect to time (FEMA, 2003)

Hydrologic Analysis—An engineering analysis of a flooding source carried out to establish peak flood discharges and their frequencies of occurrence (FEMA, 2003)

Inundation Map—A map depicting the spatial extent and depth of floodwaters in the vicinity of National Weather Service river forecast locations (<http://www.floodsafety.noaa.gov/inundation.shtml>)

Letter of Final Determination—The letter in which FEMA announces its final determination regarding flood hazard information, including (when appropriate) proposed and proposed modified BFEs presented on a new or revised FIRM, and FIS report. The letter begins the compliance period and establishes the effective date for the new or revised FIRM and/or FIS report (FEMA, 2003)

Letter of Map Change (LOMC)—A collective term used to describe official amendments and revisions to FIRMs that are accomplished by an administrative procedure and disseminated by letter (FEMA, 2003)

Leveling—The process of finding differences of elevation (Maune, 2007)

Light Detection and Ranging (lidar)—An airborne laser system that is used to acquire *x*, *y*, and *z* coordinates of terrain and terrain features that are both manmade and naturally occurring. LIDAR systems consist of an airborne GPS with attendant base station(s), inertial measuring unit, and light-emitting scanning laser (FEMA, 2003)

Limited Detailed Study—A flood hazard study based on fewer surveyed cross sections than detailed studies. The analysis results in the delineation of floodplain boundaries for the 1 percent annual chance (100-year) flood and often base flood elevations (FEMA, 2006a)

Map Modernization Program—A multiyear FEMA initiative (1) to provide a technology-based, cost-effective, long-term process for updating, maintaining, storing, and distributing the flood risk information portrayed on the flood maps; and (2) to use engineering tools and analysis to update the flood maps so that they reflect physical changes that have occurred since the original mapping (FEMA, 2006a)

Mitigation—A sustained action taken to reduce or eliminate long-term risk to people and property from flood hazards and their effects. Mitigation distinguishes actions that have a long-term impact from those that are more closely associated with preparedness for, immediate response to, and short-term recovery from specific events (FEMA, 2003)

Monument or control monument (also called reference mark)—A structure that marks the location of a corner or point determined by surveying; generally, any material, object, or collection of objects that indicates the ground location of a survey station or corner (<http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml>)

National Flood Insurance Program (NFIP)—The federal program under which floodprone areas are identified and flood insurance is made available to the owners of the property in participating communities (FEMA, 2003)

Orthophoto—A photograph prepared from a perspective photograph by removing displacements of points caused by tilt, relief, and perspective (Maune, 2007)

Peak Flow—The maximum instantaneous discharge of a stream or river at a given location; usually occuring at or near the time of maximum stage (<http://water.usgs.gov/glossaries.html>)

Photogrammetry—The science of deducing the physical three-dimensional measurements of objects from measurements on stereo photographs that photograph an area from two different perspectives (Maune, 2007)

Q3 Flood Data Product—A digital representation of certain features of the FIRM that is intended for use with desktop mapping and GIS technology. The Q3 flood data product is created by scanning the effective FIRM paper maps and digitizing selected features and lines (FEMA, 2003)

Recurrence Interval—The average interval of time within which a given flood will be equaled or exceeded once; also known as the return period (FEMA, 2003)

Redelineation—A data update method that involves no new analyses, but uses effective information and new topographic data that are more up-to-date and/or detailed than those used to produce the effective FIRM to redelineate floodplain boundaries (FEMA, 2003)

Regression Equation—An experimentally determinable equation of a regression curve; that is, an approximate, generally linear relation connecting two or more quantities and derived from the correlation coefficient (FEMA, 2003)

Resolution—In the context of gridded elevation data, resolution is synonymous with the horizontal post spacing; sometimes used to state the number of points in x and y directions in a lattice (e.g., 1,201 × 1,201 mesh points in a U.S. Geological Survey [USGS] one-degree DEM) (Maune, 2007)

Restudy—A revised study of flood hazards performed for a community that already has an effective FIRM (FEMA, 2003)

Return Period—See recurrence interval

Revision—A change to an effective NFIP map based on new or revised scientific or technical data (<http://www.fema.gov/plan/prevent/floodplain/nfipkeywords/revision_maps.shtm>)

Riverine Flooding—The overbank flooding of rivers and streams (FEMA, 2003)

Runoff—That part of the precipitation that appears in surface streams (<http://water.usgs.gov/glossaries.html>)

Shallow Flooding—Unconfined flows over broad, relatively low relief areas; intermittent flows in arid regions that have not developed a system of well-defined channels; overbank flows that remain unconfined; overland flow in urban areas; and flows collecting in depressions to form ponding areas. For NFIP purposes, shallow flooding conditions are defined as flooding that is limited to 3.0 feet or less in depth where no defined channel exists (FEMA, 2003)

Special Flood Hazard Area (SFHA)—The area delineated on an NFIP map as being subject to inundation by the base flood. SFHAs are determined using statistical analyses of records of riverflow, storm tides, and rainfall; information obtained through consultation with a community; floodplain topographic surveys; and hydrologic and hydraulic analyses (FEMA, 2003)

Stillwater Flood Elevation (SWEL)—Projected elevation that floodwaters would assume, referenced to NGVD 29, NAVD 88, or other datum, in the absence of waves resulting from wind or seismic effects (FEMA, 2003)

Storm Surge—The rise in the water surface above normal water level on the open coast due to the action of wind stress and atmospheric pressure (<http://www.fema.gov/media/fhm/champ/ot_chmp.htm>)

Stream Reach—The length of a channel for which a single gage affords a satisfactory measure of the stage and discharge (<http://water.usgs.gov/glossaries.html>)

Structure—For floodplain management purposes, a walled and roofed building, including a gas or liquid storage tank that is principally above ground, as well as a manufactured home. For flood insurance purposes, a walled and roofed building, other than a gas or liquid storage tank, that is principally above ground and affixed to a permanent site, as well as a manufactured home on a permanent foundation (FEMA, 2003)

Terrain—See topography

Topography—The form of the features of the actual surface of the Earth in a particular region, considered collectively; also called terrain (Maune, 2007)

Total Station—A tachymeter that senses angles and distances electronically. A tachymeter is a surveying instrument for the rapid determination of distance, usually together with the measurement of direction and difference of elevation (<http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml>)

Transect—Cross section taken perpendicular to the shoreline to represent a segment of coast with similar characteristics (FEMA, 2003)

Uncertainty—Degree to which an outcome is unknown or not established and is therefore in question (NRC, 2000)

- **Knowledge Uncertainty—**Sometimes called epistemic uncertainty—deals with a lack of understanding of events and processes, or with a lack of data from which to draw inferences; by assumption, such lack of knowledge is reducible with further information. The word epistemic is derived from the Greek "to know." Knowledge uncertainty is also sometimes referred to as functional, internal, or subjective uncertainty.

- **Natural Variability—**Sometimes called aleatory uncertainty—deals with inherent variability in the physical world; by assumption, this "randomness" is irreducible. The word aleatory comes from the Latin *alea*, meaning a die or gambling device. In the water resources context, uncertainties related to natural variability include things such as streamflow, assumed to be a random process in time, or soil properties, assumed to be random in space. Natural variability is also sometimes referred to as external, objective, random, or stochastic uncertainty.

Watershed—See catchment area

Wave Crest—The highest point on a ridge, deformation, or undulation of the water surface (<http://www.fema.gov/media/fhm/champ/ot_chmp.htm>)

Wave Envelope—A combination of representative wave runup elevation and the wave crest profile determined by the wave results computed using the Wave Height Analysis for Flood Insurance Studies (WHAFIS) program (FEMA, 2003)

Wave Height—Vertical distance between the wave crest and the wave trough (FEMA, 2003)

Wave Runup—Rush of waves up a slope or structure (FEMA, 2003)

Wave Setup—The increase in the stillwater surface near the shoreline, due to the presence of breaking waves (FEMA, 2003)

Wind Setup—The vertical rise in the stillwater level at the face of a structure or embankment caused by wind stresses on the surface of the water (FEMA, 2004)

Appendix D

Acronyms and Abbreviations

1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
ADCIRC	Advanced Circulation (model)
ADJREG	adjusted regional regression (equation)
AIGA	Adaptation of Geographical Information for Flood Warning
APPROX	approximate study
APPROX-NED	approximate study using the National Elevation Dataset
BFE	base flood elevation
cfs	cubic feet per second
CHAMP	Coastal Hazards Analysis and Modeling Program (model)
DEM	digital elevation model
DFIRM	digital Flood Insurance Rate Map
DS	detailed study
EST	Empirical Simulation Technique
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
GIS	geographic information system
GPS	Global Positioning System
HEC-RAS	Hydrologic Engineering Center-River Analysis System
HEC-SSP	Hydrologic Engineering Center-Statistical Software Package
ICPR	Interconnected Pond Routing (model)
IFSAR	interferometric synthetic aperture radar
IPET	Interagency Performance Evaluation Taskforce
JPM	Joint Probability Method
LDSNAT	limited detailed study, national
LDSNC	limited detailed study, North Carolina
lidar	light detection and ranging
LOMC	Letter of Map Change
MHHW	mean higher high water (datum)
MHW	mean high water (datum)
MLLW	mean lower low water (datum)
MLW	mean low water (datum)
MNUSS	Map Needs Update Support System
MTL	mean tide level (datum)
NAVD 88	North American Vertical Datum of 1988
NCFMP	North Carolina Floodplain Mapping Program

NED	National Elevation Dataset
NFIP	National Flood Insurance Program
NGS	National Geodetic Survey
NGVD 29	National Geodetic Vertical Datum of 1929
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRC	National Research Council
NWLON	National Water Level Observation Network
REG	regional regression (equation)
REGLOW	regional regression, 95 percent lower confidence limit (equation)
REGUP	regional regression, 95 percent upper confidence limit (equation)
RR	rainfall runoff (model)
SAC-SMA	Sacramento Soil Moisture Accounting (model)
SFHA	Special Flood Hazard Area
SWEL	stillwater elevation
SWFWMD	Southwest Florida Water Management District
TRB	Transportation Research Board
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WHAFIS	Wave Height Analysis for Flood Insurance Studies (model)