U.S.- Italy Research Workshop on the
Hydrometeorology, Impacts, and Management of Extreme Floods
Perugia (Italy), November 1995

REAL-TIME PREDICTION FOR FLOOD WARNING AND MANAGEMENT

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Abstract. Within the context of predicting and mitigating flood hazards, this paper motivates the development of innovative ideas in three engineering research areas: (a) spatially-distributed quantitative rainfall prediction, (b) spatially-distributed flow prediction, and (c) long-term flow prediction for water resources management. Design, operational implementation, real-time testing, and training of field personnel should be the cornerstone of such development for realizing the potential benefits in these fields.

1. INTRODUCTION

Substantial progress in the development and implementation of advanced operational hydrologic prediction and water resources management methods has been made during the last decade. In the U.S., prototype designs of prediction systems with capability for real time updating and forecast uncertainty estimation are being tested as parts of national forecast systems (Georgakakos and Sperfslage, 1995). The first coupled meteorological-hydrological models for simultaneous rainfall and flow prediction are in operational use (Bae et al. 1995). Likewise, fully distributed flash flood warning systems capable of utilizing weather radar data are in the phase of operational testing (Georgakakos, et al. 1993), and coupled forecast-control systems are now being considered seriously for improved water resources management (Georgakakos, et al. 1995). The implementation of such advanced forecast methods and their real time testing has generated important changes in original designs for more robust and reliable forecast systems. A critical prerequisite for implementation and operational use is to motivate the interest and to perform the necessary training of field personnel to understand the basis of these systems and to effectively use them. When this is accomplished, feedback from field personnel almost always results in improved engineering designs of forecast systems.

This paper reviews recent pertinent developments in which the author was involved, and motivates new research avenues for improvement. The discussion is in the context of the remaining unresolved issues and in light of the performance of existing systems.

2. LESSONS FROM RECENT DESIGNS AND IMPLEMENTATIONS

2.1 REAL-TIME UPDATING AND ESTIMATION OF FORECAST VARIANCE

In the majority of operational flood prediction cases, the variance of the precipitation forecasts is considerably larger than the measurement error associated with discharge observations. It is thus reasonable to expect that forecast errors based on discharge measurements contain useful information which, if properly utilized in real time, may lead to improved future forecasts. In addition, it is desirable to estimate the variance of the forecasts in real time, as it makes for a more complete (and in several cases more usable) description of model ability. State estimators may be (and have been) designed to accomplish both of these objectives. Although the first designs of estimators suitable for implementation with conceptual hydrologic models have appeared almost two decades ago (e.g., Kitanidis and Bras, 1978), operational implementation for flow forecasting has been rather limited and not always successful. The likely reasons for this stem from the complexity of the theory and implementation of state estimators (which poses substantial training requirements on field users of the systems), and from the variety of possible designs of state estimators with many free parameters. With respect to the latter, estimating values for the so-called model-error covariance matrix has been a source of instability in estimator performance for cases with large uncertainty in precipitation forecasts and model-parameter estimates.

Although some training on the theory of state estimation is necessary in any case, the design of robust estimators which require little or no interaction with the user is now possible (Georgakakos, et al. 1988). The important features of these new designs which make them robust and without the need for calibrating a large number of free estimator parameters are: (a) a continuous coupled form for state mean and covariance propagation, and (b) a new form for expressing the model error covariance parameter as an analytical function of the variance of precipitation forecasts and of parameter estimates. Tests performed under a simulated real time environment which were conducted by WMO (Georgakakos and Smith, 1990) showed the robust performance of the new design, operating without manual corrections. Such a design was used with the operational National Weather Service (NWS) Sacramento soil moisture accounting model, and a new operation for real-time updating and forecast variance estimation was created within the U.S. NWS River Forecast System (NWSRFS). Georgakakos and Sperfslage (1995) describe the first operational test results for the new operation as compared to the older operation of the stand-alone version of the Sacramento model. Both operations (with updating and without updating) used the same hydrologic model parameters. Three headwater basins in Oklahoma (Illinois River, Blue River and Glover Creek) with areas that ranged from 800 km^2 to 1600 km^2 and with substantially-different response to rainfall were selected for these tests, which were initiated in December of 1994. Forecast lead times up to 3 days with a 6-hourly resolution were issued and evaluated. Precipitation and discharge data were available every 6 hours. It was found (see Georgakakos and Sperfslage, 1995 for detailed results and discussion) that in almost all cases the updating operation gave better forecasts of hydrograph peak magnitude and timing than the existing Sacramento operation (Figure 1 shows the results for hydrograph peak). In addition, comparison of the root mean square error values of the two operations for each of the basins and for 12- and 18-hour lead times, showed the unmistakable improvement achieved by the state estimator design. It was also found that substantial further improvement could only be achieved after improvement of the operational rainfall forecasts.

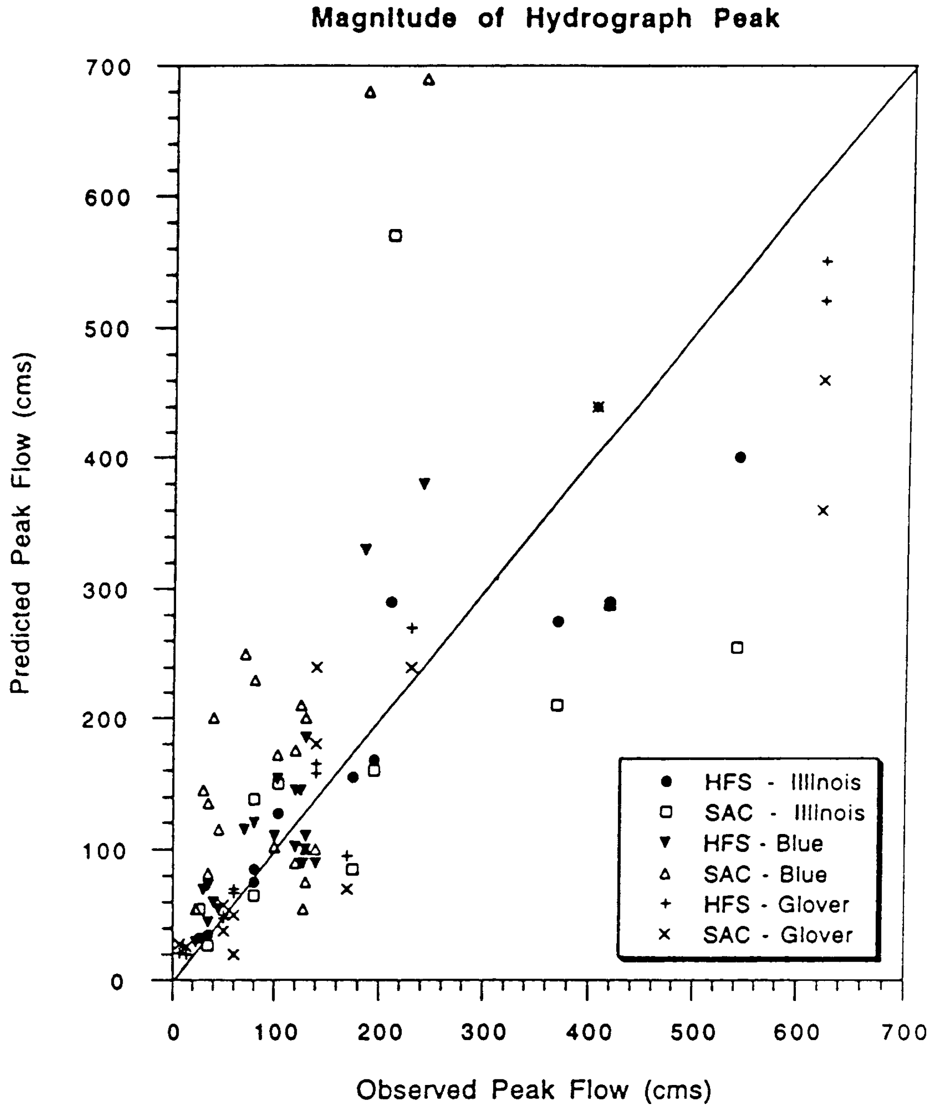

Figure 1. Predicted Versus Observed Flow Peak in m3/s for the Hydrologic Forecast System with Updating (HFS) and for the Operational Sacramento Model (SAC), for all Events in the Period Dec.1, 1994 - May, 31, 1995, and for the Three Tests Basins (adopted from Georgakakos and Sperfslage, 1995)

2.2 COUPLED METEOROLOGICAL-HYDROLOGICAL MODELS

The coupling of meteorological and hydrological models for more effective flow prediction has been supported by Georgakakos (1986, 1987). In this context coupling is both through (a) the water mass conservation enforced by the system equations, and (b) the feedback component of a state estimator used for the estimation of forecast uncertainty and for real-time updating from observations of both rainfall and discharge. Direct coupling of hydrologic and meteorological models within a state estimator framework was shown to be beneficial because of:

(a) the transfer of information from relatively accurate discharge observations to the state of the meteorological component (precipitation prediction model) in real time (mainly for flash-flood prone catchments), and
(b) the utilization of a dynamic equation for precipitation prediction as a means to obtain better estimates of the time-dependent variance of the precipitation forecasts.

Such an integrated hydrometeorological system for flow forecasting (IHFS) was designed and implemented for real time use in an operational environment at the U.S. Army Corps of Engineers Rock Island District in Illinois, U.S.A. The system operates routinely with data collected by real-time data-collection platforms and stored in a real-time database. The precipitation prediction component of IHFS is based on a water mass accounting of the vertically-integrated liquid water equivalent in a cloud column, with microphysics that allow for diameter-dependent properties for the hydrometeors comprising the state of the model (Georgakakos and Bras, 1984). Mean areal precipitation predictions over the catchment of interest are generated by the precipitation component without account of the spatial distribution of precipitation within the catchment. Five soil-water models are used in IHFS (on option) to estimate rainfall abstractions: a generic API model (as described in Georgakakos, 1987), the modified Sacramento soil moisture accounting model (as described in Georgakakos, 1986), and three soil-water options in the HEC-1 model (as described in HEC, 1981). Initial sensitivity analysis of the short-term system forecasts was performed on line with respect to: (a) the form and parameters of the soil-water model, and (b) state updating components. The results show robust system behavior in short-term real-time flow prediction (Bae, et al. 1995). Predictions at various forecast lead times were examined when the IHFS uses both precipitation and stage (or discharge) data for updating.

All soil water models showed best performance for short forecast lead times. Short-term model predictions were not significantly sensitive to the runoff-generating model component when updating is performed, in agreement with previous studies (Georgakakos, 1987). Results with updating further showed that even the predictions of peak flow with a maximum forecast lead time of 40 hours for the study catchment, with a 48-hour response time, are not very different for different soil water models. This behavior is attributed to the long memory of the Iowa soil water. It is suggested then that updating is a necessary component of operational flow prediction systems, especially during initial periods after field implementation, when parameter estimates have large uncertainty. In addition these operational results show that selection of a soil-water model to estimate hydrologic abstractions may be based on user familiarity with a certain model and the estimation of its parameters.

It has been an important outcome of the described IHFS implementation that the operational utility of state-of-science hydrometeorological models is considerably enhanced by the availability of real-time hydrometeorological data bases, such as the HECDSS data base of the USACOE at the Rock Island District in Illinois. Such databases contain <u>both</u> meteorological and hydrological data.

2.3 SPATIALLY DISTRIBUTED FLASH FLOOD PREDICTION USING RADAR DATA

The availability of weather radar data with fine spatial and temporal resolution and the production of national terrain elevation databases led to the development of national spatially-distributed systems for flash flood warning over small catchments (as small as 5 km^2). The design of the first generation of such operational systems in the U.S. is based on an artificial separation of soil water accounting and surface runoff production (Georgakakos, et al. 1993). That is, first, digital terrain elevation data and watershed delineation software generate attributes (e.g., catchment boundaries, area, channel slope) of small catchments within a region. Regional regressions relate channel cross-sectional parameters with such upstream catchment attributes, and geomorphologic unit hydrograph theory (Rodriguez-Iturbe, et al. 1988) generates unit hydrograph peaks for specified locations in streams. The amount of effective rainfall R (mm) of a given duration necessary to cause flooding at a certain channel location is then obtained by solving the equation Q=Rq, where Q (m^3s^{-1}) is bankfull channel flow (usually obtained from uniform flow formula), and q ($m^3s^{-1}mm^{-1}$) is the unit hydrograph peak for the given duration. This effective rainfall amount R is called threshold runoff and it is a hydrologic characteristic of the surface drainage system of an area. It may be computed once, off line. The operational hydrologic models (e.g., Sacramento soil water model) are run for the usual forecast points of a River Forecast Center region, and produce effective mean areal rainfall from actual mean areal rainfall in real time. Then, knowing R and the conversion from actual to effective rainfall for the given soil water state of the operational model, the amount of actual rainfall necessary to cause flooding in the small streams is computed in real time (called flash flood guidance). The main assumption of this "separation" procedure is that the soil water estimate over the large forecast basin represents conditions in all the smaller embedded flash flood prone basins. The main reason for this design was to achieve a reduction of the substantial computational burden associated with the implementation of a fully distributed soil-water accounting system suitable for large domains (10^5 km^2) with fine resolution (5 km^2). Also, utilization of existing products and expertise at the River Forecast Centers was an important consideration.

The operational implementation and testing of this system at the Tulsa River Forecast Center in Oklahoma has produced the following conclusions (Carpenter and Georgakakos, 1993, 1995): (a) computation of unit hydrograph characteristics in an automated fashion from digital terrain elevation data gives results that are in general agreement with manual estimations of unit hydrograph peaks from historical data; (b) threshold runoff estimates obtained without any calibration of the system are reasonable as compared to manually derived ones, and have the expected spatial distribution (semiarid regions with undeveloped channels have low R-values and wet regions with well developed channels have high R-values); (c) the effectiveness of the flash flood warning system rests on the quality of the radar data over 2 km x 2 km grids, with the probability of false warning becoming as high as 0.30 for a rainfall measurement variance that is locally as high as 150 percent of the radar estimate (Georgakakos, 1994).

2.4 INTEGRATING FLOW PREDICTION WITH RESERVOIR CONTROL

Large watersheds in the U.S. and elsewhere usually contain reservoir projects which regulate the flow of rivers for meeting several objectives (e.g., flood control, hydroelectric power production, agricultural water supply, water quality preservation). Operation of such large projects can be accomplished with foresight when reliable short- and long-range flow forecasts are available. A recent study in the midwestern U.S. involved the coupling of a large-scale hydrologic-hydraulic model and the USA Corps of Engineers real-time reservoir management procedure (Georgakakos et al. 1995, see also, Bae and Georgakakos, 1992, and Mullusky and Georgakakos, 1993). The model used the NWS operational Sacramento model for soil water accounting in sub-catchments, the Muskingum-Cunge routing model for river flow computations, and was complemented with a state estimator for uncertainty propagation and real-time updating from discharge observations along the river. The study was done for the 14,000-km^2 Des Moines River basin, which is controlled by the 676,000 acre-feet Saylorville reservoir. The focus of the study was to assess the value of the forecast over three different climatic periods, and the influence of climatic variability on the ability of the reservoir management procedure to meet set objectives. Forecasts were issued for a maximum forecast lead time of 4 months with daily resolution. The reservoir management component of the coupled forecast-control system was different from the original management procedure in that it was enhanced to utilize the forecast variance in addition to the forecast itself. It was found that coupled forecast-control practices show substantial reduction in flood damage over de-coupled reservoir management practices. For example, for the period from 1925 through 1988 there were 251 violations of the flood constraint when de-coupled management was used, while there were only 19 such violations when coupled forecast-control was used. The maximum violation was 875 m^3/s in the de-coupled case (when the maximum of the flow annual cycle is 225 m^3/s), while it was 383 m^3/s for the coupled forecast-control system. Analogous results were obtained for the water quality and supply violations, with 3,588 violations of the de-coupled management procedure and 209 violations for the coupled system. The same study showed also that conceptual hydrologic models are more successful in assisting reservoir management decisions than simple statistical forecast models using flow as a predictor. Although the latter did perform better than de-coupled management practices during cases and climatic periods with "average flows", they led to large violations of the flood constraint in cases of extreme events. The study concluded that well designed forecast-control practices provide a resilient defense against changes in climate fluctuations and trends.

3. RESEARCH NEEDS

- The operational studies discussed show that the improvement of short-term flow forecasts over flash-flood prone areas requires advances in our ability to forecast local intense rainfall. In the U.S. and elsewhere, aided by the ever increasing computer power, the operational numerical weather prediction models use grids with sizes as small as 40-80 km on the side. Thus, rainfall estimates are produced on scales comparable to the scales of the operational hydrologic forecast basins (1000-3000 km^2). Inadequate representation of cloud and surface boundary processes (e.g., Avissar and Pielke, 1989), and inability to utilize local information during flash flood producing storm events are reasons for limited prediction ability. Detailed numerical cloud models are too time consuming to implement for operational purposes. In addition their data input, surface boundary and turbulence parameterizations, and the property of convection to amplify small initial perturbations in atmospheric state variable fields (e.g., Rodriguez, et al. 1989, Elsner and Tsonis, 1992) do not assure us of satisfactory performance on the small scales pertinent to flash flooding. Simplified cloud models complemented by state estimators for explicit account of the (large in some cases) uncertainty associated with model parameterizations offer one solution to this problem which may be implemented and tested immediately. This is an interdisciplinary area in hydrometeorology where enhanced efforts are needed to combine engineering design with knowledge of cloud and surface hydrology. Specific issues that must be resolved are: the prediction of storm propagation characteristics, the design of computationally feasible state estimators suitable for spatially distributed simplified storm models, the characterization of radar measurement errors, and the coupling of these simplified storm models with operational numerical weather prediction models for enhancing forecast skill on longer forecast lead times. Initial efforts along these directions are reported in Lee and Georgakakos (1990), French and Krajewski (1994), and Lee and Georgakakos (1995).

- The use of spatially distributed hydrologic models provides capabilities for prediction in small ungauged catchments, enhancing forecast spatial resolution. It also substantially increases computational time and poses the requirement for soil water accounting on small scales. Traditional conceptual hydrologic models require input-output data for robust calibration and these data are not available for the operational application of distributed models on a national scale in the U.S. Research is needed for establishing (1) the extent to which we can infer effective soil water parameters from geomorphological data and from remote sensing, and (2) the extent to which we can use parameters obtained on larger scales for accounting on embedded smaller scales. Studies of the spatio-temporal scaling of soil water on pertinent scales are prerequisite to dealing with such issues (e.g., Guetter and Georgakakos, 1995a). Engineering research is also needed to develop tailored numerical algorithms for the large distributed forecast systems of the future. Initial studies showed that parallel algorithms reduce the computational burden considerably (e.g., Apostolopoulos and Georgakakos, 1991), and they should be given serious consideration.
- The improved performance of the coupled forecast-control systems compared to uncoupled management practices is due to the foresight offered by the forecast component. Using the historical data of precipitation and potential evaporation as input to hydrologic models for generating possible future scenarios of reservoir inflows may be adequate for successful operation (e.g., Smith, et al. 1991). This is likely the case when: (a) a good-quality long data record exists of historical forcing-response of the hydrosystem, (b) the reservoir capacity is such that reservoir management requires lead times comparable to the memory of the catchment deeper soil water, and (c) operation is during average flow conditions. However, in most cases this unconditional use of historical data may not be adequate to characterize true forecast error, especially for extreme events, and conditioning of the historical data is necessary. This is an important area of research for improved operational reservoir management, and recent prediction methods conditioned on El Niño Southern Oscillation (ENSO) indices (Guetter and Georgakakos, 1995b) constitute a first step in this direction.

Acknowledgments. This review was sponsored by the U.S. National Science Foundation under Award No. CMS-9520109. The author wishes to acknowledge the substantial contributions of the Staff of the Hydrologic Research Laboratory and of the Tulsa River Forecast Center of the U.S. National Weather Service during the implementation of the updating procedure and the distributed flash flood warning procedure, and their continuing support during the on-going operational tests. In addition, he acknowledges the support of the Staff of the Hydraulics Division of the USA Corps of Engineers, Rock Island District in assisting with the implementations of the coupled hydro-meteorological model (IHFS) and the coupled forecast-control models for the Des Moines River basin and the Saylorville reservoir.

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