INFUSING NEW SCIENCE
INTO THE
NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

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Abstract: An important aspect of the National Weather Service (NWS) mission is to produce forecasts for America's rivers and streams. To facilitate this activity, the NWS River Forecast System (NWSRFS) has been implemented at 13 field offices to generate forecasts at 4,000 river locations throughout the U.S. The NWSRFS is a comprehensive suite of programs and algorithms covering the end-to-end forecast process, from real time data ingest to the generation of forecast hydrographs. A variety of hydrologic and hydraulic models are available for modeling basin specific conditions. In addition, a number of system functions are available for manipulating and displaying hydrologic data.

In order to improve river and flood forecasting for the Nation, the NWS is implementing the Advanced Hydrologic Prediction Service (AHPS). Current water resource forecasting techniques within the NWSRFS make limited use of growing skill in short to long range weather forecasts. The AHPS will take advantage of these capabilities as well as new hydrologic and hydraulic models to increase the accuracy of NWS forecasts and to quantify the uncertainty in these predictions.

The AHPS will also incorporate new science into the NWSRFS. By leveraging this science infusion, applied research within the NWS Hydrology Laboratory (HL) will deliver advanced modeling techniques to NWS field offices. New calibration strategies, distributed modeling approaches, ensemble forecasting and data assimilation techniques, sophisticated data analysis procedures, flood forecast inundation maps, advanced hydraulic routing models, and improved precipitation estimation techniques will be introduced.

An overview of the NWSRFS will be presented, followed by a brief discussion of the AHPS. Specific research and development projects identified by the AHPS Science Infusion Strategy will also be highlighted.

INTRODUCTION

Overview of the National Weather Service River Forecast System (NWSRFS): The National Weather Service (NWS) is mandated to provide forecasts and flood warnings for America's rivers and streams. Currently, this water-related mission is fulfilled by providing daily and other forecasts for 4,000 points across the contiguous United States and Alaska. Thirteen River Forecast Centers (RFC) staffed by hydrologists, meteorologists, and technicians produce the river forecasts. The NWSRFS is used to generate a wide range of water quantity forecasts ranging from hours to months into the future. Interested readers are referred to Glaudemans et al. (2002), Fread et al. (1995), Larson et al. (1995), and Stallings and Wenzel (1995) for more information regarding the NWS river and flood program.

As shown in Figure 1, the NWSRFS comprises three major components: the Calibration System (CS), the Operational Forecast System (OFS), and the Ensemble Streamflow Prediction (ESP) System. For the CS, historical observations of precipitation, temperature, and evaporation are processed to create mean areal time series. These time series usually extend back to 1948, the current limit for digital information from the National Climatic Data Center (NCDC). By using the mean areal values to initialize the water prediction models, manual or automatic calibration techniques are applied to derive the optimum hydrologic and hydraulic model parameters. The calibrated hydrologic and hydraulic models are then used to generate operational forecasts within the OFS, and real-time observations of precipitation and temperature are employed instead of NCDC historical data. These real-time observations are combined with forecast estimates of precipitation and temperature derived from a variety of data sources and techniques. The combined time series are used to produce streamflow forecasts several days into the future. NWSRFS can be run in batch mode or interactively via the Interactive Forecast Program (IFP). Via the IFP, forecasters can perform run-time modifications to a number of model states or other factors in order to account for nonstandard hydrologic conditions. In the ESP system, the historical time series derived for the CS are used to generate an ensemble of simulated streamflow traces with the models being initialized by the current values of the OFS state variables. Statistical analysis is then performed to qualify the uncertainty. It is important to note that the same hydrologic and hydraulic models comprise all three systems.

Advanced Hydrologic Prediction Service (AHPS): The AHPS will meet service delivery enhancement goals by implementing hydrologic forecast models tuned to local conditions and operated to account for uncertainty in hydrologic forecasts. An ensemble approach to weather, climate and water forecasting will provide the probabilistic basis for AHPS forecast products. Numerous AHPS products will be produced to meet diverse user needs. The AHPS will deliver information for the user community to take into account the probability that flooding will occur in balance with the costs of responding and benefits to be gained. This will contribute toward improved water management via informed risk-based water management decisions. Meeting NWS service goals requires an infusion of new science into the existing forecast system. The AHPS 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.

The Mechanisms for Science Infusion: The AHPS is the overall vehicle for new science to be delivered to the NWS field offices for improved river and flash flood forecasting. There are several mechanisms for performing research leading to new advances. The HL performs basic and applied research within its Hydrologic Modeling and Science Branch (HSMB). Groups have been established in HSMB to concentrate on rainfall-runoff modeling, hydrometeorological analysis, river mechanics and mapping, and more direct scientific cooperation with other Federal agencies.

The AHPS initiative also provides an expanded mechanism by which research can be performed with leading academic institutions. Additionally, improved collaboration with the scientific community through programs such as the GEWEX America Prediction project, and the U.S. Weather Research

Program will support the AHPS science infusion goals.

AREAS OF SCIENCE INFUSION

Calibration System: The component structure of NWSRFS depicted in Figure 1 provides a convenient framework for presenting specific aspects of the AHPS science infusion strategy. New science from the AHPS initiative will touch every area of the NWSRFS. For the CS, numerous research studies offer promise for improving the ability to calibrate the NWS suite of hydrologic and hydraulic models, resulting in more accurate operational forecasts. Better manual and automatic calibration techniques are needed. Recent research has resulted in an initial strategy for deriving values of the Sacramento Soil Moisture Accounting model (SAC-SMA) from physical soil type data (Koren et al., 2000; Koren et al., 2002a; Duan et al, 2001). These values provide not only an initial estimate of the model parameters, but also an indication of the spatial variability of the parameters across a group of basins. Such knowledge helps validate the results from the manual or automatic calibration process by ensuring the parameters vary according to a logical spatial pattern. New approaches to automatic parameter calibration promise to add to the rich legacy of similar techniques developed in academia and delivered for NWS field use. For example, single objective automatic calibration techniques developed by Brazil (1989) and Duan (1992) have been available as part of NWSRFS for many years. Recently developed multi-objective calibration techniques offer to reduce some of the parameter variability associated with the use of a single objective function to measure the goodness of fit (Gupta et al., 1998). Further improvements to initial parameter sets may ensure that both single and multi-objective calibration can be constrained to result in more appropriate spatial patterns for parameters throughout basins (Koren et al., 2002a).

The ongoing Model Parameter Estimation Experiment (MOPEX, 2002) is another effort to enhance the understanding of model parameter derivation. In MOPEX, data from a wide range of climate regimes throughout the world are being assembled and used with different hydrologic models.

In addition to complex, physically-based methods for parameter estimation and optimization, tools are being developed and enhanced to aid the field hydrologist in calibration of NWS models. Among these is the Calibration Assistance Program (CAP). CAP (Calibration Assistance Program, 2002; Reed, 2001) is a GIS-based application developed to extract useful information from soil property, forest cover, satellite snow cover, rainfall climatology, and potential evaporation data layers. CAP is a national application since these data layers have been collected and processed for the contiguous U.S. and Alaska. Within CAP are procedures to derive initial estimates of SAC-SMA parameters and coefficients related to potential evaporation as well as procedures for the derivation of watershed divisions based on elevation differences. Another AHPS-funded project involves the redesign of the entire CS to achieve a unified system with improved data access and storage.

Operational Forecast System: Numerous enhancements have been identified that should increase the accuracy of the hydraulic and hydrologic models used to generate forecasts in the OFS. Included are improvements to the models themselves and advanced procedures for collection and processing of observations of precipitation, temperature, and evaporation. A major area of research in both academia and the HL is the development of distributed hydrologic models for river and flash flood forecasting. Research (Koren et al., 2002b) has led to the development of the first distributed hydrologic model for the NWS. Koren's model, the HL Research Modeling System (HL-RMS), currently uses the SAC-SMA to transform rainfall into runoff, but has been designed in a modular fashion so as to accept other rainfall runoff models. In certain cases, this model has demonstrated improvements over the current lumped application of the SAC-SMA (Zhang et al., 2001). The HL-RMS is the focus for HL's participation in the Distributed Model Intercomparison Project (DMIP). DMIP will provide direction to HL's research into distributed models by testing advanced models being developed in academia and other governmental agencies.

Research into cold season processes promises to provide improvements in simulation accuracy. Work by Koren and others (Mitchell et al., 2002; Koren et al., 1999) has focused on improving the representation of frozen ground effects on the rainfall-runoff process. This work has also resulted in practical improvements for the calibration of operational models used for snow accumulation and ablation. HL has participated in the international Snow Model Intercomparison Project (SnowMIP) to discern the benefits of using a full energy budget model instead of the current temperature index method.

Variational assimilation (VAR) of real time data to enhance the estimates of model state variables has shown the potential to improve upon the existing Kalman filter approach (Seo et al., 2001a,b). Such assimilation techniques also offer the possibility to eliminate the need for subjective operational run-time model and state modifications to account for nonstandard conditions. VAR also offers advanced methodologies for the estimation of parameters for distributed hydrologic modeling. In addition, the ongoing Land Data Assimilation System, a collaborative effort among NOAA, NASA, and several universities, is focused on the estimation of initial soil moisture and soil temperature state variables for atmospheric forecast models.

Other AHPS science is directed toward improving the accuracy of observations of precipitation, temperature, and evaporation (Bonnin, 1996). Rainfall estimates are one of the most important input variables required by the hydrologic forecast models. Therefore, it is essential to obtain accurate estimates of rainfall. To this end, several techniques (Breidenbach et al., 1999) have been developed at the HL to estimate precipitation from multi-sensor data such as rain gauges and radar observations. Research is under way to develop techniques to further improve the precipitation estimates by incorporating new data sets such as satellite rainfall estimates and lightning data (Kondragunta, 2002). Efforts are also on going at the HL to develop semi-automated rain gauge quality controlling techniques (Kondragunta, 2001).

Considerable research has been directed toward the enhancement of quantitative precipitation estimates (QPE) from the national suite of Doppler weather radars (Seo and Breidenbach, 2002; Seo et al., 2000; Breidenbach et al., 1999; Fulton et al., 1998; Seo, 1998). The AHPS is poised to infuse science for the generation of probabilistic quantitative precipitation forecasts. The current operational NWS multi-sensor rainfall algorithms produce a single field of precipitation accumulations. However, forecasters and other external water management agency users of these products lack information on the accuracy of these estimates. For some rainfall events, rainfall products might be expected to be more reliable compared to other events. Users would be better able to make informed decisions if they knew not only the best rainfall estimate but also the associated uncertainty and/or range of most likely values. This information will be obtained through various procedures including running the existing algorithms in an ensemble-like mode with variable parameter settings and/or with some procedures turned on or off. The users of these ensemble/probabilistic radar rainfall products will be NWS weather and river forecast offices and their customers. These products will be used for both larger-scale hydrologic modeling and river flood applications as well as smaller-scale, short-fuse flash flood applications on small watersheds.

The NWS also performs research and development into hydraulic flood routing procedures. These procedures solve the full St. Venant equations for one-dimensional unsteady flow (Fread and Lewis, 1988). Recent efforts have resulted in improved algorithms for handling levee failure and flow between storage components behind levees. Current research is concentrated on providing a capability to model pollutant transport in the case of spills during major flood events. Future research needs to address the existence of moveable beds in major rivers, which can result in large shifts in the rating curves used to forecast river stages. In addition, a more robust capability to model the effects of ice jams on river flow must be developed.

Corresponding to improvements to the hydraulic routing models are being accomplished via the introduction of a flood forecast mapping capability (Cajina et al., 2002). In 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. Water elevations computed by the NWS dynamic wave model are computed as part of the OFS. The water surface elevations are interpolated between cross sections and combined with other data layers to produce a GIS-based flood forecast map, which is made available to emergency managers and others via internet mapping capabilities. A major area of development is the derivation of GIS-based flood forecast maps for probabilistic water surface elevations.

Ensemble Streamflow Prediction System: Probabilistic river forecasts are currently the more visible of the AHPS products. To generate the probability statements, the NWS has pursued an ensemble approach to quantifying the uncertainty in river forecasts. Traditionally, several streamflow traces have been generated by using each year from an historical time series derived by the CS as a surrogate for the future. Analyses are performed on various time windows of those traces and statistics are computed to describe the uncertainty. Recent efforts have attempted to utilize the uncertainty information in forecast products being produced by the NOAA National Centers for Environmental Prediction (NCEP), including the Environmental Modeling Center (EMC), the Hydrometerological Prediction Center (HPC), and the Climate Diagnostics Center (CDC) of the NOAA Office of Atmospheric Research. Procedures to produce ensemble precipitation forecasts suitable for input to hydrologic forecast models are being developed and tested in collaboration with these centers (Perica et al., 2000).

The NWS is developing ensemble precipitation forecasts for use by existing hydrologic forecast models. This ESP Pre-Processor will use operational NCEP/HPC and NCEP/CPC deterministic and probabilistic forecast products for lead times ranging from 6 hours to 1 year. New ESP Pre-

Processor procedures need to be developed to incorporate NCEP/EMC ensemble forecasts. These ensembles must be corrected for biases and downscaled in space and time to correspond to the scales of the hydrologic models. This requires an archive of ensemble forecasts and corresponding precipitation observations for a period of at least 3 years for medium range forecasts and considerably more extensive for long range forecasts. For short term forecasts of precipitation, an historical archive of HPC forecasts with the corresponding observations of precipitation is needed to assess forecast accuracy and to develop improved methods to account for bias and uncertainty. In the absence of an appropriate archive, a procedure has been developed for defining the uncertainty in deterministic precipitation forecast amounts based on a record of observed precipitation amounts (Herr et al., 2001; Mullusky et al., 2001).

SUMMARY

The AHPS will stimulate an extensive suite of science infusion efforts, which will dramatically impact the variety and quality of water prediction information the NWS provides to the American public. For example a recent study by the National Hydrologic Warning Council (2002), indicates the AHPS could produce $766 million in economic benefits each year, once implemented throughout the United States. These new forecasts and information for America's rivers and streams will impact far reaching daily decisions related to flood reduction, navigation, hydroelectric power, irrigation, recreation, and water supply.

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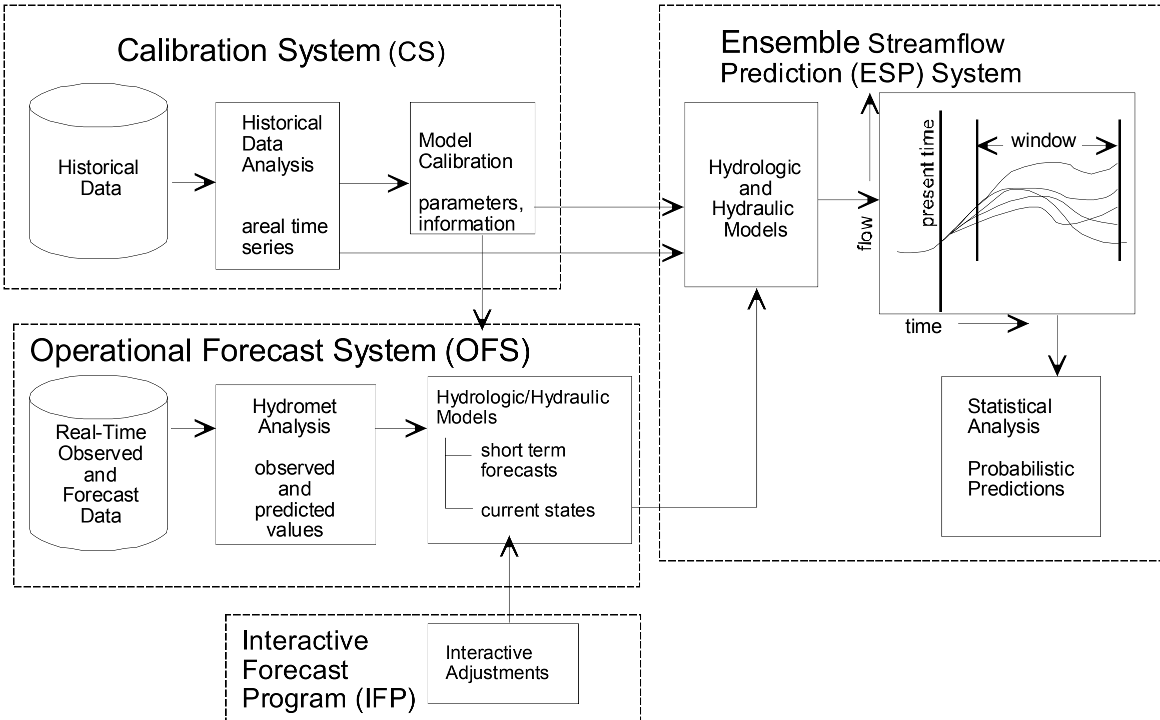

Figure 1. Major components of the National Weather Service River Forecast System.