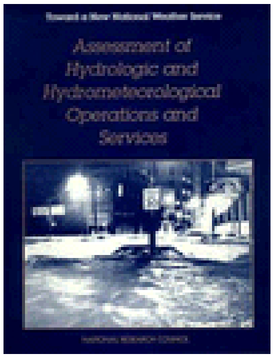

Assessment of Hydrologic and Hydrometeorological Operations and Services

National Weather Service Modernization Committee,
National Research Council

ISBN: 0-309-58995-9, 62 pages, 8.5 x 11, (1996)

Toward a New National Weather Service

Assessment of Hydrologic and Hydrometeorological Operations and Services

National Weather Service Modernization
Committee Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1996

NATIONAL ACADEMY PRESS 2101 Constitution Avenue, N.W. Washington, DC 20418

This study was supported by Contract No. 50-DGNW-5-00004 between the National Academy of Sciences and the U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Available in limited supply from:
Transition Program Office
National Weather Service, NOAA
1325 East-West Highway
Silver Spring, MD 20910
(301) 713-1090
Cover Photo: David D. Vann, The Sentinel-Record, Hot Springs, Arkansas.
Printed in the United States of America

NATIONAL WEATHER SERVICE MODERNIZATION COMMITTEE

ROBERT J. SERAFIN (*chair*), NAE, National Center for Atmospheric Research, Boulder, Colorado
RICHARD A. ANTHES, University Corporation for Atmospheric Research, Boulder, Colorado
DAVID ATLAS, NAE, Atlas Concepts, Bethesda, Maryland (beginning February 1996)
WILLIAM BONNER, National Center for Atmospheric Research, Boulder, Colorado
JOHN P. BRADLEY, Murray and Trettel, Inc., Northfield, Illinois (until February 1996)
ROBERT BRAMMER, TASC, Reading, Massachusetts
KENNETH C. CRAWFORD, Oklahoma Climatological Survey, Norman
DARA ENTEKHABI, Massachusetts Institute of Technology, Cambridge
GEORGE J. GLEGHORN, NAE, TRW Space and Technology Group (retired), Rancho Palos Verdes, California
WILLIAM E. GORDON, NAE, NAS, Rice University (retired), Houston, Texas
ALBERT J. KAEHN, Jr., U.S. Air Force (retired), Burke, Virginia (beginning February 1996)
JENANNE L. MURPHY, Hughes Information Technology Corporation, Vienna, Virginia
VERONICA F. NIEVA, WESTAT, Inc., Rockville, Maryland
DOROTHY C. PERKINS, National Aeronautics and Space Administration, Greenbelt, Maryland (beginning February 1996)
MARILYN M. WOLFSON, Massachusetts Institute of Technology, Lexington (until February 1996)
ARTHUR I. ZYGIELBAUM, California Institute of Technology, Pasadena (until February 1996)

Hydrology Panel

KENNETH C. CRAWFORD, chair
DARA ENTEKHABI
VERONICA F. NIEVA, advisor

Staff

FLOYD F. HAUTH, study director
MERCEDES ILAGAN, study associate
WANDA PRIESTLY, project assistant
COURTLAND LEWIS, technical writer

Preface

In a March 1995 contract Statement of Work, the National Oceanic and Atmospheric Administration asked the National Weather Service Modernization Committee (NWSMC) of the Commission on Engineering and Technical Systems of the National Research Council (NRC) to "review plans and progress, and assess the need for changes or improvements in the hydrology and hydrometeorology products and services of the modernized National Weather Service (NWS), with particular emphasis on the flash flood forecast and warning program." In June 1995 the Executive Committee of the NRC authorized the NWSMC to conduct the foregoing study and prepare a report. The NWSMC was asked to undertake the following tasks:

- Examine the adequacy of plans for modernization of the NWS hydrologic and hydrometeorological products and services for the nation.
- Examine the progress made by the NWS in improving hydrologic and hydrometeorological products and services for the nation.
- Assess the effectiveness of the NWS in incorporating new technology and science in hydrologic and hydrometeorological products and services for the nation.
- Identify possible unmet needs in NWS hydrologic and hydrometeorological products and services for the nation.
- Explore alternative approaches to incorporate scientific and technical developments into the modernized NWS hydrologic and hydrometeorological products and services.

The NWSMC established a Hydrology Panel to gather information, make a detailed assessment of the status of hydrology in the NWS organization and operations, and report its findings to the committee. In accordance with its charge, the committee's report identifies the most critical tasks to be accomplished by the NWS to advance the modernization program and provides recommendations to address deficiencies identified during the course of the study.

The Hydrology Panel focused on NWS flood and flash flood issues related to the planning and implementation of warning and forecast products and services. These issues include operational procedures, new science and technology, quality control, verification procedures, model deficiencies, staffing, training, and management functions.

The panel relied heavily on NWS internal documents, interviews, and correspondence at all levels of the NWS and information collected from government and private-sector participants in the overall national hydrology activities. The panel and the committee conducted their analyses and reviews in the broad context of the overall NWS modernization. The committee's recommendations are intended to increase the effectiveness of the modernization program to meet all NWS goals aimed at the improvement of hydrologic and hydrometeorological products and services.

The Hydrology Panel visited a carefully selected subset of field locations and interviewed staff members who provide flood and flash flood products and services to a wide range of users, including the public, all levels of government agencies, and specialized interests in the private sector such as emergency management, agriculture, and transportation. Staff members interviewed were from all levels of support activity within the NWS organizational structure and who covered all aspects of work processes, ranging from data collection to analysis, forecasting, interacting with users, and related research and development efforts. A questionnaire about hydrology activities and interests was distributed internally to all NWS offices with hydrology-related responsibilities. Responses were received from approximately two-thirds of those contacted. (The responses are summarized in the appendix.) In addition, representative users of hydrology products and services were contacted or interviewed to obtain their perspective on the NWS modernization of hydrology functions.

The committee reviewed the data gathered by the Hydrology Panel and analyzed it in the context of the NWS strategic plan. The committee also reviewed documents related to the modernization of hydrologic and hydrometeorological functions. The committee presents its analyses, findings, conclusions, and recommendations in this report.

This study could not have been conducted without the full and willing participation of a wide range of NWS staff members, in particular Mr. Louis G. Boezi, Deputy Assistant Administrator for Modernization, and Dr. Edward R. Johnson, Chief, Hydrologic Research Laboratory, both of whom kept the committee abreast of the status of hydrology-related plans and progress in the NWS modernization. I also thank the members of the Hydrology Panel, Drs. Ken Crawford and Dara Entekhabi, for the considerable effort they devoted to this study on behalf of the committee, including visiting NWS facilities, conducting interviews, pursuing the questionnaire activities with the help of Dr. Veronica Nieva, advisor to the panel, and drafting the report. On behalf of the committee, I express our appreciation to Mr. Floyd Hauth, study director, and Mrs. Mercedes Ilagan, study associate, for their expert organizational and logistical support, and to consultant Courtland Lewis for his assistance in the preparation of the report.

ROBERT J. SERAFIN, CHAIR

NATIONAL WEATHER SERVICE MODERNIZATION COMMITTEE

Contents

Figures, Boxes, and Tables

Figures

Boxes

Tables

Executive Summary

Floods are by far the most devastating of all weather-related hazards in the United States. The National Weather Service (NWS) is charged by Congress to provide river and flood forecasts and warnings to the public to protect life and property and to promote the nation's economic and environmental well-being (such as through support for water resources management). As part of a modernization of its technologies and organizational structure, the NWS is undertaking a thorough updating of its hydrologic products and services and the activities that produce them.

The role of the 13 River Forecast Centers (RFCs) is becoming more central in the provision of hydrologic services, and the interaction of the RFCs with 119 newly restructured Weather Forecast Offices (WFOs) will be much closer and more complex. All RFCs will now be collocated with a WFO. New technologies such as the Next Generation Weather Radar (NEXRAD) and the Advanced Weather Interactive Processing System (AWIPS) will provide more detailed and timely data and facilitate the processing of data into products.

A key feature of the modernization program is the integration of hydrology and meteorology in a new *hydrometeorological* focus, which is expected to enable the provision of more efficient operations and more effective services. As part of this integration, the NWS has established a hydro-meteorological analysis and support unit at each RFC to facilitate the increased emphasis on hydrometeorology and the interaction with WFOs. The roles and responsibilities of existing meteorological forecasters and service hydrologists at WFOs will change in accordance with this enhanced focus on hydrometeorology.

The National Weather Service Modernization Committee of the National Research Council undertook a comprehensive assessment of the NWS' plans and progress for the modernization of hydrologic and hydrometeorological operations and services. The committee's conclusions and recommendations and their related analysis and rationale are presented in this report.

The committee commends the NWS for the strides it has made in modernizing the NWS hydrology program. The effort has been well planned and diligently pursued. The implementation of major new hydrologic and meteorological technologies presents an opportunity to integrate and significantly improve NWS weather and hydrology warning and forecast services (e.g., through an increased focus on hydro-meteorology).

Although the committee has identified a number of aspects of the modernization of the NWS hydrology program in which improvements are needed, the overall results of its assessment are quite positive. The modernization is incorporating recent technological advances into field offices and thereby laying the groundwork for major benefits to be realized from improved hydrologic products and services. The availability of new tools and techniques is also having a strong, positive effect on the spirit and outlook of NWS personnel.

Chapters 1 and 2 of this report provide an introduction and background information on hydrology and hydrometeorological programs in the NWS. Chapters 3 and 4 contain the evaluation of the NWS program as well as its management and operational support and present all of the conclusions and recommendations. The 40 recommendations in this report cover a wide variety of topics. The committee has placed a relatively higher priority on 14 of these recommendations, which are presented consecutively in this summary as found in Chapters 3 and 4 along with supporting discussion. However, each of the recommendations in the report is important, and the reader is urged to review them all. It is important that each recommendation be understood in the context of the committee's analysis; therefore, this summary provides the section heading, and the chapter and recommendation number where it can be found. It should be noted that the order of presentation does not imply any ranking or prioritization among the recommendations. Again, the reader is encouraged to review the entire report, especially the conclusions, recommendations, and supporting information in Chapters 3 and 4.

PRECIPITATION PROCESSING SYSTEM

Recommendation 3-1. The NWS should continue its efforts to incorporate additional real-time precipitation data (both ground-based and remotely sensed) into hydrologic products and services. The methods used for multisensor detection and estimation of precipitation should enable accurate characterization of precipitation patterns that span seasonal, geographic, and range diversity. A capability to distinguish reliably between rain and snow must be developed. The Precipitation Processing System (PPS) methodology should be upgraded to a more scientifically sound and dynamic methodology to improve seasonal and geographic performance, especially during light rain and snow events and in mountainous areas.

One of the most important inputs to NWS hydrologic models is the spatial and temporal distribution of precipitation, derived from a three-stage PPS. Weather radars, along with rain gauges, have long been used to estimate the amount of precipitation that falls to the Earth's surface. Although radar technology and the associated computer processing have improved immensely in recent years, our knowledge about the amount of precipitation that actually reaches the surface remains primitive. As a result, the PPS provides inconsistent results for certain types of rainfall in different geographical areas and has seasonal variations as well.

Successful modernization of NWS hydrologic services depends on the ability of the NEXRAD network to provide accurate estimates of precipitation that benefit from improved spatial and temporal resolution. Furthermore, the current approach for analyzing precipitation patterns is flawed and based on outdated research. It lacks the scientifically sound and dynamic methodology needed to improve the seasonal performance of the PPS in light rain or snow and in mountainous areas.

PRECIPITATION FORECASTS

Recommendation 3-4. The NWS should accelerate its fledgling efforts to redesign, develop, evaluate, and verify quantitative precipitation forecasts (QPFs) and probabilistic QPFs (pQPFs) and assess their use in hydrologic forecast models across a range of geographic and seasonal conditions. The Office of Hydrology should determine the time and space resolution of QPFs that hydrologic models require. Users of products that incorporate QPF data should be kept informed about these developments and their potential impact on user operations.

QPFs and pQPFs represent, along with NEXRAD, an opportunity to improve significantly both flash flood prediction and regional runoff estimates that, in turn, impact hydrologic forecasts for larger basins. Thus they are of great value for the development of improved hydrologic services that have longer forecast lead times. However, the production of an accurate QPF is considered to be among the most difficult challenges in operational meteorology. The challenge increases substantially when hydrologists attempt to use the QPF as part of the precipitation input to their hydro-logic models, which require forecasts of spatial coverage and amount of precipitation.

Significant efforts are required to coordinate the possible redesign, production, and use of QPFs and pQPFs. In addition, the current QPF focus to forecast the areal coverage of precipitation needs to be reevaluated. The impact of a modernized QPF and pQPF on hydrologic models in various geographic and seasonal conditions needs to be assessed. These sets of forecasts need to undergo extensive verification studies to determine their proper design for a modern-day QPF (e.g., required time projections and spatial resolution for hydrologic models of the twenty-first century before QPF input becomes routine).

FLASH FLOOD GUIDANCE

Recommendation 3-12. The NWS should improve the scientific basis that underpins the forecasting of floods that occur in the zero to six-hour time frame. WFO and RFC staff should be enabled to contribute to this effort by facilitating their access to adequate training, continuing education, and university cooperative programs. Furthermore, they should be able to access state-of-the-art geographic information systems, digital elevation models, and drainage and land-use data.

The scientific foundations of both flash flood guidance and threshold runoff (another type of guidance product) are derived from decades-old techniques that need significant revisions. Yet few of the existing NWS research programs are related to operational flood forecasting. In addition, threshold runoff is currently estimated based on limited data. The Weather Forecast Office Hydrologic Forecasting System (WHFS), with its capabilities for both site-specific and area-wide modeling of the flash flood hazard, has great potential for dealing with the zero to six-hour flood problem if technical and scientific, training, and operational procedures problems are resolved.

WEATHER FORECAST OFFICE HYDROLOGIC FORECASTING SYSTEM

Recommendation 3-14. The NWS should reevaluate the staffing needs of WFOs with regard to their hydrologic responsibilities. The number of service hydrologists should be increased so that each WFO has a program leader for WFO hydrologic operations, at least for the first year or two following implementation of the AWIPS at each field office. (A related recommendation is provided in the Qualifications section of this summary.)

Overall, the NWS has done an excellent job of defining the requirements and planning the staffing needed in the hydrology and hydrometeorology functions of the modernized

NWS. However, although service hydrologists will manage the hydrology programs at all future WFOs, only 80 of the planned 119 WFOs will have a service hydrologist assigned full time; these 80 service hydrologists will cover all 119 WFOs. WFO service hydrologists are program leaders within their offices, not operational forecasters. But most WFO weather forecasters currently do not perceive hydrology as part of their operational duties. Furthermore, during severe weather conditions, hydrometeorological forecasting at WFOs may at times produce an excessive workload for the planned staffing; as a result, the use of interactive hydrologic forecast programs might receive less attention than is warranted. Sufficient staff must be in place who have the appropriate training to take advantage of these modernized capabilities.

The committee remains concerned about the vital and increasingly important role that the service hydrologist will play in the modernized NWS. It is possible that most, if not all, WFOs may require a full-time position. At offices where operational tests and evaluations are conducted, additional hydrologic expertise will be needed to ensure a thorough, effective test of the new systems and techniques.

Recommendation 3-15. Guidelines and procedures should be in place to ensure that the hydrologic and hydrometeorological forecasts meet NWS requirements (e.g., for accuracy and timeliness) even under the most challenging of operational circumstances. Operational tests should be performed to confirm that these requirements are met.

A suite of powerful new software tools has been developed to assist in the development of guidance and forecast products. However, during severe weather conditions, WFO forecasters are concerned primarily with generating severe weather warning products, which result in the new interactive hydrologic forecast programs receiving less attention than is warranted. There is a risk that RFC guidance products on flooding potential might sometimes be released to the user community with little modification or enhancement by WFO forecasters. The potential is even greater when factors such as hydraulic structures (e.g., dams), small-scale land-use patterns, and urban surfaces complicate the local hydrologic picture.

The full capability of an application such as the WHFS can be realized only when WFO forecasters are prepared adequately to deal with hydrologic forecasting during flood water crises and concurrent severe weather conditions. The WHFS in particular needs to be tested in the most challenging of operational environments, for example, during complex, severe weather situations when forecast and warning workloads are heavy.

DATA ARCHIVING, VERIFICATION, AND QUALITY ASSURANCE

Recommendation 3-22. The suite of precipitation products produced by the NEXRAD network, along with accompanying surface rain and stream gauge information, should be archived by the NWS for future use when new hydrologic models require calibration before they can be implemented. The NWS should ensure that appropriate access, storage, and visualization methods, such as those planned in the National Oceanic and Atmospheric Administration (NOAA) Hydrologic Data System, are developed or adapted for use with the entire spectrum of hydrologic data.

An essential element of the foundation for future improvements in the NWS hydrologic forecast system is the availability of a comprehensive data archiving and retrieval system. Although the NOAA Hydrologic Data System, now under development, is expected to meet the data archiving needs of some NWS operational activities, nevertheless the current system fails to archive and efficiently retrieve most of the data that will be needed for twenty-first century improvements in NWS hydrology.

A lengthy archive of all basin data is essential to calibrate hydrologic models (old and new) and improve model performance during critical high-water and low-water situations. For example, hydrologic models can be improved using data on the distribution in space and time of precipitation that produced floods or led to drought conditions. Yet NEXRAD precipitation estimates provide a unique opportunity to produce hydrologic guidance and forecasts with an unprecedented level of detail.

With increasing demands for hydrometeorological data in an interactive forecast environment, efficient methods for accessing, storing, and viewing these data are required.

Recommendation 3-23. The NWS should implement and provide the sustained support that is needed to continue the development and operation of the National Hydrologic Forecast Verification Program.

An essential ingredient to improve hydrologic services is an adequate forecast verification system. Such a system must provide a baseline that documents previous forecast skill levels and also detects small improvements in forecast skills that result from new models being developed, calibrated, and implemented.

Currently the verification of hydrologic forecast products is inadequate. Hydrologic model development and the incorporation of new scientific tools into a modernized work environment should be accompanied by a rigorous verification program to document what progress has been achieved. The National Hydrologic Forecast Verification Program is a recent initiative in the NWS and represents an important set of plans for overcoming verification deficiencies in the hydrology program of the NWS.

DATA SOURCE RELIABILITY

Recommendation 3-25. The NWS, along with other federal agencies and local and state governments, should coordinate hydrologic and hydrometeorological data requirements, data collection, and processing. Priorities among these data should be set and appropriate funding allocated by the parties involved to maintain a consistent, reliable set of data for national and local flood forecasting programs. The NWS should exert leadership to forge an explicit partnership for sharing these data collection resources.

Data for use in hydrologic and hydrometeorological analyses and models are the lifeblood of NWS river forecasts and flash flood guidance and warning products. Sources of these data include stream gauges, precipitation gauges, cooperative observers, flood warning systems, satellite-relayed data, telemetered data and, most importantly, data from the NEXRAD network. But ownership of these data sources is distributed across various federal, state, and local government or private networks. Abrupt funding changes and uncertainties cause some data sources to be unstable, unreliable, or subject to short-notice curtailment or elimination, sometimes with no apparent coordination or consideration for the impact of their loss on NWS operations. It is essential that a shared ownership exist for the nation's water management and flood warning infrastructure, lest this infrastructure lose its ability to meet growing operational demands.

Strengthening the vitality of the surface-observing networks is also essential; the modernization of NWS hydrology will be hindered without the real-time availability of stream and rain gauge data from a larger number of locations.

PRODUCTS AND SERVICES

Recommendation 3-26. The NWS should continue to work with the user community to determine community needs. In particular, the NWS should focus on user concerns that may develop in regions where political boundaries and basin boundaries do not coincide. In addition, improved communication technologies should be employed to share data and to disseminate warnings.

A service agency such as the NWS is known by the quality, relevance, and ease of access and use of its products. Nowhere are these traits more critical than in river and flash flood situations where lives and property are threatened—situations that often arise late at night and in rural areas. In these situations, a forecast and warning *system* provides an unacceptable level of service when the forecasts and warnings are inaccurate or difficult to decipher or when they fail to reach the population at risk. To achieve the dividends of modernization requires that the NWS and its myriad of users understand each other's needs, capabilities and responsibilities, establish highly efficient telecommunication linkages, and support or advocate mutually beneficial programs. The NWS forecast and warning system can be fully effective only if local communities accept responsibility to acquire and act on the information.

PROGRAM RESPONSIBILITIES AND PERCEPTIONS

Recommendation 4-1. The NWS must communicate the objectives of the hydrologic and hydrometeorological aspects of the modernization program and progress that has been made in the program more effectively to its employees as well as to users of its services. In particular, the NWS should ensure that responsibilities for the integrated hydrology and hydrometeorology programs are clearly assigned and understood at all levels of the NWS. Interdisciplinary advisory or working groups such as the Service Hydrologist Working Group could be essential intermediaries in this communication process.

In its contacts with field office personnel, the committee found considerable misunderstanding or distrust of modernization activities relating to hydrologic and hydrometeorological functions, products, and services. In particular, the benefits of the integration of certain hydrologic and meteorological duties and responsibilities are neither clearly understood nor readily accepted in many field offices. These misunderstandings about roles and responsibilities— particularly with respect to hydrometeorological duties— need to be resolved at all levels of the organization.

AVAILABILITY OF ADVANCED WEATHER INTERACTIVE PROCESSING SYSTEM

Recommendation 4-2. The AWIPS implementation program should be expedited to enable NWS offices to exploit the use of data from new technologies and to realize improvements in the river and flash flood forecasts and warnings.

The AWIPS (Advanced Weather Interactive Processing System) is essential for data collection, quality control, and processing and telecommunication of hydrologic and hydrometeorological data. The AWIPS is essential to the integration of data, analyses, and models that enable improvements in river and flash flood forecasting programs. Despite consistent efforts by the NWS, a variety of technical, funding, and political setbacks have slowed the AWIPS development and implementation program. At this point in the modernization and restructuring, the absence of an AWIPS is preventing full realization of the benefits of the modernization program. As data from other new technology systems have become available, the lack of AWIPS workstation capabilities presents a bottleneck in data processing and data integration that will result in less accurate and timely warnings than would otherwise be possible with the new work-station technologies.

RESEARCH AND DEVELOPMENT

Recommendation 4-5. The NOAA and the NWS should develop a formal, long-term plan for hydrologic science research that includes establishing priorities and is relevant to flood and flash flood forecasting. The NOAA and the NWS should request sufficient funding to implement and sustain the research. The plan should be communicated to field personnel so as to improve the overall NWS vision for hydrologic services in the twenty-first century. In addition, NWS headquarters should disseminate regularly to its field offices updates on research and development activities, their specific objectives, and timetables.

Considering its relatively small size, the NWS supports a significant research and development program that has produced very useful results. For example, interactive hydrology forecast applications such as the WHFS and the NWS River Forecast System are quite innovative. However, relatively little effort is under way on research issues related to the scientific underpinning of hydrologic procedures and models used in day-to-day operations.

The committee concludes that although a modest amount of hydrology research is in progress or planned within the Office of Hydrology, the overall objectives are unclear. Furthermore, the priorities, relevance, and cohesiveness of those research activities are lacking to some extent. In addition, information on NWS research and development activities is not received at field offices in a timely manner and often is not considered credible by field office staff.

ADVISORY GROUPS

Recommendation 4-8. The NWS should use internal advisory groups consistently throughout major planning, development, test, and implementation phases of the hydrology modernization program. These groups should include field office members and be encouraged to advise NWS headquarters on matters relating to research and development, operational test and evaluation, and overall modernization implementation.

Early in the modernization planning, the NWS established various working groups, consisting of field office and headquarters personnel, to review requirements and to develop plans to improve products and services in hydrology and hydrometeorology. The contributions of these groups are seen almost universally as having been beneficial and effective in the establishment of a sound modernization program. One or more similar advisory or working groups need to be reestablished with respect to the hydrometeorological aspects of the modernization and restructuring. Such a group could provide important feedback on data quality control, forecast verification, hydrologic modeling, and precipitation processing techniques.

QUALIFICATIONS

Recommendation 4-11. The NWS should review and, if warranted, modify its qualification standards for hydrology positions. The NWS should require a degree or extensive formal education in hydrology for positions that involve a hydrology emphasis.

Hydrometeorological personnel with duties that have a meteorological emphasis are required to have an extensive education in meteorology. However, those personnel that have duties with a hydrology emphasis are not required to have a comparable level of education in hydrology. NWS forecasters with a degree or extensive formal education in meteorology but no comparable training in hydrology usually are not qualified for hydrologist positions. A more substantial educational background in hydrology is necessary for personnel working in such positions.

OUTLOOK

Overall, the NWS hydrology program has taken a positive leadership role in the use of new observation networks and in developing state-of-the-art interactive forecasting systems. To be sure, there are barriers that must be overcome— financial, technological, operational, and organizational. However, the committee is confident that if the changes recommended in this report are made, there is a high likelihood that the hydrologic and hydrometeorological goals of the modernization program will be achieved.

1

Introduction

FLOODS: A SIGNIFICANT NATIONAL HAZARD

Floods are the most devastating of all weather-related hazards in the United States (see Figure 1-1). Floods often produce tragic and disastrous extremes in losses of both life and property. Over the past 30 years floods have claimed an average of 139 lives per year compared with 87 lives lost per year by lightning, 82 by tornadoes, and 27 by hurricanes (NOAA, 1994a). (In recent years, the average annual flood-related death toll has risen to nearly 200.) During the same 30-year period, property damage caused by floods averaged approximately $1 billion per year. This amount is nearly twice that associated with tornadoes and hurricanes, and recently it has averaged nearly $2 billion per year. The continuing industrialization and population growth of river valleys are increasing the economic cost and death toll of flood-related disasters. Flash floods are an especially dangerous threat. A single flash flood in 1976 on the Big Thompson River in Colorado claimed 139 lives. After the Great Midwest Flood of 1993, property damage was estimated at $15 billion. Since the 1993 Midwest Flood, seven other weather-related disasters in the United States have each caused over $1 billion in damages; five of these seven disasters were floods. Overall, 75 percent of all presidential disaster declarations are for flood damage, and more than 85 percent of disaster declarations result from weather of all types (Chapman, 1992; NOAA, 1995a).

At the opposite extreme from floods, prolonged droughts also bring major economic and social disruption by losses in agriculture and food production. Furthermore, low-flow conditions in streams and rivers associated with droughts have adverse ecological effects on fish populations and riparian zone (river-bank) habitats. Low-flow conditions also impact navigation and industrial activities that are dependent on water in the river network. For example, river commerce in the upper Midwest literally bottomed out after the devastating drought of 1988, which had an economic toll exceeding $40 billion. Drought conditions in 1996 have caused crop losses estimated in the hundreds of millions of dollars in central and southwestern regions of the United States.

Many of the nation's watersheds are now managed and controlled through flood control reservoirs, storage reservoirs, hydroelectric production, water quality and erosion control measures, and land management. The operation and optimum management of these systems require forecasts on time scales that range from hours to seasons. The economic benefit of providing accurate hydrologic projections for these activities is estimated by the National Weather Service (NWS) to approach $1 billion or more annually (NWS, 1996a).

The NWS is charged by Congress to provide flood forecasts and warnings to the public to protect life and property. The NWS mission in hydrology services also extends to the provision of basic hydrologic forecast information to promote the nation's economic and environmental well-being (Stallings and Wenzel, 1995). Many types of hydrology products and services support a wide range of user communities. User communities include the general public, the news media, emergency managers at all levels of government, public works and safety agencies, and water resource and floodplain managers throughout the United States.

MODERNIZATION OF THE NATIONAL WEATHER SERVICE

The NWS is currently undergoing a comprehensive modernization and associated restructuring program that is intended to improve substantially weather and hydrologic warning and forecast products and services [1] in the United States. The modernization of the NWS, under way for over a decade, entails the deployment of proven observational, information processing, and communications technologies and the establishment of an associated operational structure. The goal of the modernization program is to ensure that the

[1] In the context of this report, any technical output from the NWS, whether from one office to another or to external users, is a "product." The term "guidance," also used often in this report, describes products used internally or between offices.

major scientific and technological advances that have been made in the ability to observe and understand the atmosphere are applied to the practical problems of providing weather and hydrologic services to the nation.

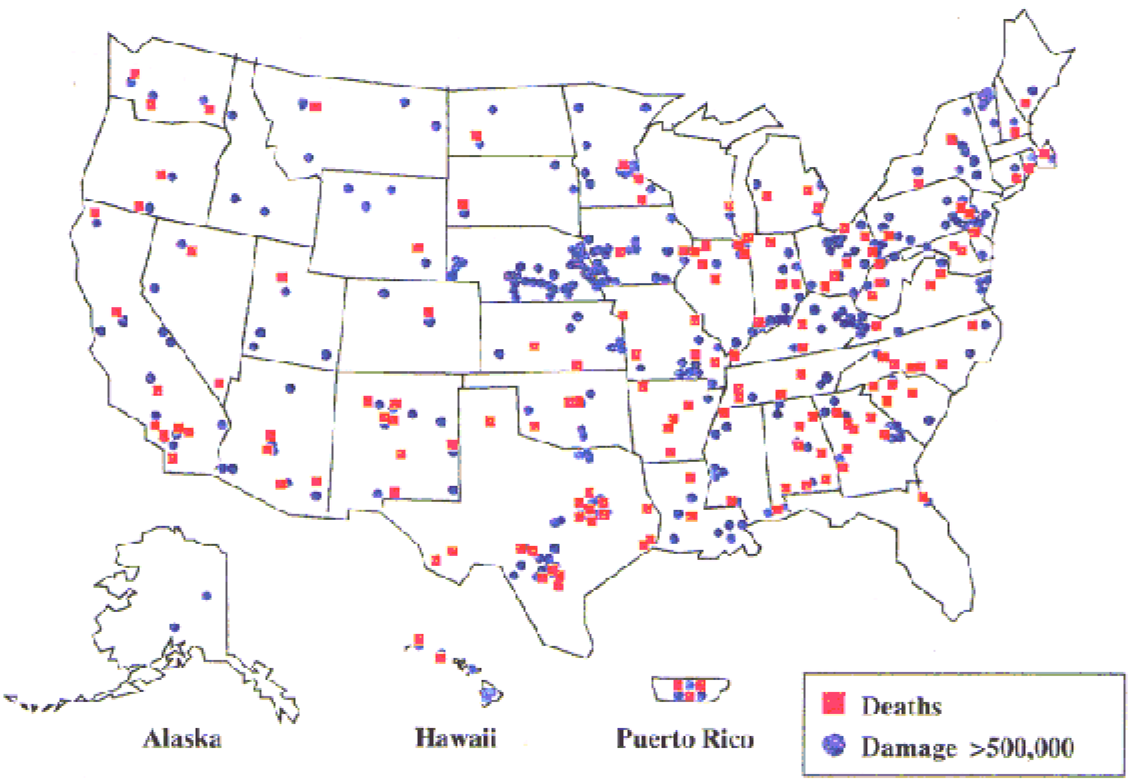

Figure 1-1
Notable floods and flash floods from 1987 to 1991.
Source: NWS (1992).

The new observing systems include the Weather Surveillance Radar 1988 Doppler (WSR-88D) Next Generation Weather Radar (NEXRAD), the Automated Surface Observing System (ASOS), and the Next Generation Geostationary Operational Environmental Satellites (GOES-Next). An Advanced Weather Interactive Processing System (AWIPS) will provide critical information processing, interactive forecast environments at each field office, and a vital, high-speed communications link among all the offices.

The associated restructuring of the NWS is driven by these new technologies. The premodernization field office structure included 52 Weather Service Forecast Offices (WSFOs); approximately 200 smaller offices (mostly Weather Service Offices [WSOs], which take manual weather observations and issue local-area forecasts based on guidance from the WSFOs as well as warnings based on a local weather radar); and 13 River Forecast Centers (RFCs). The modernized structure of the NWS includes 13 RFCs and 119 Weather Forecast Offices (WFOs)[2] at locations determined primarily by the coverage of NEXRAD systems installed nearby.[3]

In January 1991 the NWS Office of Hydrology first published its *Hydrometeorological Service Operations for the 1990s* (NWS, 1991, 1996a). This plan, most recently updated in March 1996, describes the activities at RFCs, WFOs, and regional and national headquarters offices for the various transition phases that lead up to and extend into the era of the modernized and restructured NWS. The plan includes the status of critical path decisions and policies, staffing

[2] The original strategic plan (DOC, 1989) for restructuring of the NWS called for 115 WFOs. Staffing analyses by the NWS led to the decision to assign a total of 78 service hydrologists to the WFOs. In the intervening years since the strategic plan was published, various activities, the most recent being a study of NEXRAD coverage (NRC, 1995), have led to adjusted totals of 119 WFOs and 80 service hydrologists. Although final budget approval for this planning baseline is not complete, the remainder of this report cites 119 WFOs and 80 service hydrologists.

[3] The spatial responsibilities of RFCs are determined by physiographic boundaries (watershed basins) whereas WFO boundaries are geopolitical (counties).

analysis, a master training plan, and a hydrologic systems support plan. The 1990s plan has received wide distribution within the NWS and reflects the policy, technical, and programmatic decisions coordinated by NWS headquarters, regional offices, and field office managers.

SCOPE AND ORGANIZATION OF THE REPORT

With the implementation of a new network of advanced weather radars nationwide as part of the modernization program, and with the concomitant availability of advanced communication and computation technologies, the NWS will have an unprecedented opportunity to deliver highly improved hydrology forecast and warning products and services to the public. This report addresses technical and management issues that affect the realization of that opportunity. The modernization of hydrologic services in the NWS is considered in its entirety—tools and techniques, observation systems, operations, and management are all discussed. Each component contributes to the issuance of hydrologic forecasts and warnings at some stage in the life cycle of forecast preparation. Therefore all of these topics must be critically evaluated as part of an overall assessment of the modernized NWS and its readiness to deliver advanced and improved hydro-logic forecast products and services to the public and other user communities.

In Chapter 2 the interactions between hydrology and meteorology in the NWS, both before and after the current modernization, are described. A particular focus is placed on the roles and responsibilities of the RFCs and WFOs in the modernized NWS. Chapter 3 presents a discussion and evaluation of the various tools and techniques, observation inputs, operations, and products and services that comprise the modernization of hydrologic services. In Chapter 4 management and operational support issues such as leadership, research and development, operational test and evaluation, staffing, and training are discussed. All of the committee's recommendations appear in Chapters 3 and 4. Finally, Chapter 5 presents a brief synoptic assessment of the direction and outlook for the modernization of hydrologic products and services in the NWS.

2

Background

HYDROLOGY AND METEOROLOGY PRIOR TO THE MODERNIZATION PROGRAM

The two primary operational responsibilities of the NWS are meteorology and hydrology. In the past, the hydrology and meteorology components of the NWS provided different services and evolved along divergent paths. Meteorologists and River Forecast Center (RFC) hydrologists often were located in separate offices. Moreover, the RFCs were intended to be insulated from demands for special advice. Consequently, meteorologists and hydrologists had a limited first-hand understanding of the needs of the other. The low levels of sophistication in early numerical weather prediction models and conceptually based hydrologic models, as well as the lack of computational power and communication systems to receive and process large amounts of data and produce support products, were technological barriers to a more meaningful interaction between the meteorological and hydrologic components. The need to lower the barriers that inhibited working relationships has long been recognized, but the requisite technology and resources were unavailable. Figure 2-1 describes the flow of products and guidance through NWS offices and staff positions before the current modernization program.

Improved computer and communication systems, along with more powerful observational technologies and greater scientific understanding, have begun to reduce some of the technological barriers between hydrologists and meteorologists. Their respective computer forecast models have become more sophisticated, and real-time hydrometeorological data measured over shorter time intervals have become more readily available. As a result, hydrologic forecasting stands on the threshold of attaining major improvements in forecast accuracy.

Despite these advances, the interaction between hydrologists and meteorologists is still not optimal. Educational and technological barriers are part of the problem. Also, NWS operations continue to be adversely impacted by RFC and Weather Service Forecast Office traditions established in past decades.

HYDROLOGY AND METEOROLOGY UNDER THE CURRENT MODERNIZATION PROGRAM

Advances in both the hydrologic and the atmospheric sciences have highlighted the interrelationship between the two disciplines (NRC, 1991a). For example, reliable forecasts of precipitation as well as accurate characterization of current precipitation fields[1] are critical to the preparation of hydro-logic forecasts (see Box 2-1). For this reason, the processing of radar precipitation estimates, quality control of these and other environmental observations, and discussions of precipitation forecasts and other important activities in the modernized NWS require that meteorologists and hydrologists work side by side in an efficient and integrated manner. The modernized NWS workforce will continue to have personnel specifically trained and educated in either meteorology or hydrology, but greater emphasis will be placed on relevant formal education, especially on continued training in interdisciplinary topics. To that end the modernized NWS also includes *hydrometeorologist* personnel who have degrees primarily in either hydrology or meteorology and who will receive additional and substantial education and training in topics related to their secondary specialty.

Hydrometeorology represents a blending of the sciences of meteorology and hydrology. The integration of hydrology and meteorology is to ensure maximum collaboration and interaction between the hydrologic and meteorological functions and personnel; it also takes optimum advantage of new NWS technologies to ensure the most accurate and timely NWS hydrologic products.

Figure 2-2 depicts the revised flow of products and guidance through NWS offices and staff positions under the current modernization and its associated restructuring. The figure highlights the coupling of capabilities at Weather Forecast Offices (WFOs), National Centers for Environmental

[1] Current precipitation fields characterize precipitation in terms of both space and time.

Prediction (NCEP), and RFCs. It also shows the functional joining of hydrology and meteorology that is essential for improving hydrometeorological services.

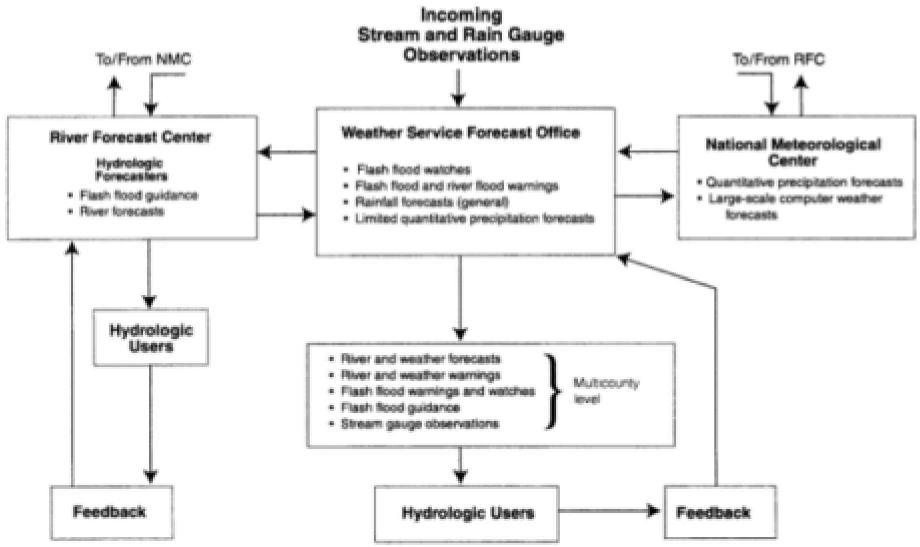

Figure 2-1
Flow of hydrologic products and guidance through NWS offices prior to modernization.

Some benefits of closer cooperation between hydrologists and meteorologists in the NWS already have been demonstrated in spite of the existing limitations. For example, meteorologists at Weather Forecast Offices [2] provide quantitative precipitation forecasts (QPFs) to RFCs during significant rainfall episodes; some of the WFOs provide QPFs to RFCs on a daily basis. RFCs, in turn, provide hydrologic guidance to WFOs in the form of river forecasts and flash flood and headwater guidance.

Collocation of RFCs with WFOs to date has demonstrated that direct personal interaction can enhance office operations. However, even at these collocated offices, potential benefits are not being realized because of limited staffing, minimal amounts of cross-training, and obsolescence of some existing equipment. The situation undoubtedly will continue to improve as the modernization program proceeds. (These issues, and possible actions to address them, are discussed in later sections of the report.)

Impact of New Technology

As new technology is implemented in the NWS, the hydrometeorological services provided by the NWS are expected to improve significantly. With the advent of NEXRAD (Next Generation Weather Radar), the Automated Surface Observing System, new geostationary and polar-orbiting satellites, and the AWIPS (Advanced Weather Interactive Processing System), the establishment of the new WFOs will foster closer cooperation between hydrologists and meteorologists and enable the production of more accurate, site-specific, and timely hydrologic forecasts. The NWS modernization will be complemented with new hydrologic software technologies that include:

- the NWS River Forecast System
- the WFO Hydrologic Forecast System
- a successor to the present Geostationary Operational Environmental Satellite data distribution system, which will be known as the Hydrometeorological Automated Data System
- the next-generation RFC computer capability
- the Advanced Hydrologic Prediction System

The implementation of these new technologies presents an opportunity to improve significantly NWS weather and hydrology warning and forecast services in the United States,

[2] WFOs will be formally identified as such after the Advanced Weather Interactive Processing System is operational and the staff are in place at Weather Service offices and Weather Service Forecast offices that are located with or near NEXRADs (Next Generation Weather Radars).

not only through the technologies themselves, but also through an increased emphasis on hydrometeorology. These services will benefit from changes in hydrologic and meteorological operations to make better use of improved hydro-meteorological data and forecasts, processing and communications capabilities, and hydrologic modeling procedures.

BOX 2-1 HYDROLOGIC PREDICTIONS

The hydrologic cycle is a composite representation of the interchange of water and water vapor between tile earth, the atmosphere, and the oceans: The cycle is a continuous process by which water is transported from the oceans to the atmosphere to the land and back to the sea. Although moisture transport in the atmosphere occurs on the planetary scale, the release of moisture as precipitation generally is confined to much smaller scales (as in a major thunderstorm or Snowstorm) where its effect is relatively local (within a specific drainage basin

Flooding results from excessive precipitation and rapid snowmelt over watersheds that concentrate the flow in drainage networks. The highly intermittent and spatially variable nature of precipitation makes it difficult to characterize its input to the hydrologic system. Temporal variability on the time of a few minutes to hours and spatial heterogeneity in precipitation intensity on scales that range from less than one kilometer to several tens of kilometers are characteristic of precipitation systems: Quantitative forecasts of precipitation are considered to be among the most challenging of all short-term predictions environmental variables related to weather. Because hydrologic forecasting requires precipitation observations and forecasts as its primary input, the accuracy of these precipitation observations and forecasts is critical to accurate hydrologic forecasting. Furthermore, because hydrologic models are indispensable tools for use in producing a river forecast or a site-specific flood warning, the *validity* of a hydrologic model for a given location and time is also a crucial determinant of hydrologic forecast accuracy

Hydrologic forecasts begin With the characterization of the precipitation input data. The precipitation input and any snowmelt are then partitioned into soil infiltration and Surface runoff (often called the rainfall-runoff transformation problem). Runoff and part of the infiltrated water concentrate in the drainage network on different time scales, depending on the path of water through the soil medium and the surface topography. The routing of the flood wave through the channel network and inundation of flood plains also are part of the hydrologic forecast problem. In addition to the intermittent and spatial variability of the input precipitation data, the surface processes themselves are heavily affected by heterogeneity in soil textures, vegetation cover, and terrain characteristics. The development of robust models for each stage of the hydrologic forecast preparation and for each component of the physical processes affecting floods, all subject to real-time application constraints, comprises a major Challenge for operational hydrology (Fread, 1995).

In the United States floods are a particularly significant threat to life and property because much of the land mass is subject to heavy precipitation throughout the year. Flash floods, which are particularly dangerous, are generally short lived and, in the forecast context, have short (less than three hours) lead times. They are caused by heavy convective rainfall over small watersheds, arroyos, and gullies. Unlike some other threats such as snowfall flash floods occur in every part of the United States. Mitigation of tile hazards they represent through advance warning is thus a concern of every NWS field office. in the near future, with the availability of more accurate precipitation estimates, digital elevation data, advanced communication and computation technologies, and other important new tools, major improvements in forecast skill[1] for floods of all types are likely to be achieved. Indeed, early indications—based and modernized operations in some field offices—show that these new technologies, together with appropriate staff training, are significantly improving the data that available to hydrologic forecasters and water and emergency managers (Fread et al., 1095).

[1] Forecast performance is measured in terms of accuracy and skill. *Accuracy* is an absolute measure defined in terms of a comparison between the forecasted and subsequently observed conditions. Forecast *skill* measures are defined so as to estimate the improvement in accuracy over certain standards such as persistence, climatology, or chance (Charba and Klein, 1980).

Hydrometeorological Service Operations

The accuracy and usefulness of river forecasts derived from RFC operations are expected to improve substantially through more frequent updating of guidance products, development and calibration of new forecast procedures, and the use of advanced processing capabilities. In addition, the increased emphasis on hydrometeorology will be facilitated through a hydrometeorological analysis and support (HAS) function, established as a unit at each RFC, and by the collocation of each RFC with a WFO. WFOs should receive real-time advice and improved support products from the RFCs. With these products and the expanded hydrometeorological databases and new technologies, the WFO will be equipped to issue more timely and accurate site-specific watches, warnings,[3] and follow-up statements for floods and flash floods, as well as provide other hydrologic services. Additional warning lead times of minutes to hours allow emergency managers and other users of NWS products and services to react more effectively to save lives and help mitigate economic losses, where possible.

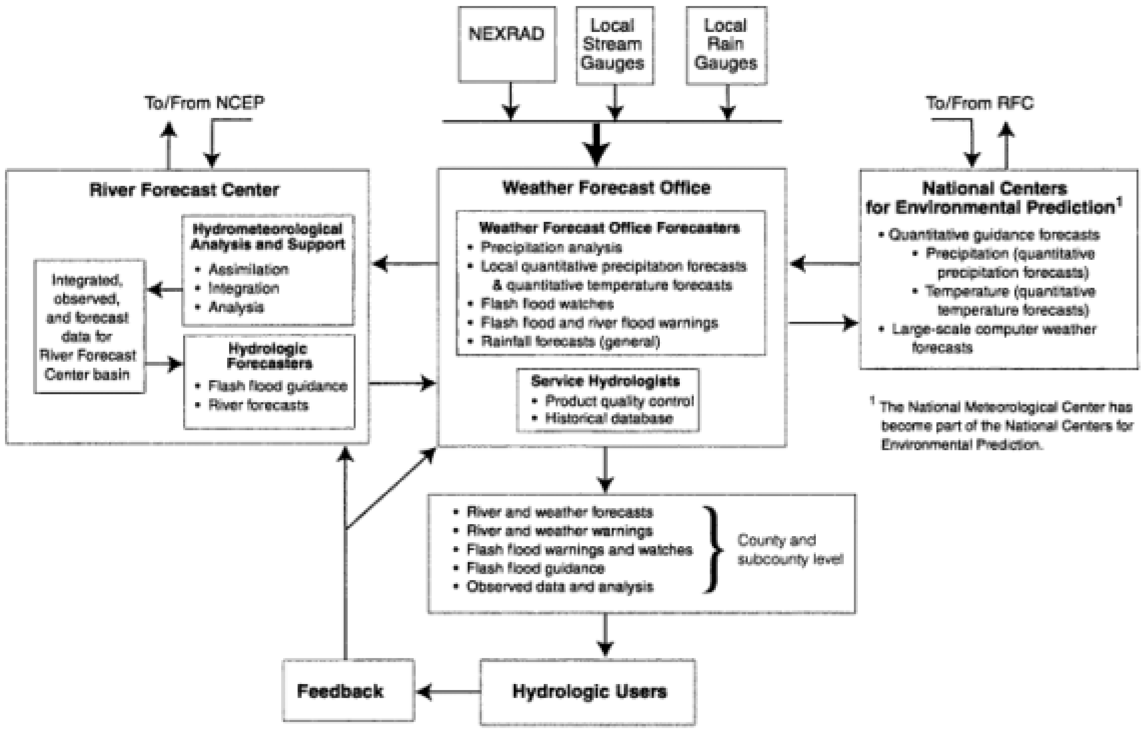

Figure 2-2
Flow of hydrologic products and guidance through NWS offices under current modernization and associated restructuring.

The hydrometeorological functions of the NCEP, RFCs, and WFOs in the modernized NWS are outlined in Table 2-1. Many of the functions in each office are dependent on support provided by other offices, as shown in the table.

River Forecast Centers

The great majority of operational hydrologic activities of the NWS are conducted at the 13 River Forecast Centers. Each RFC is responsible for a specific geographic region. The domains of these operational centers are defined along natural watershed divides and basin boundaries. The area covered by each RFC is large, ranging from 87,660 square miles for the Mid-Atlantic region to over 570,000 square miles for Alaska. Figure 2-3 shows the domain and location of the 13 RFCs, some of which are now located in new offices. In the modernized NWS, there should be greater integration of operational hydrologic and meteorological activities. Correspondingly, whereas previously less than half of the RFCs were collocated with Weather Service Offices and Weather Service Forecast Offices, now *all* of the RFCs are collocated with a WFO to foster integrated hydrometeorological operations.

Approximately 200 people staff RFCs nationwide; each center will have 14 to 19 technical personnel who perform operational duties. RFCs generally will operate 16 hours per day, although some HAS functions may extend to 18 hours. During extreme or unusual hydrologic conditions and as needed, the hours of operation may be extended to 24 hours per day.

[3] Flood warnings and watches are worded statements issued to the general public (through the news media, emergency managers, National Oceanic and Atmospheric Administration Weather Radio, and a host of other direct and indirect methods) regarding potential flooding conditions.

TABLE 2-1 Hydrometeorological Functions of the NCEP, RFCs, and WFOs in the Modernized NWS[a]

National Centers for Environmental Prediction (NCEP)	**River Forecast Centers (RFCs), Including New Hydrometeorological Analysis and Support (HAS) Functions**		Weather Forecast Offices (WFOs)
Generate national guidance products for hydrometeorological variables such as precipitation and temperature [RFCs, WFOs]	Assimilate precipitation estimates from multiple radar's in RFC area (Stage III processing) for use m on-site hydrologic model [WFOs]	Conduct hydrologic model ealibration and other procedural development activities	Execute Stage I and Stage II precipitation processing [RFCs]
		Develop hydrometerorological techniques to enhance HAS functions	
Generate regional-scale guidance products for heavy precipitation and flash flood potential [RFCs, WFOs]	Assimilate temperature forecasts. and forecasts of other hydrometeorological variables for input to RFC and WFO hydrologic models [NCEP, WFOs]	Collaborate with WFOs on joint hydrometeorological projects duting non-real-time situations [WFOs]	Provide QPFs and forecasts of other hydrometeorological variables (e g., temperature) for use in RFC hydrologic forecast operations [NCEP]
Provide computer support at NCEP Central Operations			
Assimilate national precipitation mosaic with WSR-88D-based information (Stage IV precipitation processing) [RFCs, WFOs]	Perform onsite, interactive hydrologic modeling to produce more frequent river forecasts with finer time steps and for an increased number of locations [NCEP, WFOs]	Maintain exchange of real-time support information and expertise with WFOs [WFOs]	Generate and disseminate flood and flash flood watch and warning *products for* WFO area [NCEP, RFCs]
			Provide public hydrologic forecast products and summaries [RFCs]
		Provide support for WFO hydrologic functions and models [WFOs]	
Perform verification of national-level QPF and other hydrometeorological products [RFCs, WFOs]	Produce flash flood guidance more frequently for smaller areas and with values on a grid network	Support hydrologic training for WFO personnel [WFOs]	Manage hydrometeorological data networks
		Support hydrometeorological training for WFO and RFC personnel	Perform verification of local hydrologic and hydrometeorologic products [RFCs]
	Produce hydrometeorological discussion products [NCEP, WFOs]	Perform verification of hydrologic forecast products [NCEP, WFOs]	Perform service hydrologist program leadership functions [RFCs]
			• serves as hydrologic expert in office
	Support local flood warning systems as appropriate [WFO]	Perform verification of hydrometeorological forecasts and products [NCEP, WFOs]	• conduct *liaison* activities with other federal and state agencies
			• monitor local hydrometeorological network performance
	Produce a new generation of water resources products and disseminate internally and externally over family of services or its successor (s) [NCEP, WFOs]	Ensure continuity of flood and flash flood watches and warnings across WFO boundaries [WFOs]	• conduct field work for analysis of flood risk and support of local hydrometeorological networks
	Serve as spokes-office for major river floods, droughts, and other significant hydrologic events affecting multiple WFO areas	Support accuracy and timeliness of WFO hydrologic products (e.g., QPFs and public river flow statements and forecasts)	• maintain WFO database of site characteristics and historical flood events for each river forecast location
		Provide increased Advanced Hydrologic Prediction System services [NCEP. WFOs]	• develop custom hydrologic techniques and procedures for WFO forecasters
	Provide increased interactions at the interagency level, including automated data and forecast exchange with water managers		• support local flood warning systems as appropriate
			• conduct hydrologic training for WFO forecasters

a Offices listed in brackets provide some form of direct support for the function.

Source: NWS (1996a).

RFC Abbrev.	RFC Name	RFC Area (sq. mi.)
ABRFC	Arkansas-Red Basin River Forecast Center	208,200
AKRFC	Alaska River Forecast Center	570,800
CBRFC	Colorado Basin River Forecast Center	303,450
CNRFC	California-Nevada River Forecast Center	239,424
LMFRC	Lower Mississippi River Forecast Center	209,310
MARFC	Middle Atlantic River Forecast Center	87,660
MBRFC	Missouri Basin River Forecast Center	509,550
NCRFC	North Central River Forecast Center	325,608
NERFC	Northeast River Forecast Center	106,020
NWRFC	Northwest River Forecast Center	285,786
OH RFC	Ohio River Forecast Center	178,180
SERFC	Southeast River Forecast Center	257,850
WGRFC	West Gulf River Forecast Center	403,016

Figure 2-3
River Forecast Centers. Source: NWS (1996a).

River Forecast Center Operational Responsibilities. As the main regional center for hydrology, each RFC will have both real-time and non-real-time operational responsibilities (see Larson et al., 1995). These activities are mostly in support of flood hazard mitigation through improved flood warnings and water management. They include assimilation of observations, modeling and forecasting, interaction with the user community, and training. The responsibilities of RFCs are summarized as follows:

- continuous (storm and interstorm) modeling of stream discharges and water levels for flood warning and water management activities
- development of guidance products for support of WFOs and communication with these offices through HAS functions
- technical support and interaction with relevant agencies, promotion of cooperative training, research and internship programs, and operational test and evaluation activities

The key organizational feature of operational hydrology in the modernized NWS is the consolidation of most of the hydrologic data assimilation, forecasting, and development activities in RFCs. RFCs serve as the regional centers for the assimilation of real-time hydrologic observations from WFOs and the various observation networks. They also receive guidance products from national centers. RFC staff assimilate the various data into useful products that can be integrated into forecast models at RFCs and WFOs. Thus, the hydrologic operations at WFOs are guided by RFCs.

River Forecast Center Staff Roles. There are a number of key technical and managerial positions at RFCs that warrant description. Overall management of RFC operations is supervised by the hydrologist in charge who is responsible for implementing RFC functions. Within the RFC, the hydrologist in charge supports academic liaison activities, media relations, and interagency cooperative projects. The hydrologist in charge is also in charge of training programs that support operational hydrologic activities of both the RFC and WFO.

Hydrometeorological analysis and support (HAS) is an important and central new role in RFCs, which is conducted primarily by HAS forecasters. The operational duties of HAS forecasters (see Figure 2-4) are essential to the role of the RFC in the modernized NWS. The range of responsibilities reflects the critical tasks assigned to RFCs to assimilate observations from various sources and to prepare the data for use in operational models. The assimilation of information from diverse sources and the preparation of data to initialize and update hydrologic forecast models is at the core of modernized hydrologic operations in the NWS. Thus the RFCs generally, and the HAS forecaster in particular, are critical links in blending the necessary expertise, technology, and management so that a primary thrust of NWS modernization can be advanced.

HAS analyses are based on forecasts and observations received from the WFO, as well as from national centers (such as NCEP guidance). In turn, they support WFO needs for hydrologic guidance. This two-way interaction between the RFC and WFO in NWS field operations was designed to

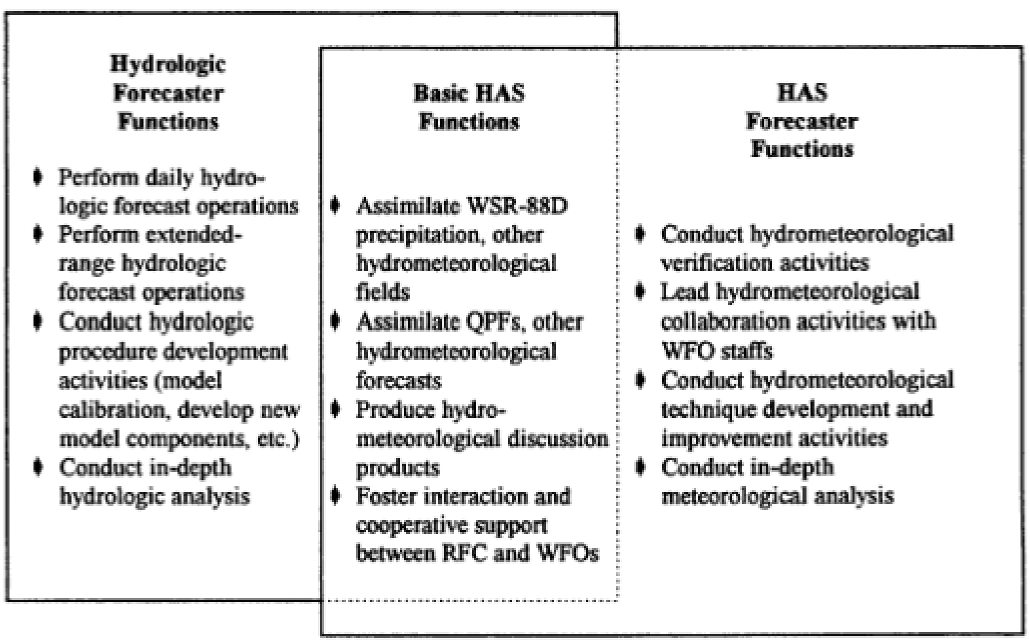

Figure 2-4
Unique and overlapping aspects of hydrologic forecaster and HAS forecaster functions in the modernized NWS. Source: NWS (1996a).

overcome the technical, scientific, and interoffice barriers that have prevailed for decades. The success of this interaction is a critical component of the modernized NWS.

Beyond the production of routine discussion and guidance products, HAS personnel are also charged with preparing forecast discussions, leading WFO-RFC interactions, and assisting with user support in each local community. Additional major duties of the HAS in the RFC include verification and evaluation of hydrometeorological products and coordination with other agencies that maintain observation networks. HAS forecasters also support cross-training and other important ancillary interactions between RFC and WFO personnel in collocated offices.

Development and operations hydrologist personnel at RFCs are responsible for the implementation and maintenance of the integrated technologies in the RFC. At each RFC they guide systems development and software modification projects. In this capacity, they work with the Hydro-logic Research Laboratory[4] to develop and integrate new software applications. Thus, like the science operations officer at a WFO, the development and operations hydrologist personnel are the in-house focal points for research and development at the RFCs.

Daily hydrologic forecast operations at a RFC are performed by a team of hydrologic forecasters. They work routinely with others in the RFC to integrate observations and precipitation forecasts into hydrologic models to produce river flow and crest predictions, flash flood guidance, and other products. Hydrologic forecasters use available forecast and modeling tools to predict and update continuous flow conditions at river forecast locations as well as to update flash flood guidance several times daily for use by WFOs in the development of their own local forecast products. Hydrologic forecasters also conduct hydrologic development activities (e.g., to improve the calibration of hydro-logic models) and perform in-depth hydrologic analyses in support of these developments. Figure 2-4 contrasts the duties of the HAS forecasters with those of the hydrologic forecasters within an RFC.

Weather Forecast Offices

WFOs are responsible for issuing hydrometeorological forecasts and warnings for the public. Hydrologic forecasts and warnings are part of these services. The 119 WFOs in the modernized NWS represent a doubling of field offices with hydrologic service area (HSA) responsibilities. With the guidance communicated from RFCs and with the hydrometeorological training and software applications provided to WFO forecasters, WFOs are charged with issuing hydrologic forecasts and warnings for the public and the broad user community. At the core of this new organization is the WFO Hydrologic Forecast System (WHFS), a computer-based tool that will enable WFO forecasters to communicate with the RFCs and perform key operational hydrology duties for the service area. (For example, responsibility for the zero to six-hour-lead flash flood forecast is assigned to the WFO, which uses guidance provided from the RFC.) See a further discussion of the WHFS in Chapter 3.

Eighty of the 119 WFOs will have a service hydrologist on site.[5] The service hydrologists are considered to be the leaders of the hydrology program at WFOs. In this capacity, they mainly provide technical and administrative support for the hydrology program. Service hydrologists will continue to be the primary managers of the WFO hydrologic program, but their responsibility in the modernized NWS will take on new dimensions. They will serve as the resident expert in each WFO on certain aspects of the new hydrometeorological technologies and will provide leadership in the internal and external execution and coordination of the WFO hydrology program. The service hydrologist in a WFO (along with a warning coordination meteorologist) will also perform liaison activities with the user community and the public. He or she must determine the service requirements for the WFO HSA.

The boundaries of WFO HSAs and RFC basins do not necessarily coincide; thus some WFOs will regularly communicate and exchange data with more than one RFC. The WFO provides RFCs with hourly NEXRAD estimates of gridded precipitation accumulation, gridded quantitative precipitation and temperature forecasts (QPFs and QTFs), hydrologic observations, hydrometeorological data reports, and river and precipitation observation summaries. The RFCs assimilate the data and use them in hydrologic models. In turn, the RFCs provide flash flood and headwater guidance to WFOs in support of the flash flood programs. The WFOs produce flood watches, warnings and statements, flood and water supply outlooks, river recreation and ice statements, and area weather updates as part of the hydrology products intended for the public and user community.

The WHFS and the training to use the hydrometeorological application are central to the hydrology program at WFOs. The service hydrologist is also responsible for calibrating and modifying the WHFS procedures. Maintaining the calibration and verification databases and updating the E-19s[6] for the HSA are principal responsibilities of the service hydrologist.

[4] The laboratory is under the administrative management of the NWS Office of Hydrology.

[5] That is, 80 WFOs have a service hydrologist assigned specifically to them, but these 80 service hydrologists will manage and support the hydro-logic warning, forecast, and information programs at all 119 WFOs.

[6] E-19s are standardized forms that report historical observations on streams and rivers. Information on past flood stages—specially with reference to local landmarks, floodplain inundation patterns, and major land-use changes—is noted in E-19s. These and other reports contained in E-19s are important in the generation of worded forecasts that facilitate effective communication with the public.

The two-way exchange of data between WFOs and RFCs, reliance on AWIPS hardware and software, and integrated hydrometeorological training for NWS personnel are the foundations of modernized operational hydrology in the NWS. Nonetheless, other components of the system, such as national and regional centers, training centers, and special programs, provide crucial support for the implementation, operation, and maintenance of modernized NWS services.

National Centers for Environmental Prediction

The NCEP is a network of centers that provide central, national- and regional-level meteorological forecast guidance, near-real-time climatic analysis, model and procedure development, and centralized computer support for the NWS. NCEP centers include:

- NCEP Central Operations
- Environmental Modeling Center
- Hydrometeorological Prediction Center
- Marine Prediction Center
- Climate Prediction Center
- Aviation Weather Center
- Storm Prediction Center
- Tropical Prediction Center

NCEP products are distributed to field forecast offices of the NWS, the U.S. Air Force, the Federal Aviation Administration, and other governmental and nongovernmental offices.

For the NWS, an important NCEP product is gridded,[7] short-term weather forecasts produced by numerical weather prediction models. These models include QPF and QTF forecasts that are highly valuable in hydrologic prediction. The numerical weather prediction models produce forecasts of evolving weather systems that rely heavily on the daily availability of observation data for the initial conditions used in the models' algorithms. Some of these data are derived from observations that are processed at RFCs and WFOs and sent to the NCEP on a regular basis. WFO forecasters modify the forecast fields and tailor them for regional hydrologic applications. Table 2-1 lists the functions of the NCEP that are relevant to hydrology.

Supporting Programs and Activities

The improvements in hydrologic and hydrometeorological products and services in the modernized NWS depend on far more than just streamlining the specialized operations in regional centers. Improved warnings and forecasts, especially short-term (zero to six-hour) events that occur on small regional and local scales, rely on advanced tools (such as the AWIPS, NEXRAD, and various environmental monitoring devices) and the research and development that produces them. Adequate training in the use of new technologies and in the requisite interoffice communication of data and intermediate products are also essential ingredients of improved warnings and forecasts.

Environmental Monitoring

Modernized hydrologic operations in the NWS are built on the availability of high-quality observations and forecasts of fields of specific variables. These observations, available at frequent time intervals, are used in continuous river-flow modeling and in the production of flash flood guidance at RFCs. Key among these data are QPFs (see Chapter 3) and NEXRAD-derived estimates of precipitation. Hydrologic and flood guidance models then partition these precipitation fields between infiltration (soil storage) and rainfall excess (or runoff). The results, when routed over the basin, form the basis for stream-flow forecasts. Clearly the accuracy of the hydrologic forecast is highly dependent on the accuracy and reliability of the observed and forecasted precipitation fields.

NEXRAD precipitation estimates are clearly among the main sources of data for hydrologic forecasts. However, telemetered data from rain gauges also contribute significantly to NEXRAD's Precipitation Processing System, which provides "calibrated" precipitation estimates to RFC forecasters. Many of the rain gauges are owned and operated by partner agencies that share data with the NWS. These partnerships are vitally important to hydrology and hydro-meteorology operations in the modernized NWS. These diverse observations are especially important in the continuous modeling of soil moisture, snow accumulation, and snow ablation.[8]

An absolutely critical source of input data for NWS hydrology derives from river gauges, most of which are operated by the U.S. Geological Survey. (Some of these gauges are managed under partnerships with other local, state, and federal agencies.) Almost all NWS river forecasts are made specifically for sites where river gauges are located. The data from these reporting stream gauges are used for both forecast updates and verification.

The NWS acquires observations from surface rain and river gauges through a variety of reporting networks. Automated Surface Observing Systems (ASOSs) are being installed at over 850 locations across the United States. This network will nearly double the number of full-time surface weather observing locations and updates observations every minute, 24 hours every day of the year. Unfortunately, the majority of these gauges are still read manually, and thus observations are updated only a few times during each 24-hour period. A smaller but growing subset of these critical gauge observations are acquired on a four to six-hour basis

[7] Grid refers to evenly spaced points at which numerical models provide temperature, wind, or other weather data for use by forecasters in producing weather forecasts and warnings for the nation.

[8] Ablation, or loss, occurs in snow by either sublimation (evaporation from solid to vapor) or by melting.

through satellite interrogation or by remote telephone access. Some community networks provide their data to the NWS on an hourly basis. This is a continual effort on the part of the NWS which is required to ensure the flow of these critical gauge reports from diverse sources to allow calibration of both the precipitation estimates from NEXRAD and the stream-flow forecasts from hydrologic models.

Satellite observations also are used in NWS hydrologic and hydrometeorological operations. The NWS plans to test and use areal coverage of precipitation estimates based on satellite information to correct for anomalous propagation in NEXRAD reflectivity observations. Another important use of satellite observations is in support of snow accumulation and ablation modeling. Snow observations from various sensors and sources are assimilated into comprehensive guidance products for RFCs at the National Operational Hydrologic Remote Sensing Center (NOHRSC) located in Chanhassen, Minnesota. The NOHRSC operates as part of the NWS Office of Hydrology and makes extensive use of satellite data to estimate nationally the areal extent and liquid-water equivalent of snow. This center also relies heavily on observations from two gamma-ray detection systems mounted on low-flying aircraft. Over 1,600 flight routes that cover portions of 25 states and 7 Canadian provinces are maintained by the NOHRSC. The snow coverage products provided by the NOHRSC are vital to hydrologic forecasting at RFCs and WFOs, especially during periods of rapid snowmelt.

Research and Development

Research and development on hydrologic forecast systems, observation systems, and related computer algorithms are primarily the responsibilities of the Hydrologic Research Laboratory, which is part of the NWS Office of Hydrology. Research and development are also performed at RFCs by field personnel. University research has played an important role in the development of models and algorithms for NWS systems. The development and testing of the new Precipitation Processing System, for example, has been largely completed by the NWS Office of Hydrology in cooperation with university researchers. Similarly, work on hydrologic modeling, which uses the next generation of hydrologic models known as distributed models, and automatic calibration procedures have been performed at both the Hydrologic Research Laboratory and research universities. Further discussion and conclusions regarding the NWS research and development program are provided in Chapter 4.

3

Modernization of the National Weather Service Hydrologic Services: An Evaluation

Four major aspects of the production of hydrologic and hydrometeorological forecast products within the modernized NWS provide a means to evaluate each component of the operational hydrology program. Four main sections in this chapter correspond to these aspects of forecast production. First, the forecaster uses *observation inputs* to produce forecasts and warnings; the availability and accuracy of these observations determine, to a large extent, the quality of the hydrologic forecast. Second, the forecaster relies on a set of forecasting *tools and techniques* to develop the required products. The manner in which data are collected and integrated into *operations* is analyzed in a third major section. Finally, the *products and services* delivered to the user community and to the general public are evaluated.

OBSERVATION INPUTS

One of the most central aspects of hydrometeorological operations is analyzing, estimating, measuring, and forecasting precipitation in the form of both rain and snow. Observational data come from a variety of sources, including NEXRAD, satellites and aircraft, and surface gauges (including the ASOS [Automated Surface Observing System]) that are read and reported by a network of observers and automated devices.

Precipitation Processing System

The goal of precipitation data processing at the NEXRAD site and at RFCs (River Forecast Centers) is to define the concise spatial distribution of precipitation over appropriate time intervals. This spatial and temporal distribution of precipitation is designed to serve as an input to continuous simulation hydrologic models. The NWS uses both rain gauge data and radar estimates of precipitation as inputs to a three-stage precipitation processing system, or PPS (see Box 3-1). Other information available to the forecaster, such as satellite imagery showing the areal extent and intensity of precipitation, can be incorporated in Stage III of the PPS.

Scientists have been using weather radars for nearly five decades to estimate the amount of precipitation that falls to the Earth's surface. Although radar technology and the associated computer processing have improved immensely in recent years, our knowledge about the amount of precipitation that actually reaches the surface remains primitive. There are numerous reasons for this shortcoming, including the outdated scientific basis of the design of the PPS, fundamental limitations in the performance of the NEXRAD, implementation flaws in the parameterization of the PPS, and operational restrictions from inadequate data transmission or computational facilities. The net impact is that most radar specialists recognize that the existing NEXRAD rainfall algorithms are outdated and seriously flawed (e.g., Atlas et al., 1996). For example, the current PPS design has essentially no features to detect or remove the effects of so-called bright band contamination due to the enhanced reflectivity of radar returns from melting snow. As another example, the current PPS implementation uses a single Z/R relationship (see Box 3-1) for most of the country—regardless of the geographical region, season of the year, or time of day—which is counter to the very science that developed the default relationship and results in its use in situations that were not represented in the original developmental data. As a third example, the Stage I PPS design incorporates a procedure to include up to 50 rain gauge reports at each radar site so as to calculate a single multiplicative bias, updated hourly, which inflates or deflates the final precipitation totals in an attempt to improve the accuracy of the PPS.

Systems to actually deliver these rain gauge reports to operational systems have not been implemented. As a final example, the PPS includes a Stage II processing procedure that performs a sophisticated merger of rain gauge and radar data, in effect a localized bias rather than a single value for the entire radar. But Stage II processing is not yet available at WFOs (Weather Forecast Offices) because of delayed AWIPS (Advanced Weather Interactive Processing System) implementation. Considering these limitations, it is not surprising that experience in NWS field offices shows that the

PPS provides inconsistent results for certain types of rainfall in different geographical areas and has seasonal variations as well.

BOX 3-1 PRECIPITATION PROCESSING SYSTEM

Two primary data sources are used in the current PPS:

Rain Gauge Data. These observations are point-source measurements of accumulated precipitation over discrete time intervals; as such, they are representative only Of tile gauge's immediate environment. Rain gauge networks that provide these observations are "owned" (i.e., managed and maintained) by a number of cooperating federal, state, and local agencies. The NWS has limited ownership of these gauge networks and thus has very little control over their operation and maintenance

Radar Estimates of Precipitation. NEXRAD provides areal estimates of precipitation over discrete time intervals. These estimates are based on an empirical Conversion into rainfall rates of tile transmitted electromagnetic power that has been returned to the radar (or backscattered) from precipitation and other particles A single conversion equation relates cloud droplet reflectivity (Z) to surface rainfall (R) through an empirical relationship known as the "*Z/R* relationship." In the NEXRAD system, a single Z/R relationship (z = 300R1.4) is used across all times, all seasons, and most NEXRAD coverage areas. (offices in tropical climates use a different *Z/R* value.)

Three stages of precipitation processing comprise the current system:

Stage I processing occurs at the radar site and uses NEXRAD computer systems, This stage of processing incorporates a limited amount of rain gauge data to determine a mean field bias of the radar estimate. A number of quality control procedures have been designed to remove erroneous radar data.

Stage II processing Be performed at the Weather Forecast Office on Advanced Weather Interactive Processing System Computers once they are installed. Additional rain gauge data are used for quality control before the two data sources (gauges and radar estimates) are merged by an automated analysis procedure.

Stage III processing occurs at RFCs, Where calibrated patterns Of precipitation from all Weather Forecast Offices in · the RFC area of responsibility are resampled into a regional mosaic to refine further the estimate of precipitation. This stage of processing is the only stage that is interactive and, therefore, it is the only stage in which the human forecaster. has an opportunity to influence the final estimate of precipitation, It is this "best estimate" of precipitation that serves as the primary input to hydrologic models.

Conclusion. Successful modernization of NWS hydrologic services depends on the ability of the NEXRAD network to provide accurate estimates of precipitation that benefit from improved spatial and temporal resolution. Furthermore, the current approach for analyzing precipitation patterns (which includes the computation of a single bias for each radar and the use of a single *Z/R* relationship for most of the country) is primitive and flawed. It lacks the scientifically sound and dynamic methodology needed to improve the seasonal performance of the PPS in light rain or snow and in mountainous areas.

The Committee on Meteorological Analysis, Prediction, and Research (NRC, 1994) recommended that "the NWS [should] work to establish the accuracy of NEXRAD rainfall estimates, especially for heavy rainfall events." The present report reemphasizes this recommendation as an area needing additional scientific investigation and study. The committee further recommends:

Recommendation 3-1. The NWS should continue its efforts to incorporate additional real-time precipitation data into hydrologic products and services. The methods used for multisensor detection and estimation of precipitation should enable accurate characterization of precipitation patterns that span seasonal, geographic, and range diversity. A capability to distinguish reliably between rain and snow must be developed. The PPS methodology should be upgraded to a more scientifically sound and dynamic methodology to improve seasonal and geographic performance, especially during light rain and snow events and in mountainous areas.

Finally, important details in the precipitation patterns from NEXRAD are not currently available to meet certain needs of the flash flood program, especially for flood-prone basins that are as small as 10 square kilometers. For example, NEXRAD precipitation initially is acquired in a polar coordinate form (azimuth and range in 1-degree × 1-km increments) with *255* data-level resolution. But NEXRAD products are "coarsened" either in spatial detail (4 km × 4 km × 255 data levels for the hourly digital product) or in both spatial detail and data resolution (2 km × 2 km × 15 data levels for other graphical products). The details lost can be critical to the timely issuance of flood warnings in ragged terrain. NEXRAD rainfall accumulation, determined at the highest resolution of the radar, represents an information data source that would permit the issuance of timely flood warnings in very small basins. The committee understands that, in software Build-9, the NWS plans to produce all graphical NEXRAD precipitation products in a polar coordinate format and to add a digital hybrid reflectivity product with high resolution. Build-9 is expected to be released in the fall of 1996.

Conclusion. In coarsening radar precipitation data for operational use, the NWS has been missing an opportunity to exploit the full power of its new NEXRAD technology for use in the WFO (Weather Forecast Office) hydrology program. The committee applauds the plan to shift to the use of polar coordinate format for NEXRAD precipitation products. This change represents an important improvement in precipitation processing for flash flood forecasting.

Recommendation 3-2. Rainfall accumulation maps that use the highest resolution possible from NEXRAD should be made available to support the flash flood program.

Although there are important areas that need improvement, the committee is encouraged by the progress made by the NWS toward improving PPS performance, as represented by new software builds for NEXRAD, reprogramming of Geostationary Operational Environmental Satellite data collection platforms, and attempts to link the NWS to new sources of data.

Quantitative Precipitation Forecasts

NEXRAD provides a valuable opportunity to improve flood forecasting and management of water resources. Detailed QPFs (quantitative precipitation forecasts) represent another opportunity to significantly improve both flash flood prediction and regional runoff estimates that, in turn, impact hydrologic forecasts for larger basins (Davis and Drzal, 1991; NRC, 1991a).

However, the production of an accurate QPF is considered to be among the most difficult challenges in operational meteorology, even when sophisticated computer models of the atmosphere are used to produce guidance information for the human forecaster. The challenge increases substantially when hydrologists attempt to use the QPF as part of the precipitation input to their hydrologic models, which requires forecasts of precipitation spatial coverage and amount. As a result, the accuracy of current QPFs is largely a function of he skill of the individual forecaster and varies considerably from one forecaster to another.

The complexity of this hydrometeorological forecast problem begins with the physical space and time scales on which precipitation occurs. For example, it is a relatively easy matter to develop a moderately accurate, 24-hour forecast of precipitation when the verifying amounts will be less than an inch or so. But when the atmosphere organizes itself to produce an extreme, often destructive precipitation event (more than 10 inches in less than 6 hours), meteorologists have almost no skill—even 6 to 12 hours in advance—to correctly anticipate these highly focused events. The forecasting difficulty derives from the fact that the physical processes that occur in the atmosphere during these extreme events are not well understood. Moreover, these processes occur on small space and time scales and thus escape detection by the current federal observing networks.

One purpose of an accurate QPF (in both space and time) is to extend the warning lead time of a critical hydrologic event. But the range of uncertainty in space, time, and precipitation volume in a modem-day QPF can create a projection of runoff in a specific basin that ranges from minimal to excessive. Even as hydrologists seek to accurately partition *past precipitation* into the critical component of actual runoff in a specific basin (with its variable terrain, soil type, and land use), the hydrologic forecaster must also answer another set of difficult questions; namely, in which specific basin will the *forecast precipitation* fall, at what rate, and over what preexisting basin conditions? In other words, the impact of uncertainties in meteorological observations as well as with complex scientific problems in the meteorological forecast process is amplified into larger uncertainties in the resultant hydrologic processes. These severe limitations, coupled with an almost nonexistent ability to accurately forecast specific amounts of precipitation in a specific basin, define the difficult task of accurately forecasting water levels in the streams and rivers of a basin. It is this situation that justified the establishment of hydrometeorological analysis and support units at each RFC.

Conclusion. Although the accuracy of QPFs has improved over the past decade (Olson et al., 1995), this improvement has had a minimal impact on the improvement of hydrologic services. Thus this current report reemphasizes a previous NRC recommendation (1991a), namely:

Recommendation 3-3. Incorporation of improved QPFs and associated uncertainties into the hydrologic models for short-range and long-term stream-flow forecast is essential and requires collaborative scientific investigation by the NWS and the academic community.

Both QPF and probabilistic QPF (pQPF) are perceived by many in the NWS hydrology program to be of great value for the development of improved and long lead-time hydro-logic services (see, for example, Krzysztofowicz, 1995).

Moreover, the pQPF methodology represents a new thrust designed to enhance the utility of the resulting hydrologic forecasts by placing more timely information into the hands of users of hydrologic data. Nevertheless, substantial improvements are needed.

Conclusion. Significant efforts are required to coordinate the possible redesign, production, and use of QPFs. In addition, the impact of a modernized QPF on hydrologic models in various geographic and seasonal conditions needs to be assessed. Both sets of forecasts need to undergo extensive verification studies to determine their proper design for a modem-day QPF (e.g., required time projections and spatial resolution for hydrologic models of the twenty-first century before QPF input becomes routine).

Recommendation 3-4. The NWS should accelerate its fledgling efforts to redesign, develop, evaluate, and verify QPFs and pQPFs and assess their use in hydrologic forecast models across a range of geographic and seasonal conditions. The Office of Hydrology should determine the time and space resolution of QPFs that hydrologic models require. Users of products who incorporate QPF data should be kept informed about these developments and their potential impact on user operations.

Snow

The ability to measure snow depth or to model snowmelt (especially in remote mountainous areas) represents a challenging hydrologic problem. The current methods are inadequate. In the first place, it is difficult to determine snow depth and water equivalent of snow over large areas to a reasonable degree of accuracy. In fact, snow depth or its water equivalent is much more poorly estimated by NEXRAD precipitation data than is rainfall. Progress has been made in recent years by the NWS National Operational Hydrologic Remote Sensing Center (NOHRSC), which has used aircraft and satellite data collection methods to improve measurements of the areal extent and depth of snowfall (Carroll and Holroyd, 1990).

Conclusion. Through its efforts, the NOHRSC has advanced the capabilities to produce guidance on areal snow coverage and snow-water equivalent. Critical measurements provided by the NOHRSC over large areas during the winter season *cannot* be obtained as effectively by any other technology.

Recommendation 3-5. Adequate resources should be provided to continue areal snow surveillance and to maintain the full complement of remote sensing technologies and activities now provided by the NOHRSC. Information from these NOHRSC activities and the use of their guidance products should be fully integrated into RFC operations.

Current snowmelt techniques are derived empirically and are not based on physical principles; the techniques are based on degree-day computation, a cumulative index related to a specific temperature threshold. As a result, during conditions of rapid melting, most hydrologic forecasts underestimate the volume of water that reaches streams and rivers. Thus flood forecasts and warnings tend to be inaccurate during periods of rapid snowmelt. The volume of water and runoff created by melting snow often makes a critical contribution to flood conditions.

Conclusion. Improvements are needed in physically based scientific techniques to predict snowmelt while retaining the positive aspects of empirically based hydrologic methods.

Recommendation 3-6. Additional resources must be devoted to improve the scientific bases to monitor and predict snowmelt, especially during situations that involve rapid melting.

Surface-Observing Networks

Surface-water observations are made by stream gauges that measure water level in rivers, streams, lakes, and reservoirs and by precipitation gauges that measure rainfall and the water equivalent of frozen precipitation (snow, hail, etc.).[1] Both stream and rain gauge data are critical sources of input data for NWS hydrologic models. Unfortunately, evidence suggests that the surface-observing networks that support hydrologic operations in the NWS and in other federal agencies are deteriorating with each passing year. There are different issues associated with each type of data network.

The backbone of the national *stream gauge network* is an intergovernmental network of continuous and partial-record gauging stations on the nation's streams, lakes, and rivers known collectively as the Cooperative Stream Gauging Network. The U.S. Geological Survey (USGS), which has a basic mission to collect surface-water information in the United States, administers the cooperative network and operates more than 85 percent of the stations in the network that support hydrologic operations in the NWS and in other federal agencies. The network is supported by funding from numerous federal, state, and local agencies. The USGS provides cooperative funding (up to 50 percent of the total) for approximately 63 percent of the national stream-gauging network; the USGS is the sole funding agency for approximately 6 percent of the national network.

Water-level data from these stream gauge stations are a critical input to the NWS hydrology program. For RFCs, the stream gauge locations determine service locations and model control point locations. Data from these reporting stream gauges are used for river forecast generation, updates, and verification.

Because of reductions in funding support, the number of stream gauge locations in the national stream-gauging network

[1] Precipitation gauges are generally referred to as rain gauges.

has become gradually smaller over time. During 1983-1994, 86 NWS service locations were affected by closures at USGS stream gauge locations; this represents 2 percent of all NWS locations nationwide. The rate of closures has increased rapidly since 1989. If model control points are included (i.e., USGS stream gauge locations used in RFC hydrologic procedures), the number of locations affected increases to 193. The decline in financial support has accelerated over the past five years because of tightening federal, state, and local budgets. This trend is disturbing because agency budgets likely will continue to tighten as pressures mount to reduce budget deficits.

Conclusion. Because the NWS does not financially support the operation of the USGS stream gauge network (except for staff gauge locations in the NWS cooperative observer network), the NWS has had a minimal influence on the placement, operation, maintenance, or potential termination of USGS stream gauges.

Issues associated with the *rain gauge network are* related not to any decrease in the number of rain gauge locations, but to the quality of data from cooperative networks, the availability of rain gauge data in real time, the geographic distribution of rain gauges, and the temporary loss of accurate precipitation data from locations where the ASOS is used to obtain local climatological data. In turn, the latter issue impacts the continuity and accuracy of the historical precipitation record.

Observations from rain gauges are available to the NWS from a variety of reporting networks. The location of these gauges is governed by the requirements of the owner agency. Many of the rain gauges are owned and operated by NWS partner agencies that share data with the NWS. These precipitation observations are especially important in the continuous modeling of soil moisture, snow accumulation, and snow ablation and in the computation of runoff in NWS hydrologic models.

The largest reporting element in the rain gauge network is the NWS cooperative observer network. The current cooperative observer network operates in basically the same manner as it did at its inception over 100 years ago. Although the network has been very successful at fulfilling its original mission in agriculture by defining the weather and climate of the United States, its data are now being used in a wider variety of ways, including precipitation processing with NEXRAD and longer-term forecasting of water resources.

The majority of rain gauge readings from the cooperative network still are acquired manually and thus are updated at most only a few times a day, based on NWS reporting criteria. The observations produced manually from the cooperative network are transmitted either daily or monthly to NWS offices by telephone or in writing on a standard form.

A primary deficiency of the cooperative network is its antiquated technology, which reduces data availability or results in inferior and missing data. In addition, the network is becoming less stable because of the growing rate at which new volunteer observers must be recruited to replace observers who are retiring or relocating. Finally, the observations are acquired at different or changing times across the United States, which makes for a very cumbersome process for using the data in the modernized NWS.

Of the 10,600 volunteer weather observer stations in the cooperative network, about 9,500 support hydrology requirements and make up the "hydrologic" portion of the network. About 5,000 of the 10,600 volunteers support the "climate" program.[2] Approximately 1,000 of the hydrologic locations provide real-time gauge readings (either rain gauge or stream gauge or both) to support modernized hydrologic operations; these can be interrogated either by phone or by satellite. The majority of the cooperative observer locations, however, can not provide real-time rain and stream gauge readings because their gauges cannot be interrogated by either phone or satellite.

Another large subset of rain gauge observations is acquired on a four- to six-hour basis from data collection platforms by way of satellite interrogation. The main concerns regarding these gauge observations are the need to receive the data in real time and the uncertain quality of the precipitation observations, especially during frozen precipitation events. The NWS is currently working with the primary owners of these data collection platforms to acquire real-time gauge readings by reprogramming data collection platforms for random transmission.

Some community (e.g., local flood warning systems) and state networks provide their rain gauge data to the NWS on a real-time basis; but here, too, the quality of the precipitation observations is sometimes questionable, especially during frozen precipitation events and high rainfall intensities. Data quality is predominantly affected by the type of rain gauge and the frequency of maintenance (i.e., routine inspection and calibration) performed by the owner agency. Clearly, data quality from these local networks is beyond the control of the NWS.

The majority of rain gauges used by state- or locally-owned networks are "tipping bucket" gauges. This type of rain gauge is often deficient during high rainfall intensities and frozen precipitation. Some local networks have added rain-rate correction equations to their data processing systems to account for errors during periods of high rainfall rates; however, few owner agencies have actually compared the corrected observations against a reference-standard rain gauge. In addition, each owner agency has its own preventive maintenance (i.e., calibration or adjustment) schedule for its rain gauges; some owner agencies do not perform any calibration on their tipping buckets. This situation obviously will affect the quality of and limit the use of the precipitation observations in modernized hydrologic forecast operations.

NEXRAD precipitation estimates are among the main sources of data for hydrologic forecasts. Remotely sensed

[2] Some cooperative stations support both programs.

rain gauges contribute significantly to the NEXRAD precipitation processing system by providing *adjusted* radar precipitation estimates to NWS forecasters. The NWS hydrology program has performed some initial assessments of the rain gauge data support for NEXRAD precipitation processing (Seo et al., 1996). In general they found that there is a strong need for additional rain gauges in many parts of the United States, including the upper Midwest, the West, the Southeast, the Southwest, and the Northern Plains. These additional rain gauges could be installed at locations in existing networks that presently do not report precipitation data, especially on data collection platforms owned by the NWS and other agencies (provided the site exposure is adequate for precipitation measurement).

There is also a need to acquire additional real-time reporting rain gauge data throughout the nation. Given the spatial distribution of the cooperative observer network nationwide, upgrading all nonrecording rain gauges in the network with rain gauges that can be automated and equipping all existing automated weighing rain gauges in the network with satellite, phone, or radio interrogation capabilities would greatly facilitate NEXRAD precipitation processing.

A continual effort must be exerted by the NWS to ensure the flow of rain gauge reports for use both in the calibration of precipitation estimates from NEXRAD and in the generation of river forecasts from hydrologic models. The simple observations represented by stream gauge or rain gauge readings are perhaps the most critical input data to hydrologic models.

Conclusion. The modernization of NWS hydrology will be hindered without the real-time availability of stream and rain gauge data. It is important for the NWS to take firm, aggressive steps to continue strengthening this major weak link in its flash flood and river flood programs.

The following are three vital areas that need attention: (1) improve the NWS' ability to efficiently retrieve observations from the cooperative observing network, from gauges owned by the U.S. Army Corps of Engineers and the USGS, and from satellite-interrogated data collection platforms; (2) work with other federal, state, and local agencies to improve the geographic distribution of real-time reporting rain gauges in data-sparse regions, so as to provide adequate rain gauge data support for each NEXRAD coverage area; and (3) strengthen coordination activities with other federal, state, and local partners to improve the quality of precipitation observations and other shared information.

Recommendation 3-7. The National Oceanic and Atmospheric Administration (NOAA) should review the status of the cooperative observing network and plan for its future in the context of the ongoing modernization. [3]

Recommendation 3-8. Additional rain gauges should be put in place in many areas of the United States where hydrologic data are sparse. These gauges should be installed at locations in existing networks that presently do not report precipitation data. To the extent possible, these should be automated, real-time reporting rain gauges equipped for remote interrogation.

Recommendation 3-9. The NWS should strengthen its partnerships with other agencies by contributing to the financial support of telemetered networks that are critical to public safety.

Inaccuracies in precipitation measurements from the ASOS rain gauge have been documented by the Office of Hydrology and by the NOAA Climate Data Continuity Project conducted by Colorado State University (McKee et al., 1996). Since 1991 these inaccuracies have affected the continuity of the historical precipitation record (especially during frozen precipitation events) at locations where ASOS records and reports local climatological data. The Office of Hydrology arranged to install and monitor a universal rain gauge at all WFOs collocated with an ASOS site so as to maintain the accuracy and continuity of the historical precipitation record for a small subset of ASOS locations that also report local climatological data (i.e., approximately 48 locations). However, the remaining ASOS local climatological data locations will not provide the same data quality and accuracy during frozen precipitation events. Engineering modifications to the existing ASOS instruments are expected to provide more accurate measurements of liquid precipitation at all ASOS locations. It also is expected that accurate inputs to the historical precipitation record will resume at all local climatological data locations after a new all-weather precipitation gauge is installed.

TOOLS AND TECHNIQUES

National Weather Service River Forecast System

The NWS River Forecast System (NWSRFS) represents a major operational and technological advance for the modernized NWS hydrology program. It is an interactive data management and forecasting software environment that replaces outdated tools and techniques used in RFCs (Page and Smith, 1993). See Box 3-2 for a technical description.

In developing the NWSRFS, the NWS Office of Hydrology has led the effort to bring advanced computation and communication technology to hydrologic forecasting. The development of the NWSRFS also represents an important initiative by a NWS team determined to move ahead with modernization plans despite delays in development of the AWIPS. As a result, the hydrology and hydrometeorology components of the AWIPS software system are among the first to be tested in the NWS.

The availability of the NWSRFS at all RFCs has generated

[3] This committee is currently coordinating with the NOAA to initiate a study of issues related to modernization of the cooperative observing network.

BOX 3-2 HYDROLOGIC PROCESSES MODELED BY THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

The National Weather Service River Forecast System (NWSRFS) is an interactive software environment with which hydrologic processes relevant to river flow conditions are modeled. Observations and forecasts of hydrometeorological variables (principally rainfall and snowfall, near-surface air temperature, humidity, and Wind speed) are used in conjunction with characterizations of surface physiographic conditions to produce discharge and stage predictions at selected points on the river networks. Key among the processes modeled by the NWSRFS is the accounting of soil moisture conditions during successive Wetting and drying episodes. Such continuous hydrologic modeling is used to track watershed and surface states that control rainfall-runoff transformation. The NWSRFS also includes snowpack and snowmelt modeling as Well as river-routing routines, its interactive system design allows forecasters to effectively use the model in testing the impact of calibration and uncertain parameters and inputs, as Well as to update the model states as observations of the modeled event are received. Development work on the NWSRFS has been focused principally on communication technologies and the interactive forecasting capabilities. Nonetheless, the NWSRFS ultimately relies on parameterizations of hydrologic processes and the success in capturing the physics of some key physical processes such as rainfall-runoff transformation and soil moisture accounting over complex terrain with variable land-use patterns.

Prior to the NWSRFS, the rainfall-runoff transformation was estimated based on antecedent precipitation index (API) measures. These rudimentary methods made estimates of soil moisture and the runoff fraction of precipitation by representing them as cumulative precipitation with a linear decay over time. Different RFCs had developed their own versions of the model, and parameter calibrations were in some cases decades out of date. The API rainfall-runoff models were mostly event based, and the interstorm period was not explicitly modeled.

The current NWSRFS alleviates some of the problems of rainfall-runoff transformation. First, it uses a modular design that allows the user to change the procedures as new tools and techniques become available. Second, the NWSRFS is · an interactive forecast program (IFP) that relies on the local platform for processors. The IFP approach to human-machine interaction is needed because of the nature of hydrologic forecast problems. Runoff processes over varied topography are difficult to capture in simple models. Rainfall-runoff models therefore are highly parameterized and require extensive calibration, even on a seasonal basis. Furthermore, precipitation observations and guidance that cause adjustments within the model processes contain substantial errors. The forecaster therefore needs to be able to use the model with different parameter choices and input sequences to determine the error structure of the forecasts.

The rainfall-runoff procedure that most RFCs will use is continuous soil moisture accounting (SMA). These moisture measurements are spatially lumped representations of the soil column as upper and lower storage zones. Nearly 20 parameters control the rates of runoff, interflow, and baseflow, all of which contribute to the stream hydrograph but with varying time scales. Clearly the calibration of these models is a central task for the RFC.

Once the calibrated rainfall-runoff model has been used to determine the precipitation excess, unit hydrographs are used to estimate the behavior of streams or bodies of water at the more than 4,000 forecast locations nationwide. Previously the hydrograph peak height was the focus of the forecast. With the incorporation of continuous SMA modeling into the NWSRFS, the entire hydrograph is used in forecasts, calibration, and verification. Once the runoff volume in the channel has been estimated, the NWSRFS contains a number of routing routines—including Dynamic Wave Operational Model (DWOPER), Flood Wave Model (DAMBRK)—to parameterize procedures for advecting the hydraulics, flood wave routing, and dam break are important and sophisticated components of both flash flood and main stem river flood hazard mitigation through forecasting.

The NWSRFS serves more tasks than IFP and calibration alone. It is also an environment for communication and exchange of data with other offices (e.g., gridded Stage II NEXRAD hourly precipitation accumulations, gridded quantitative precipitation forecasts and quantitative temperature forecasts from WFOs, headwater guidance and flash flood guidance to WFOs, and data exchanges with regional and national centers). The NWSRFS is also host to applications related to the Water Resources Forecasting System and the Extended Streamflow Prediction Program.

excitement among the RFC staff. The system allows great flexibility to manipulate observations and guidance. It also allows the forecaster to use different components effectively and efficiently.

Once the observation and guidance fields (e.g., NEXRAD and QPF fields) have been integrated into the database, the NWSRFS aids the forecaster with three major tasks. First, it uses a rainfall-runoff model to determine the fraction of the precipitation that is partitioned into infiltration and runoff. This step includes estimating the snow accumulation and its subsequent ablation. Second, it applies models that estimate the time required for the runoff to reach the river channel and flow past the forecast location. Finally, the runoff volume is tracked as it moves downstream within the channel. As part of this third stage of hydrologic forecast preparation, changes in the peak and spread of the flood wave are estimated by "river-routing" procedures.

Although the NWSRFS represents a timely and significant advance over the methods it replaces, the committee notes a serious deficiency in the system as currently configured. The science that underpins the applications lags the advanced technology considerably. The Hydrologic Research Laboratory and RFCs have redirected extensive human resources and specialized staff efforts from hydrology into systems development. Although there has been a considerable effort directed at coding and systems building, only limited resources have been directed toward expanding the scientific foundation underlying the model. Conducting technical exchanges with the USGS on modeling topics is a positive step for the NWS in improving the scientific basis for its hydrologic models.

Conclusion. A solid, technological base has been established for the NWSRFS; but because the underlying hydrologic science is out of date, the committee concludes that the NWSRFS as currently configured may not be capable of meeting future needs for improved hydrologic services. The NWSRFS should be reviewed to determine where more recent models and data sources might be incorporated into the strong technology base.

For example, digital precipitation estimates produced by NEXRAD with high spatial resolution indeed represent a breakthrough for hydrologic operations that heretofore relied on point rain gauge observations. Furthermore, high-resolution (3-arcsec, or less than 90-m) digital elevation data are now available for the entire United States. Hydrologic models based on these elevation data provide unprecedented capabilities to characterize the landscape and drainage networks. Spatially distributed, continuous simulation hydro-logic modeling[4] is now possible (Krzysztofowicz, 1995), yet it has received minimal attention in the NWS. Instead the emphasis has been on the calibration of soil moisture accounting models, a spatially lumped procedure for smaller watershed subdivisions. Such lumped parameter models were developed in the late 1960s and early 1970s when neither high-resolution precipitation data nor elevation data were available. Moreover, the limited computational capabilities at the time restricted the development of advanced models.

As another example, the current NWSRFS uses the "unit hydrograph"[5] methodology to route the precipitation that contributes to all components of the runoff (precipitation excess) over hillslopes into drainage networks. A unit hydrograph is the hydrograph associated with a unit of precipitation excess; depending on the amount and duration of precipitation excess, the unit hydrograph is scaled to produce the hydrograph at a given forecast location. The unit hydrograph essentially captures the drainage pattern and timing over the watershed drainage through the forecast location. It is an empirical tool developed decades ago in the absence of detailed topographic characterizations of drainage basins. Unit hydrographs also make an invalid assumption (one that was the best available decades ago) about the response of the basin to differing amounts of precipitation excess; that is, they assume a linear response in the behavior of the watershed.

Science and technology are two sides of the same coin. The technology that supports scientific advances must be in place before the new science can be used. If the science underpinning the technology remains static, the full potential of the technology cannot be realized.

Conclusion. It is critically important that the scientific procedures used in the NWSRFS receive increased attention and that systems development not be allowed to become an end in itself.

Recommendation 3-10. The Office of Hydrology should place greater emphasis on building the scientific foundation for the NWSRFS and integrating it with the existing strong technology base. In particular, it should consider using spatially distributed, continuous simulation hydrologic models to replace and/or augment, spatially lumped and parametric models (i.e., with heavy reliance on parameter calibration rather than physical principles to predict hydrologic conditions) in the modernized NWSRFS. Furthermore, the incorporation of empirical unit hydrographs into the NWSRFS should be reconsidered in light of the detailed and distributed digital precipitation and topography data that axe now available.

In each RFC the levels of expertise in the use of NWSRFS calibration procedures vary widely. Life-cycle support for the NWSRFS software is also necessary. This includes software

[4] Spatially distributed, continuous simulation hydrologic modeling is an approach to modeling that uses detailed, digital precipitation and topography data for collective analysis.

[5] A hydrograph is a continuous plot of instantaneous discharge, versus time, at a point along a river or stream. It results from a combination of factors related to the topography, land use, geology and, most important, storm precipitation over the area drained through the river or stream.

trouble shooting, interactions with the users, and integration of new procedures and technologies into the software. Adequate training is clearly an issue.

Conclusion. To take optimal advantage of the NWSRFS potential, perhaps the most important need is for advanced training for forecasters in the use of both the calibration features and the interactive capabilities of the system.

Recommendation 3-11. To improve consistency in the use of the NWSRFS among RFCs and within RFCs, systematic oversight and effective training programs should accompany the installation of NWSRFS systems in RFCs. Training should be provided for all appropriate RFC staff to ensure sustained proficiency in the calibration, verification, development, and use of the NWSRFS.

Flash Flood Guidance

The NWSRFS provides hydrographic forecasts at a limited number of forecast sites within each RFC' s large area of responsibility. These sites generally are located on large streams and rivers that have long lead times for flood peaks. The more short-fused flash flood hazard occurs on a considerably smaller scale that is more compatible with WFO hydrologic service areas (HSAs). To assist with the WFO flash flood program, the NWSRFS produces flash flood guidance products, which document the precipitation thresholds required to initiate flooding. Forecasters in WFOs use this guidance in conjunction with local application software to help produce flood and flash flood warnings for their HSA.

Flash floods generally result from a few hours of heavy rainfall. However, many conditions can contribute to such events. The break up of ice jams and the failure of hydraulic structures (e.g., dams and levees) are also capable of creating flash flood conditions. Other physical factors that affect flash flooding include rain intensity, antecedent soil moisture conditions, rainfall type, urbanization and extensive impervious surfaces, steep land slopes, and conditions that produce rapid snowmelt (rain on snow, warm humid air, vapor condensation, etc.).

The WFO forecaster issues flash flood warnings and watches by comparing the observed or forecasted precipitation amounts with the guidance values present in the flash flood guidance. This task is performed with the WFO Hydrologic Forecast System (WHFS) application (see next section), which incorporates "threshold runoff" values.[6]

At the WFO, forecasters may use two subsystems of the WHFS to deal with flash floods. The Site-Specific Hydro-logic Predictor System (SSHPS) works much like the NWSRFS, in that the hydrograph at a specific point in the stream represents the forecast. Headwater guidance from RFCs, along with independent calibration and soil moisture accounting, prepares the SSHPS system to predict conditions at points within the HSA. The WFO forecaster uses the second WHFS subsystem, the Area-Wide Hydrologic Prediction System, in conjunction with flash flood guidance and threshold runoff applications, to issue flash flood warnings and watches for areal zones within the HSA.

Conclusion. The WHFS, with its capabilities for both site-specific and area-wide modeling of the flash flood hazard, has great potential for dealing with the zero to six-hour flood problem if technical and scientific, training, and operational procedures problems are resolved.

Whereas the flash flood guidance is produced by soil moisture accounting with a spatially lumped model, threshold runoff is estimated based on limited data for the digital elevation model, land use, and river reach (Georgakakos, 1986, 1992). Flash flood warnings and watches are therefore produced by a mixture of lumped and distributed models.

Conclusion. The scientific foundations of both flash flood guidance and threshold runoff are derived from decades-old techniques that need significant revisions. The detailed components of both guidance products also need extensive testing as soon as is practicable before and during implementation.

Recommendation 3-12. The NWS should improve the scientific basis that underpins the forecasting of floods that occur in the zero to six-hour time frame. WFO and RFC staff should be enabled to contribute to this effort by facilitating their access to adequate training, continuing education, and university cooperative programs. Furthermore, the staff should be able to access state-of-the-art geographic information systems, databases that include digital elevation, drainage, and land-use data for use in NWS models.

Apart from purely technical issues, other issues need to be considered when flash flood warnings and watches are generated. WFO HSA boundaries may intersect RFC borders. Guidelines for the generation of flash flood guidance and its adjustment at WFOs that maintain consistency between neighboring regions have not been defined.

Conclusion. Because there is no provision to ensure the consistency of areal flash flood guidance generated from adjacent RFCs, abrupt changes in threshold runoff at RFC boundaries may result (Sweeny, 1992).

Recommendation 3-13. The NWS should develop guidelines to ensure consistency in RFC calculations and WFO-specific adjustments of area-wide flash flood guidance. The NWS also should clearly define the roles and responsibilities and the expectations for the support of site-specific flash flood forecasting at WFOs.

Weather Forecast Office Hydrologic Forecast System

The WHFS software application represents the software environment in which WFO forecasters and service

[6] Threshold runoff values are the amount of runoff required to bring streams and channels to a full bank condition.

hydrologists manage hydrometeorological data, communicate with RFCs, model hydrologic conditions within the HSA, and generate and communicate hydrologic and hydrometeorological products for the user community. As in the case of the NWSRFS, the Office of Hydrology has taken the lead in creating this application ahead of other AWIPS developments. The evolution of the WHFS has also benefited from the involvement of the Service Hydrologist Working Group.[7]

Conclusion. WHFS development at the Office of Hydrology and the interaction with the Service Hydrologist Working Group represent substantial steps toward achieving an integrated hydrometeorological system to forecast floods that have short lead times.

Similar to the NWSRFS, the WHFS is a software system with an interactive graphical user interface. The distinguishing feature of the WHFS is that it is designed to enable WFO meteorologists (as opposed to hydrologists) to handle hydrologic hazards within the HSA in an effective and skillful manner. WFO forecasters will have had some basic hydro-meteorological training and will receive assistance when the service hydrologists are available. In addition, RFC staff and the NWSRFS also influence the operational use of the WHFS system.

WFO meteorologists are expected to use the RFC guidance and the WHFS capabilities to produce flash flood and site-specific flood forecasts. They are also responsible for ensuring the availability of warning and watch products to the user community in their HSA. These responsibilities are in addition to their routine warning duties for weather hazards, which entail many user products. The effective use of the WHFS (especially of the SSHPS) during periods of severe weather when flooding is a hazard will add an unusual burden to the WFO forecaster's workload.

Conclusion. There is a potential danger that WFO forecasters may process RFC guidance products through the WHFS and issue hydrologic warning and watch products without taking adequate time for the careful scrutiny of RFC guidance. This matter is an especially acute problem in basins where hydraulic structures, small-scale land-use patterns, urban surfaces, etc., complicate the local hydrologic responses to excessive precipitation or snowmelt. In such circumstances, the hydrologic hazards of relevance to the HSA could receive inadequate attention despite the availability of high-resolution NEXRAD precipitation estimates. One essential key to the proper use of the WHFS is adequate training for service hydrologists and WFO forecasters.

Recommendation 3-14. The NWS should reevaluate the staffing needs of WFOs with regard to their hydrologic responsibilities. The number of service hydrologists should be increased so that each WFO has a program leader for WFO hydrologic operations, at least for the first year or two following implementation of the AWIPS at each field office.

The full capabilities of the WHFS can be realized only after WFO staff are adequately prepared to deal with hydro-logic forecasting during flood-water crises and severe weather conditions.

Conclusion. The WHFS needs to be tested in the most challenging of operational environments, for example, during complex, severe weather situations that create intensive forecast and warning workloads.

Recommendation 3-15. Guidelines and procedures should be in place to ensure that hydrologic and hydrometeorological forecasts meet NWS requirements (e.g., for accuracy and timeliness) under even the most challenging of operational circumstances. Operational tests should be performed to confirm that these requirements are met.

Recommendation 3-16. As WFOs and RFCs complete the transition to modernized operations, their performance should be monitored across different geographic regimes (e.g., variable climatic and hydrologic conditions) as part of the existing but expanded risk-reduction demonstration and operational test and evaluation activities. Extensive operational test and performance evaluation are especially needed for WFO functions that deal with hydrologic hazards that accompany other forms of severe weather within the HSA.

The WHFS also needs more robust quality assurance procedures for data. Such procedures will reduce the number of situations in which erroneous hydrologic forecasts are generated based on faulty observations. Both software features and user training are required to minimize this problem.

Advanced Weather Interactive Processing System

A distinguishing feature of the NWS modernization of hydrologic operations is the initiative to develop much of the AWIPS applications software in house. Consequently the NWSRFS and the WHFS interactive forecast applications are among the first components of the AWIPS to be delivered to NWS field offices. As a result of the development of the AWIPS applications in-house, many key personnel in the Hydrologic Research Laboratory and RFCs have been dedicated to the tasks of coding and programming, thereby straining already limited resources.

The Office of Hydrology has provided a minimal baseline of pre-AWIPS equipment to each RFC. This equipment has been secured through a variety of means, including allocation of government development platforms, local initiatives, and pre-AWIPS prototyping tasks.

[7] The Service Hydrologist Working Group is an advisory team, formed in July 1994, with members drawn from various field offices and headquarters staff. The working group periodically meets with regional and headquarters research and development staff to discuss issues of concern to the field service hydrologists, which may affect the evolution of the WHFS and related AWIPS software builds.

Conclusion. The AWIPS is an absolutely essential component of the NWS modernization. The software development effort at the Office of Hydrology and at RFCs has led the NWS transition into a pre-AWIPS era. However, the acquisition process and the reliance on interim solutions in advance of the full availability of the AWIPS might cause problems for future NWS operations in hydrology. The variety of interim solutions could lead to difficulties in the maintenance of operational consistency and the migration of software to the AWIPS.

Recommendation 3-17. The NWS should ensure consistency in the hardware acquisition process for RFCs and establish guidelines for consistency in the migration to the AWIPS from existing interim solutions. Issues related to the portability of the applications software that has been developed should be given high-priority attention.

Advanced Hydrologic Prediction System

As a broad suite of versatile forecasting tools, the Advanced Hydrologic Prediction System (AHPS) has been developed in response to national needs in water resources management. Water allocation under competing and increased demands (e.g., fisheries, irrigation, hydropower, and municipal use) requires higher-quality forecasts. These forecasts are also required to have longer lead times than those required for flood watches and warnings. Furthermore, both low-flow and flood conditions need to be forecast with greater precision to improve water management activities.

In support of long lead time and general (comprehensive) water resources management issues, the AHPS has tasks related to the overall NWS modernization and to the NOAA operational infrastructure (e.g., forecasting storm surge conditions on inland lakes and coastal zones, supporting activities related to in situ and remote data acquisition, and developing hydrologic coupling to atmospheric models). The AHPS also supports partnership programs with other agencies that deal with water management. This is one of the major themes in the AHPS: a group of elements collectively known as the Water Resources Forecasting System (WARFS). The WARFS is an integrated modeling, data management, and analysis program in support of comprehensive hydrologic services within the NWS. Its infrastructure includes the NWSRFS and the NOAA Hydrologic Data System,[8] in addition to other observation, modeling, and analysis systems. Long lead-time forecasts for sustainable development and efficient management of water resources are among its main objectives.

One of the key features of the WARFS is the extended stream-flow prediction (ESP) program, which involves ensemble forecasting of stream-flow with long lead times. In the ESP, the NWSRFS, with its current values of state variables, is integrated with different time-series traces of relevant historical precipitation. Clearly, a well-calibrated NWSRFS system is vital to the success of ensemble forecasts, because the "open-loop" behavior of the model[9] will strongly affect the long-lead forecasts. Each trace is weighted according to forecast conditions or occurrences of historically similar climatological settings. The advantage of the ESP is that it provides probabilistic long-lead forecast products that have important applications in water supply, flood outlook, and drought analyses. It also has the capability to deal with forecasts of minimum stream flow, which are used in the management of river navigation corridors and wildlife (e.g., fish) habitat.

Conclusion. The WARFS objectives to provide long-lead and probabilistic forecasts of low-flow and flood conditions will be important additions to the suite of products and services produced by the modernized NWS. The ensemble forecasting method used in the ESP is an innovative development in support of the WARFS. The main shortcoming of the WARFS and ESP components of the AHPS is the apparent lack of involvement by NWS field personnel and the user community during the program development.

The suite of products and services should be driven by specific external-user requirements for their particular regional environments. The committee found that the WARFS and its products and services have been, instead, principally designed in isolation at the NWS Office of Hydrology. NWS field personnel who are in routine contact with their user community, and who will ultimately be responsible for generating WARFS products and services, are well positioned to guide the design of these programs. Their responses to the committee's questionnaire (see Appendix) and comments made during committee visits to field offices indicated a lack of detailed knowledge and involvement in the program definition.

Recommendation 3-18. Field personnel and users of products and services should have greater involvement in the further definition and development of the WARFS and other components of the AHPS.

OPERATIONS

Recognizing the complexity of and urgent demand for hydrologic forecasts to meet growing societal needs, the NWS has chosen to integrate its operational missions in

[8] The NOAA Hydrologic Data System will provide the integrated data management and analysis capabilities required by the AHPS.

[9] "Open-loop" behavior refers to the use of a model to simulate long-range conditions without any correction of its forecasts (through updating the model-state variables and parameters). Such long lead-time forecasts without occasional corrections tend to reflect more the inherent characteristics of the model and less the content of observed (initial) values. As a result, the model's robustness and realism are important to the accuracy of long lead-time forecasts.

meteorology and hydrology. The new hydrometeorological focus in a modernized NWS should enable the agency to implement improved hydrometeorological operations in a more efficient and effective fashion. To achieve that benefit, it is necessary for the NWS to blend the responsibilities of WFOs and RFCs.

Conclusion. The NWS can best exploit the opportunity that the modernization affords not only by emphasizing technology but also by capitalizing on the overlapping aspects of hydrologic and meteorological science and technology and by developing new operations to aid the interaction and transfer of information between hydrologists and meteorologists. Emphasis needs to be placed on the tools and scientific principles common to the meteorology and hydrology disciplines in the NWS, while, at the same time, recognizing the distinctive nature and requirements of each.

Weather Forecast Office and River Forecast Center Interactions

With WFOs and RFCs now more than ever needing to function as a team, each has been assigned responsibilities designed to enhance and help meet their joint mission. This means WFOs will undergo a "cultural shift," with the entire forecast staff becoming involved in hydrology issues (whereas previously only the service hydrologists were involved in hydrology issues). At RFCs, an increased sensitivity to and understanding of WFO and other end-user needs are the bases for extended hours of operation and for the increased frequency of updating hydrologic guidance and forecasts.

A fundamental tenet that underpins the modernization of hydrologic operations within the NWS is the recognition that WFO service hydrologists are program leaders within their offices, not operational forecasters. However, most WFO weather forecasters currently do not perceive hydrology as part of their operational duties. Furthermore, during severe weather conditions when WFO forecasters primarily are concerned with generating warning products, the use of interactive hydrologic forecast programs might receive less attention than is warranted. This means that flash flood and head-water guidance from RFCs could be used without adjusting for locally known conditions within the HSA.

Moreover, local duties at WFOs and RFCs are event driven; they are not program based (i.e., hydrologic policies versus meteorological policies). This situation has led field personnel to express concerns about the ability of NWS management to integrate successfully hydrology and meteorology into the operational environment at WFOs. Fortunately the hydrometeorological analysis and support (HAS) unit at each RFC represents a unique opportunity to overcome the historical separations that have existed in field operations between hydrology and meteorology personnel. Indeed, the position announcements for HAS staff indicate a primary responsibility for leading the effort to improve the interaction between WFOs and RFCs—an effort that will be facilitated further by the fact that many meteorologists are being assigned to the HAS units.

Nevertheless, training and staffing are fundamental issues that are implicit in the modernized operations of a WFO and a RFC. Modernized equipment exists, along with new models and algorithms, and a new organizational structure will soon be in place. However, sufficient staff must also be in place who have the appropriate training to take advantage of these modernized capabilities. As noted in Chapter 1, only 80 of the 119 WFOs will have an assigned service hydrologist. Moreover, today's WFO forecaster will face a myriad of complex hydrometeorological issues that are not easily dealt with—specially in complex basins with physical controls such as reservoirs and dams.

Conclusion. Even with the support of HAS personnel at RFCs and service hydrologists at WFOs, hydrometeorological forecasting at WFOs may at times produce an excessive workload for the planned staffing. Responsibilities and staffing levels may have to be rethought and adjusted over time. Nevertheless, appropriate training will be crucial (see Chapter 4).

Another concern is that river basins have been apportioned among the various WFOs according to geopolitical boundaries rather than physiographic boundaries.[10] This apportionment will cause confusion among those users who do not know where to acquire hydrologic forecasts and warnings for their area. NWS field personnel are also concerned about their ability to maintain continuity and consistency in hydrologic forecast and guidance products because hydro-logic service areas of responsibility are no longer coincident with county warning areas of responsibility. For example, four different RFCs have responsibility for parts of Colorado (e.g., the Denver WFO receives guidance from three RFCs).

Conclusion. To avoid these problems, it will be incumbent on NWS management to ensure the continuity and consistency of hydrologic products issued or used by RFCs and WFOs in overlapping areas of hydrologic service responsibility.

Other operational issues of concern to field personnel include questions about how WFOs that use site-specific hydrologic models in the WHFS will be able to reconcile their results (especially at collocated forecast points) with those produced independently at RFCs. What if the two sets of forecast results disagree, especially during a short-fused emergency situation? What established protocols are in place to resolve differences that might arise between the WFO service hydrologist and RFC hydrologic forecasters? Although

[10] Geopolitical boundaries such as county warning areas are assigned to WFOs based on the severe weather detection coverage provided by the nearest NEXRAD.

the WFO is expected to coordinate any changes to RFC-issued forecasts directly with the issuing RFC, the question at the WFO is not one of revising RFC guidance, but *adapting* RFC guidance.

Conclusion. In the situation of an evolving hybrid event that is intermediate between a flash flood and a river flood, NWS policies do not make clear who has the final word in regard to the forecast and warning products actually issued to the public. The committee feels that WFOs should have the basic responsibility for continuity and consistency of flood products going to the users who receive such products from WFO communication links that operate 24 hours per day.

Recommendation 3-19. The NWS should consider the need for more personnel in the hydrometeorological forecasting function. A formal "task analysis" of this function should be considered if difficulties are identified during operational test and evaluation and risk-reduction activities. Nevertheless, adequate training and cross-training is vital for WFO and RFC staff with hydrometeorological forecasting responsibilities.

Recommendation 3-20. HSA boundaries should, to the extent practical, be divided along basin boundaries rather than geopolitical boundaries. In areas where adjacent HSAs are under the supervision of different regional offices, the NWS should ensure that the services of these offices are provided to users with the same operational philosophy and in the same format for the same product.

Recommendation 3-21. NWS headquarters should develop clearly stated policies that help WFOs and RFCs reconcile apparent discontinuities in forecasts that occur when site-specific models at WFOs produce hydrologic warnings and forecasts that conflict with RFC guidance for the same forecast point.

Data Archiving, Verification, and Quality Assurance

A comprehensive data archiving system is the essential ingredient around which future improvements in the hydro-logic forecast system of the NWS must be built. The current system fails to archive and efficiently retrieve most of the data that will be needed for twenty-first century improvements in NWS hydrology. These data include:

- the hourly precipitation summaries from Stage II and Stage III processing of NEXRAD data
- rain gauge and stream gauge observations used to calibrate NEXRAD precipitation patterns or to calibrate and validate hydrologic forecast models
- daily knowledge of basin characteristics such as vegetation indices, antecedent moisture conditions, and major construction
- stage-discharge rating curves that relate flow volumes to stream gauge readings
- records of previous stream flows documented on up-to-date E-19 forms of the NWS

The NOAA Hydrologic Data System, now under development (NWS, 1996b), represents an attempt to meet the needs of the Water Resources Forecasting System and of various climate programs. Although it has not yet been implemented, the NOAA Hydrologic Data System appears to meet the data archive needs of operational activities in river and flash flood forecasting.

Conclusion. A lengthy archive of all basin data is essential to calibrate hydrologic models (old and new) and improve model performance during critical high-water and low-water situations.

For example, hydrologic models have always suffered from a lack of knowledge about the distribution in space and time of precipitation that produced floods or led to drought conditions. Yet gauge-calibrated precipitation estimates from the NEXRAD network provide a unique opportunity to produce hydrologic guidance and forecasts with an unprecedented level of detail (i.e., at the subcounty level and on time frames of one to three hours). Satellite imagery can provide details on the areal extent and intensity of precipitation.

Conclusion. With increasing demands for hydrometeorological data in an interactive forecast environment, efficient methods for accessing, storing, and viewing these data are required.

Recommendation 3-22. The suite of precipitation products produced by the NEXRAD network, along with accompanying surface rain and stream gauge information, should be archived by the NWS for future use when new hydrologic models require calibration before they can be implemented. The NWS should ensure that appropriate access, storage, and visualization methods, such as those planned in the NOAA Hydrologic Data System, are developed or adapted for use with the entire spectrum of hydrologic data.

A second essential ingredient to improve hydrologic services is an adequate forecast verification system. Such a system must provide a baseline that documents previous forecast skill levels and also detects small improvements in forecast skills that result from new models being developed, calibrated, and implemented. The NWS is pursuing such a system in its National Hydrologic Forecast Verification Program (NWS, 1996b).

Conclusion. Currently the verification of hydrologic forecast products is inadequate. Hydrologic model development and the incorporation of new scientific tools into a modernized work environment should be accompanied by a rigorous verification program to document what progress has been achieved. The National Hydrologic Forecast Verification Program represents an important set of plans for overcoming this deficiency in the hydrology program of the NWS.

Recommendation 3-23. The NWS should implement and provide the sustained support that is needed to continue the development and operation of the National Hydrologic Forecast Verification Program.

Although a comprehensive data archive is essential to achieve future improvements in the hydrologic forecast system, *the quality of data in that archive* is at least as important. Nowhere is the phrase "garbage in, garbage out" more relevant than when applied to the data used to calibrate the performance of new or improved hydrologic models or to produce a real-time forecast during critical events. All surface-water hydrology models live and die by the quality and quantity of input precipitation patterns, state variables of the models, and stream-flow hydrographs.

The Hydrology Panel found general agreement among NWS field office hydrologists that the quality assurance of precipitation and river gauge data from telemetered networks is severely lacking. Most quality assurance is achieved by manual methods and is limited primarily to "screening" data received from the cooperative observing network. The problem becomes especially acute when the data are gathered by many different agencies at all hours of the day and night.

Conclusion. Although the NOAA is establishing the NOAA Hydrologic Data System, this system likely will not in itself improve the quality of data used in real time at the local WFO and the RFC, which determine the spatial and temporal scale at which forecasts are prepared. To alleviate this problem, the HAS units, service hydrologists, and hydro-meteorological technicians need to respond as vital components in the quality assurance effort. It is important to note that quality assurance is not limited to flagging extremes in the data stream. Instead, accepted practices in quality assurance require a mix of daily oversight that ranges from automating the detection of data extremes to tabulating frequently missed observations. A considerable effort is needed in NWS field offices before these "low-priority duties" are elevated to their proper status.

Recommendation 3-24. NWS management should take aggressive steps to implement data quality assurance procedures at the local level for archivable precipitation and river gauge data. These procedures should be automated to the extent feasible, deal with the full range of hydrometeorological data, and follow accepted standards for quality assurance. The NWS should establish guidelines for consistent use of data quality assurance procedures at both WFOs and RFCs. These guidelines should be reinforced by appropriate training of personnel. Data providers from cooperative agencies should be invited to participate in training activities where possible.

The full implementation of the AWIPS will significantly improve NWS capabilities for archiving, verification, and quality assurance of data.

Data Source Reliability

Data for use in hydrology and hydrometeorological analyses and models are the lifeblood of river forecasts and flash flood products. These data include information from automatic and manual sources such as stream gauges, precipitation gauges, cooperative observers, flood warning systems, satellite-relayed data, telemetered data and, most important, data from the NEXRAD network. Satellite precipitation estimates can contribute useful hydrologic information in some areas.

It is possible to make an accurate forecast with primitive models and complete, accurate data. It is not possible to make an accurate forecast with inaccurate or incomplete data, even with the most advanced models and interactive tools.

The NWS provides a nationwide river forecast service, with forecasts for 4,018 stream gauge locations. Of these 4,018 locations, 77 percent are operated and maintained by the USGS. Over the past two decades, NWSRFS requirements have increased because of expanding U.S. population, urbanization, and economic growth.

At the same time, as the NWS requirements for surface-water information have increased, the number of stream gauge stations has declined steadily over the last 10 to 15 years, primarily because of a general tightening of federal, state, and local agency budgets.

Another major impact is on the historical archive of surface-water information used by the NWS. The archive of surface-water information plays a pivotal role in hydrologic model calibration, development, and refinement of hydro-logic forecast procedures. The decline in surface-water information has resulted in a loss of continuity at many previously archived stream gauge stations. These losses, although not apparent in the short term, will have long-term effects on such NOAA programs as the Water Resources Forecasting System and global climate programs such as the Global Energy and Water Cycle Experiment (GEWEX) and the GEWEX Continental-Scale International Project. The NWS hydrology program will require additional real-time and archived surface-water information to support current and future river forecast services for the nation.

Conclusion. Interagency cooperative programs for hydro-logic data collection are critical to the success of river forecast and flash flood guidance forecast programs within the NWS. However, ownership of these data sources are distributed across federal, state, and local government or private networks. Abrupt funding changes and uncertainties cause some data sources to be unstable, unreliable, or subject to short-notice curtailment or elimination, sometimes with no apparent coordination or consideration for the impact of their loss on NWS operations. It is essential that a shared ownership exist for the nation' s water management and flood warning infrastructure, lest this infrastructure lose its ability to meet growing operational demands.

Recommendation 3-25. The NWS, along with other federal agencies and local and state governments, should coordinate hydrologic and hydrometeorological data requirements, data collection, and processing. Priorities among these data should be set and appropriate funding allocated by the parties involved to maintain a consistent, reliable set of data for national and local flood forecasting programs. The NWS should exert leadership to forge an explicit partnership for sharing data collection resources.

PRODUCTS AND SERVICES

A service agency such as the NWS is known by the quality, relevance, and ease of access and use of its products. Nowhere are these traits more critical than in river and flash flood situations where lives and property are threatened—situations that often arise late at night and in rural areas. In these situations, a forecast and warning *system* provides an unacceptable level of service when the forecasts and warnings are inaccurate or difficult to decipher, or when they fail to reach the population at risk. Repeated experiences demonstrate that the current dissemination technology often fails to bring critical information to those at risk. Too often, dissemination is hampered by the slow process of individually contacting city officials and emergency managers (including law enforcement and public works agencies) in various municipalities within the HSA.

The potential consequences of this situation have become more severe because of the larger percentage of the U.S. population now living in flood-prone areas, the escalating cost of repairing flood damages and the high economic toll of such disasters in a complex economy, and the increased scrutiny that government agencies are undergoing during times of diminishing resources and budget crises.

Conclusion. To achieve the dividends of modernization requires that the NWS and its myriad of users understand each other's needs and capabilities, establish highly efficient telecommunication linkages, and support or advocate mutually beneficial programs. In the committee's view, the NWS must move from a vision of providing technology to a vision of providing new services based on opportunities to implement advances in hydrologic science and technology.

Interaction with the user community is an ongoing activity that spans the NWS. It needs continual nurturing. Yet NWS field hydrologists repeatedly voiced their concerns to the committee that not enough dialogue and feedback had occurred with external agencies. Several individuals felt that external users had only a minimal impact in defining new hydrologic services. At the same time, these field hydrologists emphasized the importance of being in the pipeline of hydrologic information produced by other federal agencies so as to minimize miscommunication during critical, short-fused events. In a modernized WFO, service hydrologists and warning coordination meteorologists will have an impact on the coordination role with external users.

Recommendation 3-26. The NWS should continue to work with the user community to determine community needs. In particular, the NWS should focus on user concerns that may develop in regions where political boundaries and basin boundaries do not coincide.

Recommendation 3-27. The NWS should develop creative and affordable methods to disseminate its hydrometeorological information by means other than direct, individual contact (e.g., graphical warnings). These new dissemination methods need to be prototyped as soon as practicable at several locations.

4

Management and Operational Support

LEADERSHIP

NWS leaders have expended substantial efforts to plan the current modernization and acquire new technology. In particular, the committee commends the NWS for the great strides made in the modernization of the NWS hydrology program, especially when one considers the funding uncertainties and the pressures of many oversight groups. Notwithstanding these efforts, the committee identified a number of issues that require attention from NWS leaders; these issues surfaced during briefings at the NWS headquarters, visits to field offices, and in other interactions with field personnel.

Program Responsibilities and Perceptions

In contacts with field office personnel, including a review of questionnaire responses, the committee found many misperceptions, misunderstandings, or distrust of modernization activities related to hydrologic and hydrometeorological functions, products, and services. In particular, the benefits of the integration of certain hydrologic and meteorological duties and responsibilities are neither clearly understood nor readily accepted in many field offices. As described in Chapter 2, the coupling of hydrologic and hydro-meteorological service components in the RFCs (River Forecast Centers) and WFOs (Weather Forecast Offices) will require efficient working relationships in all RFC and WFO operations to provide timely and accurate products and services to public, private, and government users.

Conclusion. Misunderstandings about the roles and responsibilities of personnel within these operational elements of the NWS—particularly with respect to hydrometeorological duties—need to be resolved at all levels of the organization.

The committee found, for example, that flash flood forecasting is not perceived by NWS personnel in some field offices as having high-priority support from NWS headquarters. Part of that perception stemmed from delays in program testing and risk-reduction efforts caused by the unavailability of hardware and software programs to handle the vast amounts of hydrologic and hydrometeorological data and the local models for flash flood products. Another source of that perception was the seeming lack of "ownership" of flash flood programs. Program and development responsibilities are seen by field offices as being split between the Office of Hydrology and the Office of Meteorology, with neither in total charge of the entire hydrology and hydrometeorology modernization program for flash floods.

Recommendation 4-1. The NWS must communicate the objectives of the hydrologic and hydrometeorological aspects of the modernization program and progress that has been made in the program more effectively to its employees as well as to users of its services. In particular, the NWS should ensure that responsibilities for the integrated hydrology and hydrometeorology programs are clearly assigned and understood at all levels of the NWS. Interdisciplinary advisory or working groups such as the Service Hydrologist Working Group could be essential intermediaries in this communication process.

Availability of Advanced Weather Interactive Processing System

The AWIPS (Advanced Weather Interactive Processing System) is an essential element of data collection, quality control, processing, and electronic dissemination of hydro-logic and hydrometeorological data. The AWIPS is also essential to the integration of data, analyses, and models that enable improvements in river and flash flood forecasting programs. Although NWS leaders have pressed consistently to implement the AWIPS, a variety of technical, funding, and political setbacks have slowed the development and implementation program. As of November 1996, only 9 out of 147 planned units had been delivered to field offices. At this point in the modernization and restructuring, the relative absence of the AWIPS is preventing full realization of the benefits of the modernization program. As data from other new technology systems have become available, the lack of AWIPS work-station capabilities continues to cause growing inefficiencies in data processing and data integration, which, in fast-breaking weather situations, will result in less accurate and timely warnings than those possible with the newer work-station technologies. Indeed, it appears that some of the dissatisfaction with the modernization found among field office staff is due to the slow pace of the AWIPS implementation and the problems it has engendered.

Conclusion. Should the national implementation of the AWIPS continue to be delayed, it is certain that the voluminous data streams now being produced will not be used to their full potential. It is even possible that they will have a negative impact on hydrologic operations in a modernized NWS because the sheer volume of new data will at times overwhelm human processing capabilities.

Recommendation 4-2. The AWIPS implementation program should be expedited to enable NWS offices to exploit the use of data from new technologies and to realize improvements in the river and flash flood forecasts and warnings.

Responsiveness and Follow-Through Activities

The NWS has expended substantial time and effort in conducting national disaster surveys, usually in conjunction with representatives from other federal agencies. However, the committee found no cohesive effort to document NWS progress or follow-on activities in hydrologic or hydro-meteorological operations or programs in response to recommendations in previous national disaster survey reports. The same is true for hydrology recommendations made in previous National Research Council reports on the NWS modernization program. The committee also found no systematic procedures to update planning documents, such as *Hydrometeorological Service Operations for the 1990s* (NWS, 1991, 1996a), as technology and development activities progress. Such external inputs and reviews provide valuable feedback on the modernization and restructuring effort.

Conclusion. It is not enough to respond to external oversight with ad hoc adjustments that are recognized only internally; more-formal responses and follow-up reports are warranted and will improve the support the modernization and restructuring receives from the meteorology and hydrology community at large.

Recommendation 4-3. The NWS should establish a systematic method to report formally on activities related to recommendations for changes in its operations, products, or services that appear in disaster surveys and other policy-related oversight reports. NWS planning documents should be updated routinely to reflect such changes.

Funding

Some of the misunderstandings and criticisms of delays or priorities in the modernization of hydrology and hydro-meteorology programs can be traced to inadequate or inconsistent funding of these programs. NWS management often has few alternatives other than to stretch programs or delay acquisition, tests, or other modernization activities. The resultant turbulence ripples through the management and operational echelons to field offices, where the application of new technologies is sorely needed to improve products and services. Continued inefficiencies in the use of old technologies frustrate field office personnel because the effectiveness of their operations and services is hampered. These issues have been documented in various national disaster survey reports (NOAA, 1994c).

Funding cuts or reallocations by Congress, the U.S. Department of Commerce, and the NOAA (NOAA, 1994b, 1995b) have caused delays in the development and implementation programs for the Geostationary Operational Environmental Satellite, NEXRAD, and AWIPS (NRC, 1994, 1995). As a result, NWS forecasters have had to rely on old workstation technologies and outdated forecasting practices to provide forecasts and warnings. Needed improvements in forecast accuracy and in the efficiency of forecast operations have been delayed. Risk-reduction activities for hydrology and hydrometeorology were also delayed several years because of insufficient hardware and software assets in the NWS. Prior reports of this committee urged that funding commitments be kept and even increased to enable the modernization to proceed smoothly and on schedule (NRC, 1991b, 1992).

Conclusion. Inadequate or inconsistent funding of NWS hydrology and hydrometeorology programs yields additional costs, not only in the programs themselves, but also in property losses and even human lives.

Recommendation 4-4. Congressional action is needed to assure continuity of the funding required to complete the NWS modernization as expeditiously as possible.

RESEARCH, DEVELOPMENT, TESTING, AND EVALUATION

According to NWS plans (NWS, 1996a), the Office of Hydrology will focus on the development of national program policy, procedures, and service directives in support of the NWS hydrology program. The Office of Hydrology will also provide technical development, implementation guidance, and maintenance support for nationally supported hydrologic systems and procedures at both RFCs and WFOs. A major focus of the Office of Hydrology will continue to be the development and support of applications software to capitalize on the new hydrometeorological technologies of the modernized NWS. A significant effort will continue in the Hydrology Research Laboratory to develop and improve hydrologic and hydrometeorological techniques for river and flash flood forecasting on both an areal and site-specific basis. The committee commends the Office of Hydrology and the Hydrology Research Laboratory for establishing an extensive and aggressive software development effort for new tools and techniques for hydrology and hydrometeorology applications at RFCs and WFOs.

Research and Development

Given its small size, the NWS supports a relatively significant research and development program that has produced very useful results. The interactive hydrology forecast applications for pre-AWIPS workstation platforms are innovative and path breaking. Both the NWSRFS (NWS River Forecast System) and the WHFS (WFO Hydrologic Forecast System) are key contributions to the modernization, and their early completion represents two major milestones for the AWIPS.

The Office of Hydrology is also involved in climate research related to global change. The observation network maintenance, data quality control, and data assimilation activities of the NOAA and NWS personnel contribute to the national global change research program through the Global Energy and Water Cycle Experiment Continental-Scale International Project. (This project is a multiyear hydrology and climate research initiative focused on the Mississippi River Basin.) An improved understanding of the interannual variability of the global energy and water cycle is relevant to the main objectives of the Water Resources Forecasting System as well as to ensemble and long-range forecasting programs in the NOAA. Furthermore, the tasks related to the improvement of land-surface boundary representation (soil and vegetation) in numerical models of the atmosphere will contribute to improvements in guidance products from numerical weather prediction models that are used in operational hydrology and meteorology.

However, considerably less effort is under way on research issues related to the scientific bases of hydrologic procedures and models used in day-to-day operations. Of the existing research programs, few are related to operational flood forecasting. Limited work is under way to:

- test and incorporate new and innovative algorithms and parameterizations for the NWSRFS and WHFS hydro-logic components
- develop improved algorithms to estimate precipitation based on NEXRAD measurements
- test the performance and validate the use of quantitative precipitation forecast and probabilistic quantitative precipitation forecast in hydrologic models
- develop and evaluate operationally topography-based or distributed flood forecasting procedures

Conclusion. Although a modest level of NWS hydrology research is in progress or planned, the overall objectives, priorities, relevance, and cohesiveness of research activities within the Office of Hydrology are unclear or absent. In addition, information on NWS research and development activities is not received at field offices in a timely manner and often is not considered credible by field office staff.

Recommendation 4-5. The NOAA and the NWS should establish a formal, long-term plan for hydrologic science research that includes priorities and is relevant to river flood and flash flood forecasting. The NWS should request sufficient funding to implement and sustain the research. The plan should be communicated to field personnel so as to improve the overall NWS vision for hydrologic services in the twenty-first century. In addition, NWS headquarters should disseminate regularly to its field offices updates on research and development activities, their specific objectives, and timetables.

Operational Test and Evaluation

Test and risk-reduction activities are in progress at several sites in the central and northeastern United States (e.g., pre-AWIPS systems at Pittsburgh, Pennsylvania, and Taunton, Massachusetts).

Conclusion. The committee agrees with concerns expressed at field offices that some procedures and techniques used in these activities are tailored and modified for specific geographic areas and need to be tested for the full range of adverse weather experienced in other areas of the United States.

Recommendation 4-6. NWS operational test and evaluation for hydrology applications, especially flash floods, should be conducted in various regions around the country that experience different types of weather.

Recommendation 4-7. Updated information on NWS hydrology operational test and evaluation activities should be provided to field offices on a routine basis, both to keep employees informed and to encourage broader participation in development and test efforts.

ADVISORY GROUPS

Early in the modernization planning, the NWS established various working groups (e.g., the Service Hydrologist Working Group, the WFO Hydrologic Systems Group, the AWIPS Requirements Task Team, and Build-9 for NEXRAD) to review requirements and to develop plans to improve products and services in hydrology and hydrometeorology. Personnel at all echelons of NWS operations judged the contributions of these groups to be beneficial and effective in the establishment of a sound modernization program. Earlier National Research Council reports (NRC, 1991b, 1992) stated that consultation with field personnel would benefit the modernization program throughout its development and implementation phases; such benefits were realized. An advisory group, the Service Hydrologist Working Group, was established in July 1994 to assist with AWIPS software developments pertaining to hydrology.

Conclusion. Continuing involvement of field personnel in the modernization is vital. One or more similar advisory or working groups need to be reestablished with reference to the hydrometeorological aspects of the modernization and restructuring. Such a group could provide important feedback on data quality control, forecast verification, hydro-logic modeling, and precipitation processing techniques.

Recommendation 4-8. The NWS should use internal advisory groups consistently throughout major planning, development, test, and implementation phases of the hydrology modernization program. These groups should include field office members and be encouraged to advise NWS headquarters on matters relating to research and development, operational test and evaluation, and overall modernization implementation.

FIELD INITIATIVES

During visits to field offices, the committee found several examples of initiatives in which new flash flood forecasting methodologies had been developed that were potentially useful to other offices. Field forecasters who developed these new initiatives had received some help and encouragement from their regional office, but the perception in the field was that they had received little or no support for their efforts from NWS headquarters. More recently, centrally developed or modified site-specific and area-wide hydrologic prediction systems have been tested at several locations, and the feedback on their utility is encouraging.

Conclusion. The committee perceives that the seeming lack of support for local initiatives has resulted in part from competition for resources designated for centrally managed research and development activities. Local initiatives can be productive, both in the development of useful technologies and in building morale. Such initiatives deserve support at the highest levels.

Recommendation 4-9. The NWS should ensure that sufficient technical support and resources are available to support a modest level of local initiatives to develop forecasting techniques and methodologies at field offices.

INTERNATIONAL PROJECTS

The NWS has a long history of supporting international technology transfer activities that make U.S. hydrologic forecasting methods available worldwide. In recent years the NWS, through its Office of Hydrology, has contributed substantial technology and leadership to river forecasting and water resources management programs in other countries. For example, the modernized NWSRFS has been implemented and tested for river basins in China (Huai River) and Egypt (the Nile). Implementation of state-of-the-art observing and forecasting systems is the main objective of this initiative. These are valuable transfer-of-technology pilot projects for developing countries; the activities use tools and techniques developed by NOAA personnel for operations and training programs.

These projects are supported fully by international reimbursable arrangements. The projects have also benefited the NWS in that it has applied lessons learned in satellite precipitation estimation and other assessment techniques to applications in its national programs.

Conclusion. Although the committee was unable to determine clearly whether NWS resources that support international programs have had a positive or negative impact on the overall hydrology modernization programs, it is concerned that this type of activity could compete for key personnel or operational resources during critical development and implementation phases of the modernization.

Recommendation 4-10. The NWS participation in international water resources and climate studies projects should be reevaluated to ascertain its impact on scientific research needs that are more directly related to NWS modernization and hydrologic operations.

PERSONNEL

Given the substantial changes in hydrology-related roles and functions, both within and across field offices in the modernized NWS, assignment of sufficient numbers of appropriately qualified personnel to hydrologic duties is essential to the success of modernized operations.

Qualifications

The qualification standard for hydrometeorologists requires those hydrometeorological personnel with duties that have a meteorological emphasis to have 24 semester hours of core meteorology courses augmented by 6 semester hours in hydrology. Those personnel having duties with a hydrology emphasis are required to have only 15 hours of core hydrology augmented with 6 semester hours of meteorology (NWS, 1996a).

Because of the complexity of hydrologic science and operations in today's modernized weather service, many field office personnel feel strongly that all hydrologist and hydrology-emphasis positions should require a degree directly relevant to hydrology.

Conclusion. The committee concludes that NWS forecasters with a degree or extensive formal education in meteorology but no comparable training in hydrology usually are not qualified for hydrologist positions. A more substantial educational background in hydrology is necessary for personnel working in such positions.

Recommendation 4-11. The NWS should review and, if warranted, modify its qualification standards for hydrology positions. The NWS should require a degree or extensive formal education in hydrology for positions that involve a hydrology emphasis.

STAFFING

Overall, the NWS has done a thorough and exemplary job of defining the requirements and planning the staffing needed in the modernized hydrology and hydrometeorology functions of the NWS. There are two exceptions. First, service hydrologists will manage the hydrology programs at all future WFOs; however, only 80 of the planned 119 WFOs will have a service hydrologist assigned on station. Various workload factors such as the frequency of flash floods, proximity to other WFOs, number of RFC service locations, number of communities with flood problems, training of hydro-meteorologists, etc., were used to determine which WFOs would be assigned a full-time service hydrologist.

Conclusion. The committee remains concerned about the vital and increasingly important role that the service hydrologist will play in the modernized NWS. It is possible that most, if not all, WFOs may require a service hydrologist on station. Second, at offices where operational tests and evaluations are conducted, additional hydrologic expertise may be needed to ensure a thorough, effective test of the new systems and techniques.

Recommendation 4-12. The NWS should continue to review and adjust hydrology staffing to meet specific operational needs as the modernization progresses.

TRAINING

Anticipating that the new technologies and scientific advances associated with the modernization would require a massive restructuring of its training methods and courses, the NWS developed a comprehensive master training plan for the hydrometeorological service organizations for the 1990s (NWS, 1996a). An outline of this plan for hydrology and hydrometeorology training is presented in Table 4-1. The table lists the basic education courses and their contents; most courses are required of entry-level hydrologists at RFCs and WFOs. The list also includes a mix of correspondence courses, distance learning modules, and training on new systems as they are implemented at weather offices.

The plan requires RFC and WFO personnel to take a variety of hydrology and hydrometeorology training courses and modules. The Basic Operational Hydrology (BOH) course, which is offered at the National Weather Service Training Center (NWSTC) in Kansas City, Missouri, consists of 104 classroom hours and is intended mainly for hydrology interns and hydrologists who are new to the NWS. The principal focus of BOH is on operational and procedural topics. It provides an overview of hydrometeorology networks and sensors, data quality control, operational river forecasting, snow modeling, unit hydrograph theory, and basic topics in heavy precipitation and flash flooding.

At the NWSTC, the existing Flash Flood Course has been revised to include considerably more material on the modernized flash flood guidance and the WHFSs. The new course, entitled "WFO Operational Hydrometeorology Forecasting," teaches AWIPS-era hydrometeorology to meteorologists. This course chiefly provides practical training on the WHFS for meteorological forecasters who will use this system to generate flood warnings and advisories. Service hydrologist personnel will also complete this course.

The Cooperative Program for Operational Meteorology, Education, and Training (COMET) (conducted by the University Center for Atmospheric Research) and its component modules are also available to NWS personnel. The COMET course is taught over three weeks and offers basic training in the hydrologic sciences. It is specifically designed for hydrometeorological analysis and support forecasters, but other RFC forecasters may also enroll. The COMET provides training on basic hydrometeorological theory, with a focus on meteorological and hydrometeorological conditions important to hydrologic forecasts. The course is also designed to enable WFO science operations officers and service hydrology personnel to couple the hydrologic and meteorological functions at the WFO effectively.

NWS personnel working on hydrologic operations have also relied on correspondence courses; nearly 55 percent have taken at least one correspondence course in a hydrology-related discipline. However, these courses are of varying quality, and the material is often dated or not relevant to the operational duties of NWS personnel.

Other sources of specialized training exist for various hydrology and hydrometeorology positions in the NWS. Development and operations hydrologist personnel receive training at the Hydrology Research Laboratory, and workshops are organized occasionally to meet other needs. NEXRAD, Automated Surface Observing System User, and RFC Gateway courses are available to RFC forecasters. In addition, AWIPS User Training, Computer Operations and Systems Training, the COMET Field Office Managers' Course, and Hydrologic and Climatological Networks courses satisfy additional specialized training needs.

Conclusion. After reviewing the training plan and course contents in light of the operational duties and responsibilities of hydrologists and hydrometeorologists, and based on the reactions of NWS personnel to their participation in various courses and training programs (see the appendix), the committee concludes that new, specialized hydrology training modules are necessary to prepare hydrologic forecasters for their new and complex duties and to fulfill the potential of the modernization.

The committee also notes that technical materials in the NWSTC BOH course, applicable U.S. Department of

TABLE 4-1 Summary of Basic Training Courses Available for the Modernized Hydrology Program

University Education

College and/or university courses necessary to meet the Hydrometeorologist Qualification Standard (i.e., qualify as Type A or Type B hydrometeorologist) and to advance to higher positions in the NWS hydrology program.

WSR-88D Operations Course

Theory of Doppler weather radar technology, operational use of WSR-88D products.

Automated Surface Observing System Training

Operational use of Automated Surface Observing System training data

AWIPS User Training

Operational use of AWIPS.

AWIPS Systems Training

Systems, software, and database features of AWIPS.

RFC-Unique Systems Training

Operational use of Gateway II computer systems.

Computer Operations and Systems Training

NWS-identified courses and manuals on programming languages, operating systems, telecommunications packages, and applications procedure design.

Specialized Development and Operations Hydrologist Training

Annual one-week workshop at Office of Hydrology covering advanced hydrology and hydrometeorology applications.

NWS Basic Operational Hydrology Course National Weather Service Training Center

Overview of hydrometeorological networks and sensors; introduction to hydrologic modeling principles including river and reservoir routing, snowpack modeling, and model calibration; and overview of administrative reports and forms used for the NWS hydrology program.

COMET Hydrometeorology Course

Operational application of advanced hydrometeorological networks and sensors; introduction to hydrologic modeling principles including river and reservoir routing, snowpack modeling, and model calibration; and overview of administrative reports and forms used for the NWS hydrology program.

NWS WFO Operational Hydrometeorological Forecasting Course National Weather Service Training Center

Operational application WFO hydrometeorological AWIPS forecasting techniques.

Advanced Hydrology and Hydrometeorology Workshops

Background and theory of hydrometeorological analysis techniques, hydrologic modeling systems, model calibration, interactive hydrologic forecasting, and operational applications.

Meteorological Training for Hydrologic Forecasters

Training in the basic principles of meteorology. Intended for individuals with hydrology backgrounds.

Hydrologic Training for Meteorologists

Distance learning module in basic science of hydrology. Intended for individuals with meteorology backgrounds.

Hydrologic Services (Correspondence) Course H

History and current policies of the NWS hydrologic services program.

Hydrologic and Climatologic Networks Training

Distance learning modules providing knowledge on hydrologic and climatologic networks.

Field Office Managers Course National Weather Service Training Center

Management and administrative responsibilities of meteorologists-in-charge and hydrologists-in-charge in the modernized NWS.

Agriculture correspondence courses, and COMET modules are far behind the development and implementation of new tools and techniques in the RFCs and WFOs. The committee agrees with the NWS that service hydrologists are central to effective hydrologic operations in the modernized NWS insofar as WFO meteorological forecasters do not have the experience base or the educational foundation to deal with hydrographs in complex watersheds—especially those containing water control structures (such as dams).

Conclusion. Although the new WFO Operational Hydro-meteorology Forecasting course may be adequate for WFO meteorological forecasters, it does not adequately meet the needs of service hydrologists, who also serve as the scientific liaisons for WFO hydrology.

Recommendation 4-13. The NWS should develop new, specialized hydrology training modules for RFC staff and WFO service hydrologists that are compatible with the new models and procedures in the interactive hydrologic forecast environment. This training should include new quantitative forecast techniques and the use of distributed observations from a variety of new sensors and sources.

5

Epilogue: An Overall Assessment

This committee was asked to examine the adequacy of the NWS plans and progress toward the improvement of hydrologic and hydrometeorological products and services, to assess the effectiveness of the NWS in the use of new technology and science to achieve those improvements, and to identify additional steps necessary to realize the full promise that the modernization of hydrologic and hydrometeorological operations and services offers for the nation. The committee has identified many areas where improvements are needed—in the interaction between RFCs (River Forecast Centers) and WFOs (Weather Forecast Offices), in the further integration of hydrology and hydrometeorology, in staffing levels in some functions, in research planning and operational test and evaluation, in communication with field office staff regarding important aspects of the modernization, and in other areas. The report has presented specific recommendations for changes in these areas.

Nevertheless, the committee' s overall impression is positive. Modernization plans for the NWS hydrology program are incorporating recent technological advances into field offices and thereby producing a major beneficial effect on the spirit and outlook of NWS personnel. In visits to various NWS offices and in meetings with field personnel at all echelons, the committee found sincere enthusiasm. NWS staff members at all levels are truly excited about using new tools and techniques to deliver improved products and services to users. Enabling such a highly motivated workforce by providing them with the needed equipment and support clearly is in the public interest; it is an opportunity that should not be lost.

The new technological advances that have been and are being incorporated into the hydrologic and hydrometeorological operations of the NWS provide a capability to make detailed characterizations of precipitation fields, which are among the key factors needed to produce better-quality river and runoff forecasts. The NEXRAD network, coupled with Automated Surface Observing System and advanced communication links to other real-time sources of surface- and satellite-based estimates of rain and snow amounts, provides data of an unprecedented quality for hydrologic operations. Powerful computational machines will provide advanced capabilities to process the precipitation data, and thereby allow forecasts of runoff and the route of the flood wave through drainage networks to be generated in time for effective communication to the public. The new computation and communication technologies allow the introduction of interactive forecast environments that enable forecasters to use the models effectively to develop and disseminate hydro-logic products and services.

The NWS hydrology program has taken a leadership role in supporting the implementation and use of the new observation networks and in developing state-of-the-art interactive forecast systems. Most of the advances just described are contingent on the full national implementation of the AWIPS (Advanced Weather Interactive Processing System). To that end, the Office of Hydrology has led in implementing extensive and aggressive pre-AWIPS and AWIPS development efforts. NWS field personnel are eager to access these tools and observations to improve services to their user communities.

These findings are encouraging. They bode well for the eventual outcome of the modernization of NWS hydrology and hydrometeorology operations and services. To be sure, there are barriers that must be overcome—financial, technological, operational, and organizational. But such barriers are virtually universal in contemporary large-scale, high-technology endeavors, whether in the government or the private sector. The committee is confident that if the changes recommended in this report are made, the outlook for achieving the goals of the modernization will be highly favorable.

References

Atlas, D., D. Rosenfeld, and A.R. Jameson. 1996. Evolution of radar rainfall measurements: steps and mis-steps. Pp. 1-60 in Weather Radar Technology for Water Resources Management, B. Braga and O. Massambani, eds. Montevideo, Uruguay: UNESCO Press.

Carroll, T.R., and E.W. Holroyd. 1990. Operational remote sensing of snow cover in the U.S. and Canada. Pp. 286-291 in Proceedings of International Symposium, Hydraulics and Irrigation Division, American Society of Civil Engineers, San Diego, California . Reston, Va.: American Society of Civil Engineers.

Chapman, R.E. 1992. Benefit-Cost Analysis for the Modernization and Associated Restructuring of the National Weather Service (NISTIR 4867). Washington, D.C.: U.S. Department of Commerce. 118 pp.

Charba, J.P., and W.H. Klein. 1980. Skill in precipitation forecasting in the National Weather Service. Bulletin of the American Meteorological Society 61(12): 1546-1555.

Davis, R.S., and W.J. Drzal. 1991. The potential use of WSR-88D digital rainfall data for flash flood applications on small streams. National Weather Digest 16(2):1-18.

DOC (U.S. Department of Commerce). 1989. Strategic Plan for the Modernization and Associated Restructuring of the National Weather Service. National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland. 24 pp.

Fread, D.L. 1995. A pathway towards improving hydrologic predictions. Journal of Hydraulic Research, June.

Fread, D.L., R.C. Shedd, G.F. Smith, R. Farnsworth, C.N. Hoffeditz, L.A. Wenzel, S.M. Wiele, J.A. Smith, and G.N. Day. 1995. Modernization of the National Weather Service river and flood program . Weather and Forecasting 10(3):477-484.

Georgakakos, K.P. 1986. On the design of national, real-time warning systems with capability for site-specific, flash flood forecasts. Bulletin of the American Meteorological Society 67(10):1233-1239.

Georgakakos, K.P. 1992. Real-time flash flood prediction. Journal of Geophysical Research 92(D8):9615-9629.

Krzysztofowicz, R. 1995. Recent advances associated with flood forecast and warning systems. Reviews of Geophysics, July Supplement: 1139-1147.

Larson, L.W., R.L. Ferral, E.T. Strem, A.J. Morin, B. Armstrong, M.D. Hudlow, L.A. Wenzel, G.L. Schaefer, and D.E. Johnson. 1995. Operational responsibilities of the National Weather Service river and flood program. Weather and Forecasting 10(3):465-476.

McKee, T.B., N.J. Doesken, and J. Kleist. 1996. Climate Data Continuity with ASOS. Report for the Period September 1994-March 1996. Climatology Report No. 96-1. Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.

NOAA (National Oceanic and Atmospheric Administration). 1994a. A Summary of Natural Hazard Fatalities for 1994 in the United States. Washington, D.C.: U.S. Department of Commerce. 10 pp.

NOAA. 1994b. Summary of the President's Budget Fiscal Year 1995. Washington, D.C.: U.S. Department of Commerce. 81 pp.

NOAA. 1994c. Natural Survey Disaster Report. The Great Flood of 1993. Washington, D.C.: U.S. Department of Commerce.

NOAA. 1995a. River and Flood Program. Washington, D.C.: U.S. Department of Commerce.

NOAA. 1995b. Summary of the President's Budget Fiscal Year 1996. Washington, D.C.: U.S. Department of Commerce. 94 pp.

NRC (National Research Council). 1991a. Opportunities in the Hydrologic Sciences. Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources. Washington D.C.: National Academy Press. 348 pp.

NRC. 1991b. Toward a New National Weather Service—A First Report. National Weather Service Modernization Committee. Washington D.C.: National Academy Press. 67 pp.

NRC. 1992. Toward a New National Weather Service—Second Report. National Weather Service Modernization Committee. Washington D.C.: National Academy Press. 78 pp.

NRC. 1994. Advancing the Understanding and Forecasting of Mesoscale Weather in the United States. Committee on Meteorological Analysis, Prediction, and Research. Washington, D.C.: National Academy Press. 29 pp.

NRC. 1995. Toward a New National Weather Service—Assessment of NEXRAD Coverage and Associated Weather Services. National Weather Service Modernization Committee. Washington D.C.: National Academy Press. 78 pp.

NWS (National Weather Service). 1991. Hydrometeorological Service Operations for the 1990s. Silver Spring, Md.: National Weather Service.

NWS. 1992. Flash Floods and Floods: A Preparedness Guide. (NOAA/PA 92050). National Oceanic and Atmospheric Administration. Washington, D.C.: U.S. Government Printing Office.

NWS. 1996a. Hydrometeorological Service Operations for the 1990s. Silver Spring, Md.: National Weather Service.

NWS. 1996b. National Hydrologic Forecast Verification Program Plan. Draft, Part E of National Weather Service Operations Manual. Silver Spring, Md.: National Weather Service.

Olson, D.A., N.W. Junker, and B. Korty. 1995. Evaluation of 33 years of quantitative precipitation forecasting at NMC. Weather and Forecasting 10(4):498-511.

Page, D., and G.F. Smith. 1993. National Weather Service Operational River Forecast System in a UNIX Environment. Paper presented at ASCE International Symposium on Engineering Hydrology, San Francisco, Calif., July 25-30. 6 pp.

Seo, D.J., R. Fulton, J. Breidenbach, M. Taylor, and D. Miller. Final Report for interagency memorandum of understanding among the NEXRAD Program, WSR-88D Operational Support Facility, and the NWS Office of Hydrology, Hydrologic Research Laboratory, May 22, 1996. National Weather Service, Silver Spring, Md.

Stallings, E.A., and L.A. Wenzel. 1995. Organization of the river and flood program in the National Weather Service. Weather and Forecasting 10(3):457-464.

Sweeny, T.L. 1992. Modernized Areal Flash Flood Guidance. NOAA Technical Memorandum NWS HYDRO 44. Silver Spring, Md.: National Weather Service.

Acronyms

AHPS	Advanced Hydrologic Prediction System
API	antecedent precipitation index
ASOS	Automated Surface Observing System
AWIPS	Advanced Weather Interactive Processing System
BOH	Basic Operational Hydrology
COMET	Cooperative Program for Operational Meteorology, Education, and Training
ESP	extended stream-flow prediction
GEWEX	Global Energy and Water Cycle Experiment
GOES-Next	Next Generation Geostationary Operational Environmental Satellite
HAS	hydrometeorological analysis and support
HSA	hydrologic service area
IFP	interactive forecast program
NCEP	National Centers for Environmental Prediction
NEXRAD	Next Generation Weather Radar
NMC	National Meteorological Center (now reorganized as the National Centers for Environmental Prediction)
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRC	National Research Council
NWS	National Weather Service
NWSMC	National Weather Service Modernization Committee
NWSRFS	National Weather Service River Forecast System
NWSTC	National Weather Service Training Center
PPS	Precipitation Processing System
pQPF	probabilistic quantitative precipitation forecast
QPF	quantitative precipitation forecast
QTF	quantitative temperature forecast
RFC	River Forecast Center
SMA	soil moisture accounting
SSHPS	Site-Specific Hydrologic Predictor System
USGS	United States Geological Survey
WARFS	Water Resources Forecasting System
WFO	Weather Forecast Office
WHFS	Weather Forecast Office Hydrologic Forecast System
WSFO	Weather Service Forecast Office
WSO	Weather Service Office
WSR-88D	Weather Surveillance Radar 1988 Doppler

Glossary

B

Basin: The entire land area with a common outlet for surface runoff.

Basin boundary: The perimeter of a basin (or on a map, the line demarcating the perimeter) beyond which surface runoff drains away into another basin.

Calibration: The process of optimizing parameters of a hydrologic model to provide the best simulation of historical stream flow by use of precipitation, temperature, and other hydrometeorological data from the historical record.

Climate Data Continuity Project (CDCP): A NOAA-funded project to document differences in several hydrometeorological observations (i.e., temperature, precipitation, and wind) measured by pre-Automated Surface Observing System instrumentation and ASOS instrumentation at airport locations.

Climatic areas: Regions that can be grouped according to distinctive types of average weather conditions, especially patterns of seasonal precipitation and temperature. Differences in climate between two areas can have a strong effect on the corresponding hydrologic characteristics of each area.

Cooperative observer: An individual (or institution) who takes precipitation and temperature observations—and in some cases other observations such as river stage, soil temperature, and evaporation—at or near his or her home or place of business. Many observers transmit their reports by touch-tone telephone to an NWS computer, and nearly all observers mail monthly reports to the National Climatic Data Center to be archived and published.

Data collection platforms (DCPs): Devices that acquire, record, and transmit data from various types of environmental sensors. DCPs often operate on a timed basis. The term DCP is often modified to describe a data collection network to which the DCP belongs (e.g., Geostationary Operational Environmental Satellite DCP for DCPs that report environmental data by way of the Geostationary Operational Environmental Satellite).

Doppler radar: A radar capable of measuring the change in frequency of a radar wave caused by the relative motion of an object in the atmosphere within the area of radar coverage. Doppler capabilities are not used in the process of converting radar echoes to precipitation estimates.

Drought: A period of abnormally dry weather sufficiently prolonged to cause a serious hydrological imbalance.

Ensemble forecasting: In a hydrologic modeling context, a process whereby a hydrologic model is successively executed several times for the same forecast period by the use of varied data input scenarios or a perturbation of a key variable state for each model run. A common method employed to obtain a varied data input scenario is to use the historical meteorological record, with the assumption that several years of observed data covering the time period beginning on the current date and extending through the forecast period comprise a reasonable estimate of the possible range of future conditions.

Flash flood: A flood caused by water that rises rapidly from a normal level to inundation. Within the context of NWS hydrologic services, "rapidly" means within six hours.

Flood: A higher than normal flow on a stream, triggered by a causative event such as heavy rainfall, snowmelt, or reservoir release, in which the stream level equals or exceeds a predetermined flood stage. Flood forecast: Any numerical forecast product made for a stream in which at least one forecast value exceeds flood stage or flow (same as "river flood forecast").

Flood stage: An established stream level at a given gauge location at which high water begins to have an adverse impact either upstream or downstream from the gauge location.

Flood warning: An NWS product issued to provide advance notice that a specific river or rivers will equal or exceed flood stage. Actions to be taken to mitigate losses are determined by the level of severity indicated in the flood warning product.

Forecast skill: A statistical measure of how well forecasts predict what actually occurs.

Forecast verification: The process by which forecasts are later compared to observed values for the same time period to evaluate the accuracy and timeliness of forecasted values.

Hydrograph: A graphical plot of stream stage or discharge versus time that shows how stream flow varies over time at a given stream location.

Hydrologic cycle: The continual process by which water evaporates from the surface of oceans, lakes, other water bodies, and land; exists in the form of atmospheric moisture; forms into clouds and falls to the ground as precipitation; and flows through a stream network or groundwater system back to the oceans to repeat the process.

Hydrologic model: A conceptual or physically based procedure to simulate numerically a process or processes that occur in a stream basin.

Hydrologic services: A general term referring to the operations, products, verbal communication, and related forms of support provided by the NWS regarding the streams, rivers, and other areas affected by surface water.

Hydrology: The science dealing with the processes that control the movement of water across and under the surface of the land.

Hydrometeorology: An interdisciplinary science involving the study and analysis of the interrelationships between the atmospheric and land phases of water as it moves through the hydrologic cycle.

Kalman filter: A mathematical formulation that weighs two comparable pieces of information (e.g., an observation and a simulated value) to provide an optimized output based on the error characteristics of both pieces of information.

Local-area forecast: In the pre-modernization and associated restructuring of NWS, a locally tailored weather forecast that was prepared and issued by a WSO based on more general forecast products received from a "parent" Weather Service Forecast Office. This process did not apply to hydrologic forecasts, which were prepared initially by River Forecast Centers and issued to the public by NWS offices with hydrologic service area responsibility.

Local Climatological Data (LCD): A National Climatic Data Center publication that contains monthly and annual summaries of hydrometeorological parameters for surface-observing sites primarily at airport locations. The LCD is an important source of climate records.

Local flood warning system: A network of stream and rain gauges usually linked with one or more computerized terminal systems to monitor hydrologic events as they occur. These data, in conjunction with historical data and seasonal trends, provide a basis for flood prediction and forecasting.

Manual weather observation: An observation of a meteorological parameter such as temperature or precipitation that is made with the human eye and recorded by hand before it is forwarded to the NWS.

Meteorology: The science concerned with weather and atmospheric phenomena.

NEXRAD base reflectivities: Raw radar data obtained by the receiver (dish) and converted to output by the radar data acquisition computer. Base reflectivity is proportional to the sixth power of the diameter of rain drops encountered by the radar beam.

Operational test and evaluation: Demonstration of a centrally developed system at selected field offices, performed prior to nationwide implementation to ensure that field office operational requirements have been met.

Precipitation Gauge: A Device That Measures The Water-Equivalent Depth Of Precipitation That Has Fallen In The Frozen (E.G., Snow) Or Liquid (I.E., Rain) States.

Probabilistic Qpf (Pqpf): A Form Of Qpf (See Definition For Qpf Below) That Includes An Assigned Probability Of Occurrence For Each Numerical Value In The Forecast Product.

Quantitative precipitation forecast (QPF): A numerical forecast of precipitation amount—provided in a format such that the forecasted depth of precipitation is given for specified location(s), depicted graphically for an area, or computed for each grid in an area—that can be used as input to hydrologic forecast models or other applications.

Restructuring: In reference to NWS field offices, the process of converting from the two-tiered Weather Service Forecast Office-Weather Service Office configuration to the single-tiered Weather Forecast Office configuration.

Risk reduction: In the context of the NWS modernization, the process of implementing newly developed software and hardware technology and operations at selected field offices to demonstrate their operational viability and to obtain forecaster input on needed refinements prior to widespread implementation at field offices.

River crest: The highest stage or level of a flood wave as it passes a given stream location.

River-flow modeling: The continuous process by which flows and corresponding river stages are numerically simulated (see also "hydrologic model").

River forecasts: One or more numerical values prepared to predict the level (stage), flow rate (discharge), or velocity at a given location along a river for a future time or time period.

Severe weather: Weather activity of an exceptional nature that exceeds predetermined criteria at which life and/or property are known to be threatened.

Site-specific: Term used in conjunction with the words "forecast" or "warning" to highlight the fact that a hydrologic (stream) forecast is produced for an individual stream gauge location as opposed to a general area (e.g., a city or county), as is commonly done in many types of weather forecasts.

Spatially lumped parametric models: In the context of hydrologic models, one that assumes that each hydro-meteorological input (e.g., rainfall) or basin variable state (e.g., soil moisture) can be represented by a parameter that characterizes average or aggregate conditions across the entire basin.

Stage I (precipitation processing): The first level of precipitation processing, occurring within the NEXRAD computer and performed for each volume scan of the radar. Base reflectivity data are converted to a precipitation estimate for each grid in the radar umbrella, using a complex algorithm that includes quality control procedures, a *Z/R* relationship, and a bias adjustment using data from a ground-based precipitation gauge network. Several graphical and digital products are produced for Weather Forecast Office operations and subsequent processing.

Stage II (precipitation processing): The second level of precipitation processing, occurring within the Weather Forecast Office Advanced Weather Interactive Processing System and performed on an hourly basis. Stage I precipitation estimates are further refined using data from additional precipitation gauges and other sources of information such as rain/no rain determinations from satellite imagery. Stage II may also be executed at RFCs for backup purposes.

Stage III (precipitation processing): The third level of precipitation processing, performed interactively at RFCs. Stage II precipitation estimates from multiple NEXRADs are mosaicked into an RFC-wide product for use in river basin hydrologic modeling operations. RFC forecasters can review the mosaicked product, interactively edit areas of bad data, and substitute gauge-only data fields into portions of the "mosaicked" radar-based product.

State variable (also variable state): The current numerical value simulated for a given unknown (e.g., soil moisture, snow-water content) in the hydrologic modeling process. The state of hydrologic model variables at any given time control how the model will simulate response to new input such as precipitation or snowmelt.

Stream gauge: Any site along a stream where the stage (water level) is read either manually, by eye, or measured with recording equipment.

Technology transfer: The process of providing hydrologic models, systems, and procedures developed for NWS operations to the private sector, to other federal, state, regional, and local agencies, and to international interests.

Telemetered data: Hydrometeorological data, measured by a conventional sensor such as a rain gauge or thermometer, but which are read, digitized, stored, and transmitted electronically.

Telemetry networks: A collection of hydrometeorological sensors that have the capability to transmit data electronically. Transmission of data may be by land phone lines, satellites, or land-based radio-microwave equipment.

Trace: A hydrograph or similar plot for an extended-range time horizon showing one of many scenarios generated through an ensemble forecast process.

***Z/R* relationship**: The empirical conversion relationship between radar reflectivity and precipitation rate.

Appendix

Summary of Survey Responses from National Weather Service Employees with Hydrologic Responsibilities

In April 1995 the Hydrology Panel of the National Weather Service Modernization Committee (NWSMC) supplied the NWS Office of Hydrology with a questionnaire and asked that all NWS employees with hydrologic responsibilities be provided copies. Recipients were instructed to return the completed questionnaires directly to the NWSMC anonymously. Out of a total of 275 questionnaires that were distributed, 211 were completed and returned to the NWSMC. The 77 percent response rate and the commentaries received along with the questionnaires indicated a significant level of cooperation and interest by NWS personnel who have hydrologic responsibilities.

The chief objectives of the questionnaire were (1) to gather basic statistics on the background and service history of NWS personnel with hydrologic responsibilities, (2) query personnel familiarity and perspectives on various components of the NWS modernization program, and (3) provide information to the NWSMC Hydrology Panel about NWS offices not visited by the panel. The results of the questionnaire were used principally to support the NWSMC Hydrology Panel's analysis of issues leading to the conclusions and recommendations contained in this report. The questionnaire yielded a useful profile of the NWS personnel with hydro-logic responsibilities. This appendix provides a selective summary of questionnaire quantitative results that are of either historical or management interest and that are relevant to the conclusions and recommendations in the report. Differences in the responses of field personnel (primarily operational duties) and those of managers/planners/research personnel are discussed in the following sections.

PERSONNEL AGES AND SERVICE RECORDS

Of all the respondents, 75 percent had operational tasks in NWS field offices. Eleven percent worked in management and 13 percent held staff positions in the Office of Hydrology or research laboratories. Table A-1 shows the age, years of NWS service, and years of NWS service in hydrology positions. The median age was 40; two-thirds of the work force were over 35 years of age. NWS personnel with hydro-logic responsibilities had, as a median, 9.5 years of service at the NWS. The median number of years in positions that involve hydrologic duties was significantly less, at 5.5 years. This implies that possibly a large fraction of NWS personnel with hydrologic responsibilities transitioned into their current positions from other NWS jobs unrelated to hydrology.

TABLE A-1 Age and Years of Service of Survey Respondents

Age Percentile	Age	Years of NWS Service	Years in Hydrologic Operational Duties
33rd percentile	35	5	3
Median	40	9.5	5.5
90th percentile	55	25	20

TRAINING AND BACKGROUND

The educational background of the respondents also reflects this transition to hydrologic operational duties from other fields. Half of the respondents held degrees in hydrology or closely related fields. Half of the respondents were schooled formally in meteorology and received their hydro-logic training through the NWS, the Cooperative Program for Operational Meteorology, Education, and Training (COMET), or correspondence courses. Table A-2 shows the

TABLE A-2 Participation in Training Programs (in percent)

Course	Personnel with Atmospheric Sciences Degree	Personnel with Hydrology-Related Degrees
NWS Training Center: Basic Operational Hydrology	46	30
NWS Training Center: Flash Flood	35	30
COMET	52	45
Correspondence courses	75	48

TABLE A-3 Perceived Training Needs (in percent)

Training Need	Need Immediate Training	Current Knowledge Adequate
Systems	48	16
Hydrologic processes	21	46
River flood forecasting	25	42
Flash flood forecasting	19	37
Use of QPF	20	29
Use of NEXRAD products	18	35

participation of NWS personnel with hydrologic responsibilities in continuing education courses and training courses offered by NWS. The level of participation is stratified according to formal degree background. The largest difference between the two groups was the reliance on external correspondence courses by those NWS personnel with hydrologic responsibilities who earned atmospheric science degrees (75 percent for those with meteorology backgrounds versus 48 percent for those with declared hydrology backgrounds).[1] Chapter 4 of this report discusses of some key training issues.

Table A-3 shows that there were immediate needs for training on NWS systems currently in use or coming online as perceived by the NWS personnel themselves. Half of the personnel perceived an immediate need for systems training, whereas only 16 percent were comfortable with their current level of knowledge. Conversely, nearly half of the respondents believed that their knowledge of hydrologic processes was adequate, whereas 21 percent expressed a strong desire for additional education and training in this area. With respect to operational topics such as river flood forecasting, flash flood forecasting, and use of quantitative precipitation forecasts (QPFs) and NEXRAD products, approximately one-fifth of the personnel believed that they required immediate training, whereas nearly one-third believed that they did not need additional training.

When the perceived training needs are stratified according to field personnel or management and research personnel (Table A-4), it is clear that the field personnel perceived a greater need for systems training. Although only 34 percent of management or research personnel reported an immediate need for systems training, 53 percent of the field personnel stated that they required additional training immediately. Only 10 percent of the field personnel were confident about their current level of systems training, whereas 34 percent of the management or research personnel indicated no immediate need for systems training. Similarly, larger percentages of field personnel expressed an immediate need for training in hydrologic processes (25 percent), river flood forecasting (32 percent), and flash flood forecasting (21 percent). Respondents with management or research duties perceived considerably less immediate need (12 percent, 6 percent, and 12 percent, respectively).

TABLE A-4 Perceived Training Needs Stratified by Position (in percent)

Training Need	Office of Hydrology and Field Personnel	Regional Personnel
Systems	53 (10)[a]	34 (34)
Hydrologic	25 (45)	12 (57)
River flood	32 (40)	6 (52)
Flash flood	21 (35)	12 (53)

[a] Numbers indicate the percentage of respondents who reported an "immediate need." Numbers in parenthesis are the percentages reporting "no need."

FAMILIARITY WITH MODERNIZATION

In responses to a series of questions designed to gauge the familiarity that NWS personnel with hydrologic responsibilities have with the NWS modernization program, important strengths and deficiencies were identified. Table A-5 shows the range of responses to a number of topics. There were mixed responses to the questions on familiarity with the various parts of the modernization. Approximately one-third of the respondents were very familiar, and one-third or less were somewhat familiar or unfamiliar with topics such as the NWS modernization, NWS hydrology modernization, River Forecast Center (RFC) and Weather Forecast Office (WFO) operations, and NEXRAD products.[2] Apparently the Precipitation Processing System (PPS), data quality control, and Advanced Hydrologic Prediction System (AHPS) were not widely recognized as familiar topics. Only a small minority (9 percent to 17 percent) of the personnel stated that they are very familiar with these topics. The majority of

[1] The latter group includes those employees with degrees in fields such as earth sciences or geology in which hydrology is not formally included as a major focus.

the personnel rated themselves as somewhat familiar or unfamiliar with data quality control and the AHPS.

TABLE A-5 Responses to Familiarity Questions (in percent)

Aspect of Modernization	Very Familiar	Somewhat Familiar or Unfamiliar
NWS modernization	36	16
Hydrology modernization	37	22
RFC operations	34	28
WFO operations	24	41
NEXRAD products	23	33
Precipitation Processing System	17	44
Data quality control	9	77
AHPS	11	74

TABLE A-6 Responses to Familiarity Questions Stratified by Position (in percent)

Aspect of Modernization	Field Personnel	Office of Hydrology and Regional Personnel
NWS modernization	29 (18)[a]	54 (12)
Hydrology modernization	29 (22)	68 (10)
RFC operations	29 (29)	53 (19)
WFO operations	24 (38)	29 (41)
AHPS	7 (80)	43 (31)

[a] Numbers indicate percentage of respondents who reported they were "very familiar" with the topic. Numbers in parentheses are the percentages that responded "somewhat familiar" or "unfamiliar."

When these responses are stratified according to field versus management and research positions, it reveals that the perceived lack of familiarity was more prevalent among field personnel. Table A-6 shows the percentage of responses to familiarity questions stratified according to position. Whereas 54 percent of management and research personnel considered themselves very familiar with NWS modernization (68 percent for clear familiarity with modernization in hydrology), only 29 percent of the field personnel perceived that they were very familiar with either the overall modernization or hydrologic modernization activities. This difference also applies to familiarity with RFC and WFO operations, and it is most striking in the case of the AHPS. Eighty percent of field personnel considered themselves somewhat familiar or unfamiliar with the AHPS (which includes the Water Resources Forecasting System and extended stream-flow prediction). In contrast, nearly half of personnel in management or research positions at the Office of Hydrology and regional headquarters reported that they were very familiar with the AHPS. Familiarity also shows predictable trends with respect to age and years of service; personnel new to the program were less familiar with the modernization program and its components.

OUTLOOK

Table A-7 shows how NWS personnel with hydrologic responsibilities rated some general issues. Approximately half of the personnel responding were optimistic that NWS services and products will be improved as a result of the modernization. More than half of the respondents perceived that field personnel involvement had been inadequate. Mission and vision issues were also perceived by many as being inadequately defined.

TABLE A-7 Rating of Issues (in percent)

Issue	Excellent or Very Good	Fair or Poor
Improved services	49	21
Mission and vision	25	40
Field personnel involvement	11	61

[2] The standard convention in survey methodology is to group "very familiar" with "somewhat familiar," as distinct from "unfamiliar." The responses are clustered differently here to highlight the "very familiar" response, which is the desired response in terms of proficiency in carrying out hydrology-related tasks in the context of the NWS modernization.

TABLE A-8 Rating of Issues Stratified by Position (in percent)

Issue	Field Personnel	Office of Hydrology and Regional Personnel
Improved services	45 (24)[a]	68 (4)
Mission and vision	18 (45)	34 (30)
Field personnel involvement	11 (68)	16 (40)

[a] Numbers indicate percent of respondents who rated issues as "excellent" and "very good." Numbers in parentheses are the percent of respondents who rated issues as "fair" and "poor."

The stratification of these ratings by duties and positions in Table A-8 (field personnel and forecasters versus managers and research scientists) reveals that the former group was considerably less confident about the issues. Whereas a majority (68 percent) of Office of Hydrology and regional headquarters personnel believed that services will be improved, only 44 percent of field personnel shared that confidence. Mission and vision definitions show similar asymmetry. For example, 67 percent of field personnel felt that field personnel involvement in the NWS modernization was lacking. Only 40 percent of the managers and research scientists in the Office of Hydrology and regional headquarters perceived shortcomings in that area.

TABLE A-9 "Excited and Optimistic" Responses (in percent)

Service Type	Percent Responding
River flood forecasting	78
Water management	56
Flash flood prediction	76
Hydrologic use of QPF	64

In general, the NWS personnel with hydrologic responsibilities were excited and optimistic about the future potential (within seven years) to meet and exceed the public needs for NWS hydrologic services. Table A-9 shows the percentage responses from NWS hydrology staff who rated themselves as excited and optimistic in the various topic areas.