INTEGRATED HYDROMETEOROLOGICAL FORECAST SYSTEM - DESIGN AND TESTS

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1. INTRODUCTION

Improvements in hydrologic forecast lead time (the difference in time between the time of the occurrence of the forecasted hydrologic phenomenon and the time when the forecast is issued) and accuracy could be achieved if reliable quantitative precipitation forecasts (QPFs) were available for specific watersheds as input to the hydrologic forecast models. Unfortunately, current QPF models and procedures generally do not provide sufficiently accurate values (at least for forecast periods exceeding 30-60 min) for direct input to hydrologic models. Although current QPF products provided by the National Meteorological Center (NMC) provide generalized guidance information which is very useful in roughly indicating rainfall amounts and locations of rainfall areas, they do not provide the detail and accuracy required for assigning QPF values to individual watersheds. There is a need for more direct incorporation of QPF information into the hydrologic modeling and prediction procedures. This is especially important to the improvement of forecasts for small watersheds where the lag time between rainfall occurrence and outflow from the basin is short. According to a recent Program Development Plan for Improving Hydrologic Services (NWS-Office of Hydrology, 1982), 50 percent of the forecast points for communities across the U.S. have potential forecast lead times less than 10 hr and 25 percent have less than 4 hr. Clearly, accurate QPF information for even a few hours into the future would result in valuable increases in effective lead time.

In a review paper, Georgakakos and Hudlow (1984) examine various approaches to rainfall prediction that potentially can provide useful input information for hydrologic forecasting. One of these is the coupled approach to quantitative precipitation - river flow forecasting based on the work of Georgakakos and Bras (1982a). This procedure couples precipitation and drainage basin models both through the mass continuity physical law and through the update component of a state estimator that uses the residual errors in the prediction of rainfall and riverflow to correct the states of the coupled precipitation and drainage basin models.

Figure 1 gives a schematic representation of the coupled system with the links among the various system components indicated explicitly.

The integrated hydrometeorological system of Figure 1 offers high efficiency in the meshing of precipitation and streamflow forecasts, and provides real time estimates of the uncertainty associated with each forecast.

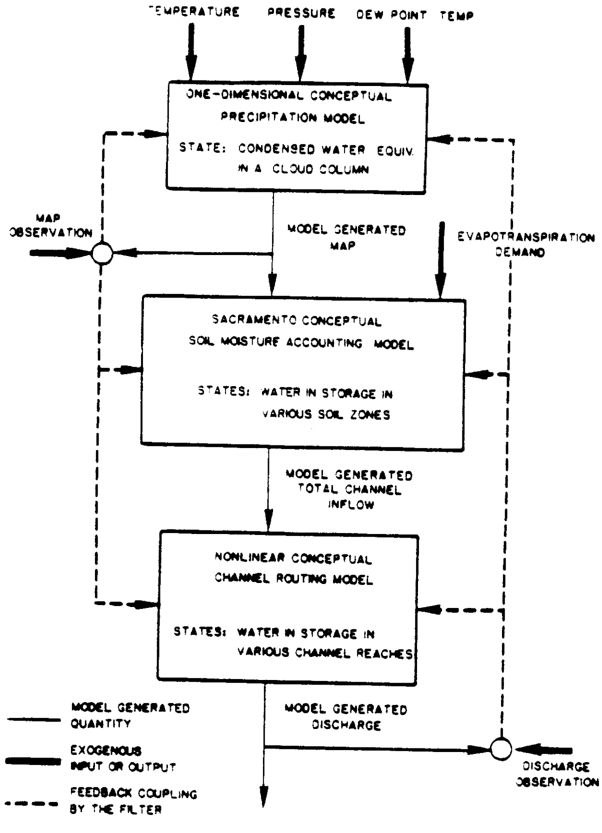

Figure 1. Schematic representation of the integrated hydrometeorological model. Explicitly shown are the model components, inputs and outputs.

It is the purpose of this paper to give a short description of the components of the integrated system and to summarize results of a real world application with six-hourly data from the Bird Creek basin in Oklahoma. At the end, the design of a flash-flood prediction system based on the integrated hydrometeorological system concept is presented. Preliminary results of its "operational" use in the prediction of flash floods in Virginia catchments are also reviewed.

2. THE PRECIPITATION MODEL

Georgakakos and Bras (1984a,b) formulated a station precipitation model in state space form. Based on the surface pressure, temperature and dew-point temperature, their model gives as an output the precipitation rate. The model state is the mass of the condensed liquid water equivalent in the area characterized by the input temperature and pressure indices. The model formulation is based on pseudo-adiabatic ascent of the air-masses and on simplified cloud microphysics with exponential particle-size distribution and linear dependence of the particle terminal fall-velocity on the particle diameter. Evaporation of the falling particles, for unsaturated sub-cloud layer, is explicitly taken into account by the model. Predictions of snowfall vs rainfall are based on the surface air-temperature.

Figure 2 presents a sketch of the physical mechanisms that are modeled. The upper part of the figure is a plan-view of the moving (velocity denoted by u) storm clouds, while the lower part is a cross-section through them. The shaded regions correspond to a cloud-column characterized by the input variables: air-temperature, T_o; air-pressure, p_o; and dew-point temperature, T_d, at the ground level. The model developed simulates the dynamics in this column. Air rises pseudo-adiabatically in the clouds with updraft velocity v (possibly height-varying), producing an input rate of condensed water equivalent I. The input mass of condensed water is distributed to different droplet diameters according to an exponential particle size distribution, n(D), whose parameters N_0 and c (see Figure 2) are possibly height-varying. Due to the action of the updraft at the cloud top, a portion of the water mass leaves the column with a rate O_t. The larger droplets fall through the cloud bottom with a rate O_b. The precipitation rate P at the ground level is computed from O_b by subtraction of the mass evaporation due to possible unsaturated conditions below the cloud base. The model dynamics equation consists of a statement of the conservation of the condensed water equivalent mass X within the cloud column. Heat-adiabatic ascent is used to determine the cloud-base (level Z_b) pressure, p_s, and temperature, T_s. Pseudo-adiabatic ascent and the terminal pressure p_t at the cloud-top (level Z_t) are used to determine the temperature T_t and, subsequently, the water vapor condensed per unit mass of moist air. The physical quantities v, c and p_t are parameterized using the input variables p_o, T_o, and T_d in an effort to obtain a storm and location invariant structure.

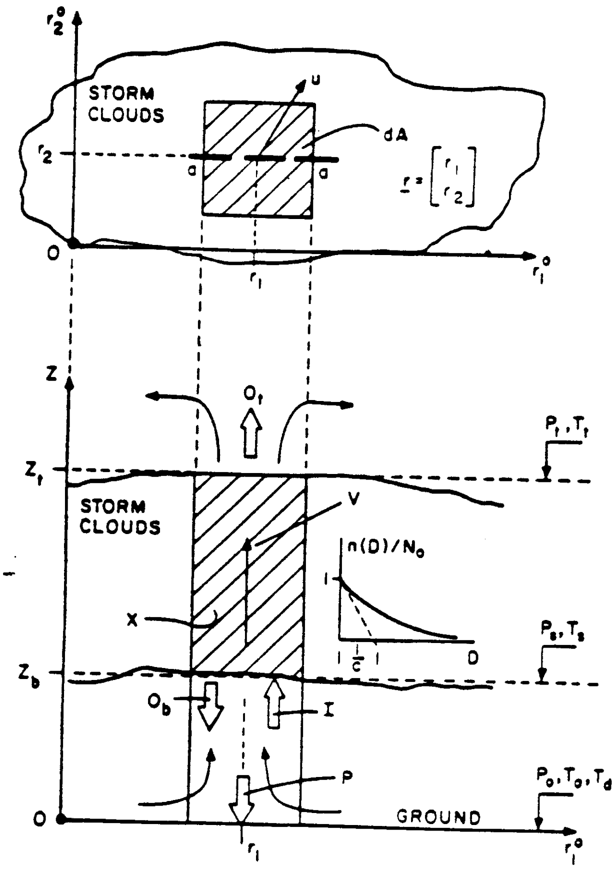

Figure 2. Schematic representation of the precipitation model physical components.

As a first step toward model verification, Georgakakos and Bras (1984a,b) considered uniform profiles of updraft velocity and cloud-particle layer-average diameter. In addition, the cloud-particle layer-average diameter was held constant independent of the input variables. The free model parameters in this case are:

1) The ratio EPS1 of the updraft velocity to the square root of the potential thermal energy per unit mass of the ascending air at the height of average updraft velocity, and

2) the time- and storm-constant cloud-particle layer-average diameter denoted by EPS4 (equal to 1/c).

Georgakakos and Bras give the details of the model formulation as well as encouraging results of model application to several storms of various meteorological characteristics.

Georgakakos (1982, 1984) examined the parameter identification issue in detail. Contour maps of various performance criteria indicated that the model is robust to parameter changes and that it may not require recalibration for different storms and topographic locations. The latter is especially convenient for real-time forecasting uses.

The most important aspect of the precipitation model under consideration is its state space mathematical form. It is this aspect that makes the model compatible with operational hydrologic models and allows the use of a

state-estimator (i.e. Kalman Filter) for real-time updating.

3. THE SOIL-MOISTURE ACCOUNTING MODEL

The precipitation forecast averaged over the basin area, obtained from the precipitation model, feeds the Sacramento Soil-Moisture Accounting model (Figure 1).

The Sacramento model is a conceptual, spatially lumped model. Its equations describe the movement of water through the various storage elements of the drainage basin (Figure 3). The model distinguishes two zones in the soil: an upper zone that represents the upper soil layer and interception storage and a lower zone that represents the bulk of the soil moisture and groundwater. Each zone stores water in tension elements and in free elements. The tension water is closely bound to the soil particles and can be depleted only by evapotranspiration. The free water moves through the various elements under the force of gravity and contributes to the channel inflow. The model accepts as input the mean areal precipitation over the basin and the potential evapotranspiration rate and produces as output the total channel inflow.

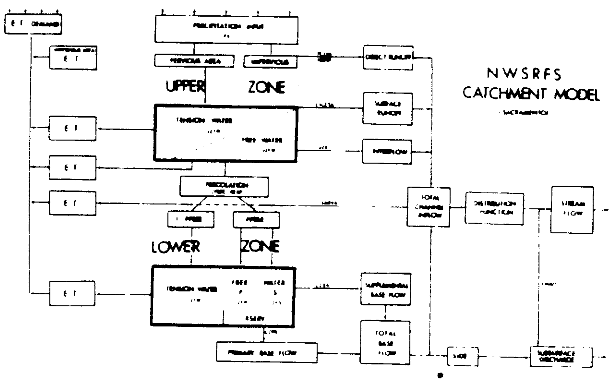

Figure 3. Schematic representation of the Sacramento Soil-Moisture Accounting scheme. See Peck, 1976, for a more precise definition of the parameters appearing in this figure.

Georgakakos and Bras (1982a) give the complete set of the differential equations that describe the state of the soil moisture of the various model storages. The equations are in state space form.

The Sacramento model in state space form has been successfully used with modern estimation theory techniques for the real time forecasting of river flows (Kitanidis and Bras, 1980a,b; Georgakakos and Bras, 1979, 1982a). Armstrong (1978) gives the physical interpretation of the model components in terms of observable soil characteristics. Restrepo-Posada and Bras (1982) study the parameter estimation issue for the model using maximum likelihood techniques.

4. THE CHANNEL ROUTING MODEL

Georgakakos and Bras (1980, 1982b) presented a conceptual, nonlinear reservoir-type channel routing model in state space form, which, when tested with the Sacramento accounting scheme, showed improved performance over linear black-box type routing models.

The drainage basin river system is subdivided into hydromorphologically homogeneous channel segments in series. Each segment is modeled as a reservoir that temporarily stores the water on its way to the drainage basin outlet. The model differential equations are the expressions of the mass continuity law for each reach. The discharge at the outlet of each reach is related by a power law to the water in storage in the same reach. The model uses as input the total channel inflow and produces as output the discharge at the drainage basin outlet.

Real world applications of the routing model with 6-hour data from the Bird Creek basin (2344 mi^2), Oklahoma, gave very good results in the real-time forecasting of flood flows. In particular, delays at the peak of the hydrograph that were observed when linear black-box type models were used in real-time forecasting, were eliminated.

Georgakakos and Bras (1980, 1982b) give the details of model formulation as well as ways of estimating model parameters from 1) the basin observable hydromorphological characteristics, and 2) input-output time-series data.

5. THE INTEGRATED HYDROMETEOROLOGICAL MODEL STATE SPACE FORM

The differential equations that describe the time-evolution of the states of the various components of the hydrometeorological model can be written as follows.

Precipitation component:

$$\frac{d}{dt} x_p = F_p \left(x_p, \underline{u}_p; \underline{a}_p\right) \qquad (1)$$

Soil-moisture accounting component:

$$\frac{d}{dt} \underline{x}_s = \underline{F}_s \left(x_p, \underline{x}_s, \underline{u}_p, u_e; \underline{a}_p, \underline{a}_s\right) \qquad (2)$$

Channel routing component:

$$\frac{d}{dt} \underline{x}_c = \underline{F}_c \left(x_p, \underline{x}_s, \underline{x}_c, \underline{u}_p, u_e; \underline{a}_p, \underline{a}_s, \underline{a}_c\right) \qquad (3)$$

The observation equations that relate the observed quantities (precipitation and runoff) to the model states follow.

Precipitation:

$$z_p = H_p\left(x_p, \underline{u}_p; \underline{a}_p\right) \qquad (4)$$

Runoff:

$$z_c = H_c\left(\underline{x}_c; \underline{a}_c\right) \qquad (5)$$

The state of the precipitation model is denoted by x_p, the vector state of the Sacramento Soil-Moisture Accounting model is denoted by $\underline{x}_s$, and the vector state of the channel router is denoted by $\underline{x}_c$. The vector $\underline{u}_p$ represents the meteorological input to the precipitation model and the scalar u_e represents potential evapotranspiration. The vectors $\underline{a}_p$, $\underline{a}_s$, and $\underline{a}_c$ are

the parameter vectors for the precipitation, the soil, and the channel components respectively. $\underline{F}_p$, $\underline{F}_s$, $\underline{F}_c$ are nonlinear (in general) functions describing the system dynamics for the precipitation, soil, and channel components respectively.

The mean areal precipitation observation over the basin is denoted by z_p and the discharge at the basin outlet by z_c. H_p and H_c are nonlinear (in general) functions relating the observations to the states for the precipitation and the channel components respectively.

The system of equations (1) through (5) constitutes the state space form of the integrated hydrometeorological model equations. In a more compact form the system is written as:

Dynamics Equation:

$$\frac{d}{dt}\,\underline{x} = \underline{F}(\underline{x},\underline{u};\underline{a}) \tag{6}$$

Observation Equation:

$$\underline{z} = \underline{H}(\underline{x},\underline{u};\underline{a}) \tag{7}$$

where,

$$\underline{x} = \begin{vmatrix} x_p \\ \underline{x}_s \\ \underline{x}_c \end{vmatrix} \qquad \underline{u} = \begin{vmatrix} \underline{u}_p \\ u_e \end{vmatrix} \qquad \underline{a} = \begin{vmatrix} \underline{a}_p \\ \underline{a}_s \\ \underline{a}_c \end{vmatrix}$$

$$\underline{z} = \begin{vmatrix} z_p \\ z_c \end{vmatrix} \qquad \underline{F} = \begin{vmatrix} F_p \\ \underline{F}_s \\ \underline{F}_c \end{vmatrix} \qquad \underline{H} = \begin{vmatrix} H_p \\ H_c \end{vmatrix}$$

6. STATE ESTIMATOR

The previous formulation presents the coupling of the equations corresponding to three different models of the storm-basin system. Thus, consideration of the set of Eqs. (1) through (3) shows that the state of the precipitation model, x_p, directly affects the equations of time-evolution of the soil states, $\underline{x}_s$. Both x_p and $\underline{x}_s$ affect the channel-states differential equation [Eq. (3)]. Coupling is due to the enforcement of the conservation of water-mass (or volume) law at the boundaries of each model. Note, however, that it is a one-way coupling. That is, the states of the channel or the soil models do not affect the precipitation state. Therefore, information on those states cannot be passed, with the present deterministic formulation, to the precipitation model.

It is this open link in the overall rainfall-runoff model that modern estimation theory techniques close, using observations on all the model outputs (Eqs. (4) and (5)). State estimators will effectively couple the state variables of the soil and channel models with those of the precipitation model. This is a different coupling from the one due to the conservation of water-mass law. The effect that each state variable has on the overall storm-basin models outputs, is monitored through the filter equations. Each state variable is updated from the system observations (see Figure 1), based on the degree of its correlation to the model outputs and to the rest of the model variables. In this way, the errors in predicting the discharge at the catchment outlet have a bearing on the specification of the initial conditions of the precipitation model variables. Similarly, observations of the precipitation state variables and parameters have an effect on the determination of the drainage basin related state variables. This assures coordination in the operation of the coupled storm and basin models in real time. Georgakakos and Bras, 1982a, develop the formulation of the stochastic hydrometeorological model in a linear state-estimator framework.

Their formulation allows for uncertain inputs with given mean and variance. Since the system equations [i.e., Eqs. (1) through (5)] are non-linear both in the system states and the inputs, the Extended Kalman Filter is used as the state estimator (e.g., Gelb, 1974). The procedure is straightforward to implement, and the interested reader is referred to Georgakakos and Bras, 1982a, for the details.

7. METEOROLOGICAL INPUT SPATIAL INTERPOLATION

The Georgakakos and Bras (1984a,b) precipitation model uses surface meteorological data as input, in order to forecast the precipitation rate in the area characterized by the input. It is often the case, with the present state of the surface meteorological data network (average distance between stations of the order of 100 km), that the precipitation rate is sought in areas where no observations (or accurate forecasts) of the input exist. Interpolation of the surface meteorological observations is then necessary. This section examines the issue of the spatial interpolation of air temperature, T_o; pressure, p_o; and dew-point temperature, T_d, near the ground surface under altitude varying terrain.

It is assumed that the surface meteorological input is the result of both the topography and the atmospheric disturbances. The input is decomposed into two corresponding parts $u_t(z)$ and u_a, according to

$$u = u_t\,(z) + u_a \tag{8}$$

where u denotes input (any of T_o, p_o, T_d); $u_t(z)$ denotes the topography component dependent on the altitude, z; and u_a is the atmospheric component.

The topography component is determined based on the thermal and water vapor properties of an air-parcel as it is forced by the topographic relief to ascend from the lowest point in the area under consideration. Thus, starting from the meteorological station with the lowest elevation in a radius of up to 200 km from the basin, one determines the topographic component of u at the altitudes of all the stations and at the altitude of the point of interest (area-weighted elevation of the drainage basin). Then, one subtracts $u_t(z)$ from the actual observations at the meteorological stations and interpolates linearly the residuals to the point of interest. The value of u at the point of interest is the sum of its topographic component at that point and the interpolated residual at the same point.

Note that dry-adiabatic ascent is used, up to the level where the parcel becomes saturated with respect to water vapor, and pseudo-adiabatic ascent is used above that level.

An important good characteristic of the procedure used is that it provides self-consistent interpolated values for T_o, p_o, T_d. Tests of the procedure for a relatively flat terrain (Tulsa, Oklahoma) and for a mountainous terrain (Lewistown, Montana) show standard errors ranging from 1 to 2 °K for T_o, from 80 to 90 kg/(m sec^2) for p_o and from 1.5 to 1.9 °K for T_d.

8. TESTING OF THE INTEGRATED HYDRO-METEOROLOGICAL MODEL

The Bird Creek basin near Sperry, Oklahoma, served as the test basin. The basin area is 2344 km^2. The elevation ranges from 200 to 350 meters. The wettest seasons are spring and summer with rainfall mainly in the form of showers and thunderstorms. Snowfall is very light. There are significant evapotranspiration losses in the period July to September due to the high air temperature (100°F common), the low relative humidity, and the good southerly breeze.

Six-hourly data were used. Periods of high flows were selected. Six-hourly discharge data are available at the basin outlet, mostly for the months in spring and summer when the flow is high. Mean areal potential evapotranspiration estimates are available at six-hour intervals computed by standard National Weather Service (NWS) procedures (NOAA-NWS, 1972; Day and Farnsworth, 1982). Six-hourly mean areal precipitation estimates are also available based on data from stations both within and outside of the basin, and on NWS procedures (Larson, 1975; Larson and VanDemark, 1979).

The meteorological input spatial interpolation procedure presented in the previous section was utilized to obtain six-hourly temperature, T_o; pressure, p_o; and dew-point temperature, T_d, data corresponding to the basin center, assuming the characteristic basin-elevation of 220 meters. Data from the meteorological stations 1) at Springfield, Missouri, at a distance of 165 km, 2) at Wichita, Kansas, at a distance of 95 km, 3) at Oklahoma City, Oklahoma, at a distance of 105 km, and 4) at Tulsa, Oklahoma, at a distance of 30 km, were used in the interpolation scheme.

The model and the state estimator parameters were obtained from previous studies (Georgakakos and Bras, 1982b; Georgakakos and Bras, 1979; Kitanidis and Bras, 1980; Georgakakos, 1984) independent of the present one. The parameters were held constant for all the integrated hydrometeorological model tests.

Figure 4 presents the frequency plot of the peak magnitude of the observed hydrographs that were included in the model tests. Hydrographs with peaks greater than 0.5 mm/6 hours (or 54 m^3/sec) in magnitude were studied. The bulk of the events were in the range 0.5 to 3 mm/6 hours (or 54 to 324 m^3/sec) and include several flood events. The test period also included some rare events that caused very high flows (at the right end of the magnitude axis).

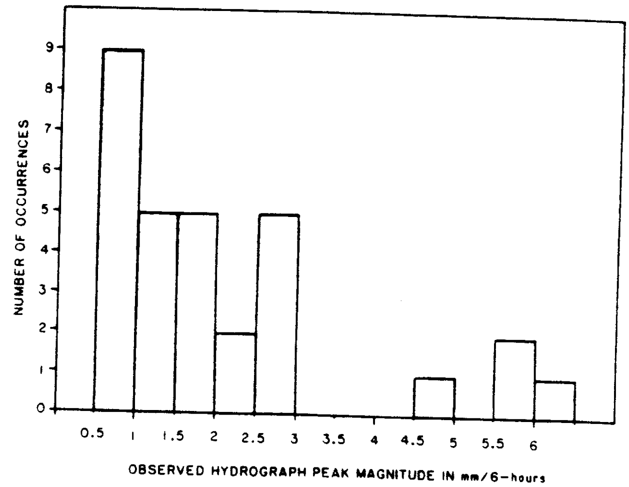

Figure 4. Frequency plot of the peak magnitude of the observed hydrographs for the Bird Creek test basin.

The frequency plot of the difference, expressed in time-steps, between predicted and observed peak flows for a six-hour forecast lead time is shown in Figure 5. Positive numbers indicate a late lag of the predicted flows after the observed ones. The model predicted the hydrograph peak on time or six hours early in more than 70 percent of the cases. Figure 5 shows that, for the majority of the events, the hydrograph peak time was accurately forecast.

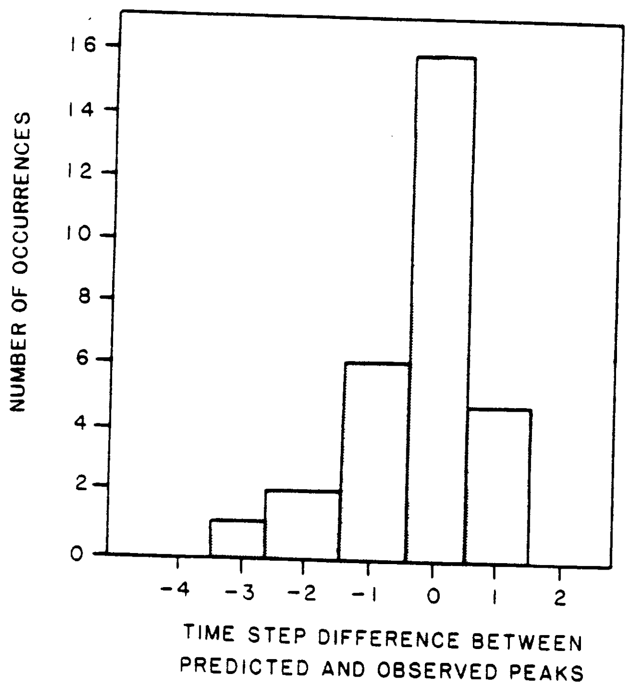

Figure 5. Frequency plot of the time-step difference between predicted and observed peaks for the Bird Creek test basin.

The frequency plot of the percent error in forecasting hydrograph peak magnitude for a six-hour forecast lead time is shown in Figure 6. Positive values on the magnitude axis signify overprediction by the hydrometeorological model. The hydrograph peak magnitude was predicted with less than 20 percent error in more than 70 percent of the cases.

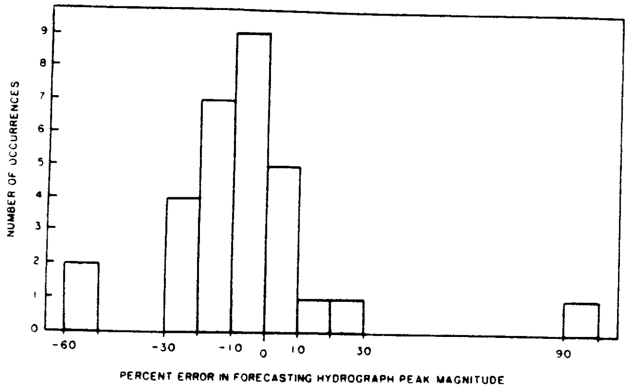

Figure 6. Frequency plot of the percent error in forecasting hydrograph peak magnitude for the Bird Creek test basin.

The results shown in Figures 5 and 6 point to the usefulness of the model as an operational tool in the real-time forecasting of flood flows.

Examination of the detailed results for a six-hour forecast lead time revealed the performance deterioration of the precipitation component in cases when the surface meteorological data are not indicative of the thermal and vapor structure of the atmosphere aloft (e.g., in cases of thermal inversions). Work is underway to incorporate upper air data into the precipitation model of Georgakakos and Bras (1984a) to alleviate the problem.

Tests for longer forecast lead times were also conducted for the hydrometeorological model. Forecast lead times up to 30 hours (approximately equal to the basin response time) were studied. Both actual meteorological data and forecasts of meteorological data were used as input to the precipitation component for the longer forecast lead times. The input forecasts were based on a persistence scheme that forecasts the current observation of the meteorological variables. A typical example of the model performance in extended forecasts is presented in Figure 7. The model discharge forecasts both with observed input and with forecast input are compared to the forecasts of a persistence scheme and an extrapolation scheme. (The forecast is the value linearly extrapolated from current and previous observations.)

The longer-range hydrometeorological model forecasts were better in a least squares sense than both the persistence and the extrapolation forecasts. Also apparent is the deterioration of the hydrometeorological model performance when forecast input is used. It is expected that a more accurate forecast procedure for the meteorological input will improve model performance for

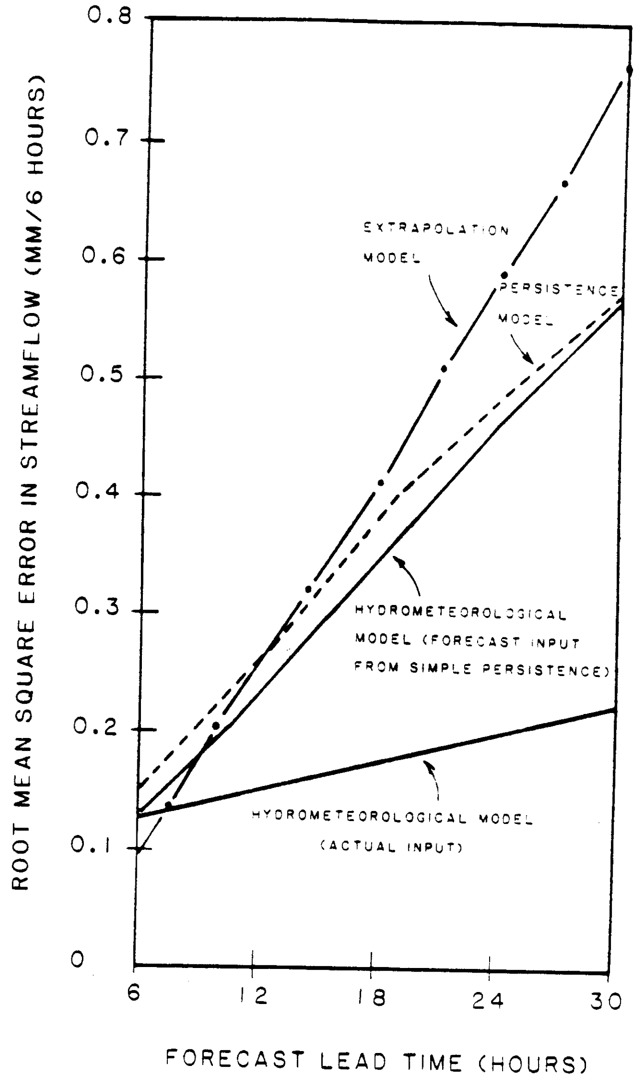

Figure 7. Extended forecasts of the hydrometeorological model (solid lines), the persistence model (dashed line), and the extrapolation model (chain-dotted line).

the longer forecast lead times. Work is underway to incorporate the operationally issued meteorological forecasts from the large scale numerical weather prediction models into the structure of the precipitation component.

The extrapolation scheme showed a better performance for the six-hour forecast lead time. Note, however, that predictions based on extrapolation and persistence will always have a late lag with respect to the observed hydrograph peak.

9. DESIGN OF A FLASH-FLOOD PREDICTION SYSTEM - IHFS

Based on the concept of coupled precipitation and catchment models, a prototype system for the real-time prediction of flash floods was designed.

The flash-flood phenomenon is characterized by very short catchment response times and by intense local precipitation. The time constants of the precipitation formation process are of the same order of magnitude as the time constants of the catchment response process. Because of the intense rainfall, only the upper layers of the soil respond dynamically to the input rainfall rates and generate the bulk of the channel inflow.

In view of the short forecast lead times in flash-flood prediction and of the characteristics of the flash-flood phenomenon (indicated above), the Sacramento Soil-Moisture Accounting model used in the integrated hydrometeorological model in the previous sections was replaced by a simple Antecedent Precipitation Index (API) procedure.

Given parameters m and D, and denoting by P the precipitation volume over time Δt, the API procedure gives the channel inflow R over time Δt as:

$$R = (P^m + D^m)^{1/m} - D$$

Use of an API procedure drastically reduces the number of states in the integrated hydrometeorological model, since it eliminates the six soil states of the Sacramento Soil-Moisture Accounting scheme. This translates into significant computational savings both in execution time and in computer storage locations. The flash-flood system under study is, therefore, suitable for implementation in mini- and micro-computers at the local level (e.g., the Weather Service Forecast Offices). We will refer to the flash-flood system as the Integrated Hydrometeorological Forecast System (IHFS) in the following.

The IHFS system is an event-oriented system designed to operate at the local level. It contains both meteorological and hydrological models together with updating procedures, and its purpose is to forecast flash-flood flows. The system uses surface temperature, surface pressure, and surface dew-point temperature as input variables and it forecasts local precipitation and discharge for a few hours (up to 6 hrs) into the future. After the collection of the observations of precipitation and discharge, an updating mechanism compares in real time these observations with the forecasts issued and makes corrections to the model states. Thus, the next forecasts are made based on improved initial conditions.

The preliminary configuration for the IHFS is depicted in Figure 8. The primary links of IHFS with existing sources of information are displayed in the figure. The meteorological input that feeds the precipitation component is obtained from the Automation of Field Operations and Services (AFOS) system.

The necessary API parameters will also be obtained from AFOS. The relevant message is sent by the River Forecast Center (RFC) in charge of the flash-flood area under consideration. The RFC will help identify the flash-flood prone areas for the system operation. After each update-predict cycle, the IHFS state variables are stored in carry-over storage on-line, so that

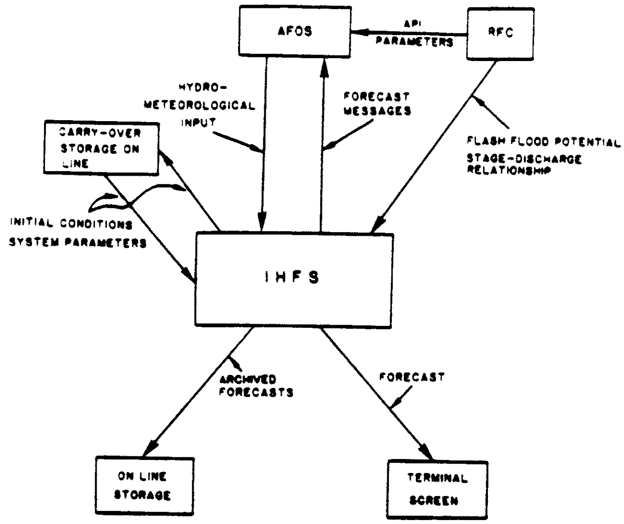

Figure 8. Preliminary configuration for IHFS.

when new data become available, a new update-predict cycle can commence.

The IHFS will produce both precipitation and flow stage forecasts and it will give the one standard deviation upper and lower bound for each forecast. Given flood-stage threshold values, the system will produce the probability that flooding will occur.

10. PRELIMINARY TESTS OF THE IHFS

In cooperation with the Weather Service Forecast Office staff in Washington, D.C., a 625 mi^2 headwater basin was selected in Virginia for the preliminary testing of IHFS in an experiment that simulated real-time operations. The watershed is located in Rappahannock County and has its outlet at Remington. Six-hourly precipitation and stage data for the period 7:00 p.m. February 13, 1984, to 7:00 a.m. February 16, 1984, were used. Daily values of the parameters of the API procedure were obtained from the Middle Atlantic RFC located at Harrisburg. The surface meteorological data that drive the precipitation model were obtained from the Washington Dulles Airport meteorological station in the D.C. metropolitan area. The station lies approximately 30 miles to the northeast of the watershed. The flood stage at Remington is 15 ft.

During the tests, real-time conditions were simulated. Forecasts were made based on currently available information only. A simple persistence scheme was used to forecast the surface temperature, pressure and dew-point temperature to serve as input to the precipitation model. The model parameters were not fine tuned for the basin under study.

Figure 9 shows the stage observations (black circles) and the six-hourly (solid line) and twelve-hourly (dashed line) IHFS forecasts for Remington, Virginia. Even for a twelve-hour lead

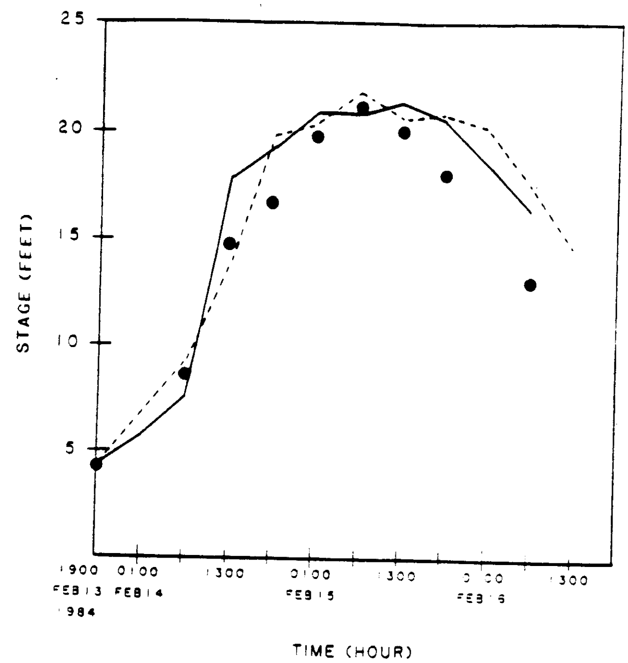

Figure 9. Six-hour (solid line) and twelve-hour (dashed line) stage forecasts of IHFS using forecast input based on persistence. The observations are in black circles. Forecasts at Remington, Va.

time the IHFS forecasts are satisfactory. In particular, the timing and magnitude of the peak are correctly forecasted.

The IHFS produces estimates for the mean and the standard deviation. Based on those estimates, and given the flood stage at the outlet of the basin, IHFS produces forecasts of the probability of flood occurrence. The ability of IHFS to predict the occurrence of flooding at Remington can be assessed from Figure 10. There, probabilistic forecasts of the occurrence of flooding are shown by black circles for a six-hour forecast lead time, and by open squares for a twelve-hour forecast lead time. Values in the (0.7 - 0.85) range were forecasted for both forecast lead times for the period when excessive flooding occurs. This indicates that IHFS produces reliable probabilistic forecasts of flooding occurrence.

11. SUMMARY AND CONCLUSIONS

A novel approach to the real-time forecasting of floods has been presented. Direct coupling of physically based precipitation, soil, and routing models through mass continuity and through a state estimator resulted in an efficient system for flood prediction.

Testing of the system in Bird Creek, Oklahoma, produced very encouraging results for a six-hour lead time, with hydrograph peaks predicted on time and with the correct magnitude, for most of the flood cases examined. The ability of the model to forecast accurately for longer forecast lead times compared favorably with the skill of purely statistical models based on persistence and extrapolation.

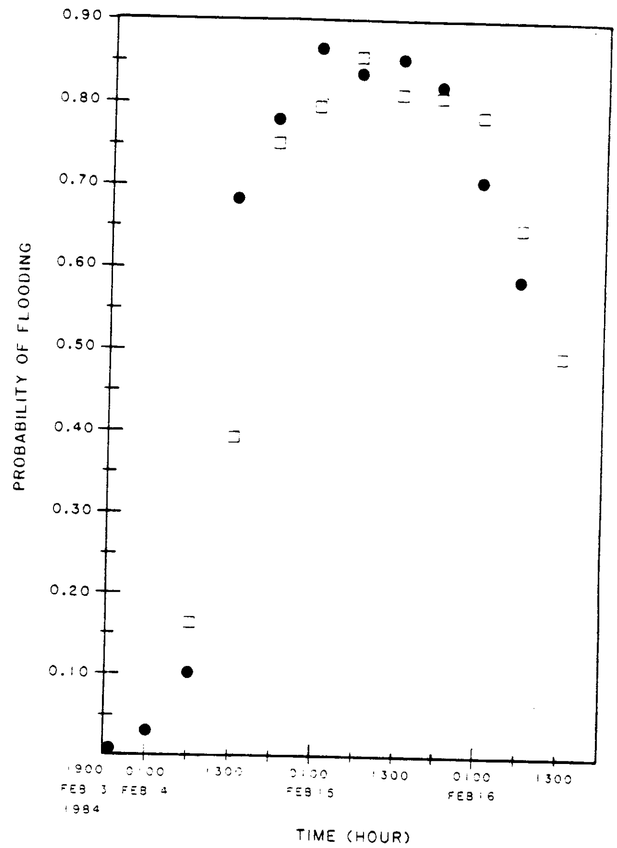

Figure 10. Six-hour (black circles) and twelve-hour (open squares) forecast probabilities that the stage will exceed the 15 ft. flood stage at Remington. The shaded region signifies times when flooding actually occurred.

Simplification of the soil component of the integrated model led to the design of a computationally efficient system, IHFS, suitable for use in flash-flood situations. Preliminary results in tests simulating real-time operations pointed to the ability of the system to predict excessive flooding periods with a good degree of reliability.

Extensive tests of IHFS in real time are planned for the future at various locations in the U.S. to establish the utility of the system in flash-flood prediction.

12. ACKNOWLEDGEMENTS

Parts of this paper were presented at the 1985 Fall Meeting of the American Geophysical Union (San Francisco, December 1985) under the title "Dynamically Coupled Precipitation and Drainage Basin Models."

13. REFERENCES

Armstrong, B.L. (1978), "Derivation of Initial Soil Moisture Accounting Parameters from Soil Properties for the National Weather Service River Forecast System," NOAA Technical Memorandum NWS HYDRO-37, U.S. Department of Commerce, Silver Spring, Maryland.

Day, G.N. and R.K. Farnsworth (1982), "Mean Areal Potential Evaporation," National Weather Service River Forecast System (NWSRFS) User's Manual, Part III, Chapter 9. Available from the Hydrologic Research Laboratory, NWS, NOAA, Silver Spring, Maryland.

Gelb, A., ed., (1974), Applied Optimal Estimation, The M.I.T. Press, Cambridge, Massachusetts.

Georgakakos, K.P. (1984), "Model-Error Adaptive Parameter Determination of a Conceptual Rainfall Prediction Model," Proceedings of the 16th Southeastern Symposium on System Theory, March 25-17, 1984, Mississippi State, Mississippi, pp. 111-115.

Georgakakos, K.P. (1982), "Structure and Parameter Determination of a Hydrologically Useful Rainfall Prediction Model," presented at the 1982 Fall Meeting of the American Geophysical Union, San Francisco, California. Available from the Hydrologic Research Laboratory, NWS, NOAA, Silver Spring, Maryland.

Georgakakos, K.P. and R.L. Bras (1984a), "A Hydrologically Useful Station Precipitation Model, 1, Formulation," Water Resources Research, 20(11), pp. 1585-1596.

Georgakakos, K.P. and R.L. Bras (1984b), "A Hydrologically Useful Station Precipitation Model, 2, Case Studies," Water Resources Research, 20(11), pp. 1597-1610.

Georgakakos, K.P. and R.L. Bras (1982a), "A Precipitation Model and Its Use in Real-Time River Flow Forecasting," Ralph M. Parsons Laboratory Hydrology and Water Resource Systems Report No. 286, MIT Dept. of Civil Engineering, Cambridge, Massachusetts.

Georgakakos, K.P. and R.L. Bras (1982b), "Real-Time Statistically Linearized Adaptive Flood Routing," Water Resources Research, 18(3), pp. 513-524.

Georgakakos, K.P. and R.L. Bras (1980), "A Statistical Linearization Approach to Real-Time Nonlinear Flood Routing," Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics Report No. 235, MIT Dept. of Civil Engineering, Cambridge, Massachusetts.

Georgakakos, K.P. and R.L. Bras (1979), "On-Line River Discharge Forecasting Using Filtering and Estimation Theory," Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics Progress Report, Sept. 13, 1978 - Feb. 13, 1979, Contract No. 7-35112, MIT Department of Civil Engineering, Cambridge, Massachusetts.

Georgakakos, K.P. and M.D. Hudlow (1984), "Quantitative Precipitation Forecast Techniques for Use in Hydrologic Forecasting,"Bulletin American Meteorological Society, Vol. 65, No. 11, November 1984, pp. 1186-1200.

Kitanidis, P.K. and R.L. Bras (1980a), "Real-Time Forecasting with a Conceptual Hydrologic Model, 1, Analysis of Uncertainty," Water Resources Research, 16(6), pp. 1025-1033.

Kitanidis, P.K. and R.L. Bras (1980b), "Real-Time Forecasting with a Conceptual Hydrologic Model, 2, Applications and Results," Water Resources Research, 16(6), pp. 1034-1044.

Larson, L.W. (1975), "Precipitation Model," National Weather Service River Forecast System (NWSRFS) User's Manual, Part II, Chapter 6. Available from Hydrologic Research Laboratory, NWS, NOAA, Silver Spring, Maryland.

Larson, L.W. and S. VanDemark (1979), "Mean Areal Precipitation Program (MAP), 1979," National Weather Service River Forecast System (NWSRFS) User's Manual, Part III, Chapter 7. Available from Hydrologic Research Laboratory, NWS, NOAA, Silver Spring, Maryland.

NOAA-NWS (1972), "National Weather Service River Forecast System Forecast Procedures," NOAA Technical Memorandum NWS HYDRO-14, U.S. Department of Commerce, Silver Spring, Maryland.

NWS Office of Hydrology (1982), "Program Development Plan for Improving Hydrologic Services," Office of Hydrology, NWS, NOAA, Silver Spring, Maryland.

Peck, E.L. (1976), "Catchment Modeling and Initial Parameter Estimation for the National Weather Service River Forecast System," NOAA Technical Memorandum NWS HYDRO-31, U. S. Department of Commerce, Silver Spring, Maryland.

Restrepo-Posada, P.J. and R.L. Bras (1982), "Automatic Parameter Estimation of a Large Conceptual Rainfall-Runoff Model: A Maximum Likelihood Approach," Ralph M. Parsons Laboratory Hydrology and Water Resource Systems Report No. 267, MIT Dept. of Civil Engineering, Cambridge, Massachusetts.