NOAA'S ADVANCED HYDROLOGIC PREDICTION SERVICE

Building Pathways for Better Science in Water Forecasting

BY JOHN MCENERY, JOHN INGRAM, QINGYUN DUAN, THOMAS ADAMS, AND LEE ANDERSON

State-of-the-art science is helping to improve operational forecasting of floods, drought conditions, and water resources, delivering more precise and accessible information to customers.

The U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) provides hydrologic forecasts through 13 River Forecast Centers (RFCs; Fig. 1) and 122 Weather Forecast Offices (WFOs). Together, these offices provide streamflow forecasts

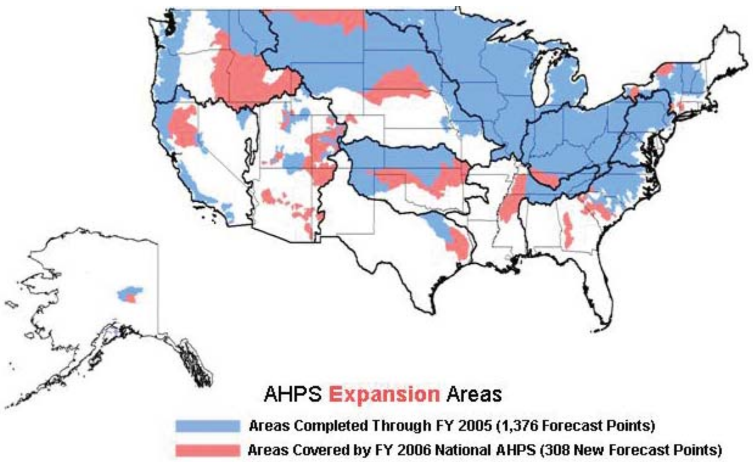

FIG. 1. Map of AHPS base expansion areas and areas covered by NWS River Forecast Centers.

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for 3,400 forecast locations. The Advanced Hydrologic Prediction Service (AHPS) program modernizes the forecast services through the improvement of flash-flood forecasts and by providing ensemble streamflow forecasting and flood-forecast maps. These improvements are occurring with the incorporation of new hydrologic, meteorologic, and climatologic science (Carter 2002). Along with the use of new verified science, AHPS uses NOAA investments in remote sensing, precipitation forecasts, climate predictions, data automation, hydrologic science, and operational forecast system technologies, thereby, redefining and expanding the utility of future water resource forecasts (Fig. 2).

IMPLEMENTATION. AHPS forecasts were provided first in March 1997 for the Des Moines River basin, Iowa (National Weather Service 1997). These forecasts provided information on the relative uncertainty of hydrologic variables, that is, river stage and discharge, with lead times out to 3 months. This was the first phase toward the implementation of AHPS. The Des Moines River basin was chosen for the first phase because of the devastating impacts resulting from the "Great Flood of 1993" (National Weather Service 1994), including severe flooding in the city of Des Moines, Iowa. AHPS has now been deployed in critical areas of the Northeast, Southeast, Midwest, and West (Fig. 1).

The next step for AHPS deployment is to accelerate implementation for the previous areas and expand to the South, the West, and Alaska. NOAA's goal is to provide AHPS forecasts for approximately 4,000 locations throughout the United States by 2014 (see Table 1).

NEW HYDROLOGIC SERVICES. Advanced Hydrologic Prediction Service priorities are to sustain current NWS hydrologic services, leverage collaborative research to transfer new science into operations, and provide better water forecasts for decision making. With these priorities, AHPS will provide improved flash-flood, river, and water resource forecasting, which should benefit a wide range of decision makers. AHPS will provide more precise and timely river forecasts, define the location of flash floods, and indicate the certainty of water resource outlooks with ensemble streamflow predictions.

For example, Eric Thomas (2003, personal communication) of Prestonburg, Kentucky, provided the following comments regarding these new hydrologic services.

> The weekend of February 15th–16th, 2003 saw my mother's house receive about 4 ½ feet of flood water from the Levisa Fork of the Big Sandy River at Mossy Bottom north of Pikeville, Kentucky. I began monitoring the river stage about 11:30 PM on the 15th, and after referring to the Jackson NWS website (especially the AHPS page) and talking by phone to the on-duty forecaster, we decided shortly after midnight to begin moving our belongings from the ground floor to the second floor of the house. Flood stage for Pikeville is 35 ft., this also puts backwater from the Levisa Fork of the Big Sandy River lapping at the garage door of my mother's home in Mossy Bottom. We ended with very minimal property loss and normal flood related damage to the structure of my mother's home as a result of this flooding event.
>
> Let me state at this time that the AHPS web page was a critical part of my decision making process. Being able to see the actual river stage, follow

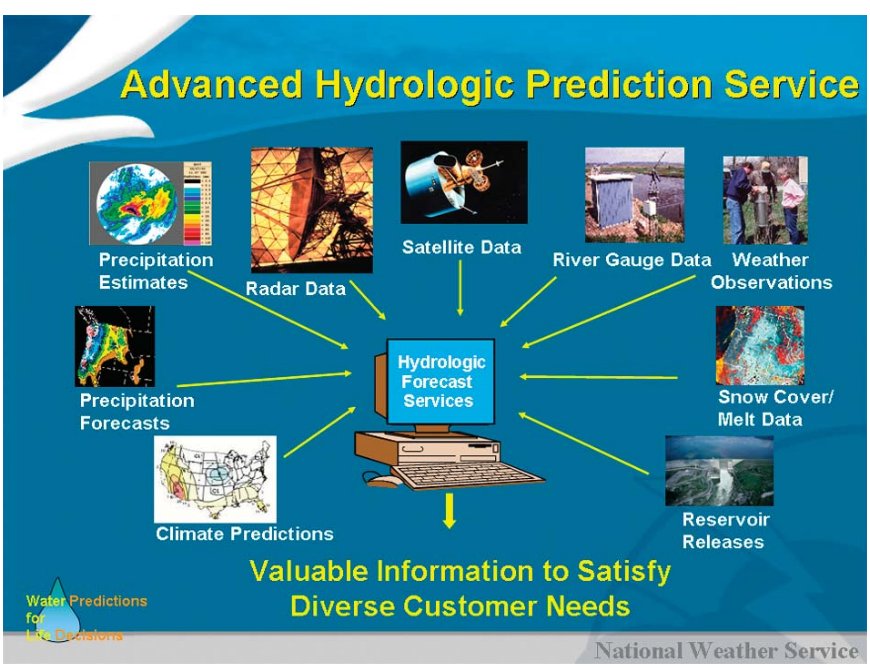


Fig. 2. Key science and infrastructure components of AHPS.

the graph to see the rate the river is rising, and the projected crest elevation and projected time of crest were very crucial elements in deciding what to move and where to move it.

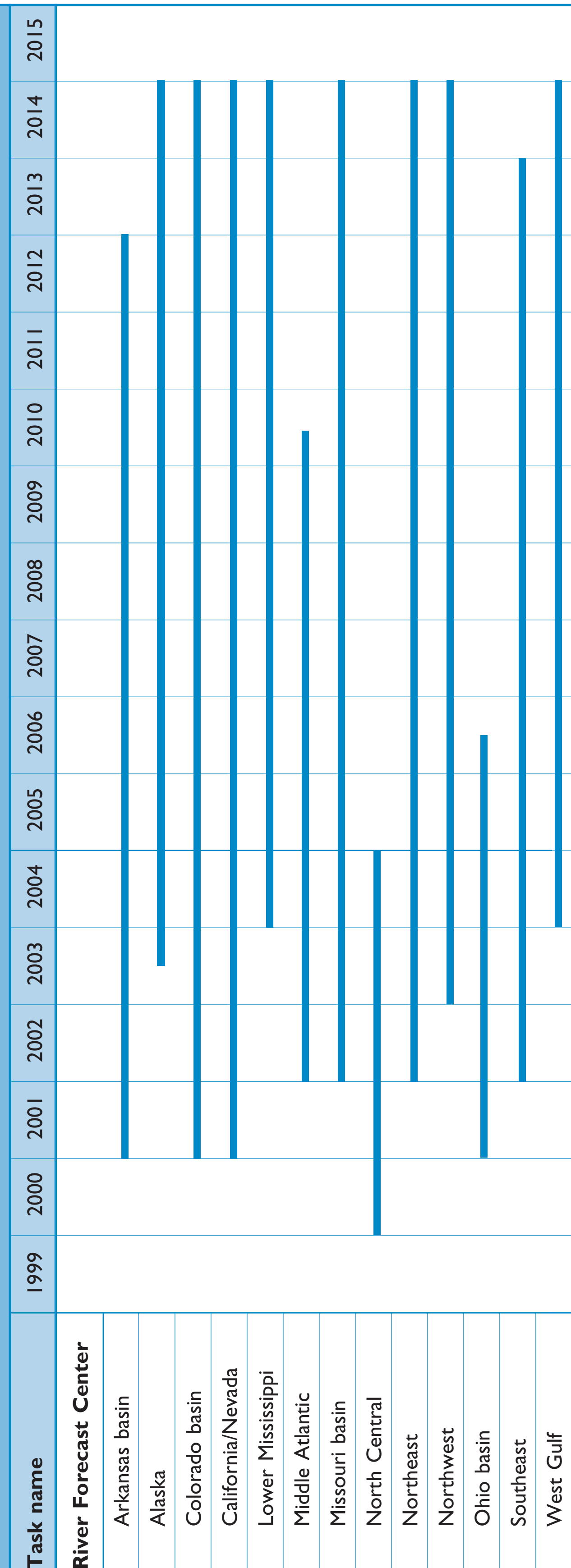
New infrastructure. Along with AHPS implementation of new verified science, computer hardware systems for the RFCs have been upgraded to accommodate increased processing and storage demands. These demands arise from the computationally intensive nature of ensemble streamflow prediction, hydrologic modeling processes, and archival processes for large volumes of historic, geographic, and verification data.

Unlike meteorologic model runs where the data assimilation is conducted automatically, NWS hydrologic forecast models use both manual and automatic methods. Therefore, a point-by-point display of the observed and simulated streamflow is essential. The NWS is developing new and enhanced tools to allow forecasters to review ensemble precipitation or temperature input to the models, to update the model runs in the observed period, or rerun and then review the ensembles. In the same way, the NWS is developing new forecast information displays to present the new high-resolution hydrologic modeled data (Fig. 3).

New products. AHPS forecast products are provided with the use of new hydrologic, meteorologic, and climatologic science. Science improvements used for AHPS include the following: new model calibration strategies, distributed modeling approaches, ensemble forecasting and data assimilation techniques, enhanced data analysis procedures, flood-forecast inundation maps, hydraulic routing models, and multisensor precipitation estimation techniques. The format and content of the hydrologic products and information are also being improved. Features of the new forecasts are

- coverage of the full spectrum of hydrologic events (This includes, for example, short-fused flash floods on small streams and in urban areas, slow-rising floods on large rivers, rivers in low-flow condition, and droughts);

Table 1. Time period for implementing AHPS at the 13 NWS River Forecast Centers.



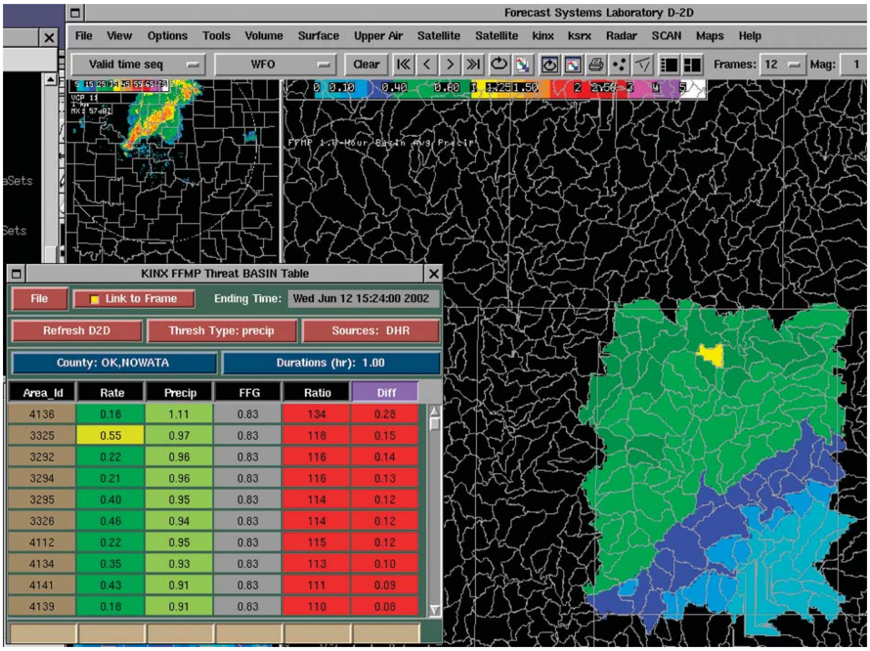


Fig. 3. Flash Flood Monitoring and Prediction (FFMP) basin threat map and table. The map image is color coded to indicate the average precipitation for small stream basins within one county. The inset table provides numerical values of precipitation within each basin and the ratio of precipitation to flash-flood guidance.

- better forecast precision by incorporating new verified science into hydrologic modeling systems, and more effective coupling of atmospheric and hydrologic models and forecast information on all time scales;
- inclusion of probabilistic flows and areas of inundation to enable users to apply decision assistance tools for improved management of risk;
- more specific and timely information on fast-rising floods for use with specific tools that highlight small basins affected by heavy rainfall, identify excessive runoff locations, and predict the extent and timing of the resulting inundation;
- consistency of format and information content of core products nationwide;
- use of geographic information systems (GISs) in the graphical depiction of flood-forecast information (Fig. 4), and forecasting the potential impacts of dam failures;
- Internet-based forecast information to broaden access to hydrologic information and facilitate efficient decision making for the private home owner, and emergency and water resource managers; and
- expanded outreach by engaging partners and customers in all aspects of the hydrologic services improvement effort.

SCIENCE INFUSION STRATEGY.

Foundation for improvement. The operational foundation for AHPS is the NWS River Forecast System (RFS; Page 1996 and National Weather Service 1972). The NWSRFS is a collection of programs and databases that provide a complete modeling and forecasting environment for the NWS RFCs. Several numerical models, functions, displays, and programs have been added since the NWSRFS became operational in the mid-1980s. This infrastructure is being upgraded to reduce the time required to produce forecasts and make it easier to implement new models. The Ensemble Streamflow Prediction (ESP) System (Day 1985) is a key component of the NWSRFS for AHPS forecasts (Fig. 5).

Areas of science infusion. PROBABILISTIC HYDROLOGIC APPLICATIONS. Probabilistic river forecasts provide additional information for risk-based decisions. To generate probability statements, the NWS has pursued an ensemble approach to quantify uncertainty in river forecasts. The traditional ESP program relies mostly on historical hydrometeorological time series data. Typically, several streamflow traces have been generated by using each year of data from a historical time series as a surrogate for future conditions. Analyses are performed on various time windows of those traces, and statistics are computed to describe the uncertainty. The new AHPS ESP program makes use of weather and climate forecasts and the associated uncertainty information provided by the NOAA National Centers for Environmental Prediction (NCEP). The enhanced ESP features a new preprocessor to generate ensemble forcing for all lead times ranging from 1 h to 1 yr (Perica et al. 2000; Herr et al. 2002; Mullusky et al. 2002). A postprocessor for ESP is also being developed. The postprocessor will serve to reduce biases in the NWSRFS models, and ensure consistency between the statistics of forecast hydrologic outputs and the observed events. The postprocessor takes into consideration in an implicit way the uncertainties in streamflow forecasts arising from initial conditions, model parameters, and model structure. Once each of those contributions to the uncertainty is explicitly included in the ensemble processor, the postprocessor will be modified accordingly.

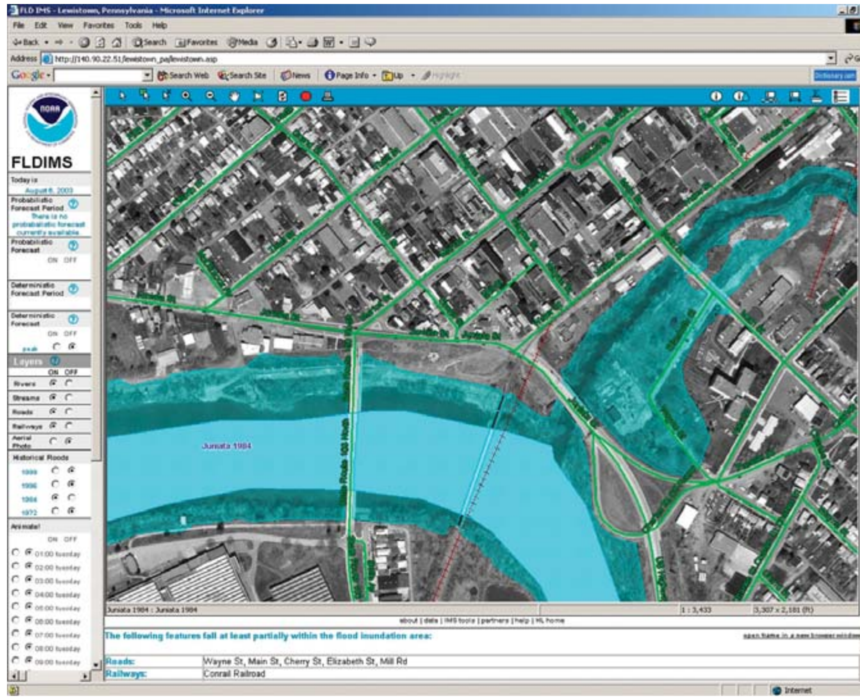


FIG. 4. **Example of AHPS flood-forecast GIS mapping product.**

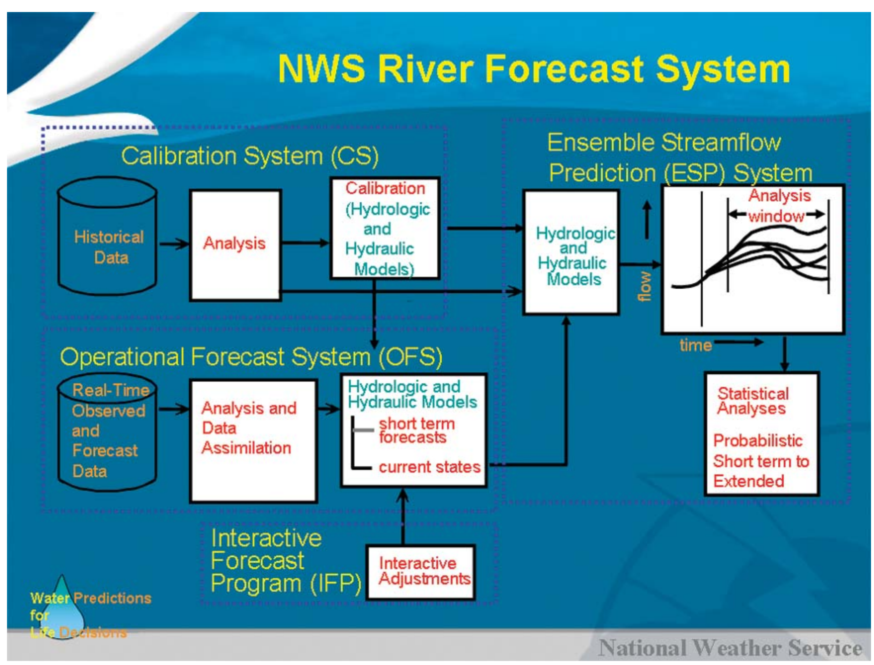


FIG. 5. **Operational flow diagram of the NWS River Forecast System.**

HYDROLOGIC MODELING. Enhancements in the NWSRFS are being developed to increase the precision and utility of the hydrologic models used to generate forecasts. These enhancements include improvements to the numerical models, as well as data management procedures for gathering and processing precipitation, evaporation, and temperature observations.

A significant research effort is in the development of a distributed hydrologic model (Koren et al. 2004). The distributed hydrologic model accounts for the greater variability of precipitation and rainfall-runoff characteristics within a basin. Some studies show improvement over the current lumped model (Zhang et al. 2001; Reed et al. 2004). Use of a distributed model makes it possible for the analyst to generate forecast scenarios focusing on more numerous areas of much smaller scales. A distributed model also makes it possible to reduce the time scale of hydrologic forecasts and allows short-term forecasts to more realistically reflect the streamflow response to precipitation (Fig. 6). The NWS Office of Hydrologic Development (OHD) has recently led the Distributed Model Intercomparison Project (DMIP). Twelve groups, including other federal agencies, academic institutions in the United States, and representatives from Canada, Denmark, China, and New Zealand, compared differing methods and approaches of distributed hydrologic models for analysis of the same predefined conditions. A special issue of the *Journal of Hydrology* documents the DMIP design and results

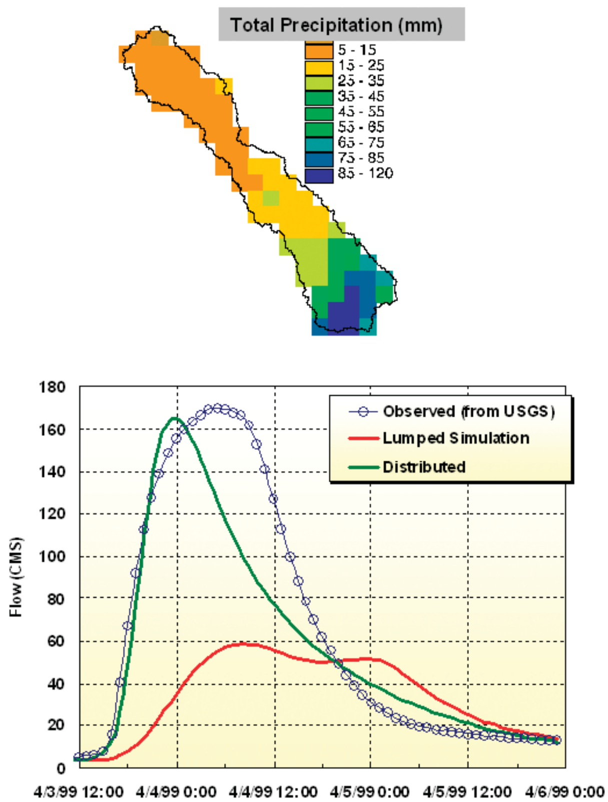


Fig. 6. An example of how a distributed hydrologic model produces more realistic streamflow forecasts that account for spatial variability in precipitation. The top figure presents the precipitation distribution for the period of the modeled storm for the Blue River basin, Oklahoma. The lower figure compares modeled output to observations. The blue line with circles is the observed streamflow response. The green line denotes the streamflow response from the distributed model, while the red line denotes that of the lumped hydrologic model.

(Smith et al. 2004). These results will guide NWS in developing the next generation hydrologic models in NWSRFS.

Improved representation of vegetation, frozen ground, snow, and the effects of heterogeneity of infiltration and precipitation will enable improved forecast accuracy and contribute to longer forecast lead times (Koren et al. 1999). AHPS supports research to include the energy budget as well as the water budget in hydrologic forecast models to improve representation of snow accumulation and ablation, and the occurrence of frozen ground.

Hydrologic model calibration. The process of generating AHPS forecasts necessarily includes prior calibration of the computational models, such as the Sacramento Soil-Moisture Accounting (SAC-SMA) (Burnash 1995), snow accumulation and ablation (Anderson 1973), streamflow routing (Fread 1973 and 1978), and reservoir simulation models (National Weather Service 1972). Without detailed hydrologic model calibrations, model errors would unnecessarily be large, and confidence in the model predictions would be in doubt (Ingram et al. 1998). Calibration of these models remains a labor-intensive exercise, as described by Smith et al. (2003) and Hogue et al. (2003). Duan (2003), Gupta et al. (2003), and Parada et al. (2003) indicate recent advancements in the calibration of watershed models, which give promise for automatic calibration methods. The international Model Parameter Estimation Experiment (MOPEX), another project led by NWS OHD, aims to develop advanced a priori parameter estimation techniques for hydrologic models (Duan and Schaake 2002). The NWS OHD MOPEX activity has resulted in a strategy for deriving the parameters of the SAC-SMA from physical soil-type data (Koren et al. 2000, 2003). As part of the AHPS initiative, NWSRFS models are being recalibrated to take advantage of those recent advances in watershed model calibration techniques.

River mechanics and hydraulic modeling. Implementation of hydraulic models on key streams allows a forecasted water surface profile to be produced for the entire length of a river as opposed to a stage elevation forecasted at a specific river location. The hydraulic flood-routing procedures can account for the influence of natural and human-induced controls on the river surface elevation, including tides, tributary streams, and downstream lakes, reservoirs, and bridges.

Where high-resolution topographic information is available, real-time flood forecasts, which depict the spatial extent and probability of inundation, can also be produced (Cajina et al. 2002). For this application, the hydraulic representation of a water surface is derived for a specific geographic area to depict the extent of flooding due to unsteady flow, backwater from tributaries, man-made structures, and levee overtopping. The water surface elevations are interpolated between cross sections and combined with other data layers to produce a GIS-based flood-forecast map (Fig. 4), which can be made available to emergency managers and others by Internet-mapping capabilities. Another area of development is the generation of GIS-based flood-forecast maps using probabilistic estimates of water surface elevations.

Hydrometeorologic data analysis techniques. Accurate, real-time data (e.g., stream stage, precipitation, and temperature) are required for hydrologic forecasting. These data may be collected from land-based sensors along rivers and by remote sensors. The NWS Cooperative Observer Modernization Program (information online at www.nws.noaa.gov/om/coop/index.htm) provides surface data with an integrated hydrologic and meteorologic network for monitoring weather and climate conditions. Streamflow data, provided by the U.S. Geological Survey and other cooperators, support river data needs. Products derived from remote sensor data (e.g., gridded multisensor precipitation and snow-water equivalent estimates) are used to provide the best possible model inputs for data-sparse areas and to improve spatial and temporal resolution of all forecasts. New approaches for the remote sensing of precipitation, snow, and other inputs are being integrated into the hydrologic forecast operations.

Data analyses and quality control are also essential to hydrologic forecasts. NWS data analysis activities are directed toward improving the accuracy of precipitation, temperature, and evaporation observations (Bonnin 1996). Accurate rainfall estimates are one of the most important input variables required by the hydrologic forecast models. To this end, several techniques (Breidenbach et al. 1999) have been developed to estimate precipitation from multisensor data, such as data from the combination of rain gauges and radar observations. Research is under way to develop techniques to further improve precipitation estimates by incorporating new datasets, such as satellite rainfall estimates and lightning data (Kondragunta 2002). Research is also directed toward the enhancement of quantitative precipitation estimates from the national suite of Doppler weather radars (Seo and Breidenbach 2002). Users will be better able to make informed decisions by knowing not only the best rainfall estimate, but also the associated uncertainty and/or range of the most likely values. Efforts are also occurring to develop semiautomated rain gauge quality-control techniques (Kondragunta 2001).

PARTNERSHIPS AND OUTREACH ACTIVITIES. *Collaborators.* Although the NWS has the lead responsibility to provide forecasts for the nation (U.S. Congress 1890), the forecasts and resulting actions occur through a number of data-sharing and science development partnerships. NWS data and science partners in the river forecasting arena include other federal agencies (including the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the Natural Resource Conservation Service, and the U.S. Geological Survey), regional river commissions, state and local agencies, the private sector, and academia.

The NWS shares with the hydrologic science community interests in basic and applied research, and the demonstration and use of enhanced or new forecast models. NWS OHD-led international projects, such as DMIP and MOPEX, have already resulted in benefits to the AHPS program and will continue to pay off as new science is infused into AHPS operations.

Service partnerships are also important to the successful delivery of AHPS forecast information. If the forecasts are to be effective, they must be accessible, timely, and understood. Acquiring and maintaining the data that are required to deliver high-quality forecast information necessitates communication and collaboration with experts within and external to the NWS. Knowing and meeting customer needs are critical for AHPS success. Therefore, an element of the AHPS program is to strengthen existing and establish new partnerships with other federal agencies and nonfederal organizations.

Training and outreach. AHPS provides new operational forecast capabilities, such as rainfall-runoff event-based forecasts with short- (hours) to long-term (weeks) probabilistic forecasts. These probabilistic forecasts provide confidence levels for when and where an event will occur. This addition of probabilistic outlooks to the traditional weather event–driven deterministic forecast has required training for forecasters and customers. Training helps forecasters and customers understand the concepts underlying the new forecast services and how to access and use the forecast information.

AHPS education is conducted on a local and national scale. Recurring customer forums and Web-based user feedback forms have been provided to obtain customer comments on existing and planned products and services. An AHPS information "tool kit" for local, state, regional, and national customers and partners is also available (information online at www.nws.noaa.gov/om/water/Ahps.shtml).

OPERATIONAL EXAMPLES. *River Forecast Centers.* The NWS River Forecast System is run at each of the RFCs. The Ohio River Forecast Center (OHRFC) is 1 of 13 RFCs providing AHPS forecast information. This section outlines the OHRFC experience with processing AHPS forecasts.

The OHRFC produces AHPS long lead time ESP probabilistic forecast products in their area of responsibility (Adams 2002). Graphical AHPS products for forecast locations are publicly available on the Internet (http://weather.gov/river_tab.php). OHRFC ESP 90-day products (forecast ranges from day 6 to

96) are produced every Monday afternoon, following routine forecast computations using the deterministic operational forecast system models. Results of the deterministic model runs also serve to initialize hydrologic model parameters for the ESP model operations. Other RFCs have similar AHPS operation schedules.

As AHPS implementation continues, computer system hardware upgrades have reduced ESP run times, allowing the OHRFC to extend the forecast horizon from 30 to 90 days, making it possible to generate seasonal outlooks. These outlooks include probabilistic forecasts (of discharge, flow volume, and river stage) both with and without reservoir simulations and with and without NOAA seasonal climate forecasts. The extended forecast horizons provide more lead time for decision makers and individuals for planning, developing contingencies, and optimizing system performance (of water supply, hydropower facilities, agriculture, etc.).

Weather Forecast Offices. WFOs serve smaller, more localized areas of responsibility than the RFCs. WFOs provide products for individual hydrologic events ranging from flash floods to slow-rising floods on large rivers. Forecast products include warnings, watches, and statements covering areas and streams of all sizes.

The Red River and Devil's Lake drainage areas in the upper Midwest offer an example of AHPS product generation and dissemination. The North Central River Forecast Center (NCRFC) in Chanhassen, Minnesota, generates AHPS forecasts and transmits them to the local WFO in eastern North Dakota. The WFO then disseminates the forecast information to users. This information includes graphical products disseminated over the Web, including probabilistic forecasts of river stage, flow, and volume (Fig. 7).

The WFO disseminates AHPS probabilistic information at the middle of each month due to the ESP model's use of temperature and precipitation outlooks that are updated midmonth by the NWS Climate Prediction Center. The dissemination of this information throughout the year is an enhancement to information issued in previous years. In previous years, spring flood information (disseminated only twice in late February and early March from the eastern North Dakota WFO) consisted of text products with only two or three river crest values (Fig. 8). The information was based only on the occurrence of current, normal, or above-normal precipitation during the seasonal snowmelt period. AHPS now allows monthly generation of text products for all river forecast locations. These products include a list of river stages expected for an incremental series of probable exceedance levels (Fig. 9).

AHPS products were a valuable planning tool during the 2001 spring flood in the Red River Valley of the North. Flood planners were able to assess the level of support required for the given exceedance probabilities and prepare for the flood level with additional guidance and protection by using AHPS products disseminated by the eastern North Dakota WFO. The AHPS 90-day (January 2001) product for the East Grand Forks, Minnesota, forecast location showed an exceedance probability of nearly 50% for moderate flooding for the period from 23 January 2001 to 18 April 2001. Outlooks disseminated in February and March 2001 indicated higher probabilities of exceeding moderate flood state at this forecast location. During the peak snowmelt period (late March through early April) in 2001, heavy rainfall exacerbated the flood threat and raised river crests to significant levels. The

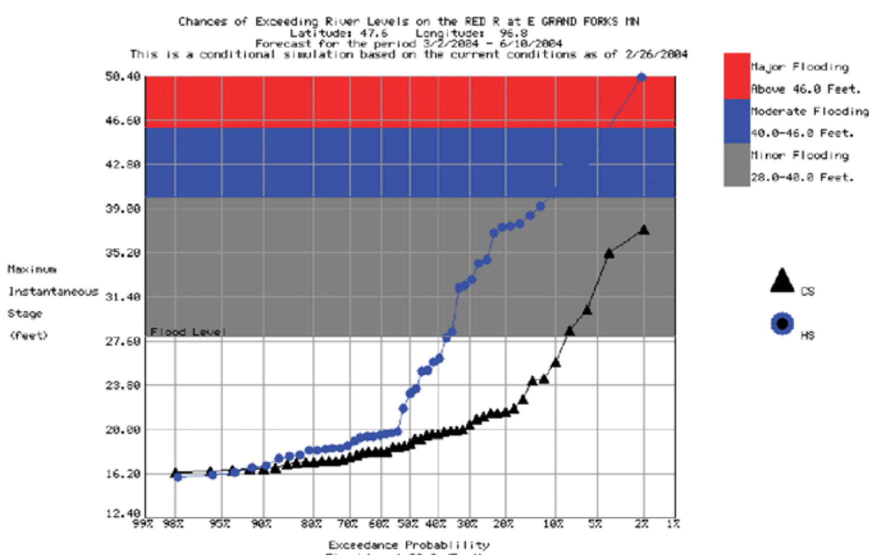


Fig. 7. Example of new AHPS graphical product. The conditional simulation (CS) for this forecast period is based on current conditions. The CS is lower than the historical simulation (HS), indicating that the chances are greater for lower river levels.

Red River at East Grand Forks crested at 44.87 ft on 14 April 2001, which is well above the moderate flood level.

AHPS provided a range of exceedance probabilities of all possible crests. More lead time for crest-outlook scenarios (and their associated probabilities) was available for users in the Red River basin in January 2001, at least 2 months before the crest occurred. Outlook values were supplied to NWS customers with a measure of certainty needed to help them formulate decisions about mitigating seasonal flooding. Information from this service helped the NWS and flood planners issue enhanced levels of public guidance in late winter of 2001.

NATIONAL WEATHER SERVICE EASTERN NORTH DAKOTA/GRAND FORKS
2000 SPRING FLOOD NUMERICAL OUTLOOK
March 2000

(1) OUTLOOK CREST BASED ON CURRENT CONDITIONS ONLY.
(2) OUTLOOK CREST BASED ON CURRENT CONDITIONS PLUS NORMAL PRECIPITATION.
(3) OUTLOOK CREST BASED ON CURRENT CONDITIONS PLUS ABOVE NORMAL PRECIPITATION. (APPROXIMATELY 150% OF NORMAL)

River Name Station Name	FS (FT)	(1) Current Conditions Only	(2) Current with Normal	(3) Conditions Precipitation Above Normal
RED RIVER				
WAHPETON ND	10	6.5	8.0.0	9.0
FARGO ND	17	15.0	16.0	16.5
GRAND FORKS ND	28	17.0	20.0	22.0

Fig. 8. Example of pre-AHPS seasonal WFO text products.

HYDROLOGIC OUTLOOK
NATIONAL WEATHER SERVICE EASTERN NORTH DAKOTA/GRAND FORKS
1145 AM CST THU FEB 26 2004

RED RIVER BASIN
LONG-RANGE PROBABILISTIC OUTLOOK
VALID MARCH. 2 2004 - JUNE. 9 2004

In the table below, the 90 through 10 percent columns give the chance the river at the given location would rise above the indicated stage levels within the next 90 days. Example: the Red River at Wahpeton has a flood stage of 10 feet. In the next 90 days there is a 40 percent chance the Red River at Wahpeton will rise above 5.1 feet and only a 10 percent chance that it will rise above 8.3 feet.

CHANCE OF EXCEEDING STAGES AT SPECIFIED LOCATIONS
VALID 3/2/2004 - 6/9/2004

LOCATION	FS(FT)	90%	80%	70%	60%	50%	40%	30%	20%	10%
RED RIVER										
WAHPETON ND	10	3.7	4.0	4.3	4.7	4.8	5.1	5.6	6.2	8.3
FARGO ND	17	14.1	14.2	14.6	14.9	15.1	15.5	16.1	16.8	20.2
HALSTAD ND	24	4.9	5.5	6.0	7.1	8.3	9.8	11.1	13.1	18.9
GRAND FORKS	28	16.6	17.1	17.5	18.0	18.8	19.6	20.4	21.4	25.8
OSLO MN	28	9.1	10.9	12.0	14.0	15.9	18.3	19.6	21.0	25.0
DRAYTON ND	32	12.2	12.9	13.7	15.3	16.6	17.5	20.4	22.4	26.0
PEMBINA ND	42	16.0	17.6	19.2	23.3	24.5	25.2	28.7	32.0	41.7

Fig. 9. Example of AHPS-enhanced monthly WFO text products.

FUTURE PERSPECTIVE.

Regional implementation for the Advanced Hydrologic Prediction Service will be completed by 2014. The services will include new science and technology advancements for flash-flood forecasts, probabilistic short- to long-term river forecasts, and flood-forecast graphics. Operational flash-flood forecasts will rely on the localized implementation of high-resolution hydrologic models to account for snowpack, watershed runoff, and small basin geomorphology. Short- to long-term river forecasts will incorporate precipitation and temperature forecasts into probabilistic streamflow predictions for periods of 1 day through 3 months. Web-based graphics for hydrologic forecast operations will be delivered by using new GIS-based displays of river stage, flood, and drought information in response to customer needs.

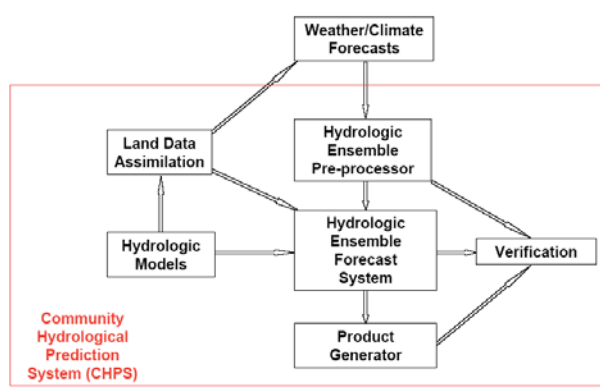


Fig. 10. Schematic of the CHPS from the Hydrological Ensemble Prediction Experiment (HEPEX).

The AHPS program is moving forward through renewed and enhanced partnerships with academia and other federal, state, and local agencies. This includes work with the science community through use of a Community Hydrologic Prediction System (CHPS; see Fig. 10). CHPS is being developed to streamline the movement of university research into NWS operations. CHPS will become the core of the future AHPS ESP program, which also includes data assimilation and verification components.

Once AHPS is fully implemented, our nation's water resource and emergency mangers will benefit from this service as people use the new information to make decisions related to flood reduction, drought impacts, navigation, hydroelectric power, irrigation, recreation, and water supply. The National Hydrologic Warning Council has reported that, once implemented throughout the nation, AHPS will provide $766 million in economic benefits each year (National Hydrologic Warning Council 2002).

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