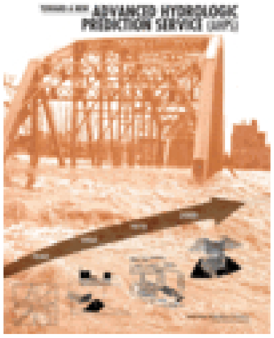

Toward a New Advanced Hydrologic Prediction Service (AHPS)

Committee to Assess the National Weather Service Advanced Hydrologic Prediction Service Initiative, National Research Council

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TOWARD A NEW ADVANCED HYDROLOGIC PREDICTION SERVICE (AHPS)

Committee to Assess the National Weather Service
Advanced Hydrologic Prediction Service Initiative

Water Science and Technology Board

Division on Earth and Life Studies

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* The activities of this committee were overseen and supported by the National Research Council's Water Science and Technology Board (see Appendix B for listing). Biographical information on committee members and staff is contained in Appendix C.

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Preface

Floods and droughts cause loss of life and enormous damage to the nation's economy. Thus, hydrologic forecasting, the primary means of obtaining warnings regarding the timing and extent of these events, is critical to public safety and the economy. The National Weather Service (NWS) operates 13 river forecast centers in the United States to produce both short- and long-term river flow/stage forecasts at about 4,000 locations.

In the interceding years since the river forecast offices were formed in the 1960s, tremendous change and growth have occurred in fields related to and affected by hydrologic forecasting. Urban, industrial, and population growth have increased occupation of flood-prone regions. The frequency of heavy rainfall events is increasing world-wide. Advanced technologies, applied research, and exponential advancements in web-based applications present both challenges and opportunities. In light of these changes, the NWS reassessed its hydrologic services and determined that enhancements are necessary to sustain its mission: to provide water information for decisions to protect life and property, and thereby contribute to the health of the nation's economy. The Advanced Hydrologic Prediction Service (AHPS) initiative grew out of this assessment.

This report is a product of the Committee to Assess the National Weather Service Advanced Hydrologic Prediction Service Initiative. This committee was formed in response to a request from the Office of Hydrologic Development of the National Oceanic and Atmospheric Administration's (NOAA) NWS and was charged to review and assess the full scope of AHPS, an NWS program, aimed at improving the nation's river forecasts. The committee was organized under the auspices of the Water Science and Technology Board of the National Research Council (NRC).

AHPS, as planned, will include a suite of web-based products designed to improve river, flood, and water resource forecasting abilities nationwide. Specifically, through AHPS, the NWS aims to provide better forecast accuracy, more specific and timely information on fast-rising floods, new types of forecast information, longer forecast horizons, easier-to-use products, and increased, more timely, and consistent access to information. AHPS products and information are planned to cover future hydrologic events on time scales from minutes to months. These new services should support more informed decisions through timely and accurate hydrologic forecasts.

The charge to our committee was to provide an assessment of the AHPS program. The committee met four times between February and November 2004 in open and closed sessions. NOAA/NWS employees, representatives from other related federal agencies, and water resource and emergency management practitioners attended and participated in open sessions. Recognizing the multiple layers involved in developing a national hydrologic services program, the committee evaluated the scientific and technical as well as the programmatic aspects of the AHPS initiative.

Mid-course in the study, the committee split into small groups and visited sites across the country to collect information and better understand how federal, state, and regional agencies use hydrologic forecast data. During these site visits, committee members conducted identical surveys (see Appendix A) to assess interpretations of the AHPS effort. Committee members visited the Northwest River Forecast Center, the Portland National Water and Climate Center, and the Bonneville Power Administration in Portland, Oregon; they also visited the National Operational Hydrologic Remote Sensing Center, the NWS Forecast Office—Twin Cities, the North Central River Forecast Center in Chanhassen, Minnesota, and the Susquehanna River Basin Commission.

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Examples and lessons learned from the field studies are interspersed throughout the report, and a synopsis is presented in Appendix A.

AHPS is on an incremental implementation timeline that started in 1997 and will be complete in 2013. This assessment of AHPS comes at a productive time, in that the program still has several years before it is fully implemented. The committee views AHPS as an important, worthy program and drafted this report to provide constructive comments to help the NWS realize its laudatory goals. Major findings and recommendations are presented in bold text.

We have many people to thank for their help over the course of this project and in the preparation of this report. The NWS Office of Hydrologic Development personnel were incredibly supportive of our committee and its progress towards report completion. We express appreciation to George Smith, Gary Carter, General D. L. Johnson, David Kitzmiller, Michael Smith, Eric Strem, and Janice Sylvestre of the NWS. We also thank Newsha Ajami, Kristie Franz, Bisher Imam, and Hamid Moradkhani of the University of California, Irvine; Gary Bardini, California Department of Water Resources; Larry Brazil, Riverside Technology, Inc.; Erik Hagen, Interstate Commission on the Potomac River Basin; Robert Hirsch, U.S. Geological Survey; Phil Pasteris, Natural Resources Conservation Service; Adam Walden, County of Los Angeles Department of Public Works; and David Wingerd, U.S. Army Corps of Engineers for their participation and insight. The report and study process would not have been possible without the hard work of NRC staff members Lauren Alexander and Dorothy Weir. Finally, I would like to recognize my fellow committee members for their long hours and dedication to reviewing the AHPS project and advancing the science and application of hydrologic prediction.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible and will ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Frederick H. Carr, University of Oklahoma; Susan L. Cutter, University of South Carolina; Witold Krajewski, University of Iowa; Dennis P. Lettenmaier, University of Washington; Fred L. Ogden, University of Connecticut; Robert T. Ryan, National Broadcasting Company; Robert J. Serafin, National Center for Atmospheric Research; and C. Larry Winter, National Center for Atmospheric Research.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Debra S. Knopman of the Rand Corporation. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Soroosh Sorooshian, *Chair*

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Summary

The National Weather Service (NWS) has the primary responsibility among the federal agencies to provide advanced flood alerts and warnings in the United States. Because hydrologic services generate nearly $2 billion of benefits each year (NHWC, 2002) through timely flood and weather forecasting, the NWS has made hydrologic understanding and forecasting a priority at national and regional scales. In 1997, the NWS Office of Hydrologic Development began the Advanced Hydrologic Prediction Service (AHPS) program to advance technology for hydrologic services. AHPS is a congressionally funded program that is intended to provide incremental advancements to hydrologic services over its implementation from 1997 to 2013. AHPS' overarching objectives are to increase the current river and flood forecasting capability and improve communication among NWS staff and offices, cooperating federal and other entities, and NWS partners and collaborators (NWS, 2002). AHPS has seven stated goals (NWS, 2004):

1. *Produce more accurate products incorporating advanced hydrologic science into NWS models*
2. *Provide more specific and timely information on fast-rising floods with increased lead time*
3. *Create new formats, including graphics, for products that are easier to use*
4. *Create more information that is useful to assess risk to flooding, including forecast probability*
5. *Provide products with forecast horizons two weeks or further into the future*
6. *Increase the distribution of products using advanced information technologies (such as the internet and web-based GIS formats) to provide broader and more timely access to and delivery of information; and*
7. *Expand outreach and engage partners and customers in all aspects of hydrologic product improvement.*

Through AHPS, the NWS seeks to provide accurate forecasts that can support timely warnings for all users of hydrologic predictions. Throughout history, and even recent history (i.e., Hurricanes Nora in 1997 and Katrina in 2005), there are examples of the important role that accurate, effectively communicated warnings play in keeping people and property safe from water-related disasters. Specifically, prediction and response together make hydrologic predictions the most valuable. AHPS, as described by the NWS, strives to provide the information needed at the right time to facilitate adequate responses to mitigate damages to life, livelihoods, and property. This provision would include predictions from the climate-scale to short-term weather-scale events with the appropriate representation of uncertainties so that AHPS users can respond to the information presented to them in the best ways possible.

AHPS is slated to be fully implemented nationwide in 2013. With seven years still remaining in its development and implementation timeline, a review of the program now is timely and poised to provide the NWS with information it needs to maximize AHPS usefulness. In 2003, the NWS requested a National Research Council (NRC) study of the science, technology, and programmatic aspects of AHPS to help ensure that the program is well founded for successful implementation and operation. To carry out the study, the NRC's Water Science and Technology Board appointed a committee to address the tasks outlined in Box S-1. The committee produced this report after reviewing documentation about AHPS, models used in AHPS applications, and other relevant information.

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BOX S-1
Statement of Task

The study will review the new program of NOAA's National Weather Service, known as the "Advanced Hydrologic Prediction Service" (AHPS). The study will assess the full scope of the program, aimed at improving the nation's river forecasts, in respect to hydrologic science and technology research, river routing and mechanics, "systems" engineering aspects, and implementation. Specifically, the study will assess and make recommendations in respect to:

1. the nation's needs in respect to operational flood and drought forecasting and the overall strategy of AHPS to meet these needs, with emphasis on promoting advances in climate and weather forecast and the application of modern hydrology, hydraulics, and modeling techniques and technologies to enhance predictions;

2. assessment of research aspects of AHPS, priorities for science and technology, and means to facilitate application of research results into hydrologic operations;

3. opportunities to assure optimal communication of warnings and other information generated by AHPS, including potential new uses of information provided; and

4. the level of coordination with other agencies and entities engaged in flood and drought warning.

KEY CONCLUSIONS AND RECOMMENDATIONS

Overall, this study found AHPS to be an ambitious program that promises to provide services and products that are timely and needed. This report identifies several opportunities to help AHPS fulfill its goals. These findings and recommendations are presented in bold text and in terms of programmatic, scientific and technical, and user-related aspects of AHPS.

Programmatic Conclusions and Recommendations

The programmatic paradigm of AHPS includes the elements needed for administrative structure: clearly stated purpose, goals, and objectives; administrative organization; development and implementation plans; measurable criteria against which to determine success of meeting goals; and adequate human and fiscal resources.

NWS documents (NWS, 2002; 2004) and website[1] present clearly the goals of AHPS that aim to increase current river and flood forecasting capability, timeliness, and accuracy. **The NWS is commended for presenting clear and well-articulated goals for AHPS.** If AHPS succeeds in providing more timely and accurate hydrologic forecasts, the program will bring significant benefits to hazards mitigation and water resources management. **Therefore, developing and implementing AHPS should continue to be a high priority for the NWS.**

AHPS program administration is managed through the AHPS Review Committee (ARC) to work from the national headquarters level down through the regional River Forecast Centers (RFCs) to the local Weather Forecast Offices (WFOs). Committee site visits to RFCs and WFOs suggest

[1] *http://www.nws.noaa.gov/om/water/ahps/Ahps-back.shtml.*

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that this top-down structure has yet to reach its full potential, and **regional and local offices should play a larger role in the administration and management of AHPS activities.**

AHPS is designed to provide products and services across offices in the NWS, the National Oceanic and Atmospheric Administration (NOAA), the federal government, and entities outside of the federal government. A plan is needed to ensure that AHPS product development and implementation are well-integrated and communicated across these different users. The NWS document, *Draft: Advanced Hydrologic Prediction Service (AHPS) Development and Implementation Plan* (NWS, 2004), was reviewed by the committee and found to be very general and in need of implementation schedule specifics, measures of success, mechanisms for incorporating user feedback, and facilitation of outreach and training. Because this is a draft document, the following recommendation is made for its next revision: **AHPS should develop a detailed and comprehensive, multi-year implementation plan that is updated on an annual basis and includes the following:**

1. **a detailed prioritization of milestones and schedule for implementation;**
2. **itemized fiscal and human resources allocated to each task;**
3. **specific metrics to measure progress towards meeting objectives;**
4. **methods for incorporating user feedback into the AHPS program for improving AHPS products and services; and**
5. **follow-on strategies to achieve longer range goals.**

Human and fiscal resources for AHPS are programmatic areas of concern. In terms of human resources, the need remains for trained hydrologic scientists to conduct hydrologic work in the NWS, just as a meteorological background is required for NWS meteorological work and forecasts. **Therefore, as recognized in a previous NRC report (NRC, 1996): the NWS should require a degree or extensive formal education in hydrology for positions that involve a hydrologic emphasis.** For fiscal resources, the budgetary history and current allocation seem misaligned with the ambitious goals of the program, and **the program's goals and budget should be brought into closer alignment.**

The AHPS goal of *expanding outreach to collaborating federal and non-federal entities* was evaluated and determined to have a very healthy start. Examples of successful collaboration are noted with organizations such as the U.S. Geological Survey and hydrologic community activities, such as the Distributed Model Intercomparison Project (DMIP), Community Hydrologic Prediction System (CHPS), and Model Parameter Estimation Experiment (MOPEX). There are difficulties inherent in working across agencies and institutions to fulfill internal goals, and **the NWS should focus its collaborations with federal, academic, and private sector organizations to advance the AHPS program and product development.**

Scientific and Technical Conclusions and Recommendations

The scientific and technical aspects of AHPS include the hydrologic science, data, and models used to generate hydrologic forecasts. The NWS uses the National Weather Service River Forecast System (NWSRFS) as its primary modeling engine for hydrologic forecasts. Developed in the 1970s and 1980s, it is a modular modeling framework that is based on FORTRAN code. For AHPS to fulfill its scientific and technical goals, numerous, specific recommendations are made to improve NWSRFS, and the major recommendations are noted here within three broad observations.

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First, precipitation inputs to the AHPS hydrologic models need improvements. The quality of the hydrologic forecast depends on the quality of its precipitation inputs, and improvements to precipitation inputs will advance the AHPS goal of *creating information that is useful to assess risk to flooding* through better, more accurate forecasts. Therefore, **AHPS should strengthen quantitative precipitation estimation (QPE) and quantitative precipitation forecasts (QPF) for hydrologic prediction through an end-to-end evaluation that assesses QPE/QPF quality and impacts on flood and streamflow products for basins of diverse size and topography**. In addition to improving QPE and QPF, **AHPS developers are encouraged to work closely with satellite precipitation groups to ensure that AHPS hydrologic requirements for precipitation are considered in other federal activities, such as the National Aeronautics and Space Administration's Global Precipitation Measurement mission**.

Second, the current modeling capability in NWSRFS needs improvements for AHPS to *produce more accurate products and incorporate advanced hydrologic science in the NWS hydrologic models*. A gap exists between the state-of-the-art hydrologic modeling capabilities and those used in AHPS product development. The current AHPS NWSRFS model needs updates, better verification, and closer alignment with models that have finer spatial and temporal resolution. **The NWS should invest in the next generation of NWSRFS that includes a flexible framework that allows alternative models, methods, or features that can be tested, verified, and implemented expediently**. **A total redesign of the NWSRFS is needed for AHPS to fulfill its scientific and technical goals. The NWS should clarify the criteria and decision–making process for selecting the next generation of hydrologic model(s) for AHPS, using an advisory group that involves modeling experts from inside and outside of the NWS to ensure that the state-of-the-art modeling advances are incorporated objectively into NWSRFS**.

CHPS, DMIP, and other collaborative activities to address the modeling capability of AHPS are commended. **The NWS should strengthen connections between these activities and AHPS goals**.

Finally, a recurrent finding in the evaluation of AHPS was that very few scientific and technical aspects of AHPS in general and the NWSRFS, in particular, are documented in written, citable form. The AHPS program needs greater publication, peer review, and dissemination of its current and recent activities to improve the hydrologic science and technology used in AHPS product development and operation.

User-related Conclusions and Recommendations

AHPS technical products and services will succeed only if they are scientifically strong and useful. The development of the AHPS program and the dissemination of AHPS products require the NWS to involve users and the public in the same way that it involves scientists and engineers in advancing the science and technology that underpins AHPS products.

As AHPS products and services will be implemented in phases over several years, a similar phased approached is reasonable for the user side of AHPS, as well. The first phase could address the needs of the RFCs and WFOs and integrate the RFC and WFO personnel into the AHPS program. Needs of these internal NWS users and designers should be addressed first because RFCs and WFOs play important roles in developing and disseminating AHPS information; RFCs and WFOs are the primary AHPS users; and the external user base is still small. The NWS expects the AHPS user base to expand to more external users as advanced products are developed and distributed; for now, AHPS users are primarily internal to the NWS. **Therefore, the NWS should focus AHPS development and implementation initially on the activities and needs of the**

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RFCs and WFOs. In subsequent User Phases, the NWS can focus on the needs of new and/or external users, as enhanced and partnered services are developed, refined, and implemented.

The user interface to access AHPS information is central to *creating new formats for products* and *widely distributing* AHPS products and services. The AHPS website is the primary portal for all of its hydro-meteorological information, and the NWS has done an excellent job in providing web access to AHPS observational data and products. Different formats of AHPS information are visible on different AHPS web pages and through different RFCs, and greater presentation uniformity is needed to increase AHPS identity and effectiveness of presenting hydrologic information. **While the NWS is making progress towards its goal of creating new formats for AHPS products, graphical formats need greater consistency across all AHPS web pages.**

AHPS has used the internet to a great extent to *increase the distribution of products using advanced information technologies (such as the internet and web-based geographic information system (GIS) formats) to provide broader and more timely access and delivery of information.* GIS holds great promise for some of the AHPS products, such as mapping flood inundated areas, areas prone to landslides or debris flows, or intensity and duration of droughts, but the degree to which GIS is used in the development and presentation of AHPS products is difficult to ascertain. In planning for AHPS product distribution, it is critical that the products and modes of presentation, whether GIS based or not, are communicating what is intended. **The NWS should consult a communications specialist to assist with developing consistent and clear modes of presentation.**

User feedback is essential to AHPS. User feedback should: involve outreach and training programs, include measures of success, and improve AHPS products and services. Site visits by our committee indicate that better communication and education about AHPS products, development, and protocol are needed for both internal NWS users and some external users, as well. Site interviews also reveal a wide range of understanding and acceptance of AHPS products among RFC and WFO personnel and suggest a need to bring all RFC and WFO personnel to a comparable level of understanding of AHPS products. **An AHPS outreach, education, and training program should be designed to ensure that AHPS products are used properly and to their fullest potential.** With respect to measuring success, it is important to know the extent to which forecasts were correct, whether they were communicated in optimal ways, and how they were used to assess risks and minimize losses.

The purpose of user feedback is to continually improve the AHPS program, its products and services. **The NWS should develop specific measures of success and a strategy to systematically collect and integrate feedback into a continuous loop of improved AHPS products and services.**

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Recommendations

- Developing and implementing AHPS should continue to be a high priority for the NWS (Chapter 2, p. 18).

- Regional and local offices should play a larger role in the administration and management of AHPS activities (Chapter 2, p. 20).

- The NWS should require a degree or extensive formal education in hydrology for positions that involve a hydrologic emphasis (Chapter 2, p. 21).

- The program's goals and budget should be brought into closer alignment (Chapter 2, p. 22).

- AHPS should develop a detailed and comprehensive, multi-year implementation plan that is updated on an annual basis and includes the following (Chapter 2, p.26):

  - a detailed prioritization of milestones and schedule for implementation;
  - itemized fiscal and human resources allocated to each task;
  - specific metrics to measure progress towards meeting objectives;
  - methods for incorporating user feedback into the AHPS program for improving AHPS products and services; and
  - follow-on strategies to achieve longer range goals.

- The NWS should focus its collaborations with federal, academic, and private sector organizations to advance the AHPS program and product development (Chapter 2, p. 29).

- AHPS developers are encouraged to work closely with satellite precipitation groups to ensure that AHPS hydrologic requirements for precipitation are considered in other federal activities, such as the National Aeronautics and Space Administration's Global Precipitation Measurement mission (Chapter 3, p. 32).

- The NWS should strengthen quantitative precipitation estimation (QPE) and quantitative precipitation forecasts (QPF) for hydrologic prediction through an end-to-end evaluation that assesses QPE/QPF quality and impacts on flood and streamflow products for basins of diverse size and topography (Chapter 3, p. 33).

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- The NWS should strengthen connections between DMIP Phase I/DMIP Phase II and AHPS goals (Chapter 3, p. 37).

- The NWS should clarify the criteria and decision–making process for selecting the next generation of hydrologic model(s) for AHPS, using an advisory group that involves modeling experts from inside and outside of the NWS to ensure that the state-of-the-art modeling advances are incorporated objectively into NWSRFS (Chapter 3, p. 37).

- The NWS should invest in the next generation of NWSRFS that includes a flexible framework that allows alternative models, methods, or features that can be tested, verified, and implemented expediently. A total redesign of the NWSRFS is needed for AHPS to fulfill its scientific and technical goals (Chapter 3, p. 44).

- The NWS should focus AHPS development and implementation initially on the activities and needs of the RFCs and WFOs (Chapter 4, p. 53).

- An AHPS outreach, education, and training program should be designed to ensure that AHPS products are used properly and to their fullest potential (Chapter 4, p. 54).

- While the NWS is making progress towards its goal of creating new formats for AHPS products, graphical formats need greater consistency across all AHPS web pages (Chapter 4, p. 55).

- The NWS should consult a communications specialist to assist with developing consistent and clear modes of presentation (chapter 4, p. 58).

- The NWS should develop specific measures of success and a strategy to systematically collect and integrate feedback into a continuous loop of improved AHPS products and services (Chapter 4, p. 63).

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1
Introduction

THE ADVANCED HYDROLOGIC PREDICTION SERVICE (AHPS) SOMETIME IN THE NOT-SO-DISTANT-FUTURE….*It has begun to rain throughout the Susquehanna River basin, and forecasts call for several days of rain due to a low pressure system stalled over the region. Warmer temperatures throughout the East have caused rapid melting of the heavy snow pack at high elevations. Emergency managers throughout the region have seen conditions like this before, sometimes with resulting floods and other times not. Two county emergency managers check the National Weather Service (NWS) AHPS website to get a flood forecast for the upcoming two weeks. In one watershed, inundation maps project a 50 percent chance of significant flooding, but no flooding is predicted in the other watershed. Evacuation procedures are reviewed and plans made, with a timeline for taking specific actions, as the time draws nearer. The emergency managers check AHPS several times a day as they put their plans in motion. Forecasts have been accurate and consistent for two days, confidence in the forecast is increasing, and industries in the floodplain are prepared to take flood-mitigating actions. Reservoir managers begin to alter their operations by increasing their flood control storage and releases in anticipation of expected flood flows.*

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Weather and climate have strong and sometimes destructive impacts on lives, livelihoods, and property. Of all weather-related hazards in the United States, floods are by far the most devastating: they claim hundreds of lives and cause billions of dollars in damages each year (NHWC, 2002; NOAA, 2001). Less dramatic, but perhaps even more serious in the long term, droughts impact vast areas of the United States sometimes for many years at a time, causing shortages of water, diminished water tables, damaged crops and other vegetation, outbreaks of noxious insects and other costly damages. As climate warms, the hydrologic cycle is likely to become more active, with more frequent and more severe occurrences of floods and droughts. It is crucial for people's health, safety and prosperity to understand connections among climate, weather, and the hydrologic cycle and to use this understanding to make accurate predictions of floods and droughts to efficiently manage water resources.

Society's health, safety, economic, social, and environmental needs depend on accurate descriptions and prediction of hydrologic events across a broad range of time and space scales. Early awareness of the timing, duration, and intensity of hydrologic events contributes to better understanding and can allow people to anticipate and respond in ways that mitigate the damage, and more importantly, save lives.

FLOOD LOSSES IN THE UNITED STATES

Two types of floods can occur. Flash-floods are the most rapid flood events that can develop very quickly after the onset of heavy precipitation. This short window of time provides limited response time to mitigate losses. Slow-rise floods can produce extensive damage over longer periods of time, but often allow enough time for evacuations and other mitigating measures. Regardless, all floods can result in damage to large- and small-scale infrastructure, disruption of business activity, property damage, and most regrettably, loss of life.

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The NWS hydrologic forecasts and warnings are effective in reducing flood damages in the United States (NHWC, 2002), and downward trends are visible in deaths attributed to floods. From 1970-2000, 3,829 deaths were attributed to floods; 128 deaths is the annual average (NHWC, 2002). Three 10-year cycles show a trend of reduced deaths: 1971-1980, 175 deaths; 1981-1990, 112; and 1991-2000, 91 (NHWC, 2002).

The recurrence of floods has remained relatively steady, flood-attributable deaths have declined, and the economic damage caused by floods has increased markedly in the last century (Institute for Business and Home Safety, 2001). This increase is due primarily to population growth in flood-prone areas, such as low-lying floodplain and coastal areas. In the 20-year interval between 1981 and 2000, the average amount of flood damages in the United States was $4.3 billion annually (Stallings, 1997). The average annual flood damage for 1981– 1990 was $3.2 billion and $5.4 billion for 1991-2000, which includes the record-setting floods of 1993 on the Mississippi River ($18.4 billion in damages) (USACE, 2000). The NWS is working to continue to reduce flood damages through the enhancement of hydrologic forecasts, warnings, and services.

HYDROLOGIC SERVICES

Hydrologic services are products that provide technical information that can be used in water resource management, water rights administration, water planning, and water resource protection[1]. Hydrologic services enhance or complement the usefulness of weather forecasts with new hydrologic science; hydrologic techniques developed for operational use; and advanced hydrologic products (i.e., river stage forecasts, flood inundation maps) that meet user needs.

As demands for hydrologic services evolve and rapidly grow more complex, the stakes of meeting those demands (whether expressed in terms of public safety, or dollars, or environmental and ecosystem protection) continue to escalate. Useful descriptions and hydrologic predictions rely on (1) science and technology; (2) the ability to communicate the information to those who need it; and (3) the timing and relevance of the information to the end users.

Uses and users of hydrologic services and products form a large and growing contingent. A broad set of users from agriculture, transportation, energy and water management, emergency management, and infrastructure planning rely on hydrologic information to mitigate damage from floods and droughts and make decisions that save lives and property, and add billions of dollars to the economy each year (NHWC, 2002). The most useful hydrologic services support forecasts that facilitate primary goals of water supply reliability, potability, and affordability and achieve high levels of timeliness and accuracy (Rayner et al., 1998). Decisions for efficient water resource use are increasingly based on hydrologic forecasts across wide-ranging temporal (day-to-day, seasonal, inter-annual, decades and longer) and spatial (local, regional, continental) scales. This diversity of needs and services requires a variety of hydro-meteorological and hydro-climate forecasts.

Damages from droughts not withstanding, the needs for timely and accurate hydrologic predictions most strongly relate to floods and fast rising river levels. The lead-time for mitigating flood damages is much shorter than that of mitigating and planning for circumstances of drought; for this reason, AHPS and other providers of hydrologic services most often emphasize accurate hydrologic predictions for flooding scenarios.

Hydrologic services in the United States predate World War II. In 1940, the Weather Bureau was transferred into the Department of Commerce, and a river division, known as the NWS Office of Hydrology, was formed. This river division divided the country into river districts, each

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[1] *http://www.idwr.state.id.us/hydrologic/.*

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with an associated Weather Bureau office to meet the hydrologic needs of that area. By the end of World War II, the expanded responsibilities of the regular Weather Bureau offices prompted separate River District Offices, which through the 1960s combined into the current 13 River Forecast Centers (RFC[2]; Figure 1-1). Today, many governmental and non-governmental organizations share the responsibility of providing hydrologic services in the United States in the collection and management of hydrologic data and information. AHPS operates as a part of this hydrologic services enterprise.

ADVANCED HYDROLOGIC PREDICTION SERVICE

The NWS has the primary responsibility among the federal agencies to provide advanced alerts via flood warnings and forecasts in the United States. Because hydrologic services generate nearly $2 billion of benefits each year (NHWC, 2002) through timely flood and weather forecasting, the NWS has made hydrologic understanding and forecasting a priority at national and regional scales. The NWS Hydrologic Services Division develops hydrologic services for use in accurate, timely, and useful forecasts with respect to many aspects of the hydrologic cycle. The AHPS program is a primary vehicle for this mission and has set out seven goals to fulfill it (see Box 1-1).

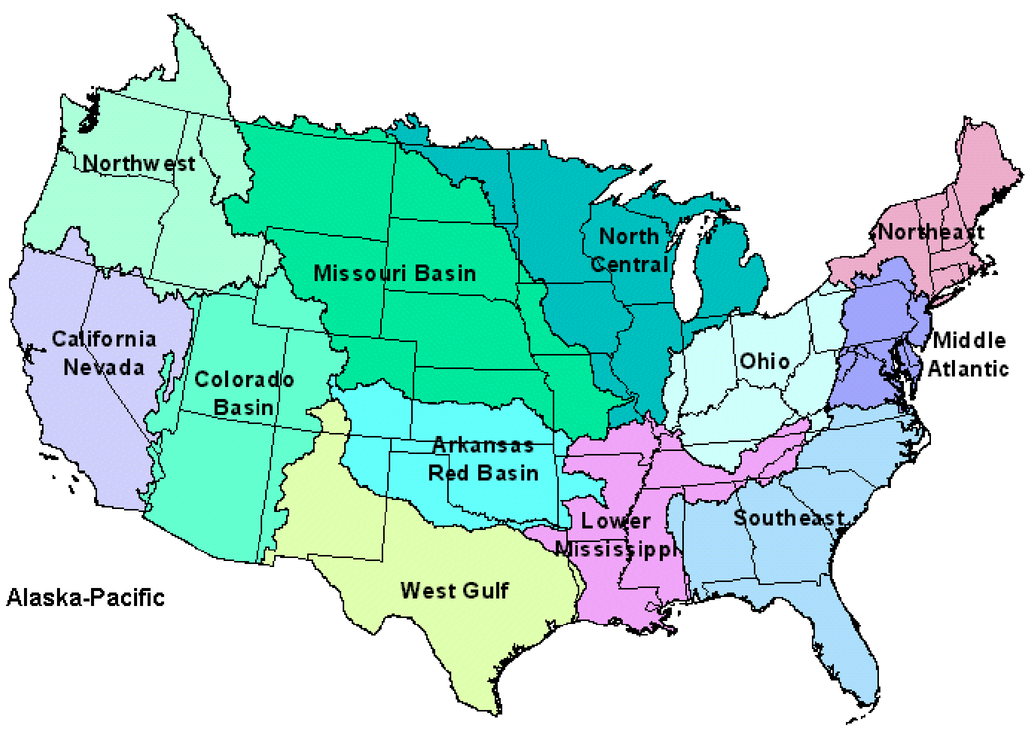

FIGURE 1-1 Map showing RFC regions.
SOURCE: *http://www.weather.gov/ahps/rfc/rfc.php.*

[2] *http://aprfc.arh.noaa.gov/resources/docs/apmission.html* .

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BOX 1-1
Goals of the Advanced Hydrologic Prediction Service

- Produce more accurate products incorporating advanced hydrologic science into NWS models
- Provide more specific and timely information on fast-rising floods with increased lead time
- Create new formats, including graphics, for products that are easier to use
- Create more information that is useful to assess risk to flooding, including forecast probability
- Provide products with forecast horizons two weeks or further into the future
- Increase the distribution of products using advanced information technologies (such as the internet and web-based geographic information system (GIS) formats) to provide broader and more timely access and delivery of information
- Expand outreach and engage partners and customers in all aspects of hydrologic product improvement

SOURCE: NWS, 2002.

The NWS began to implement AHPS technologies in the 1980s. At that time, the program was known as the Water Resources Forecasting System (WARFS). The first prototype of these technologies occurred in 1997 for the Des Moines River Basin in Des Moines, Iowa. Following this implementation, AHPS first appeared in the President's Budget Request to Congress for fiscal year (FY) 1999, and Congress first approved funding for AHPS at $1 million for FY2000. Congressionally approved funding increased to $6 million in FY2003. In FY2004 and FY2005, AHPS had more than 1,300 forecast points, and the designated $6 million annual budgets had portions redirected which resulted in effective budgeting decreases.

Through AHPS, the NWS seeks to provide accurate forecasts that can support timely warnings for all users of hydrologic forecasts. Throughout history there are numerous examples of the important role that accurate, effectively communicated warnings play in keeping people and property safe from water-related disasters. A hydrologic forecast that is accurate, timely, and relevant is most useful when it elicits a response that leads to an effective action (NWS, 1982). Two examples demonstrate this connection and application to AHPS.

First, Hurricane Katrina (August, 2005) has brought much attention to the almost unimaginable destructive power of weather systems and flooding, in particular, as a leading cause of loss of life and property. With sustained winds during landfall of 125 mph (a strong category 3 hurricane on the Saffir-Simpson scale), Katrina caused widespread devastation along the central Gulf Coast states of the U.S. New Orleans, LA, Mobile, AL, and Gulfport, MS bore the brunt of Katrina's force. The National Hurricane Center provided accurate track forecasts and predicted that Katrina would be a major hurricane 56 hours before landfall. According to emergency management estimates, 80 percent of the total population of New Orleans evacuated the city before Katrina; likely 83 percent of the residents of Jefferson Parish, LA, were evacuated (Pedro Restrepo, NWS, personal communivation, 2006).

However, extreme flooding events caused by Katrina illustrate the need for a hydrologic prediction system, such as AHPS, to work with an emergency response plan for probable or imminent flooding. Warnings and response must be much more closely aligned to realize the benefits of accurate, timely hydrometeorological forecasts. Flooding is often a major problem and concern associated with hurricanes, and Katrina displays the need for merged advanced storm surge/coastal water level models and stream flow modeling to improve flood level predictions during hurricanes and tropical storms. An advanced hydrologic prediction capability could provide

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timely and accurate flood stage forecasts for coastal and inland rivers, which, as Katrina shows, can be critical in the path a hurricane. A system like AHPS, when fully developed, could also support retrospective and scenario analyses and generation of flood inundation maps.

The second example is related to the 1997 El Nino year in the southwestern United States. Statistically, winter precipitation in the Southwest increases during an El Niño year. In fact, during the strong El Niño event of 1997, approximately a 55 percent increase in precipitation (Gelt et al., 1999) was observed over the Southwest, due in part to Hurricane Nora in September. The short-term forecasts developed within 24 hours prior to Nora's arrival predicted the path of the hurricane moving between Tucson and Phoenix, toward the eastern portion of the White Mountains of Arizona. Four to five inches of precipitation in a 24-hour period were predicted. This amount of rain would have had a profound impact on the management of the Salt River's reservoir system, upstream from the Phoenix metropolitan area (Sorooshian et al., 2002). Despite this *meteorological* prediction, operators of the largest reservoir on the system, the Roosevelt Dam, followed their usual operating guidelines and did not release any major amount of water in preparation for the incoming storm's precipitation and runoff. It is not clear whether *hydrologic* predictions were made available or used for this event. In the end, the meteorological forecast was inaccurate, and the hurricane's actual path deviated 200 miles to the west of its predicted path. Only a trace of rainfall fell in the Salt River watershed. In hindsight, the reservoir operators made the correct decision, but for the wrong reason. If the forecasted hurricane path had been correct, then major flooding downstream of the reservoir, including the greater Phoenix area, would have occurred and the reservoir operators' decision would have made them responsible for the ensuing losses and damages.

This example illustrates the need for an improved end-to-end hydrologic forecast system. Such a system would facilitate accurate and accessible hydrologic forecasts, reliable delivery of the forecasts to decision-makers, and appropriate responses to the hydrologic forecasts. A hydrologic prediction system, such as AHPS, can provide decision-makers with probabilistic estimates of potential runoff, which would allow them to formulate responses within a scientifically established framework. Without such a framework, the full potential and benefit of hydrologic predictions may not be realized. The reliability and accuracy of hydrometeorological forecasts are expected to improve over time; decision-makers will learn to use hydrologic information, or ignore it at their own peril. The operators of the Roosevelt Dam may not be as lucky the next time.

These examples illustrate how prediction and response together make hydrologic predictions valuable. AHPS, as described by the NWS, strives to provide the information needed at the right time to facilitate adequate response to mitigate damages to life, livelihoods, and property. This provision would include predictions from the climate-scale to short-term weather-scale events with the appropriate representation of uncertainties so that AHPS users can respond to the information presented to them the best ways possible.

THE NATIONAL RESEARCH COUNCIL STUDY

AHPS is slated to be fully implemented nationwide in 2013. With seven years still remaining in its development and implementation timeline, a review of the program now is timely and poised to provide the NWS with information it needs to make AHPS the most useful it can be. In an effort to help realize the vision for AHPS, the NWS requested a National Academies review of the AHPS program in the summer of 2003. That fall, the National Research Council's (NRC) Water Science and Technology Board appointed a committee to assess the full scope of the AHPS program, including aspects that relate to the nation's needs for operational flood and drought forecasting, research components of AHPS, and communication and coordination activities associated with

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flood and drought warning. The committee conducted its deliberations and its report production in response to the task statement listed in Box 1-2. This report fulfills its charge to review the scientific, technical, and programmatic aspects of the AHPS program.

Basis for Evaluating AHPS

The NWS provided the NRC committee with documents, oral presentations, and web-access to relevant AHPS information. These sources of information were used by the committee as primary descriptors of the AHPS program and formed the basis of the program evaluation. The AHPS program is described best in and evaluated against the following NWS source documents which were provided to the committee by NWS' Office of Hydrologic Development:

- NWS. 2001. *Implementation of Advanced Hydrologic Prediction Service*
- NWS. 2002. *Advanced Hydrologic Prediction Service Concept of Services and Operations*
- NWS. 2004. *Draft: Advanced Hydrologic Prediction Service (AHPS) Development and Implementation Plan*

To supplement information in these source documents, the committee conducted interviews across the country with internal and external AHPS users. These interviews were used to determine how well the AHPS mission is being communicated, how a national program is being received and implemented through local channels, and how well AHPS efforts are coordinated and incorporated into or affect changes in local operations. Together, the NWS program descriptions and the site interviews formed the information foundations from which the committee conducted its evaluation of AHPS. A major challenge that the committee encountered in evaluating AHPS, which is also

BOX 1-2
Statement of Task

The study will review the new program of NOAA's National Weather Service, known as the "Advanced Hydrologic Prediction Service" (AHPS). The study will assess the full scope of the program, aimed at improving the nation's river forecasts, in respect to hydrologic science and technology research, river routing and mechanics, "systems" engineering aspects, and implementation. Specifically, the study will assess and make recommendations in respect to:

1. the nation's needs in respect to operational flood and drought forecasting and the overall strategy of AHPS to meet these needs, with emphasis on promoting advances in climate and weather forecast and the application of modern hydrology, hydraulics, and modeling techniques and technologies to enhance predictions;

2. assessment of research aspects of AHPS, priorities for science and technology, and means to facilitate application of research results into hydrologic operations;

3. opportunities to assure optimal communication of warnings and other information generated by AHPS, including potential new uses of information provided; and

4. the level of coordination with other agencies and entities engaged in flood and drought warning.

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reflected in this report's recommendations, was the surprisingly sparse written or reviewed record of AHPS models, products, developments, or implementation plans or progress. Therefore, much of the information used as the basis for evaluating AHPS stems from personal communication with the NWS and other researchers familiar with AHPS development.

The reliance on personal communication, website information, and power point presentations provided very little structure against which specific, targeted metrics of assessment could be developed for and applied to evaluate AHPS. Instead, the committee used the stated goals of the AHPS program to provide a framework for the program's evaluation and commented on how the current modeling system, products, approaches, and developments are poised to fulfill AHPS stated goals. The report's recommendations were aligned with the program's goals to help the NWS make progress towards achieving them (listed in Box 1-1).

This committee was charged to evaluate the "full scope" of the AHPS program (Box 1-2). The committee interpreted that charge to include programmatic, scientific, technical, and user-related aspects of AHPS. Programmatic elements are evaluated against components needed to support a national program, such as description and statement of program goals, plans for development, measurable criteria for implementation, and commensurate fiscal and human resources. Scientific and technical aspects are evaluated against the state-of-the-science research and ways of incorporating modeling and technical upgrades to the current NWS hydrologic forecasting operations. User-related issues of AHPS are discussed in terms of current users, their needs, and how best to address their needs, as well as users expected to access AHPS products in the future, and how best to use resources for them. For the purposes of this review, the seven AHPS goals are grouped among programmatic, scientific and technical, and user-related aspects AHPS (Box 1-3).

The Report

The specific charges in the committee's statement of task (Box 1-2) are mapped into this programmatic, scientific and technical, and user-related framework. Chapter 2 discusses and evaluates the programmatic aspects of AHPS; it focuses on AHPS implementation and development, budget, and federal/non-federal coordination and cooperation of hydrologic services. The AHPS program goal of expanding outreach and partnerships and coordination and cooperation with other agencies (statement of task item 4), are addressed in Chapter 2. The bulk of the statement of task charges, and thus the major emphasis of this report, relate to scientific and technical aspects of AHPS, which are presented in Chapter 3. Chapter 3 evaluates progress and approaches towards AHPS goals of (1) *producing more accurate products*, (2) *forecasting fast-rising floods*, (3) *assessing risk of flooding*, and (4) *long-term forecast horizons*. These goals are evaluated based on current descriptions of AHPS models, plans for model development, and needs for these types of hydrologic services. Statement of task items numbers 1 and 2 are addressed in Chapter 3. Finally, the user-related AHPS goals are evaluated in Chapter 4 in discussions of development and distribution of graphics and formats of AHPS information and products; ways to identify and deliver products to a varied user base; and opportunities to assure optimal communication of warnings and other information (statement of task item 3).

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BOX 1-3
Categories of AHPS Goals

Programmatic Goals of AHPS

- Expand outreach and engage partners and customers in all aspects of hydrologic product improvement

Scientific and Technical Goals of AHPS

- Produce more accurate products incorporating advanced hydrologic science into NWS models
- Provide more specific and timely information on fast-rising floods with increased lead time
- Provide products with forecast horizons two weeks or further into the future
- Create more information that is useful to assess risk to flooding, including forecast probability

User-Related Goals of AHPS

- Create new formats, including graphics, for products that are easier to use
- Increase the distribution of products using advanced information technologies (such as the internet and web-based GIS formats) to provide broader and more timely access and delivery of information

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Programmatic Foundations of AHPS

Prior to evaluating the Advanced Hydrologic Prediction Service (AHPS) program in terms of its scientific and technical- (Chapter 3) or user-related (Chapter 4) goals, it is first necessary to consider the programmatic paradigm for AHPS. The programmatic paradigm includes fundamental structural elements, such as development and implementation plans; clearly stated purpose, goals and objectives; measurable criteria against which to determine success of meeting goals; and adequate human and fiscal resources.

This chapter discusses and evaluates these programmatic elements of the AHPS program. First, it describes the purpose, goals, and organization of the AHPS program. Next, it describes and evaluates AHPS in terms of (1) program administration; (2) human and fiscal resources; and (3) program development and implementation. Finally, this chapter reviews a programmatic aspect that is explicitly stated as a goal of AHPS, the issue of collaboration and cooperation with other hydrologic experts. Several findings are noted and recommendations are made.

PURPOSE AND BENEFITS OF AHPS

The National Weather Service (NWS) initiated AHPS in 1997 to develop and provide advanced technology for hydrologic services. The overarching objectives of AHPS are to increase river and flood forecasting capability and improve communication among NWS staff and offices, cooperating federal and other entities, and NWS customers. The NWS describes AHPS as a program that (1) infuses new science and technology into operations as a cornerstone of NWS Hydrologic Services modernization (NWS, 2001; 2004a) and (2) has "the primary objectives of improving the accuracy and lead time of NWS river and flash-flood forecasts, and quantifying the uncertainty of water predictions" (Carter, 2002).

The NWS plans for AHPS to provide users (1) additional time to prepare for floods or droughts, more accurate water forecasts and flood warnings, and (2) better information for decision-making (NWS, 2001; 2002). AHPS will also aim to introduce visually oriented, enhanced river and water resource forecasts. AHPS products include the probabilistic forecasts of flood occurrence for large and small areas over time scales from minutes to multi-month seasons. The overarching purpose, goals, and objectives of AHPS are well communicated by NWS personnel, web-based venues, and in NWS publications. **The NWS is commended for presenting clear and well-articulated goals of this program.**

Economic benefits have been attributed to timely, accurate hydrologic forecasts in the National Hydrologic Warning Council report, *Use and Benefits of the National Weather Service River and Flood Forecasts* (NHWC, 2002). This report quantifies benefits of accurate and timely hydrologic predictions in the United States. In it, AHPS is recognized as having "tremendous potential" for residual benefits and leading to decreases in flood-related disaster deaths and economic costs. AHPS products and services are estimated to produce up to a 15 percent (or $243 million) improvement in flood loss reduction benefits (NHWC, 2002). The total benefit of NWS hydrologic forecasting, including AHPS, other predictive services for short- and long-term events, and reservoir optimization, is conservatively estimated to be $1.86 billion annually (NHWC, 2002). This benefit increases to $2.4 billion annually when other water resources activities, such as improvements in operations for hydropower, irrigation, navigation, and water supply are included (NHWC, 2002).

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Because the goals of AHPS are laudable, and the nation needs improved hydrologic services, **continued development and implementation of AHPS should remain high priorities for the NWS.**

ORGANIZATIONAL CONTEXT FOR AHPS

AHPS is operated out of the Office of Hydrologic Development (OHD) of the NWS. The NWS is a part of the National Oceanic and Atmospheric Administration (NOAA), and NOAA is charged to assess and predict environmental changes, protect life and property, and provide decision makers with reliable scientific information. Scientific information on water resources flows across several NOAA offices, including the Oceanic and Atmospheric Research; the National Environmental Satellite, Data, and Information Service; and the NWS.

The NWS is charged to oversee a range of hydrologic and meteorological activities, and has the primary responsibility for issuing forecasts and warnings of floods to help save lives and reduce flood damages. The NWS operates 13 River Forecast Centers (RFCs) (see Figure 1-1) and 122 Weather Forecast Offices (WFOs; Figure 2-1) across the United States. RFCs conduct hydrologic modeling operations for streams, reservoirs, and lakes within large river basins. RFCs produce short-term (zero to seven days), medium-term (eight to 14 days) and long-term (90 days or more) forecasts at the regional spatial scale. The RFCs primarily focus on short-term forecasts that serve as input to WFO warnings, watches, and other information that inform decision-makers. Short-term forecasts include conventional forecast hydrograph output and probabilistic information that indicates forecast certainty. Medium-term products include conventional forecast hydrographs and probabilistic information that is produced for selected river basins. Some long-term products incorporate extended-range precipitation and temperature forecast information from the Climate Prediction Center. The NWS expects AHPS products to improve the accuracy of short-, medium- and long-term forecasts.

WFOs serve the most localized areas. WFOs produce warnings, watches, and statements covering areas and streams of all sizes that are provided via websites, radio, and television. Major hydrologic services provided by the NWS include flash-flood watches and warnings, river and flood forecasts and warnings, and water supply forecasts. The NWS depends on WFOs to facilitate flood and flash-flood warnings for counties and portions of counties and format these warnings to be issued by forecasters. The NWS expects AHPS advanced models and technical applications to support and enhance the forecast capabilities of the WFOs.

The NWS has a number of operational and research components and many of the hydrologic prediction elements of the NWS are responsibilities of OHD. The organizational structure and responsibilities of OHD are described in NWS Instruction 10-901 (2005). In collaboration, the Hydrology Laboratory, National Centers for Environmental Prediction, RFCs, and WFOs develop and apply a variety of hydrometeorological modeling, forecasting, and data analysis techniques. Some of these techniques are used in AHPS products and services, as well as in other parts of the NWS and NOAA.

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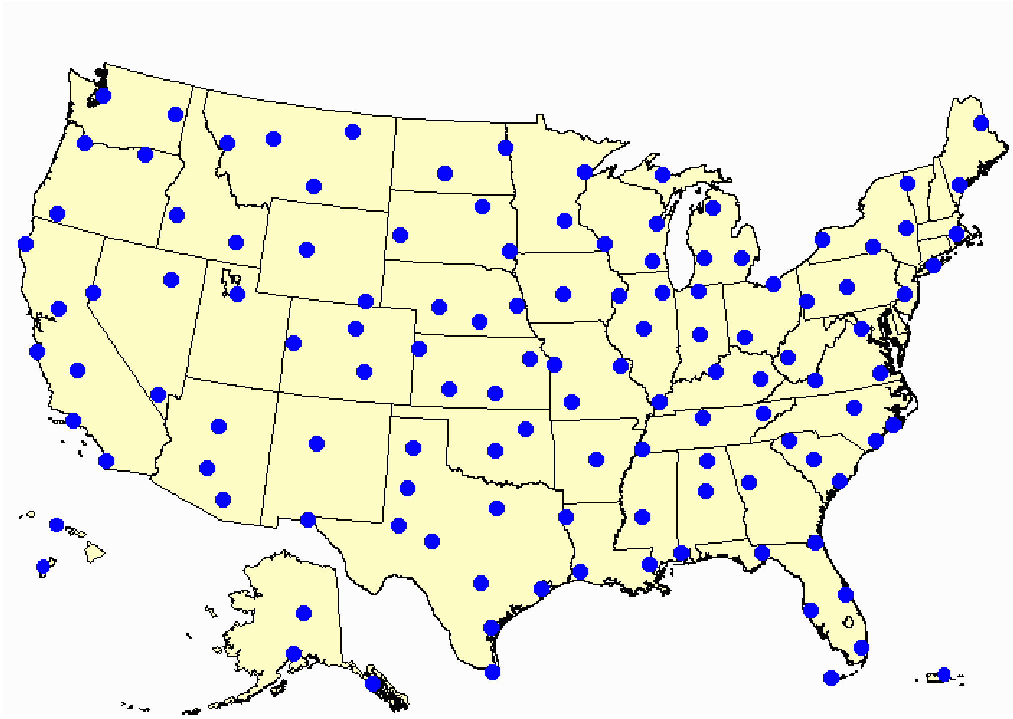

FIGURE 2-1 Location of NWS WFOs.
SOURCE: *http://www.nws.noaa.gov/om/coop/wfo-rfcmap.htm.*

EVALUATION OF AHPS PROGRAMMATIC ELEMENTS

This section begins the evaluation of AHPS with a description and review of basic programmatic elements. Programmatic topics covered are AHPS administration, human and fiscal resources, program development and implementation, and collaboration with other providers of hydrologic services and products.

AHPS Administration

The NWS designed AHPS to provide products and services at local, regional, and national levels. AHPS management is centralized in the OHD at the NWS national headquarters and is administered through the AHPS Review Committee (ARC), which is comprised of NWS employees from national (headquarters), regional, and local offices. The centralized AHPS management in national headquarters makes for a top-down management structure that is designed to provide guidance and direction at the national level and communicate guidance through the regional Hydrologic Service Divisions to and from RFCs and WFOs. The ARC reflects representation and participation from NWS local, regional, and national levels and was designed to facilitate communication and necessary information exchange. In practice, however, it is unclear how well this management structure works. Committee site visits and interviews with RFC and WFO personnel suggest that this AHPS management structure is viewed as one that has yet to achieve its full potential.

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Three areas are identified as opportunities to secure adequate administration of AHPS functions across the national, regional, and local levels. First, interviews at local-level offices suggest that **a clear chain of command through these levels needs to be stated and explained**. A clear chain of command would improve communications and hopefully overcome difficulties encountered in developing an end-to-end system (see Appendix A for survey synopsis). Although local levels are represented in the ARC, local level personnel expressed a desire for clearer communications and direction for AHPS implementation and operations.

Second, local hydrologic operatives stated the need for greater AHPS flexibility in meeting local needs with local solutions. A great deal of modeling that has direct application to AHPS is done at the local level, using locally collected empirical data. Models developed at national headquarters are often tested and implemented through regional and local offices, and local offices may need to adjust the national models for local conditions. Two-way interaction between the national-level models and local conditions is needed. Furthermore, some of the interviewed field personnel expressed frustration that they are not involved in an organized way in AHPS product development and implementation that impact their local operations. **AHPS needs clearer and stronger connections between the AHPS national management and local operations for AHPS to fulfill its stated goals.**

Finally, local solutions that work with national guidance from headquarters may help AHPS achieve its goals that reach across local, regional, and national levels on timelines of hours to multiple months. The beginnings of a framework that could facilitate this kind of interaction appear to be taking form in the NWS through the existing ARC and the regional and national headquarters-RFC-WFO relationships. Still, improved clarity in communication and chain of command is needed to ensure that the necessary interactions can facilitate the most efficient administration of the AHPS program across national, regional, and local offices. **Therefore, local and regional field offices, including RFCs and WFOs, should play a larger role in the administration and management of AHPS activities.**

Human and Fiscal Resources for AHPS

The NWS presents AHPS as a means to reinvigorate the scientific hydrologic research in the NWS OHD. In order to realize this possibility, adequate human and fiscal resources must be in place to ensure core competency and program viability.

Human Resources

The strong hydrologic focus of AHPS makes imperative the inclusion of hydrologists in AHPS administration. Hydrologic information is used in issuing NWS forecasts, watches, and warnings, and specialists in hydrologic sciences are needed to collect, analyze, and interpret these data accurately. The WFOs collect hydrologic empirical data of many kinds. WFO employees collaborate with stream gage experts at the U.S. Geological Survey (USGS) and visit stream gaging stations and flood-prone locations to acquire information on the impact of flood waters at various levels. These visits are seminal to the understanding of how stage of flood waters within and outside of the stream channel (i.e., water depths in floodplain and other flooded areas) relate to stream gage measurements. A robust AHPS program depends on acquiring and maintaining vast amounts of hydrologic data and information to deliver high-quality products that describe the local impacts of flooding.

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At the RFC level, real-time hydrometeorological data and historical data are used in and along with powerful hydrologic models (Fread et al., 1998). RFC hydrologists must possess appropriate knowledge to ensure accurate and reliable input data and validate model output accuracy.

The success of AHPS depends on the underlying hydrologic and hydro-meteorological sciences. Current AHPS scientific and modeling development is primarily focused on improving systems architecture, and this development is occurring through heavy contractor input. Engaging the best contractors and leveraging relevant research conducted at universities and other government organizations are reasonable under many different circumstances. However, in-house core competency is required to develop new procedures and to adapt and integrate externally-developed research products into improved operations. Strong hydrologic training at the WFO, RFC, and headquarters levels could address the need for stronger OHD core capability for hydrologic research and development.

It may seem obvious that the hydrologic activities performed by the WFOs and the RFCs should be fulfilled by hydrologists. The history of the NWS, however, shows a preponderance of meteorological experts, even for efforts focused on hydrology. For example, hydrometeorological personnel with duties that have a meteorological emphasis are required to have an extensive education in meteorology. In contrast, personnel with duties with a hydrology emphasis are not required to have a comparable level of education in hydrologic sciences. This staffing issue in the NWS must be addressed because ultimately AHPS depends on recruiting and retaining the best professional talent and leadership to operate, optimize, manage, and maintain AHPS system(s) at all administrative levels. A more substantial educational background in hydrologic science is necessary for personnel working in such positions on the AHPS program. A recommendation from NRC (1996) is repeated here: **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."**

Fiscal Resources

AHPS operates on a budget of $6M/year (fiscal year (FY) 2005), increased from $ 1 million in FY1997. The budget allocation is divided among implementation costs, science/software research, science/software flash-flood services, science/software for short- to long-term forecasts, science/software for flood forecast mapping, and other products and services. The Susquehanna Flood Forecast and Warning System[1] received a $1 million line item allocation in FY2004 and FY2005 (NWS, 2004a) from the AHPS budget; in FY2005, an additional $1 million was redirected to the NWS. Therefore, the $6 million budget was reduced to an effective $5 million in FY2004 and to $4 million in FY2005.

Differences noted between meteorological and hydrologic NWS staffing are also reflected in the allocation of fiscal resources at the NOAA level. For example, NOAA's Weather and Water Goal[2] claims that "weather and water services make a tremendous contribution to the Nation's health and economic vitality." NOAA requested $904 million for this total effort for FY2007. The division of resources between the "weather" and "water" portions of this budget is roughly 95 percent for weather ($862 million) and 5 percent for water ($42 million). NOAA's Hydrology

[1] *http://www.susquehannafloodforecasting.org/.*
[2] *http://www.corporateservices.noaa.gov/%7Enbo/FY07_BlueBook/PDFs/WWOnePagerFeb9.pdf.*

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Program is the "water" portion of the goal, and AHPS is part of NOAA's Hydrology Program. For AHPS, NOAA requested a $6 million budget for FY2007 that reflects the value assigned to improving *hydrologic* forecasts. This amount seems misaligned with the importance of providing accurate, timely hydrologic forecasts that mitigate annual flood costs estimated by NOAA to be $5 billion, plus the 80 lives lost each year to floods[3]. This amount also seems out of sync with resources needed to fulfill the basic mission of AHPS, including developing advanced hydrologic models and producing peer-reviewed publications of AHPS research activities. **Therefore, to ensure a viable and sustainable program over the long-term, the program's goals and budget should be brought into closer alignment.**

AHPS Development and Implementation

This review of AHPS development and implementation plans is based on two sources of information. This review reflects information shared in presentations and discussions in committee meeting open sessions and to a greater degree, it is based on an NWS document, *Draft: Advanced Hydrologic Prediction Service (AHPS) Development and Implementation Plan* (NWS, 2004b), which describes the NWS AHPS efforts. The information is then evaluated against basic elements of an implementation strategy, such as prioritization and schedule for implementation; itemized resources allocated to each task; specific metrics of success for program goals and progress towards meeting those goals; methods for incorporating feedback into the implementation process; and follow-on strategies for longer-range goals.

AHPS has been in incremental implementation since its start in 1997 and is expected to be completed in 2013. Starting in 1997 in the Des Moines River Basin, AHPS products first provided forecasts on the relative uncertainty of hydrologic variables with lead times out to three months (McEnery et al., 2005). Today, river and flood forecasts are now provided at approximately 3,400 locations across the country. Of these locations, AHPS information was available at 1,376 locations at the end of FY2005 (Figure 2-2), and by the end of FY2013, AHPS information is expected to be available for 4,011 forecast locations (NWS, 2002). As developed, AHPS forecast and probabilistic information will be rolled out through the regional RFCs and the local WFOs.

Prioritization, Timeline, and Allocated Resources of Implementation Tasks

In *Draft: Advanced Hydrologic Prediction Service (AHPS) Development and Implementation Plan* (NWS, 2004b), the NWS describes its implementation strategy as a three-tiered approach, which establishes implementation priority on the technical, modeling, and forecasting AHPS products and services. The approach is tiered to provide "basic" services to all AHPS forecast locations. "Enhanced" services are to be implemented at the "appropriate" AHPS forecast locations. "Partnered" services are to be implemented at the "most appropriate" AHPS forecast locations. Partnered services are co-financed by federal and other funding sources, such as state and local governments. No guidance is given as to how forecast locations are determined to be "appropriate"

[3] *http://www.corporateservices.noaa.gov/%7Enbo/FY07_BlueBook/PDFs/WWOnePagerFeb9.pdf.*

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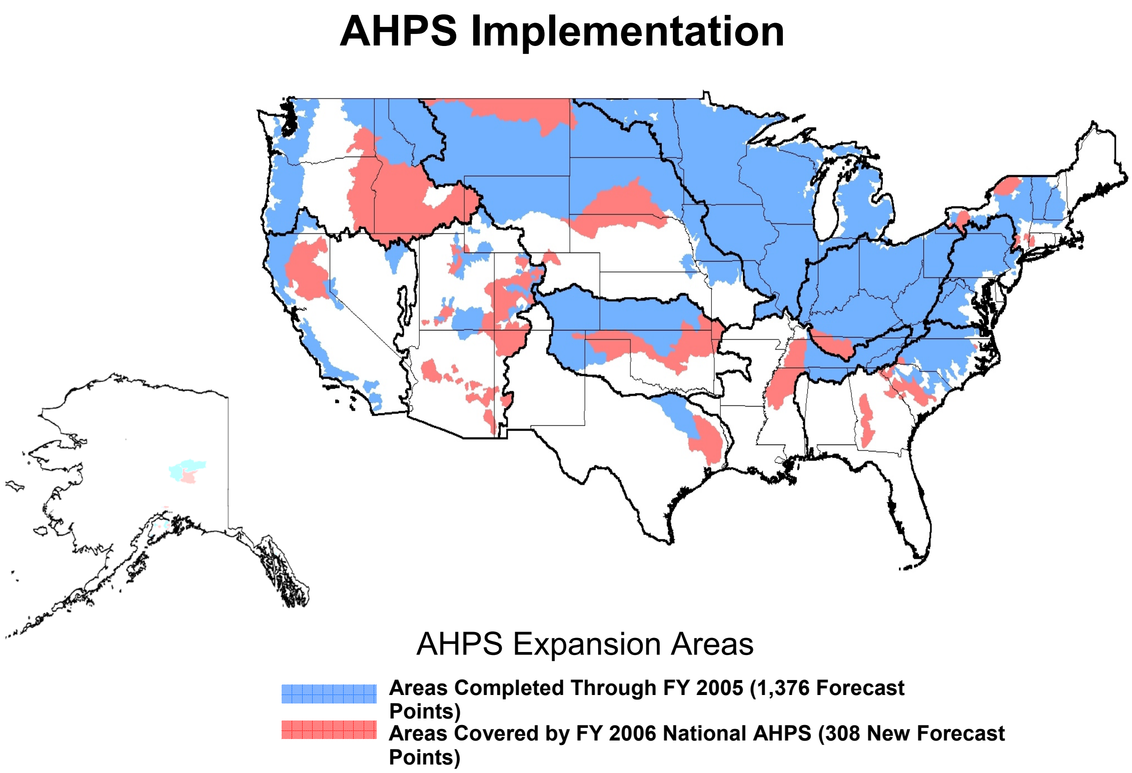

FIGURE 2-2 Map of AHPS Expansion Areas through FY2006.
SOURCE: George Smith, NWS, personal communication, 2005.

or "most appropriate." Development program activities are divided among these priority tiers (Box 2-1). Details of the planned products and services are discussed in the scientific and technical evaluation in Chapter 3.

Although technically AHPS is in its eighth year, the thrust of AHPS activity started with the increase in fiscal resources in FY2003. NWS (2004b) offers a timeline of implementation (Figure 2-3) that is reasonably presented by geographic region across the country. However, information in this timeline is not clearly aligned with the specific program development tasks (Box 2-1). A more useful timeline would incorporate: tiers of service, program development tasks, geographic location, expected implementation timeframe, and necessary resources to complete that implementation. The NWS does itemize resource allocations to program development tasks in the program development and implementation documentation, but allocation itemization is presented in individual fiscal year authorizations (i.e., NWS, 2004a). Adding itemized information to the development and implementation strategies is important to convey budgetary and personnel needs through the process of program implementation.

Specific Measures of Success

Setting goals is important to establish the direction of a program and the overall purpose of related efforts. Implementation plans should be closely aligned with those goals and designed such that progress towards those goals can be measured against specific measures, or metrics, of success. Examples of setting specific metrics can be found in *Draft: Advanced Hydrologic Prediction Service (AHPS) Development and Implementation Plan* (NWS, 2004b). Although incomplete, AHPS

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BOX 2-1
Implementation Tiers of AHPS Program Development Activities

1. **Basic Services to be provided at all AHPS forecast locations**
    a. For flood forecast locations
        i. Observed and forecast river levels and/or flow
        ii. Probabilistic forecast information
    b. For water supply forecast locations: water supply volume forecasts
2. **Enhanced Services to be provided at all appropriate AHPS forecast locations**
    a. Flash-flood services
        i. Site-specific models that allow WFOs to generate streamflow predictions
        ii. Flash-flood guidance
        iii. Distributed models
        iv. Statistical distributed models
        v. Dam break
        vi. Multisensor quantitative precipitation estimation (QPE)
        vii. Flash-flood monitoring and prediction (FFMP)
        viii. Basin legacy support
        ix. Training
    b. Short-to long-term forecasting services
        i. Ensemble streamflow prediction (ESP) system
        ii. Training
3. **Partnered Service to be provided at the most appropriate AHPS forecast locations is the Flood-forecast Mapping Service**
    a. Flood-forecast mapping activities
    b. Flood-forecast map evaluations
    c. FLDXS
    d. FLDVIEW
    e. Hydraulic models
    f. FLDIMS
    g. FLDAT
    h. DamAT
    i. Training

SOURCE: NWS, 2004b.

performance measures are established for several metrics, and a baseline and a target value is set for each metric (Table 2-1). In addition to these performance measures, some specific performance metrics are included for flash-flood services. Specific goals are cited, such as increasing flash-flood forecasts made from 48 minutes with 88 percent accuracy in 2004 to 52 minutes and 90 percent accuracy in 2008. In addition, August 2004 is cited as a specific date for full deployment of Beta testing of the Sacramento Soil Moisture Accounting model (SAC-SMA) in San Juan, Puerto Rico (NWS, 2004b). These examples, and others sprinkled throughout the NWS 2004 document, mark the beginning of an effort to provide specific, measurable metrics for each goal and implementation timeline established **that should be enhanced and reflected throughout AHPS development and implementation documentation.**

AHPS Long-range Goals

The long-term possibilities for AHPS should receive some consideration in the development and implementation plans. Already, AHPS is the second generation of hydrologic prediction

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	Base	New Service Locations	Total	AHPS Operational Forecast Locations															
				FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	Total
Alaska Pacific Region																			
APRFC	103						1	6	6	10	12	12	10	10	9	9	9	9	103
		19	122														4	15	19
Western Region																			
CBRFC	262						20	28	22	24	30	30	26	24	20	19	19		262
		48	310														19	29	48
CNRFC	184						13	14	19	19	19	22	19	19	19	10	11		184
		34	218														13	21	34
NWRFC	404						12	16	38	38	45	49	47	47	46	33	33		404
		75	479													25	25	25	75
Southern Region																			
ABRFC	268					7	20	51	36	36	36	29	27	26					268
		49	317										12	12	12	13			49
LMRFC	207							25	7	27	27	30	25	15	15	16	20		207
		38	245												9	9	10	10	38
SERFC	217					3	10	34	14	26	26	29	25	14	13	12	11		217
		40	257											10	10	10	10		40
WGRFC	314							33	3	37	37	40	40	38	35	34	17		314
		58	372												14	14	15	15	58
Central Region																			
MBRFC	505					45	26	26	22	55	55	55	55	55	55	56			505
		93	598											18	18	19	19	19	93
NCRFC	366			27	79	72	112	49					9	9	9				366
		67	433										13	13	13	13	15		67
Eastern Region																			
MARFC	171					3	60	72	11	15	10								171
		31	202											6	6	6	6	7	31
NERFC	130					14	20	24	27	13	12	12	8						130
		24	154												6	6	6	6	24
OHRFC	257				56	45	72	48	28	8									257
		47	304												9	10	18	10	47
Total	3,388	623	4,011	27	135	189	366	426	233	308	309	308	316	316	318	314	280	166	4,011
Cumulative Forecast Locations					162	351	717	1,143	1,376	1,684	1,993	2,301	2,617	2,933	3,251	3,565	3,845	4,011	

FIGURE 2-3 AHPS operational forecast locations.
SOURCE: Updated from NWS, 2004b.
NOTE: See acronym list.

services (the Water Resources Forecasting System was the first generation), and it is unclear how AHPS fits in the long-range view of the NWS and NOAA, more generally. In open session presentations, NWS personnel described AHPS goals as being met through a number of related, but distinct NWS and NOAA programs. Some of these other programs include the Integrated Water Science Plan (NWS, 2004c), the Advanced Weather Interactive Processing System, the Hydrologic Services Program, and the Water Resources Data Assimilation effort. Connections between and among AHPS and these other programs were not described. **Some long-range plans for AHPS should mention how AHPS does (or does not) relate to these other efforts and how, if at all, they may share objectives, goals, or resources.**

Overall, the NWS development and implementation plans for AHPS provide a good start. The 2004 document, *Draft: Advanced Hydrologic Prediction Service (AHPS) Development and Implementation Plan* (NWS, 2004b), sets out the main elements of the program's mission, tasks, and some timeline plans. Missing from NWS documentation, however, is an overall description of measurable milestones in getting AHPS to full implementation by 2013. A scheduled timetable, complete with fiscal and human resource allocations, tasks, and geographic locations is needed to give structure and

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TABLE 2-1 AHPS Performance Measures

	Metric	Rationale	Baseline (year)	Target (year)
Government Performance and Results Act (GPRA)	Flash-flood warning lead time (minutes)	Contribute to the protection of life and property	41 (2003)	54 (2010)
	Flash-flood warning accuracy (%)	Contribute to the protection of life and property	89 (2003)	91 (2010)
Non-GPRA	AHPS forecast locations	Increases information to manage water resources	717 (2003)	4, 011 (2013)
	River Flood Warning Accuracy (%)	Leads to increased confidence in forecasts	TBD (2005)	TBD
	New Science Operations (%)	Science enhancements implemented into operations	TBD (2005)	TBD
	Probabilistic forecast reliability (%)	Leads to increased confidence in forecasts	TBD (2005)	TBD

SOURCE: NWS, 2004b.

defense to AHPS development and implementation activities. A single overarching plan is also needed to connect program goals and program development tasks to measurable criteria, performance measures, fiscal resources, integration of user feedback into AHPS operations, or other aspects of an overarching implementation plan.

The NWS (2004b) development and implementation document was still in draft form at the time of this report's printing. As the NWS revises and finalizes this document, it is recommended that the following items be included for consideration. **AHPS should develop a detailed and comprehensive, multi-year implementation plan that is updated on an annual basis. This plan should include the following:**

1. **a detailed prioritization and schedule for program development tasks;**
2. **itemized fiscal and human resources allocated to each task;**
3. **specific metrics to measure progress towards meeting objectives;**
4. **methods for incorporating user feedback into the AHPS program for improving AHPS products and services; and**
5. **follow-on strategies to achieve longer range goals.**

AHPS Collaborators and Partners

AHPS has an explicit program goal to expand outreach by *engaging partners and customers in all aspects of the hydrologic services improvement effort* (NWS, 2004b). In setting out to meet this goal, the NWS is benefited by the large group of scientists in government, academe, and the private sector who share interest and expertise in hydrologic research, services, and products. Collaborative

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pursuits increase support from all organizations involved and help strike a proper balance between taking advantage of internal and external expertise, programs, and technologies.

The NWS has a history of collaboration with other federal and non-federal agencies to make efficient use of resources and fulfill NWS objectives. The full list of collaborators[4] is long; the main players include the USGS, the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers (USACE), and the Natural Resource Conservation Service. One reason for collaboration on hydrologic activity stems from a need to share the costs of providing hydrologic services across temporal and spatial scales. Few entities outside of the federal government can afford the costs of hydrologic data collection, analysis and modeling. For this reason and for reasons of efficiency, cooperation and collaboration among involved agencies and entities are important aspects of a functional hydrologic prediction system.

An excellent example of federal collaboration is between the NWS and the USGS in developing hydrologic forecasts. The USGS is the principal source of data on river depth and discharge in the United States (Wahl et al., 1995) with its stream gage network of more than 7,300 stream gages under its National Streamflow Information Program (NSIP[5]; Figure 2-4). During a flood, the USGS collects streamflow data, and the NWS collects precipitation data. Together, both types of data are used by the NWS (Figure 2-5) to develop and calibrate complex mathematical

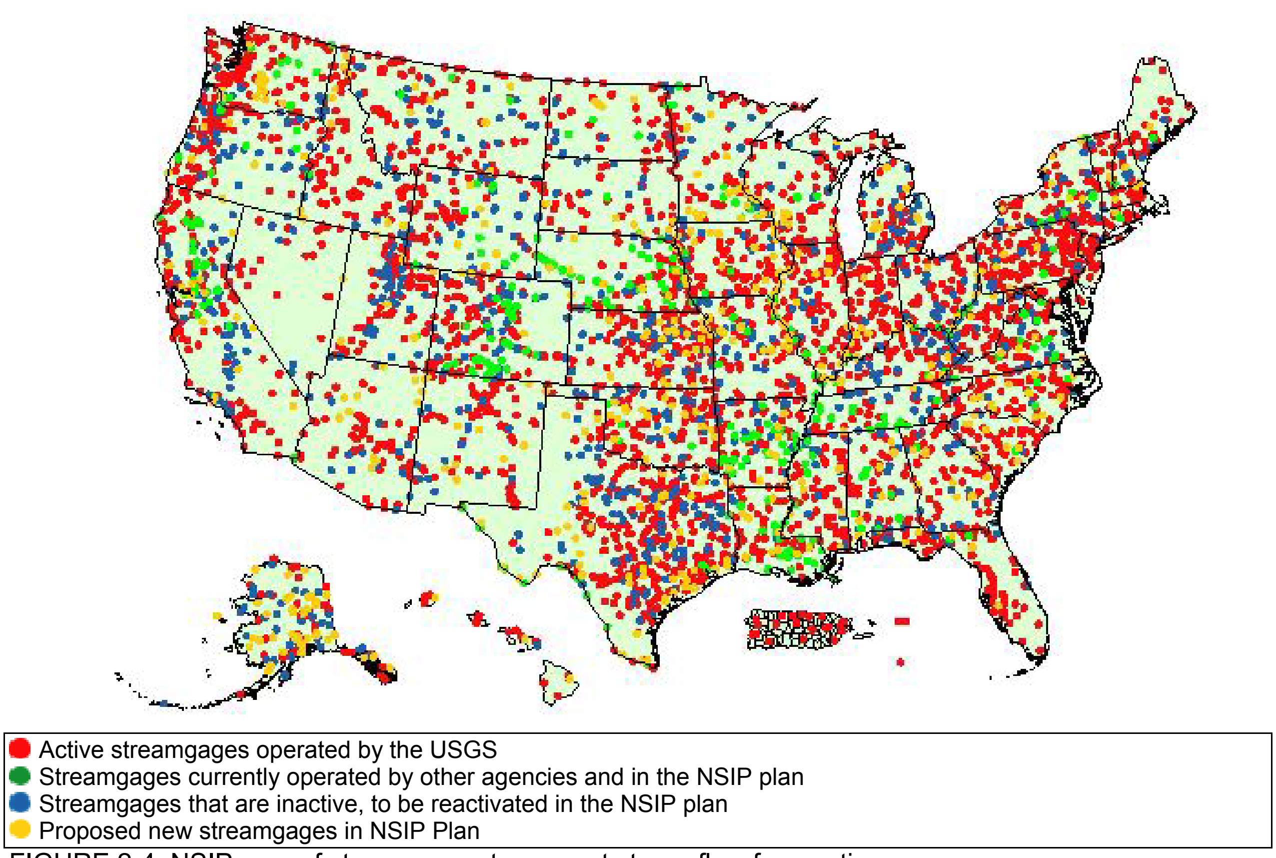

FIGURE 2-4 NSIP map of streamgages to support streamflow forecasting.
SOURCE: Adapted from *http://water.usgs.gov/nsip/nsipmaps/federalgoals.html*.

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[4] See *http://www.crh.noaa.gov/-ahps/nws_partners.php* for further information.
[5] Further information on the USGS NSIP program is available online at *http://water.usgs.gov/nsip/* and *http://water.usgs.gov/nsip/nsipmaps/currentgages.html*.

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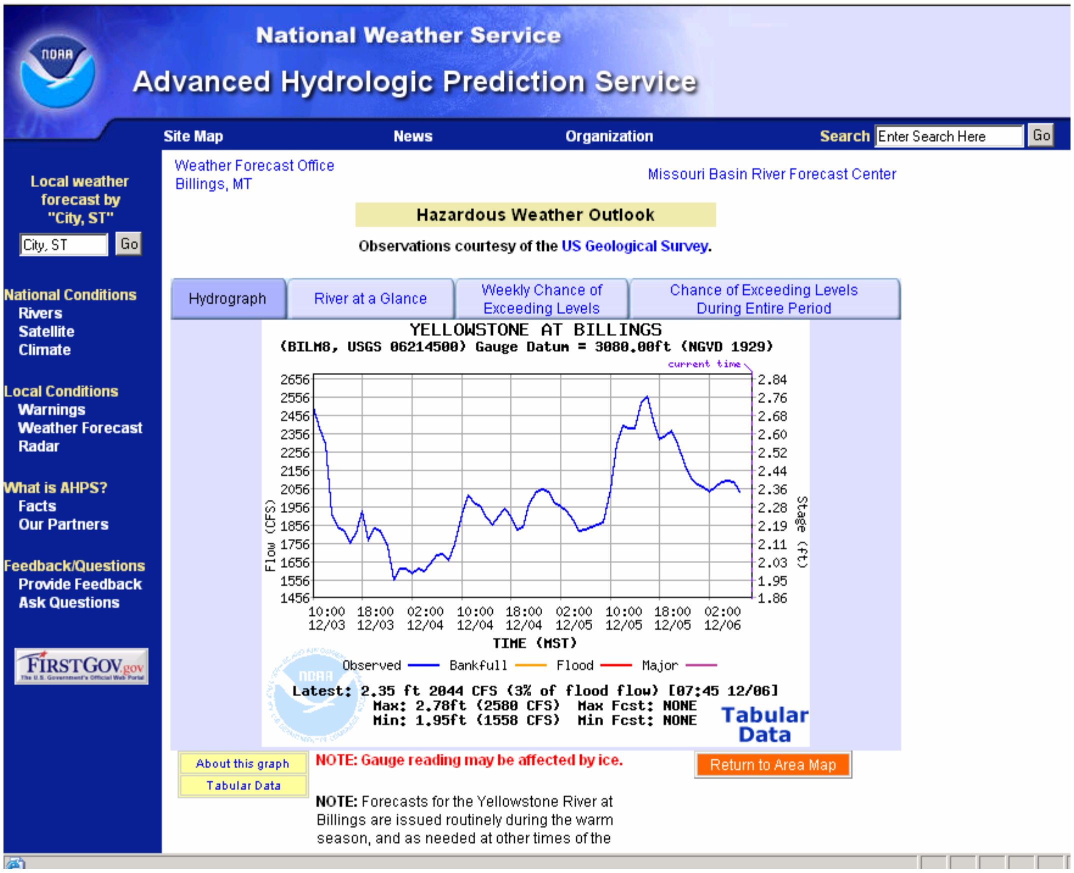

FIGURE 2-5 Example of how AHPS hydrograph information is linked to USGS gage data.
SOURCE: *http://ahps2.wrh.noaa.gov/ahps2/hydrograph.php?wfo=byz&gage=bilm8&view=1,1,1,1,1,1.*

models of how rivers and streams respond to rainfall and snowmelt and make hydrologic forecasts (Fread et al., 1998).

The NWS also collaborates with state (e.g., California Department of Water Resources and the Colorado Climate Center), local (i.e., Automatic Local Evaluation in Real Time [ALERT] Network) and academic organizations (i.e., National Center for Atmospheric Research [NCAR]) to disseminate information to the public, transmit information to local flood control districts, and conduct research, respectively.

Whereas many of these collaborations are successful (i.e., USGS, ALERT, and NCAR, etc.), expanding outreach for the sake of outreach may not advance the purpose and mission of AHPS. Collaborative efforts need to be closely aligned with the specific program development tasks that the NWS has established as priorities for AHPS (Box 2-1). Otherwise, collaboration among different entities may yield mixed results. Each agency has its own hydrologic modeling program. Despite some progress through interagency collaborative activities over the years, it is unclear whether these activities achieve or advance AHPS program goals.

Development of models and software is a major thrust of AHPS collaborations. Discussed more fully in Chapter 3, the DMIP, the CHPS, and the Model Parameter Estimation Experiment are working examples of collaboration on modeling, technical, and scientific aspects of hydrologic products and services. These activities demonstrate that the NWS engages the hydrologic science research community to infuse ideas from academic and governmental research laboratories and help establish the research agenda for AHPS. The degree to which these collaborations are aligned with AHPS goals and objectives needs clarification.

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The USACE collaborates with AHPS researchers on a regional basis, but the model alterations used in the USACE Hydrologic Engineering Center (HEC) (see Chapter 4, Box 4-1) suggest that additional collaborations could benefit AHPS model developments. The HEC has incorporated gridded and lumped versions of the SAC-SMA (see the Chapter 3 section on Hydrologic Models of NWSRFS) into their Hydrologic Modeling System (HMS) through various mechanisms of making adaptations to the SAC-SMA (USACE, 2001). The HEC approaches to integrate and make adjustments to model parameterization and calibration may benefit the NWS; AHPS modelers might consider for AHPS applications some of the positive features of the HEC-HMS user friendly interface.

AHPS has shown a promising record in collaborative work and research with federal, state, local, and academic liaisons, and **the NWS should continue and focus collaboration activities with federal, academic, and private sector organizations to advance AHPS program and product development.**

CHAPTER SUMMARY

This chapter describes the programmatic aspects of AHPS. The purpose and benefits of the program are discussed and the organizational structure for the program is explained. The AHPS administrative structure, human and fiscal resources, plans for AHPS product development and implementation, and collaborative efforts among AHPS partners are evaluated. The chapter's recommendations are in Box 2-2.

BOX 2-2
Recommendations

- Local and regional field offices, including RFCs and WFOs, should play a larger role in the administration and management of AHPS activities.
- A recommendation from NRC (1996) is repeated: 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."
- A better, closer alignment between AHPS goals and the budget dedicated to fully achieve those goals is needed for AHPS longevity and viability.
- Some long-range plans for AHPS should mention how AHPS does (or does not) relate to other NWS and NOAA water-related programs and how, if at all, they may share objectives, goals, or resources.
- AHPS should develop a detailed and comprehensive, multi-year implementation plan that is updated on an annual basis. This plan should include the following:
    - a detailed prioritization and schedule for program development tasks;
    - itemized fiscal and human resources allocated to each task;
    - specific measures (metrics) to measure progress towards meeting objectives;
    - methods for incorporating user feedback into the AHPS program for improving AHPS products and services; and
    - follow-on strategies for the NWS and the program's longer range goals.
- The NWS should continue and focus collaboration activities with federal, academic, and private sector organizations to advance AHPS program and product development.

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3
Scientific and Technical Aspects of AHPS

This chapter discusses the major scientific and technical aspects of the Advanced Hydrologic Prediction Service (AHPS) as they relate to the following four scientific and technical goals of AHPS: to *produce more accurate products by incorporating advanced hydrologic science into the National Weather Service (NWS) model*; to *provide products with forecast horizons two weeks or further into the future*; to *create more information that is useful to assess risk to flooding*; and to *provide more specific and timely information on fast-rising floods with increased lead time*. The chapter concentrates on the current models and techniques used by AHPS, with an emphasis on the NWS River Forecast System (NWSRFS), and it discusses limitations, research needs, and options to update those techniques so that AHPS can provide the "basic," "enhanced," and "partnered" hydrologic products that it promises. Major elements of the statement of task are addressed in this chapter, including discussions about operational flood forecasting and the overall strategy of AHPS to meet these needs, applying modern hydrology and modeling techniques and technologies to enhance hydrologic predictions, and an assessment of the research needs, priorities, and application of research into AHPS operations. The chapter opens with a description of precipitation inputs to hydrologic models. The next section discusses NWSRFS, its limitations, and its areas that need updating to achieve AHPS goals. A section on flash-flood guidance closes the chapter.

PRECIPITATION INPUTS TO HYDROLOGIC MODELS

Precipitation inputs are used in hydrologic runoff and snow-melt models to generate estimates of rates and stages of streamflow. AHPS is predicated on these hydrologic models; therefore, hydrometeorological inputs, generally, and precipitation inputs, specifically, strongly influence AHPS hydrologic forecasts. AHPS hydrometeorological inputs consist of quantitative precipitation estimations (QPEs), satellite-based precipitation measurements, and quantitative precipitation forecasts (QPFs). The skill ("skill" is used here as it is used by meteorological community to mean the accuracy of a forecast) of NWSRFS hydrologic products is largely dependent on the accuracy of QPE and skill of QPF.

Quantitative Precipitation Estimations

QPEs come from rain gages or a combination of gages and radar estimates. Historically, precipitation analysis operations have been based on interpolation of gage observations to mean areal precipitation within individual hydrologic basins. Certain functions of the radar-based precipitation processing system are controlled from Weather Forecast Offices (WFOs). Final control of NWS radar operation and the choice of adaptable parameters for most processing algorithms reside with WFO staff. These operations include decisions on the Z-R relationships (continental convective vs. tropical) used in processing reflectivity data from individual radars, and liaison with other agencies that maintain gages. During major tropical storm rain events, WFOs and River Forecast Centers (RFCs) consult on the choice of a Z-R relationship for radars within their areas of responsibility.

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Recognizing the importance of accurate QPEs as input to hydrologic models, the NWS is developing AHPS techniques for multisensor precipitation estimation that include the use of the national network of Doppler weather radars (Seo and Breidenbach, 2002) and satellite and lightning data (Kondragunta, 2002). The NWS is also working towards quantifying the uncertainty of QPEs (McEnery et al., 2005). These activities are positive; however, better documentation is needed to evaluate the effectiveness of these efforts. Publication and dissemination of AHPS activity allow the academic community and others to learn about and participate in algorithm development, verification and uncertainty estimation. Publication, peer review, and information dissemination will help the continual advancement of hydrologic science in AHPS models. **AHPS researchers should periodically publish progress of the development of and improvements to precipitation products.**

Satellite-Based Precipitation Estimations

Researchers at the National Oceanic and Atmospheric Administration (NOAA)[1], the National Aeronautics and Space Administration (NASA)[2], and some universities[3] have made remarkable progress in the development of satellite-based precipitation estimation algorithms. This new generation of algorithms is capable of merging and blending multiple types of observed information from both geostationary and low polar-orbiting satellites, and they generate estimates for precipitation at various spatial and temporal scales (Hong et al., 2004; Joyce et al., 2004). These research efforts progressively improve precipitation estimation over regions with limited ground-based observations. They also show much promise to improve coverage over mountainous terrains, especially in the western U.S., where gage and radar coverage are very sparse. Recent research (Yilmaz et al., 2005) shows encouraging results with respect to the use of high-resolution satellite-based precipitation as input to a hydrologic model.

Like precipitation estimation algorithms, plans for a new generation of satellite systems are underway. NASA, with a group of international partners, is developing a constellation of satellite systems called the Global Precipitation Measurement[4] for launch around 2010 that is capable of producing global coverage of precipitation every three hours. **AHPS developers are strongly encouraged to work closely with satellite precipitation groups (NASA, NOAA, and those in the academic community) to ensure that AHPS hydrologic requirements for precipitation are included in the Global Precipitation Measurement mission.**

Quantitative Precipitation Forecasts

A QPF is a prediction of the amount of precipitation that will fall at a given location in a given time interval. QPFs are issued routinely by the NWS as a part of meteorological forecasts. Intuitively, QPFs would be useful in producing hydrologic forecasts, but there is no strong evidence that QPFs are being used that way to extend flood and streamflow predictions. There may be several reasons why hydrologists do not use QPFs extensively. One reason could be that typical QPFs provide values averaged in 6-hour aggregations or blocks. Finer temporal scales would be

[1] *http://www.cpc.ncep.noaa.gov/products/janowiak/cmorph.html.*
[2] *http://trmm.gsfc.nasa.gov/publications_dir/precipitation_msg.html.*
[3] *http://hydis8.eng.uci.edu/CCS.*
[4] *http://gpm.gsfc.nasa.gov.*

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more useful to AHPS forecasts for fast-rising flood waters. The standard, 6-hour QPFs show great variation in accuracy in basins with complex topography or shorter hydrologic response times.

Another reason that hydrologists may not use QPF extensively is that QPFs were developed for meteorological, not hydrologic, purposes, so verification aspects of accuracy and performance are neither consistent nor calibrated with other hydrologic models. The skill of QPF for hydrologic forecasting is relatively unknown and results from tests and applications of QPF to date have fallen short of convincing many hydrologists of their operational value. For these and maybe other reasons, QPE and QPF remain underutilized in generating hydrologic forecasts.

AHPS could serve as a vehicle to connect the meteorologists who generate QPF to the hydrologists who have yet to embrace it (Droegemeier et al., 2000). In order to be useful in hydrologic products, QPE and QPF need systematic evaluation and verification for hydrologic applications. Systematic evaluation and verification would guide further development and refinement of the hydrometeorological QPE and QPF at the National Centers for Environmental Prediction, across the NWS, and potentially for use in AHPS. To ensure that QPE and QPF meet the nation's needs and needs of hydrologic forecasters, **the NWS should strengthen QPE and QPF for hydrologic prediction through an end- to-end evaluation that assesses QPE/QPF quality and impacts on flood and streamflow products for basins of diverse size and topography.**

THE NWS RIVER FORECAST SYSTEM

"Basic" services will upgrade static, diagnostic river gage hydrographs[5] to show AHPS river forecasts in a range of predicted information, including forecasted river levels[6], weekly flow probabilities[7], and monthly flow probabilities[8]. Other hydrologic products and services are also envisioned, such as "enhanced" services of flash-flood guidance information presented graphically[9], and "partnered" services, like an internet-based flood map service that uses geographic information systems (GIS; Figure 3-1). These, and all AHPS products and services, rely on the current NWS primary modeling engine, the NWSRFS.

NWSRFS was developed in the 1970s and 1980s (NWS, 1972) in a modular framework, and it is based on FORTRAN code. Over the intervening years, it has been incrementally upgraded with new models, functions, and displays (McEnery et al., 2005). However, more updates are needed to: *incorporate advanced hydrologic science into NWS models*; *provide forecasts for two weeks or further into the future*; *create information that is useful to assess risk to flooding*; and provide other products and services promised by AHPS.

NWSRFS Modules

The basic structure of the NWSRFS includes a calibration system (CS), an operational forecast system (OFS), an interactive forecast program (IFP), and an ensemble streamflow

[5] *http://www.crh.noaa.gov/ahps2/hydrograph.php?wfo=fgf&gage=lkbm5&view=1,1,1,1,1,1.*
[6] *http://newweb.erh.noaa.gov/ahps2/hydrograph.php?wfo=aly&gage=wtfn6&view=1,1,1,1,1,1.*
[7] *http://newweb.erh.noaa.gov/ahps2/weekly.php?wfo=aly&gage=wtfn6&view=1,1,1,1,1,1.*
[8] *http://newweb.erh.noaa.gov/ahps2/period.php?wfo=aly&gage=wtfn6&view=1,1,1,1,1,1.*
[9] *http://www.cnrfc.noaa.gov/flashFloodGuidance.php?cwa=RSA&hour=1.*

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FIGURE 3-1 Flood Internet Map Service prototype for Lewiston, PA.
SOURCE: *http://www.nws.noaa.gov/oh/ahps/floodims_news.html.*

prediction (ESP) system (Figure 3-2). The hydrologic model(s) is calibrated for basin-specific conditions in the CS; the calibrated model output is used to develop forecasts in the OFS, IFP, and ESP. Generating a hydrologic forecast using the NWSRFS involves a multi-step process that begins in the OFS. First, precipitation information is collected and analyzed. Next, the appropriate hydrologic model(s) are applied depending on whether the forecast area is due for rain or snow, and the precipitation data are input into the model. The IFP is then used to analyze the short-term streamflow forecasts generated by the OFS and to make system adjustments to improve the model simulations and forecast. Model states from the OFS are used by the ESP component, in conjunction with calibrated models and historical data, for the generation of longer-term probabilistic predictions. The functions, limitations, and research needs of each of the NWSRFS components are described in the following sections.

Functions of NWSRFS Hydrologic Models

NWSRFS allows hydrologists to combine the appropriate models in a manner that is descriptive of the basin, the available data, and the forecast products desired. NWSRFS hydrologic applications include conceptual rainfall-runoff models, snow, and the Antecedent Precipitation Index (API) model.

The Sacramento Soil Moisture Accounting model (SAC-SMA; Burnash et al., 1973) is the primary conceptual rainfall-runoff model used at the RFCs. The main snow model is the Snow-17 model originally developed by Anderson (1968; 1973; 1976). Snow-17 is a temperature-index version of a full energy budget model. SAC-SMA and Snow-17 are lumped conceptual models that convert frozen and liquid precipitation into runoff. Conceptual models do not explicitly represent

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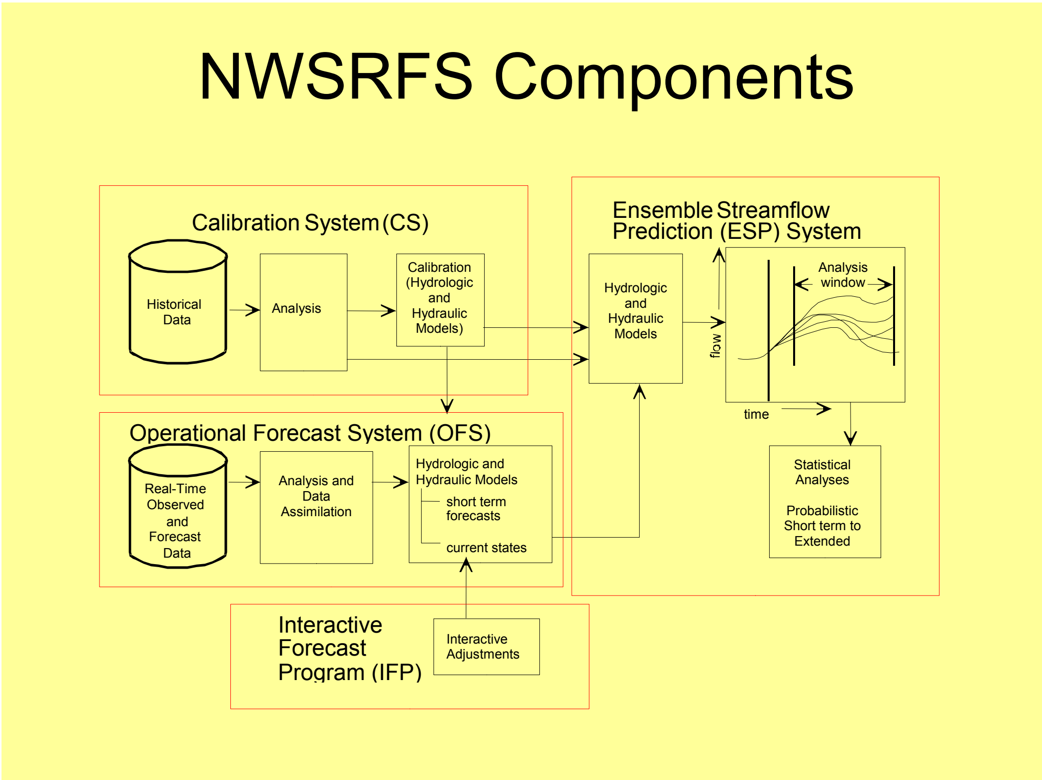

FIGURE 3-2 Main components of the NWSRFS.
SOURCE: Adapted from McEnery et al., 2005.

the measurable physical characteristics or processes of a basin, and are therefore limited to forecast locations equipped with river stage observations for calibration purposes. For this reason, conceptual models are typically run in lumped mode, compiling information over coarse spatial areas or homogenous conditions (i.e., similar elevation or topography). SAC-SMA and Snow-17 are sometimes used in a semi-distributed capacity, where a diverse basin is subdivided into smaller, more homogenous areas, so that the lumped models are better able to describe the dominant hydrological processes within each sub-basin area (McEnery et al., 2005). In some RFCs, the API model is used. The API empirical method estimates the amount of surface runoff that will occur in a basin from a given rainstorm based on an index of moisture stored within a drainage basin before a storm, physical characteristics of the basin, time of year, storm duration, rainfall amount, and rainfall intensity.

Limitations of and Research Needs for NWSRFS Hydrologic Models

The current lumped conceptual hydrologic models used by the NWS and in the NWSRFS are functional and relatively accurate (Reed et al., 2004), but have some limitations associated with their use. One limitation is that these models are based on the original empirical, lumped water balance accounting procedure and the FORTRAN computer coding standards of 20-30 years ago. The Office of Hydrologic Development's Hydrology Laboratory (HL) recognizes that the hydrologic modeling approaches used for AHPS products need to be updated from the current NWSRFS. HL has started making some modifications, such as addressing issues of modeling at

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finer spatial and temporal scales and incorporating more physically based process equations in future versions of the models (Koren et al., 2004; Smith et al., 2004a, b).

Model resolution has been at the center of a debate in the hydrologic community about the advantages/disadvantages of lumped versus distributed models (Figure 3-3). One side of the debate notes that lumped models create coarse but accurate results, even though they do not effectively represent spatial variability of hydrologic processes, or intra-basin differences in elevation or terrain. Distributed models are designed to work at spatial and temporal scales finer than lumped models. The other side of the debate, the argument in favor of distributed models, posits that because distributed models can account for differences in site specific characteristics, including basin size, topography, land cover, they are more appropriate for AHPS products and services (McEnery et al., 2005). Fueling both of these arguments are recent research efforts that focus on downscaling and improving spatial and temporal resolution of hydrologic models (Reed et al., 2004; Zhang et al., 2001).

The selection of lumped or distributed models for AHPS products is non-trivial because the type of hydrologic model(s) used in AHPS development will strongly impact AHPS products and services. AHPS currently uses lumped models, but the NWS is keenly aware of some of the benefits that distributed models may bring to AHPS. Therefore, the NWS is considering (1) making a switch from lumped models to distributed modeling for AHPS products; and (2) whether a single distributed model or a suite of distributed models will best achieve AHPS goals and purposes. The NWS must also determine how it will reconcile the incompatibility of the existing NWSRFS software structure with distributed modeling applications.

To help address whether to switch to distributed models from the current lumped models, HL launched the Distributed Model Intercomparison Project (DMIP; Smith et al., 2004c) to guide AHPS' future distributed modeling research and applications. HL invited researchers from the academic and non-academic communities to participate in the DMIP project. DMIP Phase I has been completed and its results are summarized in Box 3-1; DMIP Phase II is being planned to address complex basin issues of snow and orography.

The experimental design of DMIP Phase I was based on the comparison of distributed models applied to a common set of test data. Model simulations were compared to observed streamflow data as well as simulations generated from a lumped application of SAC-SMA. Results of DMIP Phase I have been published as a series in a special issue of Journal of Hydrology in 2004 (Box 3-1). Perhaps the first finding is the most critical and challenging for AHPS (Finding 1, Box 3-1): overall, the lumped hydrologic models performed better than, or slightly inferior to, a well calibrated distributed model. The NWS initiated DMIP to assist with the distributed modeling choice for AHPS, but DMIP Phase I research results do not clearly delineate whether AHPS products should use lumped or distributed models.

The NWS has expended resources for research on the issue of distributed models and comparison studies and now needs to make clear how the final model choice(s) will be made. A decision-making framework that will be used to select the next hydrologic model(s) is as important as the DMIP research efforts. A decision-making process should establish a template for the HL to select its model(s) and methods that standardize the mechanisms that will be used across RFCs and WFOs as they adjust hydrologic models to local conditions. An advisory group comprised of experts from outside of an internal to the NWS could help NWS develop this framework and guide its implementation across the NWS. From NWS personnel and written materials, it is difficult to

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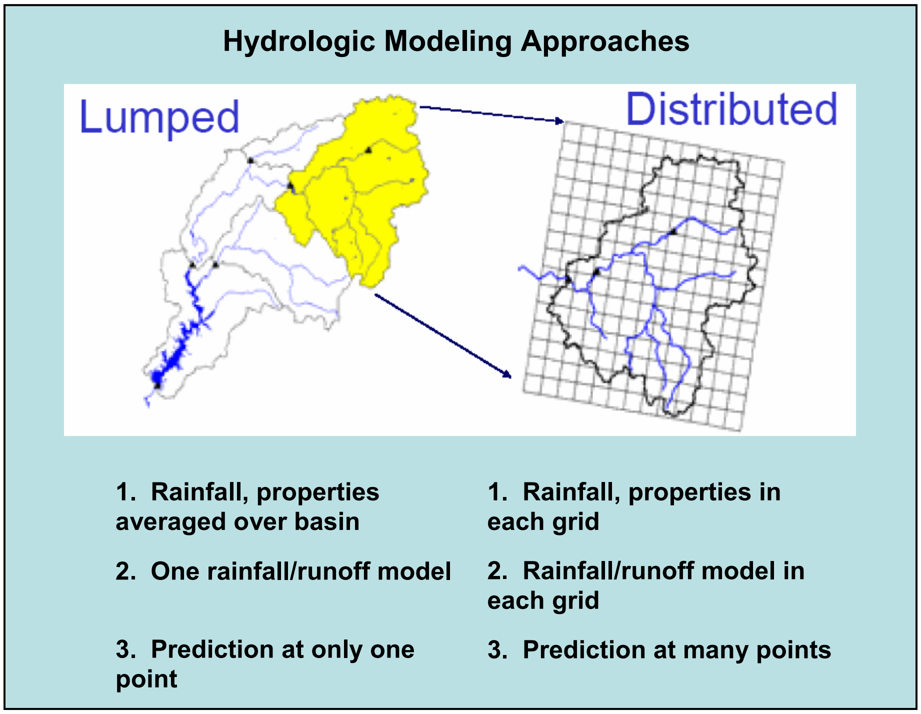

FIGURE 3-3 Differences between lumped and distributed model approaches.
SOURCE: Adapted from Smith et al., 2004a.

ascertain the mechanism used to guide AHPS model selection and implementation. DMIP has been a valuable effort to compare various models and has identified additional research questions that need to be addressed to provide a robust suite of AHPS models, but it is not clear how or when DMIP will converge to an ultimate decision about AHPS model choice(s). DMIP Phase II, like DMIP Phase I, has no stated strategy that outlines steps from DMIP results to the selection of the next generation of model(s) for AHPS. **Therefore, the NWS should strengthen connections between DMIP Phase I/DMIP Phase II and AHPS goals. The NWS should clarify the criteria and decision-making process for selecting the next generation of hydrologic model(s) for AHPS, using an advisory group that involves modeling experts from inside and outside of the NWS to ensure that the state-of-the-art modeling advances are incorporated objectively into NWSRFS.**

Another limitation for DMIP and similar exercises is the lag time between research and implementation into AHPS operations that may be too long to be effective. Protracted intervening time may inhibit AHPS developers from fully exploiting new modeling capabilities and achieve the AHPS goal of producing advanced hydrologic products.

Finally, there is a general observation about the mixed level of documentation of hydrologic models used in NWSRFS. While advancements and modifications to the SAC-SMA and NWSRFS have taken place over several decades and have been reported from time to time in conferences, proceedings, and in peer-reviewed journal papers, there needs to be more publication and documentation of the internal activities related to model development and decision making. The NWS has been proactive in publishing its work on some modeling research and development efforts (distributed modeling, cold seasons, and model calibration) but less in other areas (ESP, verification, etc.). A good example of documenting updates to hydrologic models is the U.S. Army Corps of

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BOX 3-1
Summary of DMIP Phase I Findings

1. Although the lumped model outperformed distributed models in more cases than distributed models outperformed the lumped model, some calibrated distributed models can perform at a level comparable to or better than a calibrated lumped model (the current operational standard). The wide range of accuracies among model results suggest that factors such as model formulation, parameterization, and the skill of the modeler can have a bigger impact on simulation accuracy than simply whether or not the model is lumped or distributed.

2. Clear gains in distributed model performance can be achieved through some type of model calibration. On average, calibrated models outperformed uncalibrated models during both the calibration and validation periods.

3. Gains from applying a distributed simulation model at NWS forecast basin scales (on the order of 1,000 km^2) will depend on the basin characteristics.

4. The Christie basin is a small basin nested in the Eldon Basin, and is distinguishable in the DMIP study because of its small size. Christie, compared with larger basins, showed improved calibrated, peak flow results likely because the lumped “calibrated” model parameters (from the parent basin calibration, Eldon) are scale dependent and distributed model parameters that account for spatial variability within Eldon are less scale dependent. The Christie results indicate that more studies on small, nested basins are needed to confirm and better understand these results.

5. Among calibrated results, models that combine techniques of conceptual rainfall-runoff and physically-based distributed routing consistently showed the best performance in all but the smallest basin. Gains from calibration indicate that determining reasonable *a priori* parameters directly from physical characteristics of a watershed is generally a more difficult problem than defining reasonable parameters for a conceptual lumped model through calibration.

SOURCE: Reed et al., 2004.

Engineers Hydrologic Engineering Center’s series (see Box 4-1 in Chapter 4). **The NWS needs to provide stronger documentation to allow the research community to learn about and contribute to AHPS research and development.**

Function of the NWSRFS Calibration System

The NWSRFS hydrologic models use hydrometeorological inputs (precipitation and temperature) to generate hydrologic outputs (streamflow and evapotranspiration). These models contain empirical coefficients and parameters that require site-specific calibration and proper estimation of model parameters for the hydrologic model to work successfully. Calibration and parameterization occur in the CS phase of NWSRFS. Extensive research related to hydrologic model calibration has been reported in the literature (see Duan et al., 2003). In the NWSRFS, simulated streamflow is calibrated statistically and visually against the observed streamflow to determine which model parameters need adjustment to improve alignment. After the models have

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been calibrated for a specific basin, the optimal set of parameters can be combined with real-time hydrometeorological data in the OFS to predict streamflow (Koren et al., 2003; Smith et al., 2003).

Limitations of and Research Needs for the Calibration System

The primary limitation of the NWSRFS CS is a gap between the state-of-the-art calibration capabilities and what is used in operations in the NWS RFCs. The NWS is aware of the need for closing this gap and recently has made needed improvements along these lines. One such improvement is the interactive Calibration Assistance Program, which incorporates GIS and interactive user interfaces into the NWSRFS (Smith et al., 2003). Another improvement has been the development of a regional parameter estimation scheme that relates soil information to the parameters of the SAC-SMA (Koren et al., 2003). These efforts are commended. The benefits of these advancements to AHPS will be realized as they are translated into NWSRFS operations. RFC and WFO staff training on the purpose, protocol, and function of calibration and parameterization improvements will help ensure appropriate and consistent use of new techniques. **The NWS should continue efforts to improve and expand AHPS calibration capabilities, accelerate the rate of transfer of the latest calibration techniques into its operational AHPS-NWSRFS version, and conduct adequate training of modeling personnel to ensure appropriate and consistent use of the new techniques.**

Like calibration advancements, model parameterization improvements in coupled climate/hydrologic models need to be transferred into AHPS operation. With the increasing demand for longer-term hydrologic predictions, and the AHPS goal to *provide longer range forecasts of two weeks or further into the future*, it is necessary to improve the interface between climate/land-surface models and hydrologic rainfall runoff models. The HL has recently spearheaded the international Model Parameter Estimation Experiment (MOPEX) to develop enhanced *a priori* estimates of hydrologic model parameters for both gaged and ungaged basins (Duan et al., 2006). MOPEX would provide valuable support to the incorporation of more physically based modeling capabilities into AHPS. MOPEX, and efforts like it, are expected to have a strong connection to the DMIP effort, as model calibration was identified (see Box 3-1) as the possible and pivotal component of model performance in DMIP Phase I. **The development of MOPEX is commended, and the goals of DMIP and MOPEX should be compatible with each other and with AHPS**.

Functions of the NWSRSF Operational Forecast System and the Interactive Forecast Program

The elements of OFS and IFP are similar, but they perform slightly different functions. The OFS is larger than IFP and includes pre-processing data (computing areal and temporal averages), model setup (storing parameters in the data base), and model computations. OFS reads raw station data in near real-time, estimates missing data as required, and then it uses these data to calculate mean areal time series of precipitation, temperature and potential evapotranspiration. Calibrated models in the OFS are forced with these processed time series to generate river forecasts with lead times that typically range from one day to two weeks.

The IFP is the graphical interface to the forecast component of OFS. Through the IFP interface, forecasters manually adjust the model simulations to match the current observations as closely as possible. The forecasters can adjust the model inputs, model states, model parameters (in a few cases) and model outputs. The forecasting component of the OFS maintains an account of the current model states that describe the hydrologic condition of the basin, including snow cover,

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soil moisture and channel storage, by storing these values in the operational database. The same models used in the forecast component of the OFS are used in the IFP. The model states stored by the OFS reflect the modifications made by the forecasters in IFP. The updated model states are needed as starting points for the subsequent forecasts made with the ESP system.

Limitations of and Research Needs for OFS and IFP

From the information available about the OFS/IFP component of the AHPS NWSRFS, a few observations and recommendations are noted. First, site visit interviews and other interviews with NWS forecasters indicate that the current design of the OFS/IFP is difficult to use. This difficulty is attributed to missing or hard-to-use- graphical interfaces. **The NWS should review the current suite of operational software and develop a comprehensive plan for refreshing that software.**

Two other, related concerns with the current configuration of OFS/IFP include the lack of a "model only" forecast run and automatic data assimilation. The OFS/IFP model state updating process is done manually, and at least two problems are associated with the manual approach. First, a strong possibility exists for an individual forecaster to introduce error or bias when manually adjusting models. Manual adjustments are based primarily upon forecaster expertise, which will vary among individuals. The resulting ad-hoc, inconsistent methods do not constitute a robust scientific approach to assimilating observations into a model simulation in real-time. Second, forecasters' manual control of model output may obscure or thwart scientific advances that improve forecast skill and certainty. An NWS staff member stated that, "you might improve the [hydrologic] models 100 fold, and never see any improvement [in forecasts] because the forecasters are always sticking their fingers into the mix." To avoid these problems, AHPS developers could adopt current practices from the meteorological forecast side of the NWS. NWS meteorologists run their models, "hands off" or "model only," and then transfer the forecast outputs "hands off" to the forecast offices. NWS meteorologists use post-processing techniques to make forecast adjustments prior to public issuance and they document these adjustments for future verification purposes. **Like their meteorological counterparts in the NWS, hydrologic forecasters should run hydrologic models primarily in a "model only" mode, make forecast adjustments with post-processing techniques, and document these adjustments for future verification purposes.**

Elements of current real-time hydrologic data assimilation are recognized as problematic. There are many sources of error with routing, snow, runoff, and precipitation, and current data assimilation uses only a single data point (typically river stage) for updating. The current lack of a fully automated, robust data assimilation component precludes "model only" forecast runs. Without a "model only" forecast system, it is not possible to assess the impact of a new calibration or other scientific advancements. These limitations, in addition to the problems associated with manually produced forecasts, suggest that the NWS should automate real-time hydrologic data assimilation. **AHPS developers should consider automating the OFS/IFP component of the AHPS-NWSRFS and develop a systematic mechanism to include new research results and error analysis techniques into the operational OFS/IFP component.**

A switch from a manual to "model only" and an automated data assimilation process will impact current forecasters' responsibilities. Although the responsibilities of the individual forecasters would change with an automated process, the role fulfilled by forecasters in the forecast process is essential and will continue to be important with automated data assimilation. **In no way should forecasters be removed from the forecast process, and the NWS is urged to redefine the role of the hydrologic forecaster in a fully automated data assimilation process.**

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Function of the NWSRFS Ensemble Streamflow Prediction System

The final component of the NWSRFS is the ESP system. The current version of the ESP component of NWSRFS has a modular design (Figure 3-4) and allows future streamflow traces to be analyzed for peak flows, minimum flows, and flow volumes. ESP assumes that historical meteorological data are representative of possible future conditions and uses past traces for the same-season and location as input data to produce probabilistic hydrologic forecasts. Knowledge of the current climatology is often used to weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year. More specifically, the ESP component blends together historical temperature and precipitation data sequences and deterministic meteorological forecasts to form ensemble inputs to hydrologic models that produce forecasts out to several months (Werner et al., 2005). A well designed and implemented ESP would progress AHPS towards fulfilling its goal of *providing products with forecast horizons of two weeks or further into the future.*

Limitations of and Research Needs for ESP

In the past decade, there have been significant advances in the development of ensemble tools in the fields of atmospheric and hydrologic sciences. Based on a recent spate of published works by NWS personnel or about ESP improvements for the NWSRFS, AHPS researchers appear to be developing and presenting these advancements for incorporation into AHPS products and forecasts. Published or written documentation exists for some, but not all, ESP sub-systems in the NWSRFS. ESP sub-systems with published documentation include: the ESP pre-processor (Schaake et al., 2005); ESP verification (Bradley et al., 2004); medium-range forecasts (Werner et al., 2005); climate index weighting (Werner et al., 2004); and the ESP post-processor (Seo et al., 2006). These recent publications reflect strong advancements of ESP tools and their potential incorporations into the NWSRFS and by extension to AHPS products and forecasts.

Through these and other research efforts, AHPS aims to improve the ESP system and produce seamless and consistent probabilistic forecasts. Probabilistic forecasts explicitly quantify levels of uncertainty associated with each ensemble forecast. Quantified uncertainty for hydrologic forecasts offers several advantages, including the ability to archive forecasts and assess the overall skill of hydrologic forecasts over time based on comparisons against observed conditions. NWS meteorological forecasts consistently have associated, quantified uncertainties, but hydrologic forecasts historically have not. Fortunately, recent developments in hydrologic modeling and tools steadily increase the number and percentage of probabilistic hydrologic forecasts. The NWS and AHPS researchers are commended for advancing the ESP tools for possible incorporation into the NWSRFS, and for publishing and documenting their results. Still, the NWS needs to more strongly connect these advancements to the overall AHPS Development and Implementation plan and specify how they fit into the envisioned sequence of implementation of the ESP (Figure 3-5).

Figure 3-5 presents the proposed sequence of the enhancements for short- to long-term forecasting services with the approximate delivery to RFCs. From this documentation (NWS, 2004),

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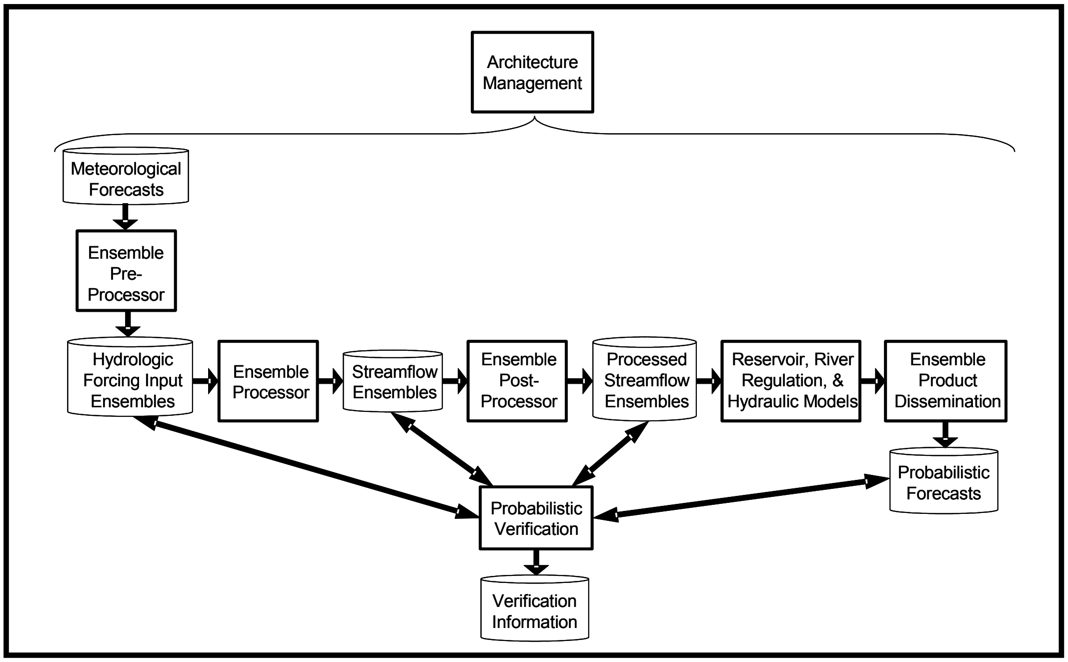

FIGURE 3-4 System components for the ESP.
SOURCE: NWS, 2004.

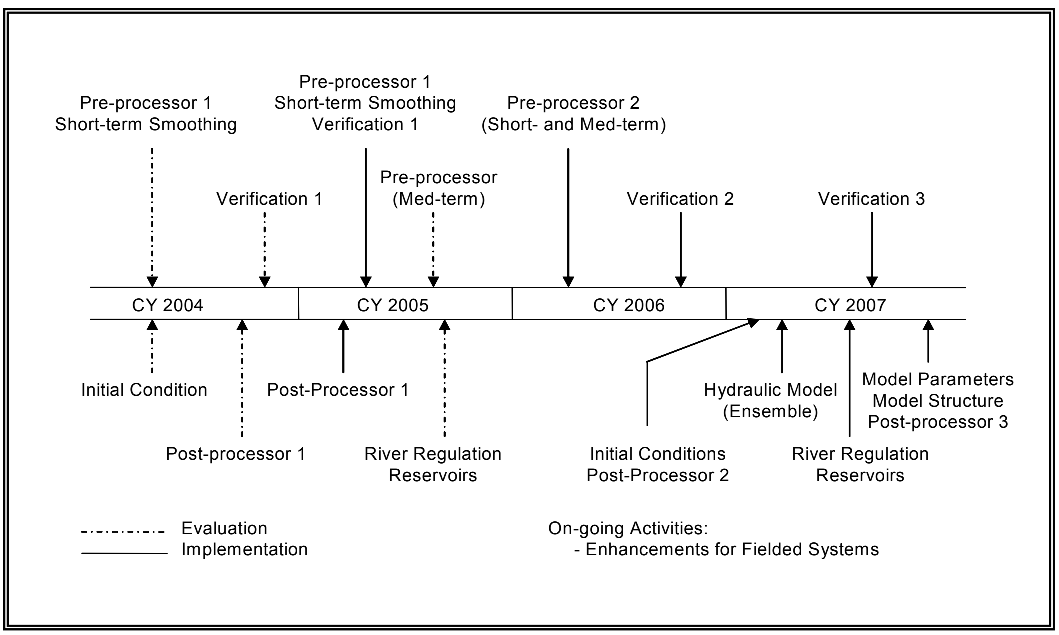

FIGURE 3-5 Envisioned sequence of implementation of the ensemble system.
SOURCE: NWS, 2004.

it is unclear what experimental design and methods are being used to develop the ESP sub-systems and whether a prototype of this framework is being tested before implementation in this succession (Figure 3-5). Furthermore, this schedule seems incomplete because it omits important elements such as research, analysis, and operational development, and the supporting text (NWS, 2004) does not fully describe all development activities associated with implementing this sequence. **Therefore, AHPS should document its overall strategy about ESP, including priorities for the ESP system and sub-system development, testing, and implementation. The AHPS approach to**

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quantifying uncertainties in operational forecasts must be articulated. In addition, AHPS should clarify connections between current and future research activities and the AHPS overall development and implementation and ESP sequencing plans.

Function of NWSRFS Verification

Verification includes documenting the uncertainty expected for each forecast and monitoring over time the accuracy of the forecasts against observed conditions. AHPS developers are commended for including verification in the NWSRFS, which could provide long-term statistics on the skill of AHPS and all NWSRFS forecasts. Quantification of uncertainty in forecasts should include measures of bias or accuracy and measures of variability of the ensemble forecasts. Bias measures can derive from comparisons of forecasts and observed field conditions; variance measures can be calculated from the statistical variability of the forecast. Inclusion of verification sub-systems in the ESP system design (Bradley et al., 2004), as well as in the OFS, is needed and long overdue.

Unlike meteorological forecasts, little is known about hydrologic forecasts and actual river forecast skill. The assumption that forecasts have been improving over time may not be true because it is not documented whether the forecasts have skill over simple persistence forecasts. The importance of verification was highlighted in a recent Ph.D. dissertation (Welles, 2005) when 10 years of NWS river stage forecasts for 5 locations and 20 years of NWS forecasts for 11 locations were evaluated using standard verification metrics. The improvement in the forecast skill was not as great as had been anticipated (Welles, 2005), although these results are not definitive due to the limited sample size of the study. This research underscores the need to implement a long-term verification strategy and maintenance of a forecast archive for future forecast verification and NWSRFS evaluation.

Limitations of and Research Needs for Verification in the NWSRFS

Hydrometeorologists need to understand the skill characteristics of their forecasts, and this can only be accomplished through rigorous verification of the forecasts, including quantification of uncertainty of the forecasts, and quantifying the accuracy and variability of ensemble forecasts compared to observed field conditions. It is possible to make available verification information, such as river forecast skill, as an AHPS product for each forecast point. **While the inclusion of a verification sub-component in AHPS NWSRFS is commended, there is a pressing need for a long-term strategy and maintenance of a forecast archive for future verification and NWSRFS evaluation.**

Overarching Limitations of NWSRFS

The software architecture of NWSRFS is a major limiting factor in the development and implementation of AHPS. The NWSRFS software is based on antiquated FORTRAN-based algorithms of the 1970s and 1980s, and current distributed, statistical, and probabilistic models that are in various stages of research for use in AHPS products are not aligned with it.

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The NWS recently started to address the NWSRFS system software problems through the Community Hydrologic Prediction System (CHPS)[10]. CHPS is an effort to redesign forecast system architecture based on a web-service architecture. CHPS would enable sharing of modeling applications across the hydrologic "community," which is composed of people from research, government, and academic organizations. As described, CHPS would provide a modular modeling framework for the development, enhancement, integration, and application of a wide variety of models and associated analysis and forecasting tools. CHPS is made up primarily of NWS employees and it has a strong NWS focus. Similar frameworks to CHPS are in development at other federal agencies and research centers. The U.S. Geological Survey's Modular Modeling System[11], the U.S. Department of Agriculture's Object Modeling System[12], the U.S. Department of Energy's (DOE) Framework for Risk Analysis in Multimedia Environmental Systems (Whelan, et al., 1997), and the DOE's Dynamic Information Architecture System[13] are examples of major software development efforts. **The experiences gained from other federal modeling collaborations should be considered in the development of CHPS.**

Even with CHPS and other NWS efforts to address the NWSRFS software problems, the current NWSRFS system must operate until new AHPS functionality is developed and implemented. The NWS will either fit new AHPS capabilities into the existing framework or abandon NWSRFS for a new, redesigned approach. The addition of new hydrologic methods into NWSRFS in some cases, such as in distributed modeling, may be impossible given the current structure. Furthermore, site specific hydrologic conditions may require alternative or even multiple models and techniques to be applied at a particular location in order to optimize forecast skill.

The NWSRFS is a barrier to the AHPS goal of *producing more accurate products by incorporating advanced hydrologic science into the NWS model.* The existing forecast system severely limits the ability to: (1) test research advances within the NWSRFS framework; (2) add new and diverse hydrologic features to the system; and (3) accelerate the transfer of new technology to operations. **To incorporate the state-of-the-art hydrologic modeling capabilities, the NWS should invest in the next generation of NWSRFS that includes a flexible framework that allows alternative models, methods, or features that can be tested, verified and implemented expediently. A total redesign of the NWSRFS is needed for AHPS to fulfill its scientific and technical goals.** A redesign would involve updating NWSRFS to current state-of-the-art software and hardware standards and using software that is more modular in design to support future modifications and enhancements of AHPS.

FLASH-FLOOD GUIDANCE

Flash-floods occur within a few short hours from the onset of heavy precipitation, and rank among the top natural hazards in the U.S because they cause major losses of life and property. Like the NWSRFS, the scientific foundations of current NWS flash-flood guidance and flash-flood warnings generation are derived from 1970s and 1980s techniques. Primarily, flash-flood forecasting has remained in the meteorological domain, and few, if any, hydrologic tools and models have been developed to forecast flash-floods (Droegemeier et al., 2000). AHPS has a goal to *provide more specific and timely information on fast-rising floods with increased lead time.* In order to achieve this goal, AHPS will

[10] *http://www.nws.noaa.gov/om/water/ahps/BAMS_Article.pdf.*
[11] *http://wwwbrr.cr.usgs.gov/projects/SW_precip_runoff/mms/.*
[12] *http://oms.ars.usda.gov/.*
[13] *http://www.dis.anl.gov/DIAS/.*

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need to update the hydrologic scientific basis for flash-flood guidance. The needs of updating the scientific basis for flash-flood guidance have been identified before (NRC, 1996) and the following recommendation is repeated here to help guide the NWS to fulfill the AHPS flash-flood goal:

> **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.**

There is no evidence of any significant progress in development of hydrologically-based flash-flood modeling systems; hence, the issues identified in 1996 (NRC, 1996) still apply today.

According to NWS presentations, there are plans to develop site-specific SAC-SMA to determine local hydrologic preconditions for flash-flooding for AHPS. The NWS is considering using this "semi-distributed" model at RFCs (see earlier section, Hydrologic Models of NWSRFS), and perhaps eventually employing a statistical distributed model to replace the current flash-flood guidance. The statistical model would be based on developing the frequency distribution of flooding at ungaged locations based on retrospective QPE data. The technical basis for these various approaches to flash-flood guidance and the flash-flood problem are not well documented. The utility and importance of the choice of hydrologic model for AHPS products is noted (see earlier section, Hydrologic Models of NWSRFS), and the same issues discussed with respect to NWSRFS models apply to flash-flood forecasting because model selection will be central to flash-flood forecasting envisioned for AHPS. Like with hydrologic models in NWSRFS, the step-by-step testing and evaluation plans are not defined for transitioning to distributed modeling for flash-flood forecasting.

The NWS plans to implement a national verification program for its flash-flood monitoring and prediction (FFMP) effort (NWS, 2004). Verification is welcome, but more detail about deliverables and milestones needs to accompany it. The plans for improvements in the production and use of QPE and QPF in FFMP are mentioned as well, and again, a schedule for deliverables and milestones along with an evaluation plan is required. Therefore, **the NWS should provide adequate documentation within AHPS of the scientific details and the implementation strategy for its end-to-end flash-flood hazards forecast generation and dissemination.**

Coordination between RFCs and WFOs in hydrological and hydrometeorological analyses and modeling will be required for producing and delivering forecasts, warnings and watches at local scales where the information is useful and actionable for the public. AHPS should include the forecast of flash-flood hazards and generation of warnings (dissemination) at the local WFO-level in its suite of activities. **As a core capability, AHPS should include support for the forecast of flash-flood hazards and generation of warnings at the local WFO-level.**

CHAPTER SUMMARY

This chapter describes and evaluates the scientific, technical, and modeling aspects of AHPS. The NWSRFS is the primary modeling engine for hydrologic forecasts, and each of the modular elements of NWSRFS is discussed, and recommendations are made to improve NWSRFS and help the NWS to fulfill the scientific and technical goals of AHPS. The evaluation of these scientific and

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technical aspects of AHPS resulted in numerous, specific recommendations throughout the chapter, and the major recommendations are noted here as three broad observations.

First, improvements are needed to the precipitation inputs to the hydrologic models that are used to generate AHPS hydrologic forecasts. The quality of the hydrologic forecast depends on the quality of its precipitation inputs, and improvements to precipitation inputs will work towards fulfilling the AHPS goal of *creating information that is useful to assess risk to flooding* through better, more accurate forecasts. Therefore, AHPS should strengthen the QPE and QPF through an end-to-end evaluation that assesses QPE/QPF quality and impacts on flood and streamflow products for basins of diverse size and topography. In addition to improving QPE and QPF, AHPS developers are encouraged to work with satellite precipitation groups to ensure the AHPS hydrologic requirements for precipitation are considered in other federal activities, such as NASA's Global Precipitation Measurement mission.

Second, the modeling capability needs improvements for AHPS to *produce more accurate products and incorporate advanced hydrologic science in the NWS hydrologic models.* Also noted in the modeling evaluation was a gap between the state-of-the-art hydrologic modeling capabilities and those used in AHPS product development. The current AHPS model, the NWSRFS, is described as needing updates, better verification, and better alignment with models that have finer spatial and temporal resolution. Therefore, AHPS should invest in the next generation of NWSRFS that includes a flexible framework that allows alternative models, methods, or features that can be tested, verified, and implemented expediently. CHPS, DMIP, and other collaborative activities to address the modeling capability of AHPS are commended, and the committee recommends that the NWS strengthen connections between DMIP Phase I/DMIP Phase II and AHPS goals. The committee also recommends that the NWS clarify the criteria and decision–making process for selecting the next generation hydrologic model(s) for AHPS, using an advisory board that involves modeling experts from inside and outside of the NWS to ensure that the state-of-the-art modeling advances are incorporated objectively into NWSRFS.

Finally, a recurrent finding in this evaluation was that very few scientific and technical aspects of AHPS are documented. The program will benefit from greater publication, peer review, and dissemination of its current and recent activities to improve the hydrologic science and technology used in AHPS product development and operation. The full list of this chapter's recommendations is presented in Box 3-2.

BOX 3-2
Recommendations

- AHPS researchers should periodically publish progress of the development of and improvements to precipitation products.
- AHPS developers are strongly encouraged to work closely with satellite precipitation groups (NASA, NOAA, and those in the academic community) to ensure that AHPS hydrologic requirements for precipitation are included in the Global Precipitation Measurement mission.
- The NWS should strengthen QPE and QPF for hydrologic prediction through an end- to-end evaluation that assesses QPE/QPF quality and impacts on flood and streamflow products for basins of diverse size and topography.

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BOX 3-2 Continued

- The NWS should strengthen connections between DMIP Phase I/DMIP Phase II and AHPS goals and clarify the criteria and a decision-making process for selecting the modeling engine for AHPS. To do so, the NWS should form an advisory structure that involves modeling experts from inside and outside of the NWS to ensure that the state-of-the-art modeling advances are incorporated into NWSRFS operations.

- The NWS needs to provide stronger documentation to allow the research community to learn about and contribute to AHPS research and development.

- The NWS should continue efforts to improve and expand AHPS calibration capabilities, accelerate the rate of transfer of the latest calibration techniques into its operational AHPS-NWSRFS version, and conduct adequate training of modeling personnel to ensure appropriate and consistent use of the new techniques.

- The goals of DMIP and MOPEX should be compatible with each other and with AHPS.

- The NWS should review the current suite of operational software and develop a comprehensive plan for refreshing that software.

- Like their meteorological counterparts in the NWS, hydrologic forecasters should run hydrologic models primarily in a "model only" mode, make forecast adjustments with post-processing techniques, and document these adjustments for future verification purposes.

- AHPS developers should consider automating the OFS/IFP component of the AHPS-NWSRFS and develop a systematic mechanism to include new research results and error analysis techniques into the operational OFS/IFP component.

- In no way should forecasters be removed from the forecast process, and the NWS is urged to redefine the role of the hydrologic forecaster in a fully automated data assimilation process.

- AHPS should document its overall strategy about ESP, including priorities for the ESP system and sub-system development, testing, and implementation. The AHPS approach to quantifying uncertainties in operational forecasts must be articulated. In addition, AHPS should better specify connections between current and future research activities and the AHPS overall development and implementation and ESP sequencing plans.

- While the inclusion of a verification sub-component in AHPS NWSRFS is commended, there is a pressing need for a long-term strategy and maintenance of a forecast archive for future verification and NWSRFS evaluation.

- The experiences gained from other federal modeling collaborations should be considered in the development of CHPS.

- To incorporate the state-of-the-art hydrologic modeling capabilities, the NWS should invest in the next generation of NWSRFS that includes a flexible framework that allows alternative models, methods, or features that can be tested, verified and implemented expediently. A total redesign of the NWSRFS is needed for AHPS to fulfill its scientific and technical goals.

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BOX 3-2 Continued

- 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 NWS should provide adequate documentation within AHPS of the scientific details and the implementation strategy for its end-to-end flash-flood hazards forecast generation and dissemination.

- As a core capability, AHPS should include support for the forecast of flash-flood hazards and generation of warnings at the local WFO-level.

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4
AHPS Users

The primary emphasis of the Advanced Hydrologic Prediction Service (AHPS) is a continuum of models and product delivery approaches (see Chapter 3), but AHPS' value ultimately will be determined by the users of AHPS products. Perhaps this is the reason AHPS has two goals that target AHPS users. One goal is to *create new formats, including graphics, for products that are easier to use*; the other is *to increase the distribution of products using advanced information technologies (such as the internet and web-based geographic information system (GIS) formats) to provide broader and more timely access and delivery of information*. Through fulfilling these goals, the National Weather Service (NWS) may realize opportunities to assure optimal communication of hydrologic information generated through AHPS. These goals provide direction for the format and presentation of AHPS information, but other user-related issues also need to be considered in the development, implementation, and execution of AHPS for the wide-ranging user base that AHPS developers expect. This chapter addresses these user-related issues.

RANGE AND NEEDS OF AHPS USERS

The NWS intends AHPS products to reach a wide range of users with an equally wide range of needs for hydrologic information. AHPS users include the general public and hydrologic professionals in various government agencies and the private, academic, and non-profit sectors. AHPS products, once fully developed, will reach users through the internet, GIS maps and data layers, television and other media outlets, and communicated advisories and warnings. The challenge of meeting the needs of a broad range of users is critical for the success of the AHPS program, as AHPS products must reach many and varying users and accommodate different levels of user technical sophistication. AHPS products must also be delivered at the right time, at the right spatial scale, and with the right level of hydrologic forecast certainty to each AHPS user.

AHPS users include those who use the specific technologies and models developed for AHPS and those who use the output developed as part of AHPS (Table 4-1). For example, hydrologic professionals from government, academia, and the private sector may use AHPS models and algorithms, whereas travelers may need to know whether low-lying roads will be flooded out. Currently, most AHPS users are internal to the NWS or involved in professional activities related to the monitoring of hydrometeorological data, but the number of public and external users is expected to grow. Some River Forecast Centers (RFCs) are responding to this growth already; for example, the Colorado Basin RFC[1] provides information for users interested in water-based recreational activities and snow conditions. With the growing user base and different needs of users, optimal application of AHPS products and technologies should accommodate the associated range of skills and needs.

AHPS users need hydrologic data on different time and spatial scales (see Table 4-2). Timing of needs spans hours, days, months, seasons, and years. Emergency managers are usually concerned with short-term predictions related to floods and features of floods, such as peak flow and areas of inundation. Daily to multi-day predictions are needed by water resource managers who focus on issues of power generation and flood control. Monthly to seasonal predictions are

[1] For further information on the Colorado Basin RFC see *http://www.cbrfc.noaa.gov.*

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TABLE 4-1 Users and Potential Users of AHPS

Individuals	**Academics**	**Government**
- Personal decision-making during disasters - Recreational decision making - Farmers	- Research and development applications - Teaching and training - Public education and outreach	- Transportation - Public health - Environment - Recreation - Water utilities - Emergency management
Private Sector	**Nonprofits**	
- Insurance companies - Planning and design consultants - Corporate risk managers - Private water companies - Water-based recreation companies - Farmers and ranchers - Power generators	- Watershed organizations - Disaster/relief organizations (i.e., Red Cross) **Critical Facilities** - Schools - Nursing homes - Hospitals - Power plants	

TABLE 4-2 Characteristics of Potential Users and of Information Needed

User	Spatial Scale (km^2)	Temporal Scale	Staff Size	Technical Capability	Engagement Time
RFCs	$10^2 – 10^4$	Days to weeks	Medium	High	Before/during
WFOs	10^1 -10^3	Hours to days	Medium	High	Before/during
River basin commissions	$10^1 – 10^4$	Hours to weeks	Medium	High	Before/after
State emergency managers	$10^2 – 10^4$	Hours to weeks	Medium to large	Low to high	Before/after
Local emergency managers	$10^0 – 10^3$	Hours to days	Small to medium	Low to high	Before/after
Water supply managers	$10^3 – 10^4$	Weeks to Months	Small	Medium to high	Before/during/ after
Dam managers	$10^3 – 10^4$	Weeks to Months	Small	High	Before/during
Floodplain managers	$10^2 – 10^4$	Hours to weeks	Small	Low to high	Before/during

needed for managing water supplies for municipal or agricultural purposes. Decadal and longer predictions can be used for long-range assessment of operational strategies and policy. Spatial scales of interest range from small headwater basins of a few tens of square kilometers to large, integrated river basin operations. Emergency managers are concerned with their areas of jurisdiction, such as a town or a county, while water resource managers have interests in larger basin areas.

AHPS models (see Chapter 3) work to reduce uncertainty in forecasts and minimize the frequency and implications of false predictions. Different AHPS users have different thresholds for hydrologic forecast certainty. For example, Weather Forecast Offices (WFOs) need hydrologic

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forecasts with high levels of certainty. WFOs use forecasts in the short temporal scale (hours in many cases), and will use these forecasts before or during the onset of heavy precipitation to develop warnings and watches that will be communicated directly to the public and the media. The public has come to expect very accurate and accessible forecasts, and the implications of false predictions for WFOs include loss of life or property or wasted response resources. Other end-point users, such as water supply managers, may not need highly certain precipitation and hydrologic forecasts because their lead-times are longer and some of their operational decisions are made after events have passed (Table 4-2).

REACHING AHPS USERS

The optimal communication of AHPS information involves phasing the AHPS users into AHPS operations, educating and training users to fully exploit the range of available AHPS products on a regional basis, and making uniform the user interfaces of AHPS information.

A Phased Approach

Because AHPS reaches the public and other users through the RFCs and WFOs, the NWS needs to recognize and focus on its internal users first. As described in Chapters 2 and 3, AHPS products range from the "basic" services to more elaborate "partnered" services, and these products and services are planned to be developed and implemented incrementally through 2013. An incremental approach for AHPS users is also reasonable. The rationale for a phased approach is two fold. First, RFCs and WFOs are central to AHPS because they are the public interface for AHPS products; and second, RFCs and WFOs comprise the vast majority of the AHPS user base.

The first phase of such an approach should address the RFCs' and WFOs' needs and fully train and integrate RFC and WFO personnel into the AHPS program. WFOs are the current first-level users of AHPS products; they use hydrologic information from the RFCs to develop watches, warnings, and forecasts that they then communicate to the media, emergency managers, and the public. However, site visits (see Appendix A) indicate a wide range of understanding and acceptance of AHPS products and suggest a need for bringing all RFC and WFO personnel to a comparable level of understanding of AHPS products. **WFOs are the most proximate users of hydrologic forecasts, and RFCs and WFOs are the primary AHPS users. The NWS should focus AHPS development and implementation initially on the activities and needs of the RFCs and WFOs because RFCs and WFOs play critical roles in disseminating AHPS information.** In subsequent User Phases, the NWS can focus on the needs of new and/or external users, as enhanced and partnered services are developed, refined, and implemented.

A part of the phased approach includes outreach, training, and educational activities to (1) inform users of the full range and operation of AHPS products as they are developed and (2) provide a venue for user feedback on current AHPS products. NWS professionals already conduct outreach activities to disseminate information about their products and foster understanding of AHPS products and services. For example, the NWS worked with the Susquehanna River Basin Commission and held training workshops throughout the basin. This effort and others like it are productive and need to be continued and expanded. As more AHPS products are added, as capability among current users increases, and as new users become familiar with AHPS, a new structure for outreach activities will be required. Outreach activities can include the following:

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1. establishing dissemination methods and channels;
2. developing educational resources, including people;
3. structuring around key users; and
4. coordinating with others who serve the same users.

Site-visit interviews conducted by the committee during the course of this study made clear that outreach and training about AHPS protocol, products, and services could be improved. Training, especially, may be an easy way to alert and familiarize WFO, RFC, and other personnel with AHPS development and implementation and operations. Training can be tailored to users external to the NWS, as well. For instance, if WFOs successfully use AHPS products, but local emergency managers are less inclined to incorporate AHPS into their operations, then appropriate training could be directed towards these emergency managers. **An AHPS outreach, education, and training program should be designed to ensure that AHPS products are used properly and to their fullest potential.**

The AHPS User Interface

The user interface to access AHPS information is central to fulfilling AHPS user-related goals of creating new formats for products and widely distributing AHPS products and services. The AHPS website, *http://www.weather.gov/ahps/*, is the primary portal for all of its hydro-meteorological information. The NWS has done an excellent job in providing web access to AHPS observational data and products. In this way, AHPS information can be accessed by the public and used by all those involved in the hydrologic and meteorological enterprise (NRC, 2003).

As noted earlier, AHPS products are being used and disseminated via the RFCs and the WFOs. AHPS information is presented in different ways, depending on the issuing RFC. Greater uniformity in the presentation of AHPS information would enhance the effectiveness and the identity of the AHPS site(s) and reduce the potential for misinterpretation of AHPS information. Some of the differences in graphic presentation reflect the different phases of implementation. Many, but not all, sites have the "basic" services operational. Some RFCs have graphic flash-flood guidance available. GIS information is available at some, but not all, forecast sites. Similarly, formats of AHPS information span a wide range, from satellite and radar imagery[2] and graphical forecasts[3], to area/regional maps[4] that suggest that graphical designs are also in various phases of development. Differences are bound to emerge as advancements in hydrologic models are tested and phased in across the RFCs. These differences aside, there is a need to present the same kinds of information in the same ways and to ensure that the information is being communicated as intended. A number of examples illustrate opportunities to improve consistency in the format and presentation of AHPS information:

- Northeast RFC (Figure 4-1) is testing a new hydrograph generation program that will ultimately be used at all RFCs. For now, however, only Northeast RFC is using it to generate hydrographs and forecast plots. Consequently, the Northeast RFC hydrograph has

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[2] *http://www.cnrfc.noaa.gov.*
[3] *http://www.srh.noaa.gov/rfcshare/precip_analysis_new.php.*
[4] *http://aprfc.arh.noaa.gov/ahps2/hydrograph.php?wfo=pafc&gage=sixa2&view=1,1,1,1,1,1&type=2.*

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a different format than other RFCs, and differs in color scheme and other appearances from other RFCs, such as the Missouri Basin RFC (Figure 4-2).

- The map legends for flooding-stage are different on the "Rivers" page (Figure 4-3) and forecast locations pages for the Lower Mississippi RFC (Figure 4-4)
- Some forecast plots and hydrographs show only stage and not discharge or flooding thresholds (Figure 4-5).
- Different color schemes and presentations are used for flash-flood guidance (Figures 4-6 and 4-7)
- If information is unknown at a specific location (i.e., flood stage, GIS coverage, etc.) it should be noted on the website.

While the NWS is making progress towards its goal of creating new formats for AHPS products, graphical formats need greater consistency across all AHPS web pages.

AHPS has used the internet to a great extent to increase the distribution of products using advanced information technologies (such as the internet and web-based GIS formats) to provide broader and more timely access and delivery of information. GIS is a powerful geostatistical tool that can present and analyze spatially complex layers of information. It holds great promise for some of the AHPS products, such as mapping flood inundated areas, areas prone to landslides or debris flows, or intensity and duration of droughts. The degree to which GIS is used in the development and presentation of AHPS products is difficult to ascertain; GIS data layers are available for users to download at some of the forecast sites, and some RFCs present AHPS information in GIS forms. Prototypes for the most select, "partnered," services are planned to

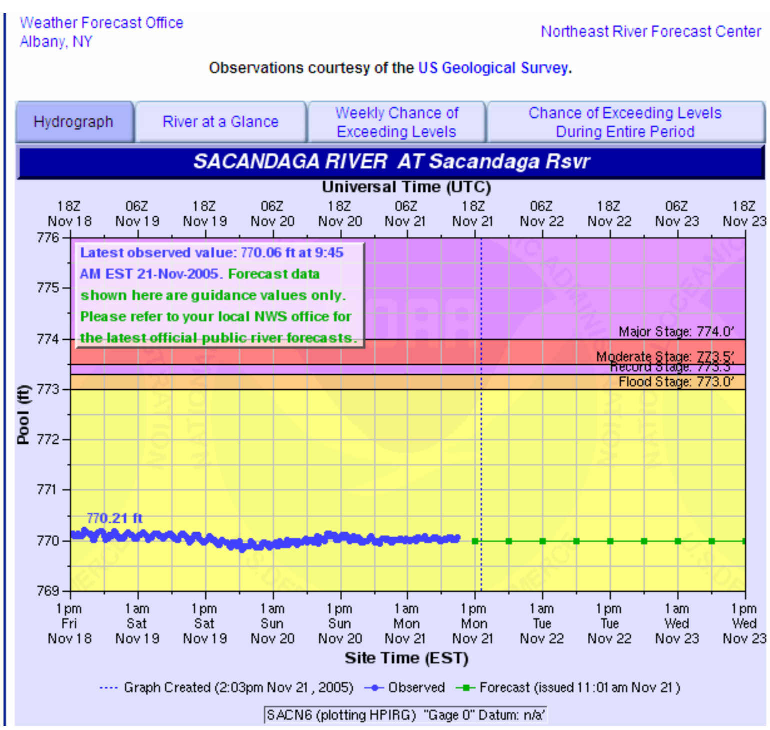

FIGURE 4-1 Hydrograph and forecast plot (Northeast RFC).
SOURCE: *http://newweb.erh.noaa.gov/ahps2/hydrograph.php?wfo=aly&gage=sacn6&view=1,1,1,1,1,1.*

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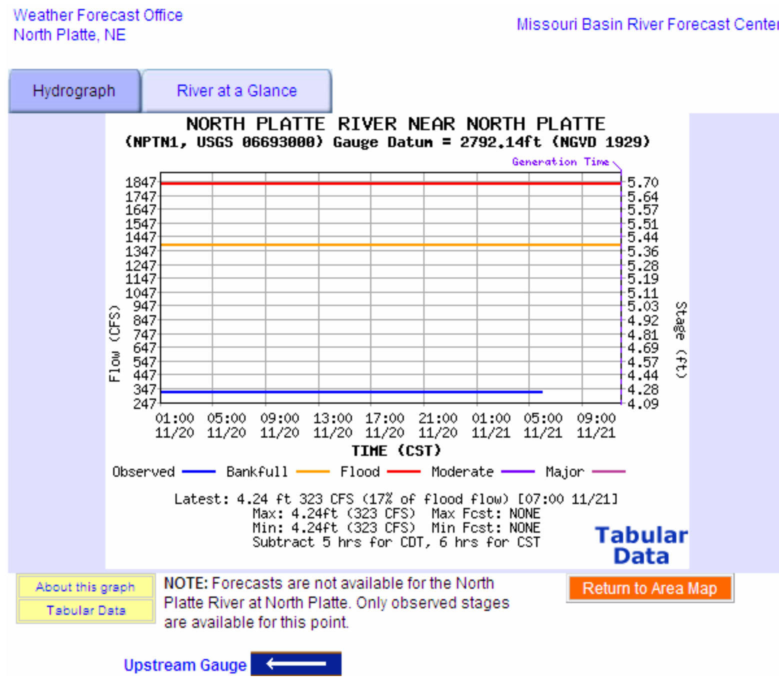

FIGURE 4-2 Hydrograph of Missouri Basin RFC.
SOURCE: *http://www.crh.noaa.gov/ahps2/hydrograph.php?wfo=lbf&gage=npsn1&view=1,1,1,1,1,1.*

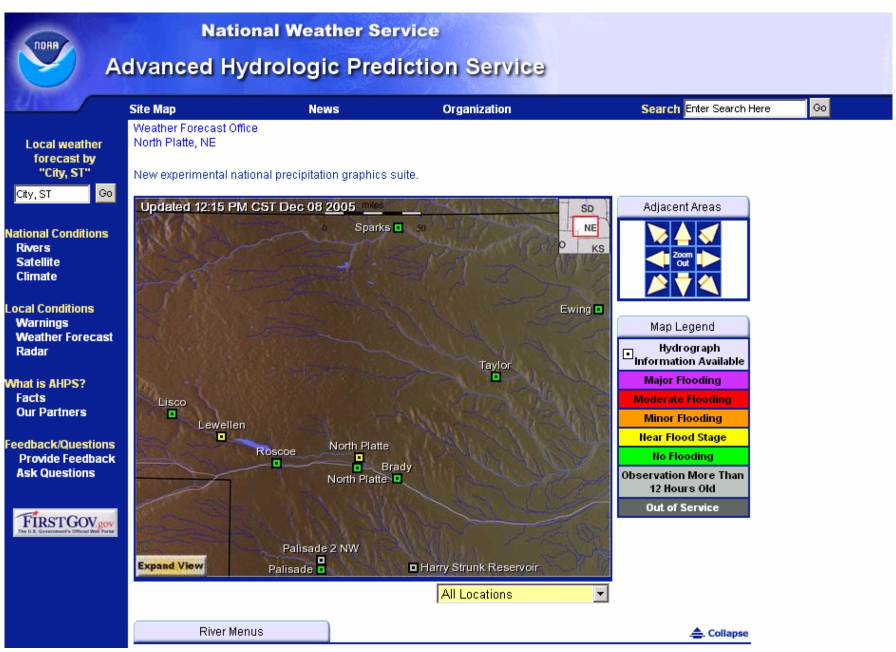

FIGURE 4-3 Color scheme for flooding-stage legends from "rivers" page (Missouri Basin RFC).
SOURCE: Adapted from *http://www.crh.noaa.gov/ahps2/index.php?wfo=lbf*.

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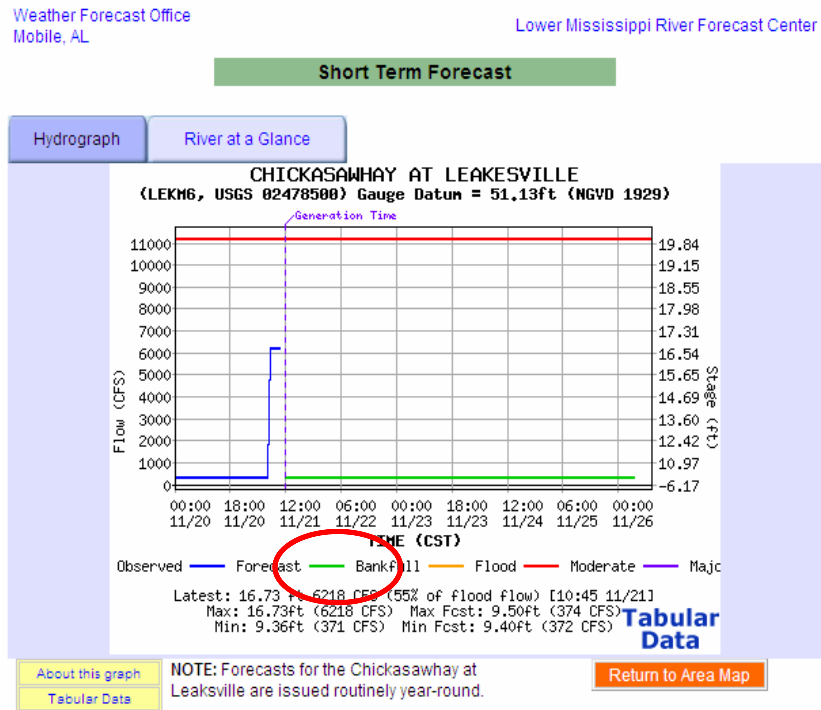

FIGURE 4-4 Color scheme for flooding-stage legends for hydrograph and forecast (Lower Mississippi RFC).
SOURCE: Adapted from *http://ahps.srh.noaa.gov/ahps2/hydrograph.php?wfo=mob&gage=lekm6&view=1,1,1,1,1,1.*

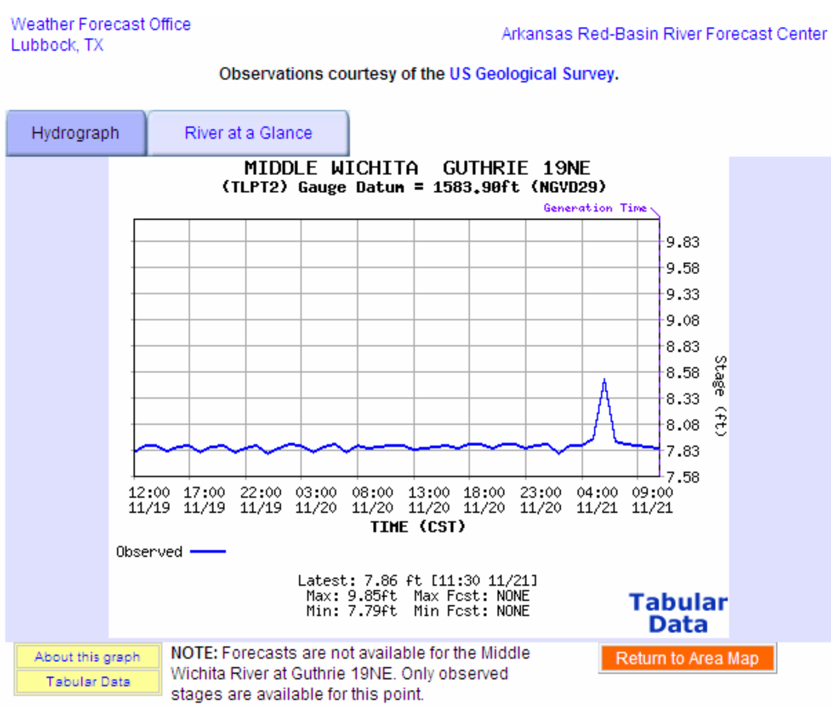

FIGURE 4-5 Hydrograph without flooding threshold and discharge (Arkansas Red-Basin RFC).
SOURCE: *http://ahps.srh.noaa.gov/ahps2/hydrograph.php?wfo=lub&gage=bpst2&view=1,1,1,1,1,1.*

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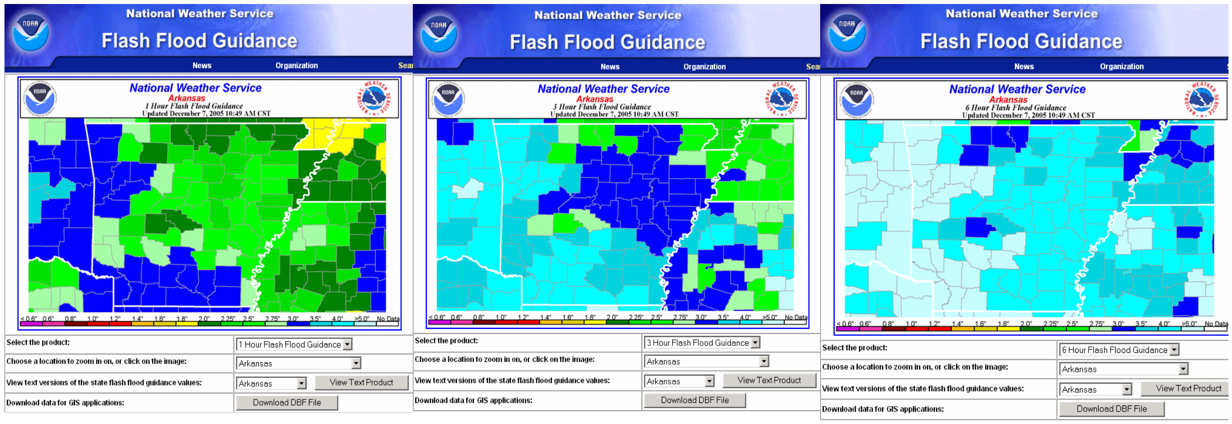

FIGURE 4-6 From left to right, flash-flood guidance for 1-hour, 3-hour, and 6-hour durations for Arkansas.
SOURCE: *http://www.srh.noaa.gov/rfcshare/ffg.php?location=AR&zoom_map=state&duration=1.*

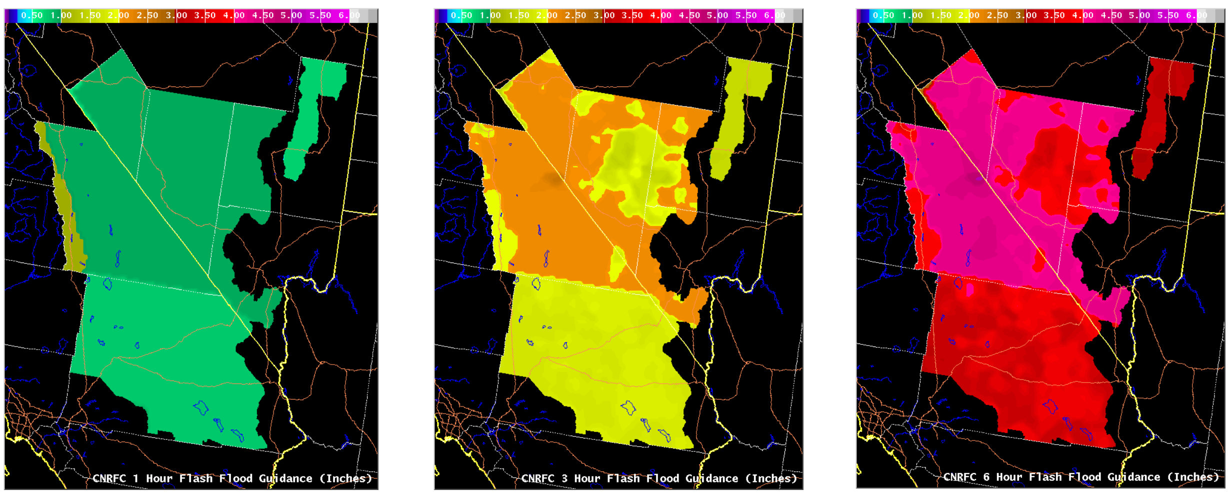

FIGURE 4-7 From left to right, AHPS products for flash-flood guidance for 1-hour, 3-hour, and 6-hour durations (California Nevada RFC, Sacramento, CA).
SOURCE: *http://www.wrh.noaa.gov/cnrfc/flashFloodGuidance.php*.

utilize GIS, as well (see Figure 3-1). In planning these services, it is critical to ensure that the products and modes of presentation, whether GIS based or not, are communicating what is intended. **The NWS should consult a communications specialist to assist with developing consistent and clear modes of presentation.**

FEEDBACK FROM AHPS USERS

User feedback is important in the continual development, implementation, and execution of AHPS products. It can be used to structure training and outreach efforts about AHPS products and services, conduct long-term monitoring of meeting AHPS goals and objectives, provide a database of information to support programmatic changes over time, and build a reliable foundation to keep AHPS current and useful to its wide range of users. Together with a phased development, outreach,

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and training approach, user feedback can help guide the continual evolution of AHPS products and services. User feedback approaches for AHPS should include internal users, external users, and ways to integrate feedback received from users.

Internal User Feedback

The WFOs are the primary, internal NWS users, but RFC, headquarters, and regional field staff also use AHPS products. To this end, the NWS has organized teams around themes to receive and process internal user feedback. These teams consist of both headquarters and field staff to identify needs with respect to flash-flood services, short-to long-term forecasts, flood mapping and graphical dissemination, collaborative research, program management, and other topics (George Smith, NWS, personal communication, 2004). Feedback from these teams is to be used to guide the development of various AHPS products or services.

The use of teams is a good first step towards the integration of field and headquarters staff, but the number of RFC and WFO personnel involved on these teams is quite limited. Given the top-down structure of AHPS management (see Chapter 2), RFCs may seem to be AHPS *users* at first glance. However, as AHPS reaches full maturity, RFCs are more likely to be primary *developers* and *disseminators* of AHPS information that supports WFOs and a wide variety of other users. Fully integrating the RFCs into the development of AHPS will be essential to the program's ultimate success, and their presence on the NWS internal teams needs to be commensurate with the role that RFCs play in the AHPS enterprise. Of course, RFCs are but one player in the AHPS program, and there is needed integration and two-way communication among the NWS Headquarters (HQ), RFCs, National Operational Hydrologic Remote Sensing Center (NOHRSC), National Centers for Environmental Prediction (NCEP), National Severe Storms Laboratory (NSSL), WFOs, the public, and other users (Figure 4-8). **Better integration is needed to incorporate feedback from the RFCs and WFOs in the development of AHPS products and priorities.**

External User Feedback

External AHPS users include the media, emergency managers, and the public, among others (Table 4-1). As stated earlier, the WFOs are the most proximate users of AHPS products and are the gateway to many AHPS external users. Although undocumented in NWS materials, WFOs, as the public interface for many of the AHPS products, would provide a suitable venue to receive input and feedback from external users who are not web-based users. This type of communication through the WFOs would echo the two-way communication stressed in internal communications (Figure 4-8).

Currently, the NWS uses the AHPS website as the primary venue to solicit and collect feedback from external users about AHPS products, services, and delivery. This strong web-based focus seems fitting, considering that AHPS is a program that concentrates on the web-interface and internet access to hydrologic information[5]. The standard NWS survey is available on AHPS pages; the survey identifies the program being surveyed and asks nine questions:

1. On a scale of 0 to 10 (10 highest), rate technical quality of this product/service (e.g., forecast accuracy, timeliness, problems with display).

[5] The AHPS website also invites feedback via phone and postal mail entries.

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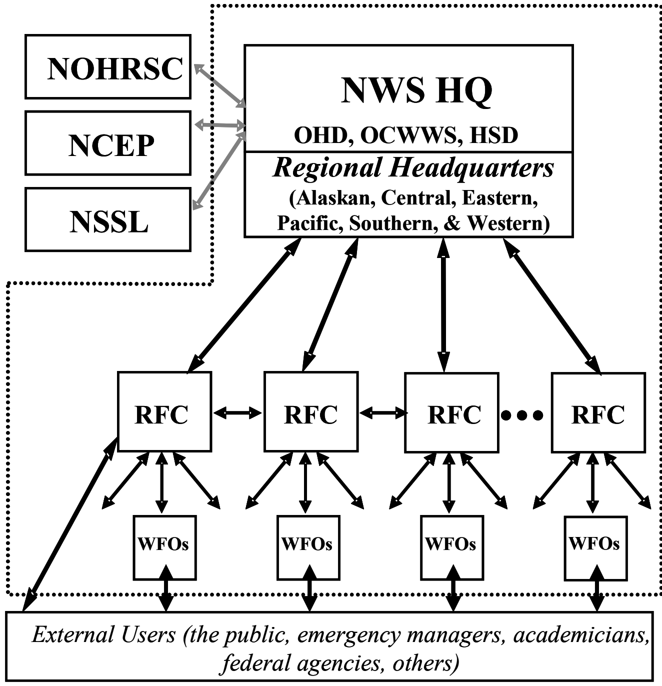

FIGURE 4-8 Integrated internal NWS communication for AHPS products and information.
NOTE: See acronym list.

2. On a scale of 0 to 10 (10 highest), rate how easy you found the product/service to interpret and use.
3. What features did you like or find useful?
4. What features did you not like? (Explain briefly)
5. How often do you use this product/service?
6. Tell us how you plan to use the information provided in this product/service (e.g., information only, to support personal decision-making, to support business decision making, etc)?
7. Comments on the Product/Service Description Document (documentation) provided.
8. Any additional comments/suggestions concerning this product/service.
9. What is your affiliation?

This type of information, collected on a regular basis, is available to the NWS to review the usefulness of AHPS products. Because the survey is NWS-wide, it can also be used to assess AHPS in comparison to other NWS programs. Information from the AHPS survey can be used to ascertain which AHPS aspects work as anticipated, which ones work, but not as anticipated, and those that do not work at all.

Integrating User Feedback

The NWS website survey provides an excellent opportunity to document how AHPS products, services, and delivery are being received and used by AHPS users. It remains unclear, however, how the NWS is using the information it receives via the website or any other feedback venue. Integrating feedback from other user groups will require a plan or strategy within the AHPS

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program. Other federal agencies have undertaken similar user-based feedback and integration tasks, and the NWS might learn from them in developing its own user feedback integration strategy (see Box 4-1).

While the NWS is applauded for inviting user feedback, there are several aspects about this web survey feedback that need more clarification or better documentation. For example, it is not clear how the information from the web-based surveys is processed or integrated into subsequent development and implementation of AHPS. Important elements of the web-based surveys that remain undocumented or difficult to ascertain are:

- how long this information has been collected;
- how this information is used;
- how long the information is retained at the NWS;
- how many responses are received;
- who receives the completed web-surveys; and
- how the information is processed.

After collecting the information, organizing the responses is the next step in a strategy to integrate user feedback. At a minimum, user feedback could be organized by the utility of the products (including ease of use of models and ease of interpretation of results), user or user type (WFO, RFC, local emergency managers, public, etc.), type of use (warning, water resource management), or time frame (short-, medium-, or long-range forecasts). Feedback from users could be used to evaluate AHPS usage to determine future needs and answer several key questions in this regard:

1. What are the specific products being used?
2. How have AHPS products been implemented and used?
3. How does actual use of AHPS products align with NWS expectations for AHPS use and implementation?
4. In what areas are strengths noted?
5. In what areas are weaknesses noted?
6. What ways does the public use AHPS products?

These questions could form the basis for improving program development. In order to facilitate this, however, an organized approach is needed to collect, organize, process, and maintain important feedback. Such an approach should be developed to use feedback to its greatest potential to improve AHPS products and services and make progress towards fulfilling AHPS goals. To improve the integration of AHPS user feedback, the AHPS program needs to expand venues beyond the internet for users to provide feedback on AHPS products and services, documentation of the user feedback to date, and development of a structure to include user feedback into AHPS product development and implementation. **Before AHPS is fully developed and implemented in 2013, it is necessary to develop a strategy for systematically collecting and processing feedback from AHPS users.**

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BOX 4-1
Users and Other Federal Programs

Like the NWS, several other federal agencies distribute technology or technical information to a broad user base. The challenge with integrating users is not a new issue for federal agencies that deal with the distribution of technology. Perhaps unique among federal agencies, the NWS distributes technology as well as distributing public communications based on that technology, whereas most other federal programs are dealing with a more technical user base. There are, however, lessons that might be learned by evaluating similar efforts with other federal agencies. Two examples could help the NWS guide and develop its interaction with the AHPS user base, Federal Emergency Management Agency's (FEMA) HAZUS and the U.S. Army Corps of Engineers' (USACE) Hydrologic Engineering Center (HEC).

FEMA over the past decade has been developing HAZUS, which is a GIS-based tool for modeling/integrating wind, flood, and earthquake events, and then evaluating the damages associated with a specific event. The user community is broad with a decided emphasis on FEMA regional staff, and state and local emergency management officials and planners. It is also understood that there will be a broad range of potential users that include the private sector, industry, academia, and others. While FEMA is still ramping up in supporting the user community, two key actions have taken place:

1. The encouragement and support of geographically based user groups. The user groups provide a network that links users within an area, and allows them to exchange lessons learned as well as provide group feedback to FEMA on the development of HAZUS.
2. The development of training that is open to a wide range of potential users. The training is held at FEMA's Emergency Management Institute, as well as in locations that coincide with a gathering of practitioners. For example in 2004, HAZUS training was held at the end of the Association of State Floodplain Managers annual conference, providing some of the participants an opportunity to be trained in HAZUS.

Over the past 35 years HEC has developed a number of critical hydrologic and hydraulic engineering and water resource planning models. These models have received national and international distribution. Due to documentation, ease of use, reliability of results, and availability at no cost, the HEC models have gained wide acceptance. However, because of budgeting issues, the HEC support of users has changed dramatically over the years. Up to the mid-1980s non-USACE staff were eligible to participate in training held at HEC on a space available basis. Likewise, free support was available from HEC staff over the phone assisting all users with model applications. In the mid-1980s however, HEC shifted its focus to primarily supporting the needs of USACE district staff. While the general public could still obtain models and documentation to support the models, USACE no longer provided training and support. During this transition, USACE encouraged the creation of a cottage industry that specifically supports training and support as an element of a broader business. Today, USACE models and documentation are available over the web, and there is a well-developed user community that is able to train and support new users.

Measuring Success

Measures of success can be used to monitor progress, integrate user feedback, and document program successes. Certain questions can help frame success measures for AHPS:

1. Was the forecast accurate for your purposes (scale from 0-10, etc.)?
2. Were lead times increased compared to previous forecasts or warnings?
3. Was something done with the forecasts to minimize losses?

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The NWS has developed a set of performance measures that address the first two questions. Specifically, the 2003 goal for flash-flood lead times is 50 minutes and the goal for flash-flood warning accuracy is 87 percent. The 2008 target for lead time is 58 minutes and the 2005 goal for accuracy is 90 percent (NWS, 2003).

While such improvements are important and would be expected to reduce losses, there is little proof that these improvements actually lead to more effective responses by those receiving the warning. On one hand, having additional lead time should allow people to take actions they would otherwise have not been able to undertake. On the other hand, additional time may encourage people to procrastinate or not take any action at all. These types of data are missing, but would be useful to understand how people are using AHPS products and to derive approaches to producing risk reductions commensurate with the improved forecasts.

Data that quantify levels of user satisfaction with AHPS products and services are also needed. Surveys of various user groups can be distributed following specific events, at training sessions, or at other pre-determined intervals. The NWS has conducted surveys (i.e., following a demonstration on AHPS in the Middle Susquehanna sub-basin in November 2003) to gauge user interest and satisfaction. In addition, the results from surveys can be used to understand better whether AHPS is meeting needs and where additional work is required to do so. Similarly, successes of AHPS can be documented clearly and used to promote the program to others and help quantify the economic benefits resulting from investment in AHPS.

Specific success measures can help structure surveys and interpret survey results to improve AHPS. Some success measures currently exist, in the form of metrics, like customer satisfaction indices, and these should continue to be collected. Metrics that quantify improvements in user responses to hydrologic events can be useful in the development and implementation phases and can be used to support continued or increased funding of the AHPS program. **The NWS should develop specific measures of success and a strategy to systematically collect and integrate feedback into a continuous loop of improved AHPS products and services.**

CHAPTER SUMMARY

This chapter discusses the user aspects of the AHPS program. It describes the range of the type and needs of the users that the NWS expects of AHPS products and makes recommendations about reaching and receiving feedback from AHPS users. The range of AHPS users is noted to be potentially very broad, but for now, the RFCs and the WFOs comprise the majority of AHPS users. The recommendations from this chapter are presented in Box 4-2.

BOX 4-2
Recommendations

- RFCs and WFOs play important roles in disseminating AHPS information; WFOs are the most proximate users of hydrologic forecasts; and RFCs and WFOs are the primary AHPS users. Therefore, it is recommended that the NWS focus initially on the activities and needs of the RFCs and WFOs.

continues

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BOX 4-2 Continued

- An AHPS outreach, education, and training program should be designed to ensure that AHPS products are used properly and to their fullest potential.
- While the NWS is making progress towards its goal of creating new presentation formats for AHPS products, the AHPS information should be presented with greater consistency across RFCs and WFOs.
- It is recommended that the NWS consult a communications specialist to assist with developing consistent and clear modes of presentation.
- Before AHPS is fully developed and implemented in 2013, it is necessary to develop a strategy for systematically collecting and processing feedback from AHPS users.
- Feedback from the RFCs and WFOs should be more thoroughly integrated into the development of AHPS products and priorities.
- The committee recommends that the NWS develop specific measures of success together with a strategy to systematically collect and integrate feedback into a continuous loop of improved AHPS products and services.

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Acronyms

ABRFC	Arkansas-Red Basin River Forecast Center
AHPS	Advanced Hydrologic Prediction Service
ALERT	Automatic Local Evaluation in Real Time
AMS	American Meteorological Society
API	Antecedent Precipitation Index
APRFC	Alaska-Pacific River Forecast Center
ARC	AHPS Review Committee
CBRFC	Colorado Basin River Forecast Center
CHPS	Community Hydrologic Prediction System
CNRFC	California Nevada River Forecast Center
CS	calibration system
CY	calendar year
DMIP	Distributed Model Intercomparison Project
DOE	U.S. Department of Energy
ESP	ensemble streamflow prediction
FEMA	Federal Emergency Management Agency
FFMP	flash-flood monitoring and prediction
FY	fiscal year
GIS	geographic information system
GPRA	Government Performance and Results Act
HEC	Hydrologic Engineering Center
HL	Hydrology Laboratory
HMS	Hydrologic Modeling System
HQ	NWS Headquarters
HSD	Hydrologic Services Division
IFP	interactive forecast program
LMRFC	Lower Mississippi River Forecast Center
MARFC	Middle Atlantic River Forecast Center
MBRFC	Missouri Basin River Forecast Center
MOPEX	Model Parameter Estimation Experiment
NAE	National Academy of Engineering
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCRFC	North Central River Forecast Center
NERFC	Northeast River Forecast Center
NHWC	National Hydrologic Warning Council
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRC	National Research Council
NSIP	National Streamflow Information Program
NSSL	National Severe Storms Laboratory

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NWRFC	Northwest River Forecast Center
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
OCWWS	Office of Climate, Water, and Weather Services
OFS	operational forecast system
OHD	Office of Hydrologic Development
OHRFC	Ohio River Forecast Center
PQPF	probabilistic quantitative precipitation forecast
QPE	quantitative precipitation estimation
QPF	quantitative precipitation forecast
RFC	River Forecast Center
SAC-SMA	Sacramento Soil Moisture Accounting Model
SERFC	Southeast River Forecast Center
UCAR	University Corporation for Atmospheric Research
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WARFS	Water Resources Forecasting System
WFO	Weather Forecast Office
WGRFC	West Gulf River Forecast Center

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Appendixes

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Appendix A
Site Visits

Members of the committee made site visits to several field offices in which the Advanced Hydrologic Prediction Service (AHPS) is used in one form or another. These were not all National Weather Service (NWS) field offices, but rather represent a range of agencies and organizations that use or generate hydrologic models and forecasts. All were quite familiar with AHPS and each has used either AHPS data, models, and/or products. Some serve other users who, in turn, use AHPS data or products, either directly or through the organization visited. Each group of professionals interviewed voiced strong support for AHPS and encouraged its continued development. Each pointed to different aspects that they believe are essential elements of AHPS, reflecting their specific needs and interests, and all had suggestions for improving AHPS. Despite the differences among the offices in responsibilities and needs, their responses to the interviews can be grouped into three categories: the science, interaction and connection, and identifying needs. Though each is discussed separately below, they are not mutually exclusive.

THE SCIENCE

Several people interviewed expressed concerns about the data and models that are the foundation of AHPS. For instance, many hydrologists who use AHPS products remain unconvinced about the adequacy of precipitation and temperature data as they affect quantitative precipitation forecasts (QPFs) and quantitative precipitation estimations (QPEs). Advances are needed to ascertain the correct usages of QPE, QPF, and probabilistic quantitative precipitation forecasts (PQPFs). Also needed is a long-term strategy to address systematic deficiencies such as these.

Other examples were given, but most modeling and scientific concerns centered around the need for shorter-term forecasts. Shorter-term forecasts require more frequent updating. They are based on sufficiently sensitive models, and model input needs to be verified and validated for accuracy. These elements of the shorter-term forecast models were seen as critical to the success of AHPS. It appears to some in the field that short-term pressures to produce results are a stronger focus than the development of an end-to-end hydrologic prediction system. Others interviewed suggested that too much of AHPS seems to offer discrete solutions to localized problems, rather than an approach that addresses system-wide issues such as data availability and model accuracy. Therefore, those interviewed were clear that high priority must be given to advancing the science associated with the forecasting that is at the root of AHPS.

Another theme that surfaced was the need to shorten the time between the inception of ideas and their implementation. Distributed modeling has been of concern for almost two decades, yet it has still not been used in operational forecasts. Similarly, QPE from radar have been discussed as a priority for sometime, but sufficient advances have not been made. These are examples of elements that are critical to the ultimate success of AHPS. That we have not gotten to where we need to be is a function of a number of factors, many of which are not easily controlled by the NWS. Because much of the data collection and some of the modeling are done through field offices and other agencies, there is a need for close interaction between NWS field offices and cutting-edge research.

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INTERACTION AND CONNECTION

The need for communication among all players, those in various field offices and related organizations and those at headquarters, is clearly evident from the data sharing and model building that take place in various locations. A great deal of modeling that has direct application to AHPS is done in the field, and much of the necessary data are collected there. Conversely, models that are developed at headquarters can be most easily tested and implemented by regional and local offices. Clearly, improved communication can benefit all: ideas can get into operational settings more quickly and models developed in the field can more easily be incorporated into the AHPS process at headquarters.

Absence of a clear, integrated chain of command and communication not only leads to difficulty in developing and implementing an end-to-end system, but it also confuses users who may need immediate answers and face uncertainty as to where they can go for those answers. For instance, the River Forecast Centers (RFCs) produce forecasts but do not officially issue them. Users, then, cannot contact the RFCs directly regarding feedback or problems associated with the forecasts.

Connections and cooperation are also necessary among the numerous agencies that develop and use hydrologic data and models. Frustration at the time it has taken to see some ideas become operational may be lessened by agencies working together rather than by each doing its own modeling. This is probably a lower priority than the "in-house" cooperation that is discussed above, but it may be a way to leverage resources to better advantage and to avoid duplication of efforts.

IDENTIFYING NEEDS

One fact that became abundantly clear during the site visits is that hydrologic information is used by a wide range of users. The needs of these users vary significantly, as do their levels of sophistication. An important concern of those interviewed relates to the move to probabilistic forecasts in which a suite of values is provided, each with a given probability of exceedance. While supportive of this approach, all recognized the implications of this, which will end up shifting managerial decisions to users. Some will find it very useful, some will not.

A current problem with AHPS that was cited by several of those interviewed is the lack of consistent data and products available at all locations. It was recognized that such consistency will take time as necessary data are collected and models developed and calibrated at new locations, but this is not always as easily recognized by different users and user groups. Some locations have flood inundation maps available; others don't. Some users look for long term forecasts; others require short term forecasts with frequent updates. For some users, the 6 hour time step of hydrologic models works; for others, a 3 hour time step would be more appropriate. Working in close collaboration and interacting regularly along the chain of command would help identify and prioritize the varying needs.

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Appendix B

WATER SCIENCE AND TECHNOLOGY BOARD

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Appendix C

Committee and Staff Biographical Information

Soroosh Sorooshian (NAE) is Distinguished Professor of Civil and Environmental Engineering and of Earth System Science at the University of California, Irvine. Dr. Sorooshian's research focuses on surface hydrology, primarily in the area of rainfall-runoff modeling. He has devoted much of his effort to model identification and calibration issues and has developed special estimation criteria to account for the uncertainties of calibration data. Other research interests include the application of remote sensing data for characterization of hydrologic parameters and fluxes and the implication of climate variability and change in water resources. He also consults on problems related to surface hydrology and flood forecasting. Dr. Sorooshian has been a member of seven NRC committees as well as serving as chair for the Global Energy and Water Cycle Experiment Panel. He received his B.S. in mechanical engineering from California Polytechnic State University and his M.S. in operations research and Ph.D. in systems engineering from the University of California, Los Angeles.

Richard A. Anthes has served as president of the University Corporation for Atmospheric Research (UCAR) in Boulder, CO since 1988. Prior to joining UCAR, Dr. Anthes was the director of the National Center for Atmospheric Research where he also headed up the Atmospheric Analysis and Prediction Division. He is a prolific author of books and refereed articles on various aspects of meteorology and meteorological phenomena. Dr. Anthes has served on 15 NRC committees and chaired four of those committees. He was also a prior chair of the Board on Atmospheric Sciences and Climate. Dr. Anthes earned his B.S., M.S., and Ph.D. from the University of Wisconsin.

Dara Entekhabi is a professor in the Department of Civil and Environmental Engineering and the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology. His research interests include coupled surface, subsurface, and atmospheric hydrologic systems that may form the basis for enhanced hydrologic predictability. Specifically, Dr. Entekhabi conducts research in land-atmosphere interactions, remote sensing, physical hydrology, operational hydrology, hydrometeorology, groundwater-surface water interaction, and hillslope hydrology. He served on the National Research Council's Committee on National Weather Service Modernization, chaired the Committee on Hydrologic Science, and is a current member of the Water Science and Technology Board. Dr. Entekhabi received his B.A. and M.A. degrees from Clark University and his Ph.D. in civil engineering from the Massachusetts Institute of Technology.

Efi Foufoula Georgiou is a Professor of Civil Engineering and co-director of the National Center for Earth-Surface Dynamics, a National Science Foundation Science and Technology Center headquartered at St. Anthony Falls Laboratory of the University of Minnesota. Her research focuses on understanding and modeling the complex spatio-temporal organization and interactions of hydrologic processes over a range of scales, with emphasis on precipitation and landforms. Dr. Foufoula-Georgiou obtained her diploma in civil engineering from the National Technical

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University of Athens, Greece and her M.S. and Ph.D. in environmental engineering from the University of Florida. She is a Fellow of the American Geophysical Union, a Fellow of the American Meteorological Society, a member of the European Academy of Sciences, and serves on several national and international science advisory panels and editorial boards. Dr. Foufoula-Georgiou is a past member of the Water Science and Technology Board of the National Research Council.

William H. Hooke is a Senior Policy Fellow and the Director of the Atmospheric Policy Program at the American Meteorological Society (AMS) in Washington, DC. Prior to arriving at AMS in 2000, he worked for the National Oceanic and Atmospheric Administration (NOAA) and antecedent agencies for 33 years. After six years of research with NOAA, Dr. Hooke moved into a series of management positions of increasing scope and responsibility including Chief of the Wave Propagation Laboratory Atmospheric Studies Branch, Director of NOAA's Environmental Sciences Group (now the Forecast Systems Lab), Deputy Chief Scientist, and Acting Chief Scientist of NOAA. He currently chairs the Disasters Roundtable of the NAS/NRC, and is a member of the ICSU Planning Group on Natural and Human-Induced Environmental Hazards and Disasters. He is a member of the American Philosophical Society. Dr. Hooke holds a B.S. from Swarthmore College and an S.M. and Ph.D from the University of Chicago.

George H. Leavesley is a research hydrologist for the Water Resources Division of the United States Geological Survey. Dr. Leavesley currently serves as the chief of the Precipitation-Runoff Modeling of Watershed Systems project under the USGS National Research Program. His principle research interests include precipitation-runoff modeling, coupling of atmospheric and hydrologic models, model parameter estimation using physical measures from digital databases and remotely sensed data, simulation of the processes of snow accumulation and melt, and the development of a modular modeling system. He also serves as an affiliate faculty member to the University of Colorado and Colorado State University. Dr. Leavesley earned his B.S. and M.S. degrees from Pennsylvania State University and received his Ph.D. in watershed sciences from Colorado State University.

Glenn E. Moglen is an associate professor in the Department of Civil and Environmental Engineering at the University of Maryland and recently completed a sabbatical leave at the U.S. Geological Survey, Office of Surface Water, in Reston, Virginia during the 2003-2004 academic year. His research is based on the central theme of the hydrologic effects of land use change, particularly urbanization, and his research makes extensive use of GIS technology. Dr. Moglen has worked extensively in the development of GIS-based tools to automate hydrologic analysis and modeling. He is part of an interdisciplinary study team from Maryland and Delaware that is closely examining the effects of land use and climate change on hydrology, geomorphology, and stream ecology. Dr. Moglen also conducts research on the development of hydrologically sound smart growth objectives and policy. He earned his B.S. from the University of Maryland , his M.S. from Colorado State University , and his Ph.D. in civil and environmental engineering from the Massachusetts Institute of Technology.

Burrell E. Montz is a professor in the Department of Geography and is Associate Director of the Center for Integrated Watershed Studies at Binghamton University in New York. Dr. Montz has more than 25 years of experience with research in natural hazards, water resources management, and environmental impact analysis. Her interests in natural hazards research center on social science aspects of response and policy development. She has evaluated the effects and effectiveness of

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various mitigation measures for flooding and more recently has focused on warning systems and the flow and use of information by various levels of users. In addition, she has looked into vulnerability and has used geographic information systems to understand better the spatial dimensions of multiple hazards and of vulnerability to those hazards. Among other professional affiliations, she is an active member of the Great Lakes Research Consortium and has served on the Advisory Board of the Association of State Floodplain Managers for several years.

Doug Plasencia is Western U.S. Water Resources Practice leader at Michael Baker Jr., Inc. in Phoenix, Arizona. Before joining that firm, he served as Technical Director of Water Resources at AMEC Earth and Environmental in Tempe, Arizona and engineer and vice president of Kimley-Horn & Associates in Phoenix, Arizona. He has over 20 years of experience in the field of floodplain management and stormwater management working for public agencies and most recently as a consulting engineer in Arizona, Nevada, and Virginia. Mr. Plasencia develops watershed and river-based plans that integrate technology, policy, and implementation into long-term management strategies. He worked with the U.S. Army Corps of Engineers in Sacramento to develop the nation's first nonstructural emergency recovery program for a long-term reassessment of the Sacramento and San Joaquin river basins. Mr. Plasencia was also a hydrologist with the Flood Control District of Maricopa County, Phoenix, Arizona and chief of flood protection for Virginia's Department of Conservation and Recreation. He received his B.S. degree in forest resource management form the University of Minnesota and his M.S. degree in watershed management from the University of Arizona.

Liming Xu is a senior research scientist at FM Global Research, an industrial insurance and risk management corporation. Dr. Xu's interests include natural catastrophe risk analysis, hurricane modeling, flood forecasting, statistical modeling of insurance business, application of remote sensed data in hydrology, impacts of climate change on frequency and severity of natural hazards, simulation of insurance loss due to hurricane and flood, data mining, operational research, and actuarial science. Before joining FM Global in 2002, Dr. Xu worked as a research scientist at the National Aeronautics and Space Administration's Goddard Space Flight Center where he developed prediction models using advanced statistics and satellite data. He received his B.S and M.S. degrees from Dalian Maritime University in China and earned his Ph.D. in hydrology at the University of Arizona.

STAFF

Lauren E. Alexander is a senior program officer with the NRC's Water Science and Technology Board. Her research interests include hydro-geomorphic processes and plant diversity in forested wetlands, and she has studied these issues in different coastal plain systems in the United States. Dr. Alexander received her B.S. in applied mathematics and her Masters of Planning in environmental planning from the University of Virginia and her Ph.D. in landscape ecology from Harvard University. She joined the NRC in 2002.

Dorothy K. Weir is a research associate with the Water Science and Technology Board. She has worked on a number of studies including Water Quality Improvement in Southwestern Pennsylvania, Water System Security Research, and Everglades Restoration Progress. Ms. Weir received a B.S. in biology from Rhodes College in Memphis, TN and an M.S. degree in environmental science and policy from John Hopkins University. She joined the NRC in 2003.

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