J1.5 ENSEMBLE STREAMFLOW PREDICTION (ESP): PROGRESS AND RESEARCH NEEDS

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1. INTRODUCTION

This paper summarizes current activities in the National Weather Service to make improved use of quantitative precipitation forecast (QPF) information in hydrologic forecasting at the River Forecast Centers (RFC's). The goal is to predict future streamflows and river stages as accurately as possible, and at the same time quantify the uncertainty in the forecasts. Because forecasts of future precipitation amounts, especially high intensity events over small river basins involve some degree of uncertainty; and because users need to consider the effects of this uncertainty, the forecasts that are being made in a probabalistic framework.

One of the most general probabalistic forecast frameworks is ensemble prediction. An ensemble contains members that are called sample functions (which may vary in both space and time). Each sample function is an equally likely representation of future events that might occur, given the available information that can be used to predict future events. Members of an ensemble are not "totally" random, but must preserve the internal space time correlation structure of actual events. The values of the set of sample functions at a given point in space and time form a marginal probability distribution which varies in space and time. Together, the members of an ensemble represent the uncertainty in the events that might actually occur.

ESP is an important approach to river forecasting, because it can provide consistent probabalistic information about the joint occurrence of events at multiple locations in a river basin. This is an extremely important feature for decisions involving the operations of systems of reservoirs, downstream diversions and downstream flood prone areas.

The approach to developing ESP in the NWS includes taking advantage of significant improvements are being made at several levels of the National Weather Service forecast system, including improvements in short term precipitation forecasting though NCEP's new Eta model, new ensemble forecasts from the global model, experimental ensemble forecasts from the Eta model, and improvements in medium and long range prediction.

ESP is part of an initiative in the National Weather Service to develop an Advanced Hydrologic Prediction System (AHPS) that includes implementation of improved hydrologic models and application of new data analysis techniques including use of precipitation estimates using data from the new WSR88D radar systems.

2. OBJECTIVES

This strategy has several objectives:

I. Produce bracketed confidence limits or associated probabilities to provide likelihood of occurrence for a range of specific stage, flow or volume forecasts.

Ii. Resolve the inherent scale mismatch in incorporating precipitation forecasts into river forecast models that occurs because runoff response to precipitation is highly non-linear and is sensitive to space and time variability of precipitation over a wider range of space and time scales, depending on drainage area, than is included in present precipitation forecasts.

iii. Use stochastic methods to compensate for the limitations of current scientific capability for detailed positioning of future high intensity small-scale rainfall centers. (This problem increases as both the duration of the forecast interval and target area (i.e. subbasin) decrease and as the forecast period moves further into the future.)

iv. Build upon the existing Extended Streamflow Prediction (ESP) framework to include uncertainty in meteorological and climatological predictions in river forecasts and to account for the sub-scale space and time variability not included in these forecasts.

v. Provide a robust framework for producing consistent forecasts throughout a large river basin that accounts for all of the joint relationships between precipitation events at different parts of the basin in space and time.

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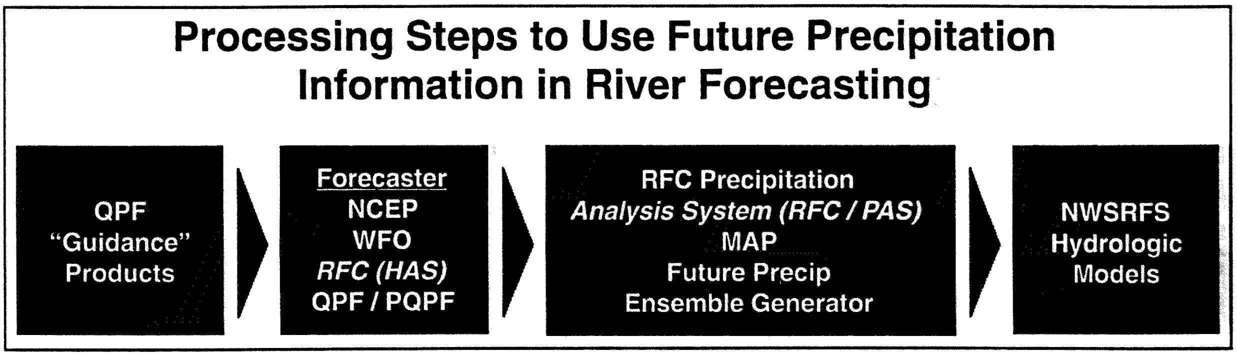

Figure 1

3. STRATEGY

ESP is part of an end to end forecast system. A section of this end-to-end system is illustrated in Figure 1. The ESP outputs will be produced by the National Weather Service Forecast System (NWSRFS) at RFCs. Both the forecaster and QPF guidance products elements will provide input information to the RFC Precipitation Analysis System (PAS).

A key part of the development and implementation strategy for AHPS and ESP is to conduct pilot projects to demonstrate the value of the forecasts and to reduce the risks associated with implementing the techniques elsewhere. One demonstration project was recently completed for the spring snowmelt season in the Des Moines River Basin, Iowa. Another is just beginning in the Upper Monongahela River Basin, West Virginia. In the Des Moines basin, the forecast period of interest was 60 days and the focus was on spring snowmelt runoff. In the Monongahela basin, the immediate objective is to use Probabalistic Quantitative Precipitation Forecasts (PQPF) produced by forecasters at Weather Forecast Offices (WFO's) to produce Probabalistic River Stage Forecasts (PRSF's). Below, some of the technical elements of these projects are described.

4. ESP OUTPUT AND INPUT

The output of ESP is an ensemble of equally likely streamflow hydrographs at each forecast point that can be used to create probabilistic forecast products or that can be used directly by water managers in water resource management models to make operational management decisions. ESP outputs are produced at RFCs by hydrologic models that are part of the NWS River Forecast System (NWSRFS). To do this, NWSRFS requires as input an ensemble of mean areal precipitation (MAP) amounts for each model time step and each model subarea.

The precipitation ensemble required by NWSRFS are produced by an Ensemble Precipitation Processor (EPP) that assimilates short term probabilistic quantitative precipitation forecasts (PQPF) provided by field forecasters at WFO's as well as long term PQPF provided by forecasters and forecast models at the National Centers for Environmental Prediction (NCEP). Required information about the spatial and temporal correlation structure of precipitation is derived directly from climatology and by analysis of numerical model gridded products. The EPP is one part of an RFC Precipitation Analysis System (PAS) that is operated at the RFC as part of the Hydrometeorological Analysis and Support (HAS) function.

5. ENSEMBLE PRECIPITATION PROCESSING

A key part of this strategy is to develop the Ensemble Precipitation Processor. If there were no skill in precipitation forecasts at any lead time, it would be sufficient if the EPP were simply to produce MAP time series taken directly from the historical climatological data set. There would be one member of the ensemble for each historical year of data. This actually has been done in limited applications of Extended Streamflow Prediction for water supply forecasting in the west.

A goal of this strategy is to do short duration ESP for flood forecasting and to include medium range and climatological forecast information for longer durations in ESP. The short range would use PQPFs from forecasters at WFOs and NCEP. These PQPFs are marginal distributions of precipitation amounts that are expected over different periods of time at different locations. These would be represented in terms of gridded fields of statistics of these distributions.

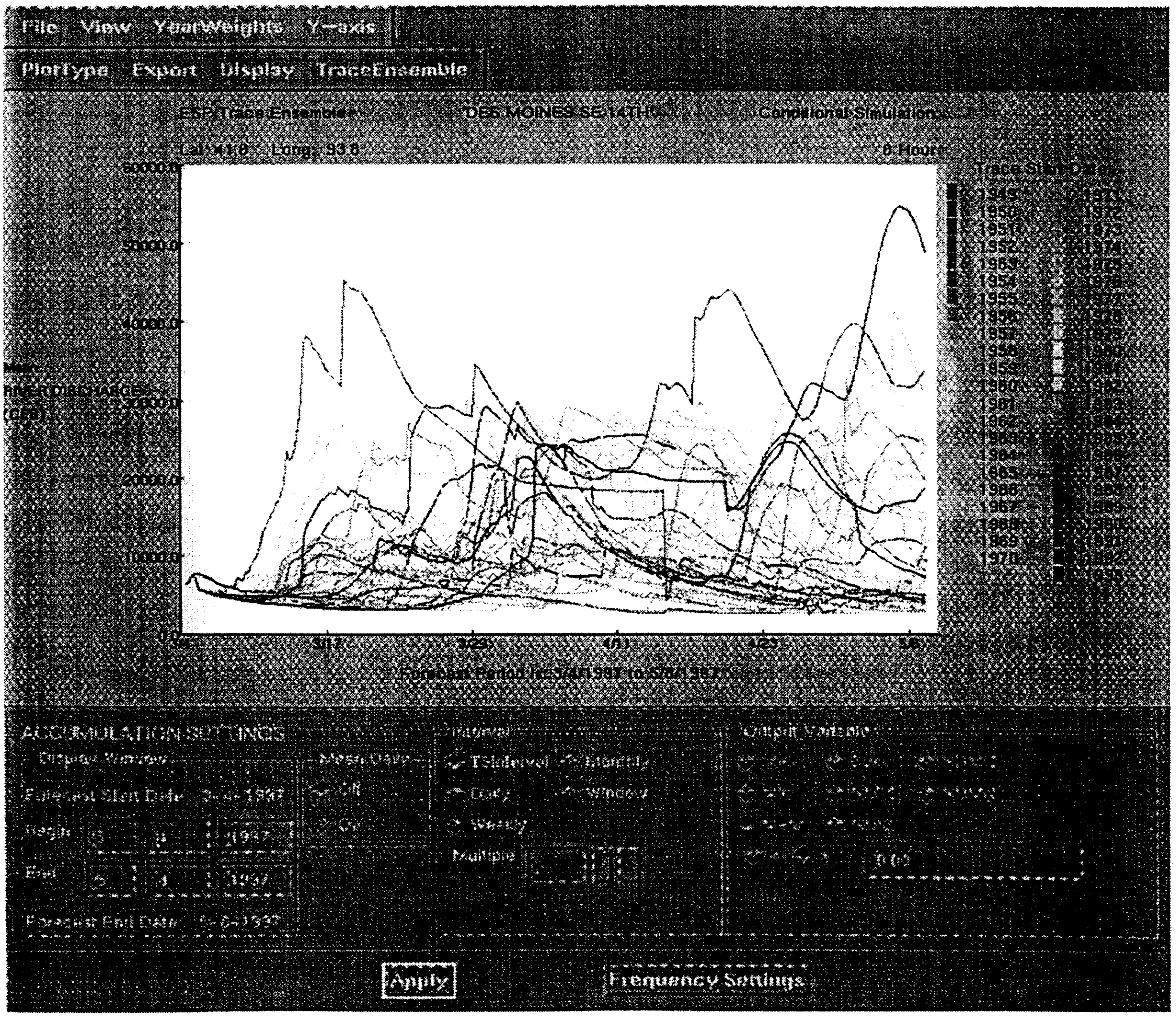

Figure 2 - Example ESP Streamflow Hydrographs

These PQPFs characterize, in part, the joint distribution over space and time from which the precipitation ensemble members must be sampled. Other characteristics of this joint distribution are related to the space-time structure of the precipitation events that could occur. Information about this structure can be derived from a number of sources, including climatological data and gridded numerical model outputs. If weather forecast models have been run in an ensemble mode, these ensemble members provide some of the information required.

6. DES MOINES DEMONSTRATION PROJECT

The Des Moines River is regulated for flood control by Saylorville and Red Rock reservoirs by the U. S. Army Corps of Engineers. They are operated together to provide both flood protection at key downstream locations and low flow for water supply and water quality control. Recreation as well as fish and wildlife are secondary benefits. One of the primary objectives of this project was to provide probabalistic forecasts of the flows into these reservoirs and the river stages downstream. Future precipitation forecast information was obtained from several sources within the NWS. A 24-hr precipitation forecast was provided by the Weather Service Forecast Office. A deterministic forecast out to 5 days was provided by NCEP's Hydrometeorological Prediction Center (HPC). A categorical forecast out to 10 days was provided by NCEP's Climate Prediction Center (CPC). A probabalistic forecast for the next month is issued at the middle of each month by CPC as well as probabilistic forecasts for overlapping three months periods for successive months out to one year. All of these forecasts were used to construct an ensemble of precipitation time series for each of the hydrologic forecast subareas of the Des Moines basin. The approach was to use the various forecasts to adjust the historical precipitation time series so that the marginal distributions for different periods of the adjusted series agreed with the corresponding forecast.

An example of ESP streamflow hydrographs produced during this demonstration is shown in Figure 2. This is an example display from the forecaster's workstation. From the information in the streamflow hydrograph ensemble, many different probabalistic forecast products can be produced. An example forecast of the maximum river discharge during the period 3/11/97 to 5/3/97 is shown in Figure 3. The Des Moines project is continuing to operate. More information and forecast products an be found on the Internet at **http://www.crh.noaa.gov/dmx/ahps/index.html.**

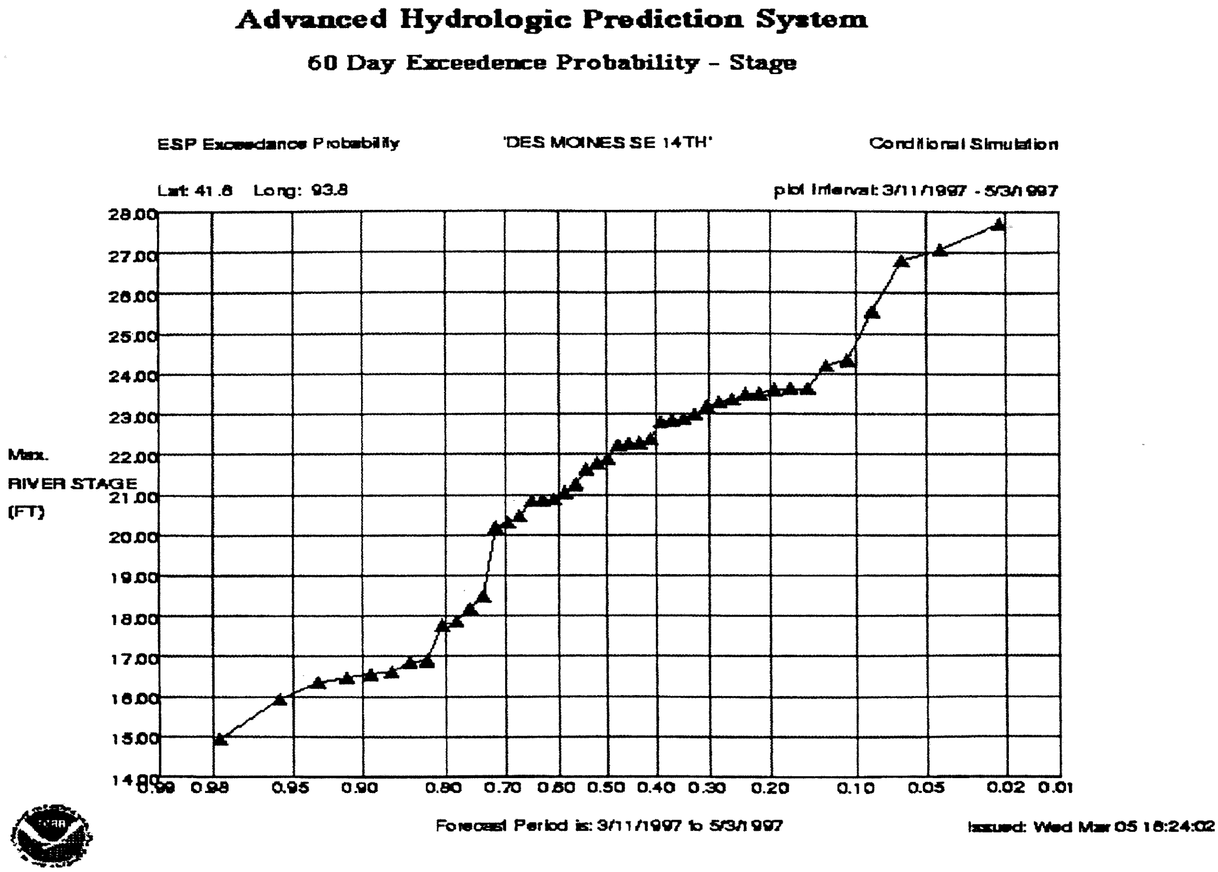

Figure 3 - Example Probability Distribution

7. UPPER MONONGAHELA DEMONSTRATION PROJECT

A project is underway between NWS and the University of Virginia to develop techniques for probabalistic river stage forecasting. A key part of this project is a methodology (Krzysztofowicz and Drake, 1992) for HPC and WFO forecasters to produce the required PQPFs which quantify the degree of confidence in future precipitation. To produce ESP outputs, it is necessary to know the future space/time variability of the precipitation at a high degree of space/time resolution. This is a high-dimensional problem that is too complex for a forecaster to address directly. So some approximations must be made. This involves breaking the problem into parts. The first is for the forecaster to predict the marginal distribution of 24-hour precipitation in terms of 3 parameters:

Probability of Precipitation (POP), where

$$POP = P\{W>0\}$$

and two exceedence fractiles:

$$P\{W>Xp|W>0\} = p \text{ for } p=0.50, 0.25$$

Next, the forecaster predicts the expected distribution [Z1,Z2,Z3,Z4] of W over four six-hour periods, where

$$Z1 + Z2 + Z3 + Z4 = 1$$

so it is enough to have only three of these values. The final result of the forecaster component is six gridded fields of the parameters POP, X50, X25, Z1, Z2, and Z3.

The cumulative distribution function of W depends on the spatial scale over which W is averaged. For example, the probability distribution of point precipitation is much more variable than for precipitation averaged over a large area. It is not clear exactly what actual area is for present forecasts of W. The PQPF technique has been developed and tested over areas of about 5000 square kilometers. The effective area of W is the area over which the observed precipitation can be averaged so that the distribution for many forecasts of the forecast exceedence probability of the observed W is uniformly distributed.

Guidance information for the distribution of W may not be at the same spatial scale as required. The only existing operational objective probabilistic guidance is the probability of precipitation amount (POPA) products produced by TDL's MOS technique. These apply to point precipitation and so must be re-scaled to apply to the distribution of W.

PQPF products from different weather forecast offices must be mosaiced at the River Forecast Center.

The next step is to use these fields to produce Probability of River Stage Forecasts (PRSF's). Two parallel approaches are being taken in this project and these are illustrated in Figure 4. One approach (Kelly and Krzysztofowicz, 1996) uses stratified sampling of precipitation together with Bayesian theory to account for

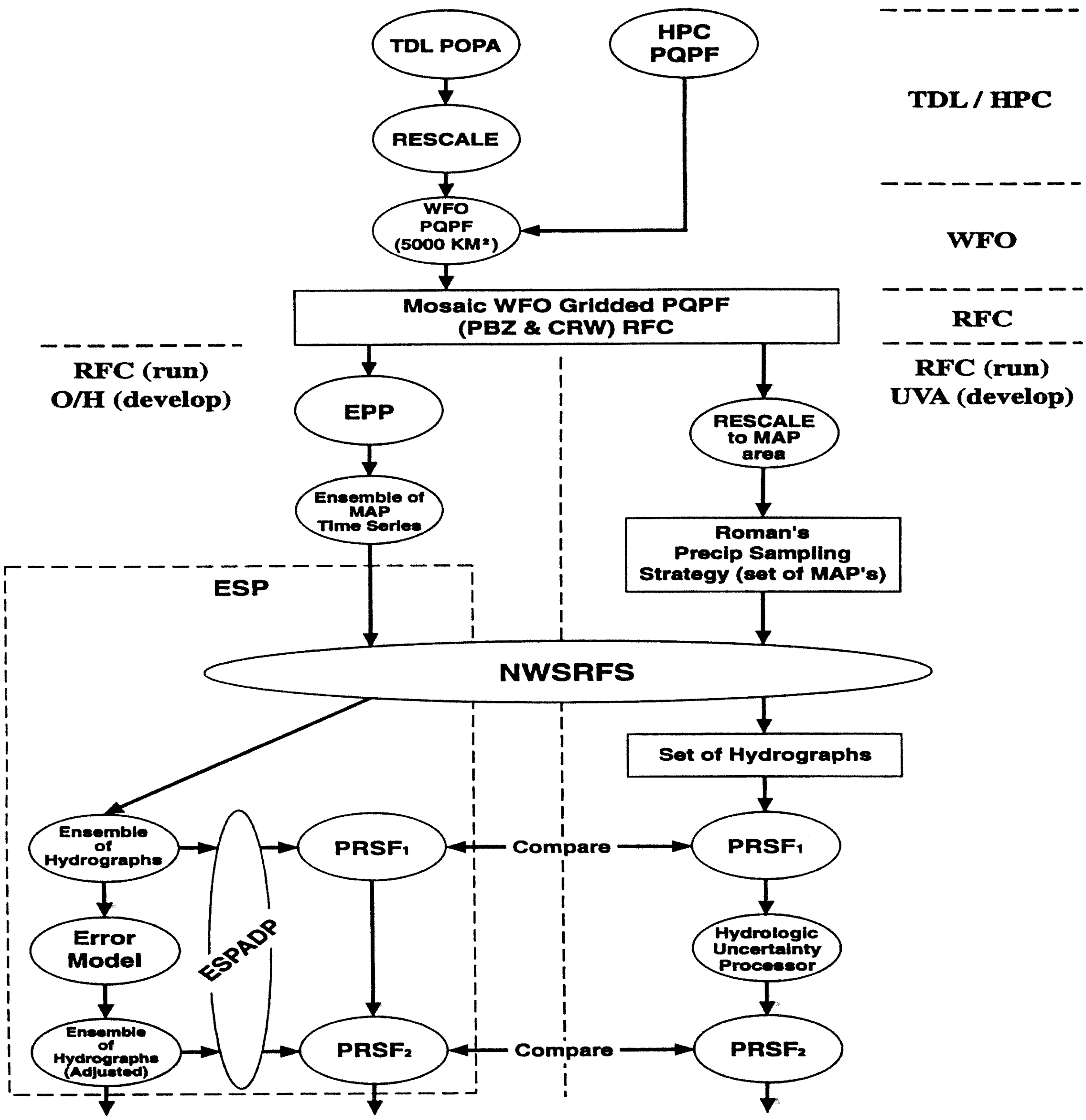

Figure 4 - Parallel Paths to Produce PRSF

the total uncertainty, including that associated with future precipitation and that associated with hydrologic transformations. The other uses an Ensemble Precipitation Processor (EPP) to generate space/time sample functions of precipitation.

The EPP is being developed as a modular system. Several different approaches are being developed and tested for each of the components. It is essential that the EPP precipitation fields preserve the marginal distributions of areally averaged precipitation that are appropriate for each forecast situation.

The EPP output precipitation sample functions are converted into time series of mean areal precipitation (MAP) for each hydrologic subarea of the river basin. The ensemble of MAP time series are used to produce the ESP hydrographs.

These ESP streamflow hydrographs account for uncertainty in future precipitation, but they include various model biases and do not include the effects of uncertainty in the hydrologic model or in the initial conditions. Accordingly, an "error model" is used to adjust the ESP output hydrographs. This error model adjustment is designed so that when it is applied to a continuous simulation, the monthly distributions of adjusted daily flows will be the same as the distributions of observed daily flows.

8. RESEARCH NEEDS

Techniques for the EPP are being developed by the NWS Hydrologic Research Laboratory, but this is an area where more research is needed.

New, hydrologically relevant methods for QPF verification are needed, and HRL is developing some of these, focusing on precipitation forecasts from the Eta model and from NCEP's Hydrometeorological Prediction Center (HPC).

Continued work is need to perfect the PQPF methodology and to find alternative ways for forecasters to combine meteorological and probabalistic reasoning to add value to forecast guidance products.

Improved forecast guidance products are needed, including techniques for adaptive regression between model outputs (from models which change frequently) and the precipitation that actually occurs.

Methods are needed to use ensemble forecasts from global and regional weather forecast models and from coupled ocean/land/atmosphere climate forecast models to produce precipitation ensembles that can be applied to hydrologic models. This involves bridging the gap between the scales of the atmospheric and hydrologic models as well as removing atmospheric model biases in the mean and higher moments of the forecast ensemble variables.

Techniques are needed to condition the downscaling of atmospheric model information on the state of the atmosphere.

9. REFERENCES

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