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HYDROMETEOROLOGICAL COUPLING FOR EXTENDED STREAMFLOW PREDICTIONS

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1. INTRODUCTION

Current water resources forecasting techniques make limited use of growing NOAA skill in short- to long-range weather and climate forecasts. The Water Resources Forecasting System (WARFS), including Extended Streamflow Prediction (ESP) enhancements, will take advantage of these accomplishments by incorporating much of this information into its technology and procedures. ESP enhancements will enable WARFS to provide for analyses of streamflow trace ensembles within specified future time windows, objectively couple meteorological/climatological forecasts in the ensemble analysis, provide for a variety of probabilistic analyses of ensembles, and package probabilistic streamflow forecast products with extended lead times. Thereby, WARFS will provide river forecasts which not only account for precipitation already on the ground but which also will probabilistically account for estimates of future precipitation. This coupled prediction system will greatly improve the Nation's capability to take timely and effective actions that will significantly mitigate the impact of major flood and drought situations. The system will also provide better overall information for use in water resources management (e.g. better management of the competing water demands between irrigation, fisheries, and hydropower).

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2. BACKGROUND

The Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), in partnership with other major cooperators, are committed to the development and implementation of an Advanced Hydrologic Prediction System (AHPS) to improve prediction services for the Nation. This effort is a key component in the *NOAA 1995-2005 Strategic Plan* (Baker, et.al., 1993) to enhance NOAA's role in environmental prediction. The key to providing improved forecasts of surface water quantities depends on establishing and maintaining an Advanced Hydrologic Prediction System (AHPS).

The Water Resources Forecasting System (WARFS) is one of four major components that will form the AHPS. Along with WARFS, the other components are: 1) NOAA's current scientific and operational infrastructure, including the National Weather Service River Forecasting System (NWSRFS; Fread, et.al., 1991); 2) National Weather Service (NWS) modernization technologies, especially NEXRAD (NEXt Generation Weather RADar - WSR-88D) and AWIPS (Advanced Weather Interactive Processing System); and 3) cooperative and supportive partnerships with other government agencies, universities, and the private sector. WARFS implementation activities have begun within the upper Mississippi River basin at the North Central River Forecast Center, located in Minneapolis, Minnesota. As an increase in resources become available, WARFS implementation activities can be expedited within the Mississippi Basin as well as early implementation in one or more additional basins in the United States, e.g. the Columbia River Basin which is of critical economic and environmental importance to the Nation.

3. ADVANCED HYDROMETEOROLOGICAL MODELING

WARFS is an integrated real-time modeling and data management/analysis system which includes provisions for the use of historical hydrologic/hydrometeorologic data and meteorological/climatological forecasts for input to Extended Streamflow Prediction (ESP) simulations (Figure 1). ESP is the portion of NWSRFS which produces probabilistic forecasts out to several months. Long-range probabilistic forecasts will greatly improve the capability of emergency managers and water facility managers to take timely and effective actions to mitigate the impact of major flood and drought situations. They also provide better support for overall water resources management (e.g. better management of competing water demands between irrigation, fisheries, and hydropower). In order to implement these services, WARFS builds upon the NWSRFS and NWS modernization technologies and is divided into three interdependent functional requirement areas: Integrated Data Management and Analysis, Advanced Hydrologic/Hydraulic Modeling, and Advanced Product Packaging/Dissemination.

3.1 INTEGRATED DATA MANAGEMENT AND ANALYSIS

The NOAA Hydrologic Data System (NHDS) will provide the nucleus of capabilities required by WARFS to handle the integration of real-time/historical station and gridded data, and model generated (forecast) outputs. The data sets will be large having sizes comparable with up to 50 years, at temporal resolutions of hourly to daily for gridded (50,000 - 150,000 grid points at resolutions as small as 2 km) estimates of surface hydrometeorological parameters such as precipitation, temperature, snow water equivalent, and evapotranspiration; and, time series of point estimates for parameters such as river flow, river

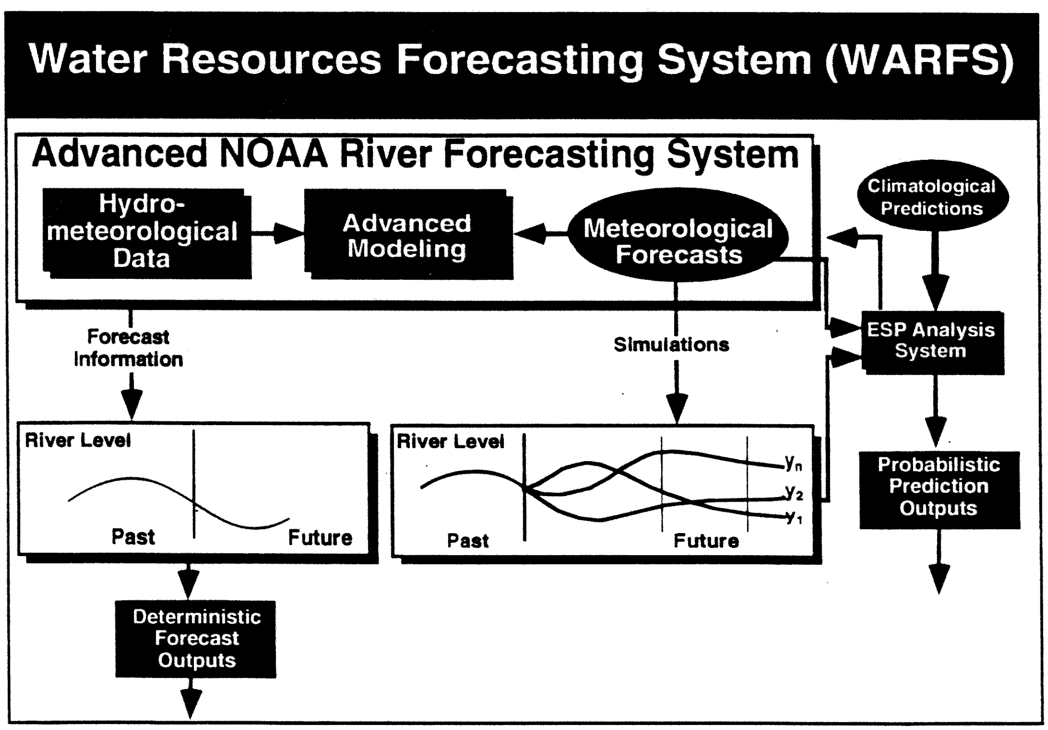

Figure 1. Schematic of the Water Resources Forecasting System (WARFS) integrated real-time modeling and data management/analysis system.

level, and reservoir discharge. NHDS will access, assimilate, analyze and maintain the required data and information. The information maintained by the NHDS spans the time domain from historical to real-time, and spans the quality domain from observed, or raw data, to high quality derived products. The data handled by the NHDS will be acquired from a variety of sources which also provide data which span the quality and time domains. Characteristics of current and potential operational and archive data sources are now being identified, and plans and techniques for acquisition of these data by the NHDS are being developed.

The data volumes and analysis techniques contemplated for WARFS require the use of specialized computer-based techniques for both data management and computational effectiveness. In addition, these large data volumes will require the use of relatively automated approaches with minimal manual intervention. The advanced mathematical/statistical analyses to be performed upon the data involve the production of high quality estimates of fields and time series of hydrometeorological physical and derived elements using multivariate analysis techniques.

3.2 ADVANCED HYDROLOGIC/HYDRAULIC MODELING

The infrastructure for WARFS is the current National Weather Service River Forecast System (NWSRFS). The NWSRFS is a software system (over 350,000 lines of computer code) consisting of many programs, including deterministic hydrologic/hydraulic modeling components, which are used to perform all steps necessary to generate streamflow forecasts. The system includes the Calibration System (CS), the Operational Forecast System (OFS) and the Extended Streamflow Prediction (ESP) System. The CS performs the tasks needed to process historical hydrometeorological data and to estimate model parameters for a specific basin. The OFS enables the processing of data and the development of forecasts of hydrologic variables using operations (models/procedures) selected by the forecaster. ESP is the portion of the NWSRFS which enables a hydrologist to make extended probabilistic forecasts of streamflow and other hydrologic variables, such as soil moisture and snow water content.

3.2.1 STREAMFLOW FORECASTS

As depicted in Figure 1, the advanced modeling module of WARFS applies hydrometeorological data in order to produce deterministic streamflow forecast products. As Figure 1 also illustrates, these same advanced models may be coupled with historical hydrometeorological data and meteorological/climatological forecasts/predictions to produce deterministic simulations of future river flows. Additionally, analyses may be performed upon the simulations in order to produce long-term probabilistic predictions of streamflow. ESP is the heart of WARFS for the production of probabilistic predictions and, when hydrometeorological coupling capabilities are included, will provide objective probabilistic predictions of greater accuracy other than those currently possible with just deterministic procedures.

The existing ESP procedure assumes that meteorological events which occurred in the past are representative of events which may occur in the future. Using these data, a separate streamflow time series is simulated for each year of historical data using the current soil moisture and streamflow conditions as the starting point for each simulation. Before an ESP analysis is performed upon these potential future streamflow trace ensembles, the forecaster can subjectively weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year. Since subjective weighting is unreliable, a forecaster usually assigns an equal weight for each simulated year. However, this approach disregards the relative importance of the recent past, present, and predicted future meteorological and climatological states. The need for objective procedures to assign weights to each simulation is the basis for the development of a hydrometeorological coupling procedure for ESP analyses.

3.2.2. ESP PREDICTIONS INCLUDING HYDROMETEOROLOGICAL COUPLING

The enhanced ESP system used with WARFS will take advantage of NOAA's growing skill in short- to long-range weather and climate forecasts by coupling much of this information into its technology and procedures. One approach to such coupling involves the development of objective techniques for the assignment of weights to the individual traces included in the ensembles analysis based on multiple streamflow simulations using 25 or more years of historical records. Probabilistic streamflow forecasts can then be developed using mathematical/statistical analyses upon the traces obtained for each year of data. These analyses can be performed for different forecast periods and additional hydrologic variables of interest.

Meteorological/climatological forecasts would be the most useful if detailed quantitative precipitation forecasts (QPFs) could be directly input to streamflow predicition models. Unfortunately, current QPF models and procedures do not consistently provide sufficiently accurate values for direct input to hydrologic models (NWS, 1994). Although current QPF products provide generalized guidance information indicating rainfall amounts and locations of rainfall areas, they generally do not provide the necessary detail and accuracy required for assigning QPF values to individual watersheds, especially for time windows beyond 12 to 24 hours.

In the absence of sufficiently precise meteorological forecasts, enhanced ESP ensemble analyses approaches will be developed to objectively extract the skill contained in the meteorological forecasts through coupling of the historical time series of precipitation with the precipitation forecasts for the current year. This coupling can be achieved through application of the singular decomposition theorem which leads to a class of mathematical procedures called singular value decomposition (SVD) [Bretherton, Smith, and Wallace; 1992].

The singular decomposition theorem states (Jalickee and Ropelewski, 1979) that every $N \times M$, $N \leq M$, matrix $A = \{A_{i,j}\}$* can be represented by a series of the form

$$A_{i,j} = \lambda_1 x_i^{(1)} y_j^{(1)} + \lambda_2 x_i^{(2)} y_j^{(2)} + \ldots + \lambda_N x_i^{(N)} y_j^{(N)}$$

where the $\{x_i^{(k)}\}_{i=1,N}$ is known as the kth left singular vector, $\{y_i^{(k)}\}_{j=1,M}$ as the right singular vector, and the λ's are the singular values with

$$\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_N \geq 0.$$

* For our purposes, matrix A is an array of precipitation values.

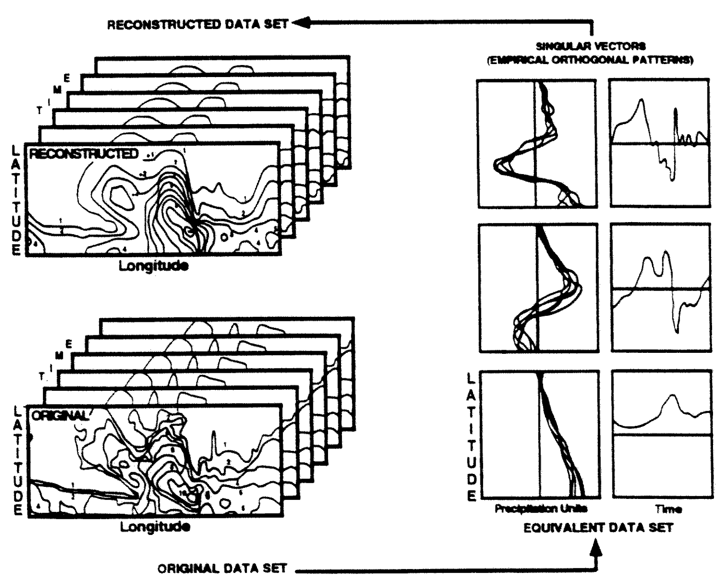

Figure 2. Conceptual illustration of data decomposition/reconstruction using the singular value decomposition (SVD) technique (based upon Jalickee, Sullivan, and Rozett, 1975).

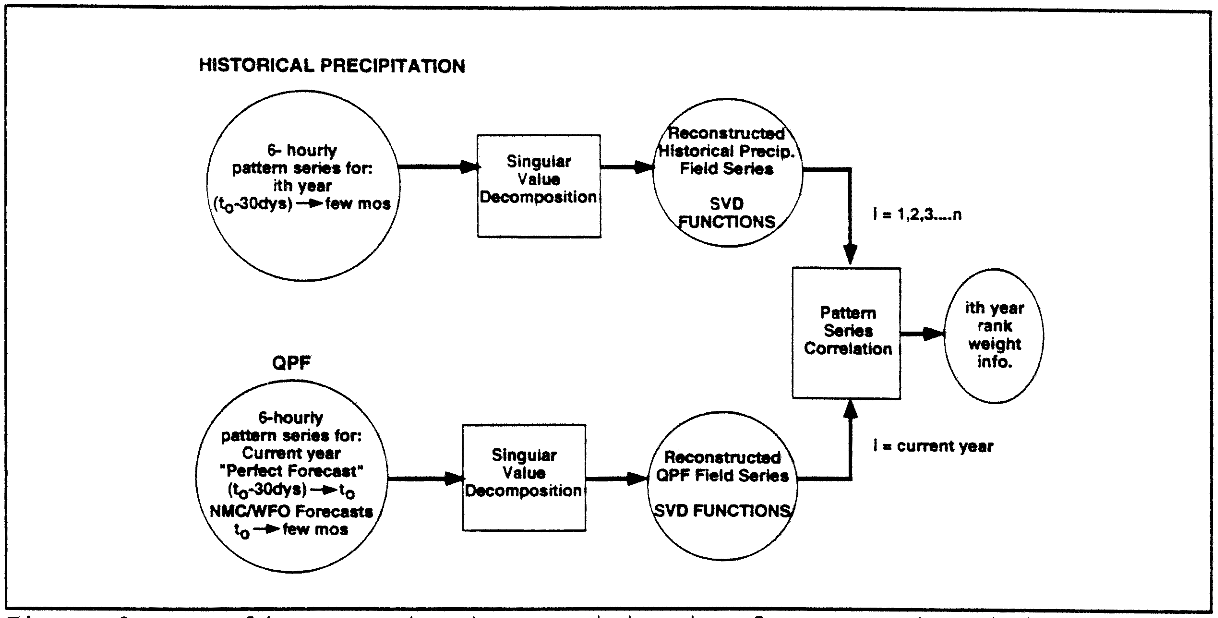

Figure 3. Coupling quantitative precipitation forecasts (QPFs) into Extended Streamflow Prediction (ESP) ensemble analyses using singular value decomposition (SVD).

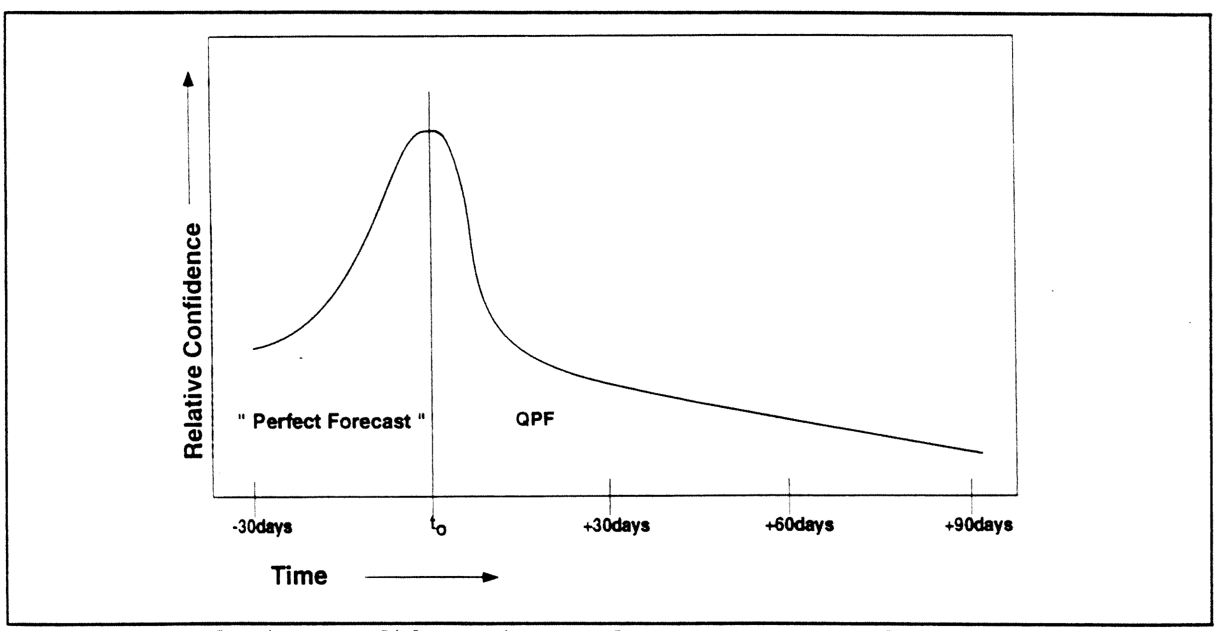

Figure 4. Relative confidence in "Perfect Forecast" and quantitative precipitation forecast (QPF).

Figure 2 provides a pictorial illustration of an example application of the SVD technique to specific humidity data that was presented by Jalickee, Sullivan, and Rozett (1975). For purposes of illustration here, their example was modified to provide a conceptual illustration for precipitation data. Figure 3 schematically illustrates the SVD approach for coupling QPF into the ESP ensemble analyses. A measure of relative confidence in the QPF information for the various time horizons (Figure 4) will be applied as part of the pattern series correlation to arrive at the relative weights for use in the ESP ensemble analyses (Figure 1).

3.3 ADVANCED PRODUCT PACKAGING/DISSEMINATION

NOAA has the national responsibility to provide river and flood forecasts and warnings for the protection of life and property and for the economic and environmental well-being of the Nation. The advanced hydrometeorological modeling provided by WARFS will greatly improve NOAA's capability to provide more timely and accurate forecasts. For these multiple uses, NOAA will provide advanced forecast products through WARFS which meet multiple objectives including the following: 1) support forecast service requirements of government and quasi-government water and emergency managers; 2) satisfy needs for forecast services at near-, mid-, and long-term time scales for a wide variety of water use situations nationwide; 3) provide critical information on forecast reliability; 4) improve hydrologic forecast sensitivity to weather and climatic forecasts; and, 5) provide water resources forecasts to private sector intermediaries, who in turn serve specific industries.

4. SUMMARY

The existing ESP procedure assumes that meteorological events that occurred in the past are representative of events that may occur in the future. Within ESP, simulations of potential future streamflow trace ensembles are produced using historical precipitation data starting with current hydrologic state conditions. Through enhancements to ESP, including SVD analyses, relationships between the temporal and spatial distributions of historical precipitation and precipitation forecasts will provide an objective basis for coupling the hydrometeorological forecasts as part of the ESP ensemble analyses. The coupling procedure will provide relative weights to be applied to each hydrologic simulation trace. A variety of probabilistic analyses of the weighted trace ensembles can then be performed in order to produce WARFS products for specified future time windows.

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