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# Quantitative Precipitation Forecast Techniques for Use in Hydrologic Forecasting

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## Abstract

Quantitative hydrologic forecasting usually requires knowledge of the spatial and temporal distribution of precipitation. First, it is important to accurately measure the precipitation falling over a particular watershed of interest. Second, especially for small watersheds and/or for longer forecast lead times, forecasts of precipitation are critical to the achievement of the greatest possible hydrologic forecast accuracy and longest possible lead time. This paper describes the current hydrologic forecasting program of the U.S. National Weather Service (NWS) and highlights the relevance of Quantitative Precipitation Forecasting (QPF) products to real-time hydrologic forecasting. Specific requirements for QPF products in support of hydrologic forecasting applications are defined and current operational QPF procedures are reviewed to determine to what extent they meet these requirements. It is concluded that no known QPF procedures capable of fulfilling all desired requirements are currently available operationally, although much valuable QPF information is available to meet parts of these requirements. Some recent advances in mesoscale QPF research are examined and these techniques are treated in two categories: those uncoupled dynamically from and those dynamically coupled to hydrologic forecasting procedures. Finally, a summary of possible future directions toward achieving improved use of QPF information in hydrologic forecasting applications is presented.

## 1. Introduction

One definition of hydrologic forecasting is: "that branch of science and engineering which deals with the assimilation and analysis of hydrometeorological data and information, and the input of such information into hydrologic modeling and prediction procedures to arrive at forecasts of the present and future states of the various components of the hydrologic cycle, especially the streamflow conditions in streams and rivers." Thus, hydrologic forecasting involves the application of hydrological and meteorological principles in an engineering and, most often, a systems framework.

Of the various hydrometeorological variables that are important as inputs to hydrological forecasting techniques, precipitation is typically the most significant. Yet, accurate precipitation estimates are often the most elusive of all estimates because of the great variability of precipitation in space and time. This fact accounts for the formidable problems associated with achieving accurate mean areal estimates of precipitation that has already occurred. The accurate quantitative prediction of future precipitation represents one of the most challenging problems facing the hydrometeorologist.

Additional improvements in hydrologic forecast lead time (the difference in time between the time at which a forecasted hydrologic phenomenon occurs and the time at which 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) give generalized guidance information that 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. Fig. 1, constructed from data presented in a recent Program Development Plan for Improving Hydrologic Services (National Weather Service, Office of Hydrology, 1982), illustrates that 50% of the forecast points for communities across the U.S. have potential forecast lead times (maximum possible times with uniform distribution of rainfall over the basin) of less than 10 hours and 25% have less than 4 hours. Clearly, accurate QPF information for even a few hours into the future would result in valuable increases in effective lead time.

This paper examines various approaches to rainfall prediction, specifically those quantitative techniques that potentially can provide useful input information for hydrologic forecasting. Rainfall prediction methods can be grouped into various categories. One general category of methods deals with the use of numerical meteorological models which are physically/dynamically based. These models range in scale from the very large ones such as the Limited-Area Fine Mesh (LFM) model [used for Numerical Weather Prediction (NWP) by the NMC], which covers the United States and surrounding areas with a grid mesh size of approximately 150 km, to the very small-scale ones consisting of one-dimensional microphysical cloud-physics models. Another category of rainfall prediction methods comprises those that use statistical regression techniques to correlate rainfall on a station or areal basis with other hydrometeorological, and possibly climatological and orographical, variables and/or out-

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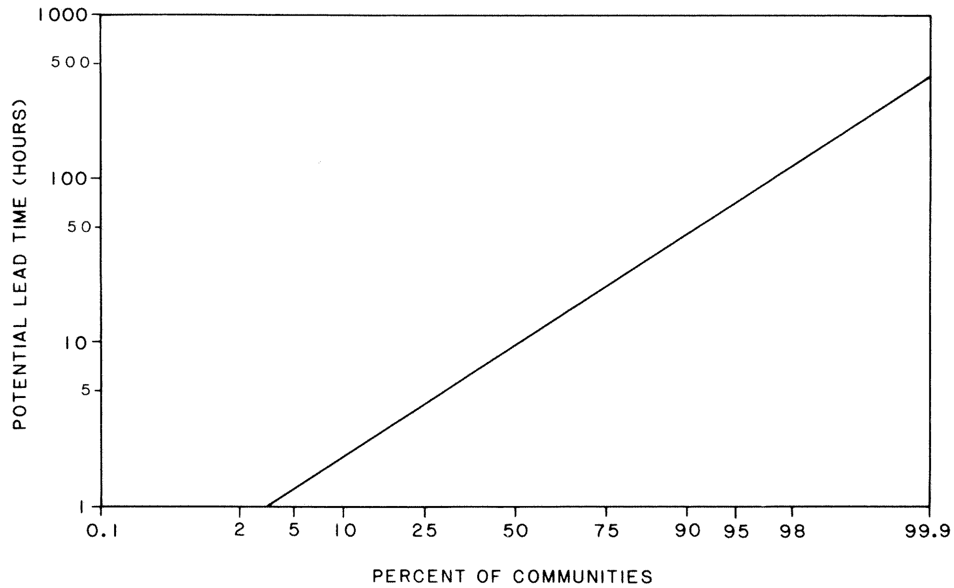


FIG. 1. Distribution of potential forecast lead times for 20 000 communities across the United States.

puts from the large-scale NWP models. An example of the latter approach is represented by the Model Output Statistics (MOS) method. A final category includes those methods which employ "nowcasting" procedures. Simply stated, nowcasting refers to any of a variety of techniques which use recent past and/or current conditions as a basis for establishing trends for use in providing very short period forecasts.

QPFs are not all derived strictly from computer models and methods. Meteorologists at NMC and at the local Weather Service Forecast Offices (WSFOs) apply their hydrometeorological skills to diagnose weather features from current hydrometeorological observations, climatology, knowledge of local influences such as orography, and current and past weather patterns, as well as outputs from the models and numerical computer techniques. The forecaster then uses this diagnosis to prepare the best QPF products feasible, given the current state-of-the-art, using the skill of the model(s) combined with his/her own interpretive skills. This type of human-machine approach to weather forecasting has been applied for many years and probably will continue with enhancements for many years into the future.

Current operational rainfall prediction approaches are examined in this paper from the viewpoint of potential use in support of various hydrologic forecasting applications. Also, a relatively new approach, which is designed specifically for use in watershed modeling, is presented. This approach is a coupled one, which links a precipitation model with streamflow models.

Finally, this paper will describe some future directions in the area of more effective use of QPF information in hydrologic forecasting. Specifically, avenues will be suggested for more effectively integrating or numerically coupling the hydrological and meteorological computer resources, data bases, and model computations. Such linking of systems and procedures is important if we hope to achieve a comprehensive hydrometeorological solution to the hydrologic prediction problem, especially for small-scale applications, e.g., the identification and prediction of flash floods. Future plans for linking systems should consider the new technology that is available for providing and using rainfall observations from automated *in situ* sensors (rain gages) and remote sensors (satellites and radars).

## 2. Outline of the hydrologic forecasting program of the U.S. National Weather Service

Current hydrological forecasting activities of the NWS can be thought of as generally falling into two basic levels (scales) of forecasting: 1) the local level consisting of those procedures applied by the Weather Service Offices (WSOs) and WSFOs, with support from the River Forecast Centers (RFCs) in conjunction with the flash-flood watch/warning program, and 2) regional (large basin) forecasting performed by the RFCs (National Oceanic & Atmospheric Administration, National Weather Service, 1981a). Presently, these two levels of forecasting are relatively loosely coupled. However, plans call for a closer interfacing of the activities to form a more tightly-coupled hydrologic forecasting system with greater amounts of information being shared between the two levels of forecasting.

The current procedures employed for identification of potential, or actual, flash flood conditions are largely based on determination of whether rainfall amounts exceed, or are expected to exceed, specified flash-flood guidance criteria provided by the RFCs to the WSFOs or WSOs. Reports of flooding also prove to be a catalyst in many situations. The flash-flood guidance values typically apply to areas the size of counties or to zones consisting of several counties. In addition, approximately 700 Local Flood Warning Systems

(LFWSs) are located in individual communities where flash-flooding has historically caused major problems or where the potential for flooding is high. The LFWSs, which are implemented by local communities with assistance from the RFCs, generally are located in specific small drainage basins. The LFWSs range from simple rainfall-stage "look up" tables to fully-automated stream-gage and/or rain-gage networks that feed information to micro- or mini-computers where a rainfall-runoff model is used to predict stream stages [e.g., the Automated Local Evaluation in Real Time (ALERT) System described by the Hydrologic Services Division, National Weather Service Western Region (1981)].

The second level of the hydrologic forecasting system is the larger-scale system running at the RFCs. The forecast system's architecture and its component procedures vary somewhat among the 13 RFCs, although several currently use, and most others plan to use in the future, the National Weather Service River Forecast System (NWSRFS). NWSRFS (Hudlow and Brazil, 1982) provides a standard software framework that is flexible enough to allow the incorporation of unique operational procedures that may be required by a particular RFC's mission or by the presence of special hydrometeorological conditions. NWSRFS consists of data entry, preprocessing, and forecast components, along with numerous utilities and supporting programs. It contains continuous conceptual hydrologic models that, for example, keep track of soil moisture conditions (e.g., Peck, 1976). This information is not only essential for forecasting runoff contributing to outflow from a larger river system, but also can be used for establishing initial conditions for local flash-flood forecasting procedures. The upper zone moisture contents provided by the soil moisture accounting model may also prove very useful for establishing boundary conditions for mesometeorological forecasting models.

The spatial and temporal scales of the soil moisture accounting model are the spatial extent and the response time of the drainage basins. NWSRFS is designed to handle forecast lead times down to one hour and up to several days. Typically, the system is run with a six-hour computational forecast step. The spatial extent of the drainage basins varies several orders of magnitude. As an example, 28 basins within the forecast area of the Tulsa RFC cover a total area of 36 500 square kilometers with an average of about 1300 $km^2$ per drainage basin. The vertical extent of the upper zone varies with soil composition and season of the year. A typical value would be of the order of 30 cm.

QPF information is important to both levels/scales of forecasting as described above. It is especially important for the smaller-scale areas where forecast lead time is minimal. Even general guidance information about future expected precipitation can be extremely useful in planning RFC operations and in identifying potential problem areas where flood or flash-flood conditions may arise. However, QPF products could be much more useful if their quantitative accuracy and site specificity could be improved. Knowledge of the uncertainty associated with each precipitation forecast also is needed for determination of the weight that should be placed on the information. The site specificity desired is that corresponding to individual watersheds (or counties, in the case of the current flash-flood watch/warning program). A primary objective of this paper is to explore current and projected procedures in order to suggest how QPF information might better be tailored to the scales required for hydrologic forecasting applications.

## 3. Specific requirements for quantitative precipitation forecasting techniques in support of operational hydrologic forecasting

Currently available techniques for forecasting precipitation rates, which might be used as input to hydrological forecasting techniques, are reviewed in Sections 4 and 5 of this paper. An essential first step in such a review is the examination of the requirements imposed by the users of the QPFs and by the operational forecasting practices.

Murphy and Brown (1981) define the most important characteristics of user requirements to be: the forecast variable or event; the spatial domain; the temporal domain; the lead time; the form of information and the mode of expression of the uncertainty inherent in the information; and the communication or dissemination media. When QPFs are used in conjunction with hydrologic forecasting procedures, the spatial and temporal domains of interest usually are those associated with a drainage basin. The basin area can vary from a few square kilometers to several thousand square kilometers, with associated response times ranging from less than an hour to several days. The operationally used lead times for river flow forecasting typically range from six hours to five days, except in the case of rapidly evolving local flash floods, for which the lead times of interest are less than six hours. Given the operational nature of the river flow forecasts, it is desirable to have operational QPFs for the aforementioned spatial and temporal scales. It is also important to have a measure of the typical errors in each QPF, since there are improved hydrologic forecasting techniques (e.g., Kitanidis and Bras, 1980a, 1980b) that utilize this error measure. With respect to the communication or dessimation media, it is desirable to have a direct link between the precipitation forecasting procedure and the hydrologic forecasting procedure for reasons of time and cost efficiency.

Perhaps the most restrictive requirement of any precipitation rate predictor to be used in an operational environment is that it should perform well with only operationally predicted or observed variables as inputs. Furthermore, it is desirable that the prediction technique be flexible enough to incorporate, as input variables, any variables that will become operationally available in the future because of the advancement of technology (e.g., radar or satellite observations of the atmospheric variables).

There is a wide range of errors and reporting delays associated with the different observing systems. In general, the ground-based observing stations provide the most accurate data, although objective analysis procedures to merge observations from *in situ* and remote sensors hold great promise for the future (e.g., Krajewski and Crawford, 1982).

The spatially lumped nature of the current operational hydrologic forecasting techniques offers the advantage of the requirement for forecasts of *areally averaged* precipitation rates (vs forecasts of the highly variable *point* precipitation rates).

In the case of flash–flood forecasts, the precipitation forecasting technique should be computationally efficient and suitable for implementation on mini– or micro–computers. It is the local nature of the flash floods and the usually very short forecast lead time associated with them that necessitate the use of the relatively modest local computational resources.

## 4. Summary of current operational QPF procedures in the U.S.

The current operational forecasts of precipitation quantity and time of occurrence over a certain area are based on: 1) the use of large scale models that simulate atmospheric dynamics, with spatial resolutions on the order of 150 km grid size; 2) the use of statistical regression models that correlate the predictions of the large–scale atmospheric models with observations on a smaller scale; and 3) the experience of forecasters with weather patterns and conditions. The following discussion concentrates on the QPF procedures currently used operationally in the United States. For a summary of dynamical and statistical–dynamical operational QPF procedures in use in some other countries, the interested reader is referred to a recent report of the World Meteorological Organization (Bellocq, 1980).

*Operational Forecast Procedures.* The LFM model is the principal contributor to the U.S. National Weather Service's numerical guidance over the United States. The model is documented in Gerrity (1977) and more recently in Newell and Deaven (1981). It is based on a hydrodynamic system of partial differential equations (primitive equations). The primitive equations are usually sufficient to describe the predominant aspects of the meteorological behavior of the atmosphere for phenomena with horizontal length scales greater than 1000 km and time periods of a few days (Gerrity, 1977). The grid size of the current version of the LFM model (LFM–II) is 127 km at 60° N latitude, and the North American continent comprises the land model domain.

The LFM model provides various forecast outputs including forecasts of precipitation, temperature, pressure, and humidity for various levels in the atmosphere and for each grid point. Forecasts are available every 12 hours, and forecast lead times extend up to 48 hours with both 6-hour and 12-hour resolutions. The LFM model accounts for: 1) a large-scale precipitation process and 2) a subgrid convective precipitation process. The determination of the large–scale precipitation rate is based on whether the value of the relative humidity computed at each grid point is larger than an empirically reduced saturation value of the relative humidity, determined by the solution of the hydrodynamic equations. The convective precipitation is related solely to the prediction of the existence of a conditionally unstable air mass with vapor content exceeding an empirical threshold value. Large-scale precipitation is computed internally in the LFM model every six minutes, while convective precipitation is computed every hour.

Water vapor transport is assumed to be determined by the velocity field of *dry* gas. The saturation value of specific humidity is determined from the temperature of the dry gas. Thus, the hydrodynamic equations are treated as being applicable to pure dry air only. The influence of atmospheric water is restricted to the production of diabatic heating effects that result from water phase changes or indirect influences upon radiative heat transport.

Initialization of the LFM runs consists of using interpolation methodologies to assign observations from various sensors, taken at irregular spacings, to the grid points of a regular grid.

Apart from the LFM model, other models that form the basis of the NMC's QPF guidance forecasts are: the spectral model, the current version of which is referred to as SMG3C (Sela, 1980); and the movable fine mesh (MFM).

Instead of using the finite–difference representation of the forecast domain, the SMG3C model employs spectral functions (sine and cosine series) to represent the system variables. The major physical effects modeled are: orography, surface friction, subscale horizontal dissipation parameterized by diffusion, both large–scale and convective precipitation, and evaporation and sensible heat effects from the ocean. There is a global and a hemispheric version. Comparative studies have found this model to be comparable in accuracy to primitive equations grid–point models with 191–km grid size. Forecast lead times for precipitation products up to 48 hours are routinely available. Guidance beyond 48 hours also is available.

The MFM model is used for cases of severe storm or hurricane development (National Weather Service, Meteorological Services Division, 1979). It has the characteristic that its computational grid moves with the storm during its development. It is run only when an operational requirement exists, mainly for hurricane forecasting or when a flood or precipitation threat is suspected. Apart from small changes in the primitive equations and the fact that the grid is movable, the MFM model is the same as the LFM model. The MFM computational grid is 60 to 100 km on a side and the time resolution of the forecasts is 6 hours, with a maximum lead time of 48 hours.

With respect to the dynamical models presented, it should be noted that accuracy is restricted by the available computing power, since this constrains the computational grid size. Greater resolution in space is attained at the expense of reduction of the maximum reliable lead time. In this case, one has to limit the total forecast area to a magnitude significantly less than a hemisphere. As a result, the forecast becomes contaminated in time from the propagation of boundary condition errors. In addition, as the grid size becomes smaller, the necessary input data to run the models have to be of a finer scale. Lack of quality observations at fine scales constrains the computational grid size.

The localization of the large–scale numerical model results is currently attempted by the use of regression models. The Model Output Statistics (MOS) method documented in Glahn and Lowry (1972) and in Lowry and Glahn (1976) and the regression techniques used in the very short–term forecasting of severe local storms and thunderstorms (National Weather Service, Meteorological Services Division, 1981), are two examples of such models used operationally.

The MOS method provides forecasts of variables that are not computed explicitly in a numerical weather prediction model (such as localized rainfall rates on subgrid scales) or of

TABLE 1. Characteristics of the current (1983) operational, numerical QPF procedures used to issue guidance from the National Meteorological Center of the National Weather Service.

| | LFM-II | MFM | SMG3C | MOS | Probabilities for heavy precipitation from thunderstorms & severe local storms |
|---|---|---|---|---|---|
| Total forecast area: | North America | Area of the conterminous United States magnitude | Both global and hemispheric | Conterminous United States | Most of the United States east of the Rocky Mountains |
| Characteristic spatial scale: | 127 km | 60 km | Comparable to grid range | Local, up to point models of 191 km grid-size | 75–85 km several states |
| Initial data times: | 0000 and 1200 GMT | When operational requirement exists | 0000 and 1200 GMT | 0000 and 1200 GMT | 1200 1500 1800 2100 0000 GMT |
| Time resolution of forecasts: | 6 and 12 hr | 6 hr | 12 hr | 6 and 12 hr | 4 hr |
| Maximum forecast lead times: | 48 hr | 48 hr | 48 hr (Guidance beyond 48 hr is available.) | 36 hr/6 hr resolution, 48 hr/12 hr resolution | 6 hr |
| References: | Gerrity (1977), Newell and Deaven (1981) | National Weather Service, Meteorological Services Div. (1979) | Sela (1980) | National Weather Service, Meteorological Services Div. (1980) | National Weather Service, Meteorological Services Div. (1981) |

variables forecasted by the large-scale dynamical models that are subject to systematic errors. The method involves the development of a multiple linear regression equation whereby the predictand (variable to be forecasted) is a linear function of a number of predictors. The coefficients of the equation are computed, based on the assumption that the residual forecast error is uncorrelated to the predictors.

Because of the existence of a finite sample size for calibration, screening techniques have been developed to limit the number of predictors to those that contribute significantly to the reduction of the variance of the predictand. The predictors are selected from numerical indices such as indicators of the potential moist hydrostatic instability of the atmosphere computed from most recent observations, and from the output of the large-scale dynamical models.

A concept similar to MOS is used in the forecasting of the probability of thunderstorms and severe local storms and associated precipitation probabilities. The forecast domain here is comprised of the conterminous United States east of the Rocky Mountains. Based on a combination of the classical statistical and MOS approaches, probabilities of occurrence of the severe phenomena within a period two to six hours after the forecast preparation time are forecasted for regions of about 100 km on a side. Predictors are selected from observed surface atmospheric variables, manually digitized radar data (Moore and Smith, 1979), local climatic frequencies of severe weather, and basic variables as predicted by the LFM model.

An important aspect of the regression-based methodologies is their capability to supply probabilistic forecasts. These forecasts are particularly useful to those who wish to maximize their expected gain or minimize their expected loss (National Research Council, 1977).

Table 1 summarizes the operational characteristics of the primary numerical models used at the NMC of the NWS for the production of QPF forecasts. Characteristics included in Table 1 are: total forecast area, characteristic spatial scale, initial data times, time resolution of forecasts, and maximum forecast lead times. For easy reference, pertinent reports on the models are included in the table.

Apart from the numerical models, current QPF products are prepared by forecasters at the NMC, based on experience and observed data and on the guidance of the numerical models. The input of the forecasters to the whole forecasting effort of the NWS is described characteristically in the Forecast Procedures section of the NWS Forecasting Handbook No. 1—Facsimile Products, Supplement No. 2 (National Oceanic and Atmospheric Administration, National Weather Service, 1982). A quotation from this handbook which summarizes the role of the forecaster at NMC (WSFO forecasters often carry out a similar plan of attack) follows:

> ". . . The forecast effort begins with a thorough review of the past (1–2 days) with special emphasis on the 0–6 hour period when considering snowfall and excessive precipitation. This is followed by a detailed analysis and interpretation of current available data (conventional, satellite, radar). Analysis of the current state of the atmosphere is essentially a continuous process, including detailed hourly surface analyses in regions of very active weather, with due consideration of satellite imagery and radar data. Upper-air data plots are typically analyzed in considerably more detail than the objective or numerical analyses. New analyses are carefully compared with preceding forecasts to see if the currently verifying forecasts are correct with an eye to correcting or modifying later portions of that forecast. Satellite pictures (stills and animated) are carefully scrutinized and compared to both model initial and predicted fields, in a search for apparent discrepancies.
>
> With analysis and diagnosis essentially complete, the forecaster tackles the future. Short-term subjective projections of circulation based largely on analyses and trends are made, to provide initial fields for the forecast periods. Substantial effort is made in evaluating the various models' output packages, reconciling them with each other, with previous runs and with the initial conditions. At times, significant modifications to model circulation predictions are considered, based on previous typical model errors and on developments during the first few hours of the forecast.
>
> The final product is a blend of the skill of the numerical models, objective MOS guidance, and the forecaster's individual expertise and experience . . ."

Once the QPF guidance products are received from the NMC at the local field offices (WSFOs and WSOs), they are used with other information about the local terrain and hydrometeorological conditions to arrive at the final forecasts, which are released to the public and provided to the RFCs in support of their hydrologic forecasting operations. Maddox (1979) has presented a methodology that aids the meteorological forecasters in reanalyses and enhancements of NMC diagnostic charts and forecast guidance products. Maddox points out that certain characteristics and features seem to be common to most heavy precipitation events that produce flash floods:

1) Heavy rains associated with convective storms.
2) Very high surface dew point temperatures.
3) Large moisture contents through a deep tropospheric layer.
4) Weak to moderate vertical wind shear through the cloud depth.

Some local offices currently use objective techniques or simple regression models, which implicitly or explicitly draw on principles presented by Maddox, to arrive at their final forecasts. For example, Mogil and Groper (1976) discuss attempts to establish criteria for detecting heavy rainfall potential before it occurs by using knowledge of synoptic and mesoscale features with local surface and upper air information.

Belville *et al.* (1978) and Mortimer *et al.* (1980) have developed a limited area QPF procedure for West Texas. They have developed regression equations and diagrams for four climatic regions of West Texas and for six types of 500 mb flow patterns with which precipitation generally is associated in that region. Two of the meteorological predictors giving the highest correlations were the lifted index from the LFM model and the mean relative humidity from the surface to 500 mb. (Relative humidity is also a variable forecasted by the LFM model.)

Muller (1983) has developed a simple orographic modeling procedure, for the North Carolina mountain area, which produces precipitation estimates for an 8 mi × 8 mi grid network. The output is based on a linear regression technique that relates topographic vertical motion to actual precipitation distribution in heavy rain occurrences over the past ten years. The technique can use precipitation guidance information from the NMC and upstream observed rainfall from rain gages. Muller states that the procedure is relatively reliable, provided that a reasonable broad-scale rainfall estimate can be obtained and the forecaster knows which quadrant the wind is blowing from during the heavy rain period.

A further extension of the MOS procedures to multiple stations in and near a specific river basin has been reported by Dallavalle and Bermowitz (1981). They have developed MOS probability of precipitation equations for use by the Bonneville Power Administration in the Columbia River Basin.

Mogil (1982) discusses the status of localized QPF procedures. His report emphasizes that such local procedures as those highlighted above are becoming increasingly more coordinated among the field offices and are beginning to result in improvements in the short-term prediction of rainfall for more site-specific localities. However, as will be described in the next subsection, much work remains, especially in terms of finding improved ways to directly and automatically input QPF information into hydrologic prediction procedures. The typical current scenario for passing this information from the local meteorological forecaster to the hydrological forecaster still relies on too much manual subjectivity and suffers from a lack of coupled feedback.

It might be helpful to consider one specific example where QPF guidance modified by local WSFO forecasters was used operationally for a critical flood situation. In February 1980, a series of disastrous storms caused serious flooding in Central Arizona and Southern California (National Oceanic and Atmospheric Administration, National Weather Service, 1981b). Because of extreme sparsity of rainfall data, the Colorado River Basin RFC was compelled to use QPF information not only for future precipitation estimates but also for observed data over parts of the affected area. After considerable dialogue between the meteorological and hydrological forecasters, and trial-and-error runs using a rainfall-runoff model with various QPF inputs, the forecasters did arrive at QPF products that were certainly superior to no information. However, it became clear during the investigation by a National Oceanic and Atmospheric Administration Disaster Survey Team (National Oceanic and Atmospheric Administration, National Weather Service, 1981b) that some of the results may have been fortuitous and that future similar episodes might lead to grossly inaccurate streamflow predictions unless certain steps were taken to improve procedures. Accordingly, the Disaster Survey Team made the following recommendations: "NWS personnel involved in the derivation and use of QPFs should work together to develop software for implementing computerized procedures whereby certain physical consistency checks can be made before the final QPF values are released. For example, significantly overestimated magnitudes and/or spatially smeared QPF values may be identified because they can result in runoff amounts that would produce physically impossible or unrealistic streamflow estimates."

In summary, at the present limited state-of-the-art in quantitative rainfall prediction, the only QPF approach that can currently be used routinely by the RFCs as direct input to their hydrologic modeling procedures is that of "contingency QPFs." This is simply a set of "what if" forecasts—i.e., streamflow forecasts are made for various assumed amounts of future precipitation (including zero) and the validity of the streamflow forecast is contingent on which rainfall scenario actually develops. At the WSFO and WSO level, where QPFs are used with other information to assess flash-flood potential, there generally does not exist a numerical flash-flood modeling system suitable for interfacing with the locally derived QPF products.

*Forecast Skill.* Although limited progress has been made in the last few years, recent evaluations (Charba and Klein, 1980, and National Research Council, 1980) of operational quantitative precipitation forecasts show relatively poor performance. Several factors contribute to this fact. Some of the most important are summarized in the following paragraphs.

It has been recognized for some time (e.g., Gleeson, 1967) that the atmosphere is unstable in the sense that two slightly different initial states will evolve into states ultimately bearing no resemblance to each other. In other words, small errors in the initial conditions of the forecast procedures will grow substantially in time. Therefore, a major contributor to forecast errors, for the longer forecast lead times, is the [observation and interpolation] error in the specification of initial conditions for the large-scale numerical models. Large-scale atmospheric models fail to adequately consider the mesoscale aspects of precipitation (National Research Council, 1980).

The use of statistical regressions to partially bridge this gap between the mesoscale and the scales resolved by large-scale numerical models involves difficulties such as: 1) the identification of all the relevant meteorological variables that will be used as "explanatory" variables for each location, and 2) the absence of high temporal correlation in the station precipitation records. In addition, no guarantee is provided regarding the invariance of the regression parameters for different storms, because of the absence of explicit physics in the statistical regression models.

The process by which forecasters combine information from different sources prior to issuing operational forecasts varies with each case. However, they often rely heavily on the LFM and MOS forecasts for routine weather situations.

In a report by the Panel on Severe Storms of the National Research Council (National Research Council, 1977), the following were identified as the most important inadequacies of the current forecast system for severe storms:

1) The severe-storm watch message (issued some hours before the storm matures) covers too large an area (about 200 km × 300 km). Often, the area actually affected by severe weather is two or three orders of magnitude smaller than the watch area, leading to a credibility problem for future watch messages.
2) The warning message (issued when a severe-storm event has been detected or is believed imminent), if at all issued, often comes too many hours after the watch message and provides little time for reaction. Further-

more, the likelihood of not detecting the storm and therefore issuing no warning message is believed to be too high.

The same points could be made with regard to the forecast system for flash floods.

In the same report, the suggestion is stressed that a good warning system should result from a coordination of user-specific needs with available technology. This reveals another important difficulty associated with the currently available QPFs, namely, the fact that the operational QPF procedures cannot be directly coupled to the hydrologic forecast procedures, in a conceptually appealing and efficient hydrometeorological system operating as a whole. In a review of the current status of precipitation research in hydrology, Court (1979) comments that the need is evident for a generalized rainfall–runoff system.

## 5. Some recent advances in mesoscale QPF research

*QPF Techniques Uncoupled Dynamically from Hydrologic Forecasting Procedures.* Lately, considerable research conducted both within and apart from the Federal government has been devoted to the development of theoretical models and observing mechanisms for improving understanding and prediction of mesoscale (same order as the drainage basin scale) storm systems. The National Research Council (1981) in a review of the current mesoscale research in progress throughout the Federal government states: ". . . the time is ripe for important scientific and technological advances in this [mesoscale meteorology] subject that would be of significant benefit to the nation." The National Research Council panel members propose a decade-long National Mesoscale Program to focus and enhance research on the mesoscale aspects of extratropical cyclones and severe local storms, resulting in major significant improvements in short-range weather forecasts of precipitation. A plan for this program, the STORM Program (STormscale Operational and Research Meteorology), has been formulated (University Corporation for Atmospheric Research, 1982). The National Research Council panel members point out that recent technological developments should provide opportunities to improve local weather forecasts in the time-frame from less than one hour up to 12 hours. Among those technological developments that appear promising, they list: higher resolution satellite imagery, Doppler radar, acoustical probes, other remote sensing devices, improved methods of communicating and analyzing observations, and emerging techniques for the rapid dissemination of forecasts and warnings to special users and the general public. The National Research Council review also recognizes that the smaller spatial scales and more rapid development and evolution of mesoscale weather systems require substantially finer spatial resolutions and more frequent observations than are routinely available from current networks.

One of the biggest problems in dynamical mesoscale modeling is how to simulate the feedback between moist convection and large-scale processes with the very broad range of interacting eddy scales (Hobbs and Reed, 1979). Dynamical numerical models of the mesoscale require grid sizes of the order of 40 km or less. Defining initial conditions for a model of 40 km grid size is a problem in itself, given today's observing systems. The sparsity of data in mountainous regions, and the even greater variability of the hydrometeorological variables there, make initialization of detailed numerical mesoscale models even more difficult. However, in cases where data exist and computer time is not a limitation, these models present the most reliable option.

A three-dimensional mesoscale model, with parameterized cloud–microphysics, and with explicit modeling of the terrain boundary layer, has been developed by Nickerson and Richard (1981). It has 15 vertical computational levels with horizontal grid length on the order of 10 km and model domain covering an area of $230 \times 230$ square km. The computational time step is 15 seconds. The model QPF results are, in general, in agreement with corresponding observations, with respect to area and magnitude. The authors attribute the errors to the poor spatial resolution of the initial conditions. As with all models of this type, the disadvantages are the long computational time and the large amount of good quality data required for initialization. Because of the current deficiency in real-time atmospheric observations, models of this type are not presently operationally useful for real-time forecasting applications. However, a series of mesoscale model runs, to which forecasters may refer for guidance, can be archived for typical synoptic situations for a particular drainage basin. This type of approach can be particularly useful for terrain-induced mesoscale systems such as orographic precipitation processes (Pielke, 1981).

For forecast lead times up to one or two hours, there is an observation-intensive approach to local weather forecasting commonly known as "nowcasting." This approach relies heavily on the timely use of current data in which remote sensing observations (i.e., weather radar data and satellite cloud imagery) play a dominant role. Because of the very short forecast lead times, the resulting forecasts have to be distributed to the users very quickly. Thus, depending upon the magnitude and type of event, a nowcasting system may rely heavily on improved communication systems, both in volume and in rate of transmission.

Weather radar data currently comprise the major observation group in very short-range forecasting because of the ability of individual radars to detect and track severe weather and precipitation conditions that have life cycles of less than six hours. Satellite data provide the bridge from the larger scales and forecast periods of several hours to the convective storm scale and warning times of a few minutes. Thus, the combination of radar and satellite data appears most promising for increasing our effectiveness in mesoscale precipitation nowcasting (Browning, 1982). Several countries, including the United States, are becoming increasingly involved in development of modern nowcasting systems. Characteristic examples of nowcasting procedures are those in use in Japan and Canada. A short description of those two systems follows. For more details, the interested reader is referred to the articles by Tatehira, Hitsuma, and Makino for the Japanese procedures, and by Austin and Bellon for the Canadian procedures, in the book by Browning (1982).

The system used in Japan has been in operation since 1979 and uses weather radar data with 2 km resolution, precipitation observing stations of 17 to 21 km spacing, and a Geostationary Meteorological Satellite System with 2 km resolution in the visible channel and 7 km resolution in the infrared channel. The time delay between initial observation time and dissemination, for very short range forecasting, is about 40 min. The short-term projection is accomplished by means of simple extrapolation techniques.

The Canadian system, based on digitized radar map extrapolation, was developed at McGill University. It is referred to as the SHort-term Automatic Radar Prediction (SHARP) technique. It is applicable to a single radar system and is suitable for those parts of the world where the weather patterns display a motion in one predominant direction. The technique relies on the calculation of the values of the cross-correlation coefficient for all possible displacements until the maximum value has been identified. Then, the translation is applied in the direction of maximum correlation and is assumed common to all the radar map points. Studies show reasonable efficiency in hourly forecasts (spatially averaged error of the order of 25%). They prove, however, that the technique does poorly beyond three to four hours. Extensions of this technique to cover a larger domain than that covered by the current radar network through the use of satellite (SMS/GOES-E) images, are in progress. The biggest problem appears to be the blending of the satellite display products with the radar display products.

One can include time-series models similar to the MOS approach within the nowcasting procedures group (e.g., Charba, 1983). Thus, for very short forecast lead times, regression models using observations of precipitation, temperature, pressure, wind, and other atmospheric variables can be very effective tools in the real-time forecasting of precipitation, given their low requirements for computer time. In particular, they can provide QPF input to hydrologic models for very rapidly evolving flash floods. However, for successful application of the time series models, one has to effectively solve the problem of the calibration of the regression parameters.

A statistical approach was followed by Johnson and Bras (1980) in the development of a method of very short-term forecasting of precipitation (forecast lead times ranging from five minutes to one hour). Their model is calibrated solely from telemetered rain-gage data and allows for spatial and temporal variation of the precipitation-field mean and standard deviation. Their basic assumption is that the precipitation rate at each point is the sum of a time- and space-dependent mean and a lag-1 Markovian residual with zero mean. They also assume a time- and space-dependent covariance function. The model is presented in state-space form and was tested with a Kalman filter in real time applications.

The results of the Johnson and Bras statistical approach indicate skill in capturing the fine structure of the observed rainfall for forecast lead times ranging from five to ten minutes. Poor performance was reported for one-hour forecast lead times for station precipitation. The authors conclude that, for a rain gage network of reasonable size, the model is computationally feasible and, at the same time, it explains part of the variance in the observed rainfall records. Because the model depends solely on rain-gage data for calibration, it is obvious that real-time operation requires a rather dense gage network for good performance.

*A Dynamically Coupled Approach to Precipitation and Streamflow Real-Time Forecasting.* The previous types of mesoscale models reviewed, although useful for particular situations, all have the common disadvantage of being completely decoupled from the hydrologic models that will use the QPF information. The primary reason for this is the fact that they have not been developed to serve for operational hydrologic forecasting applications. Therefore, they are not necessarily compatible, in mathematical structure and spatial and temporal scales, with hydrologic models used in real-time river flow forecasting. In addition, apart from the regression-type models and the Johnson and Bras (1980) model, they do not give any information as to how the inaccuracies of the observations, initial conditions, and model structure affect the confidence of each of their forecasts. In other words, no measure of the error in the QPFs is computed in real time. Finally, because of the lack of coupling between models describing precipitation processes and those describing catchment processes, there is no feedback from the forecast errors in the discharge to the states of the precipitation models. (Observations of discharge are generally much more accurate than areal precipitation estimates derived from precipitation gage observations.) Therefore, at the next time step, the precipitation model has no feedback information available for updating the initial conditions.

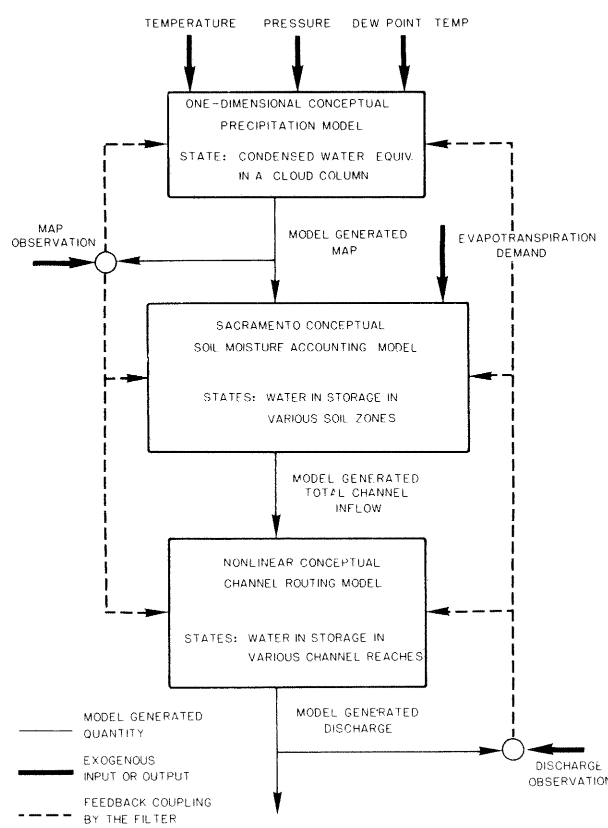


FIG. 2. Schematical representation of the stochastic-dynamical hydrometeorological model of Georgakakos and Bras (1982b). Explicitly shown are the model components, inputs and outputs.

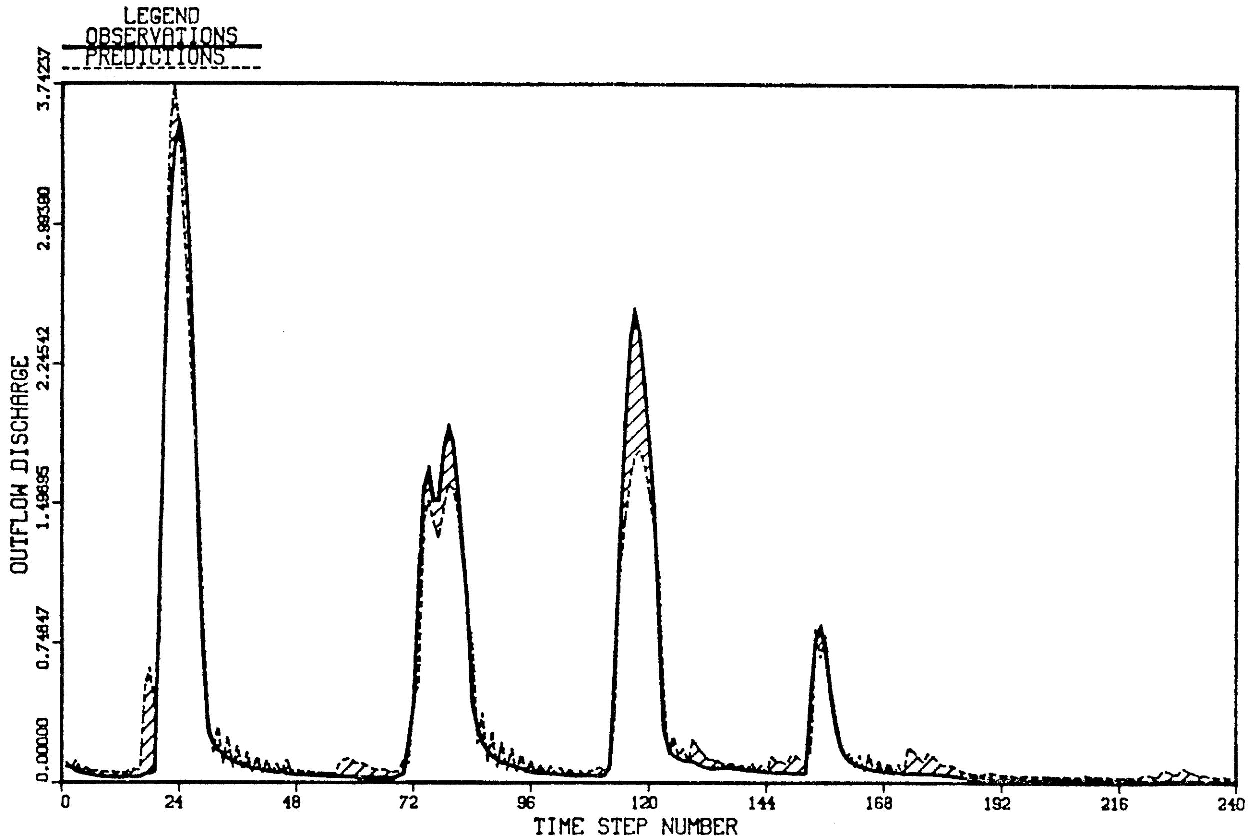


FIG. 3. Six-hour forecasts (dashed line) vs observations (solid line) of discharge in mm/6-hr for the Bird Creek basin, Oklahoma, 1 May to 30 June 1960, based on the integrated hydrometeorological model of Georgakakos and Bras (1982b).

From the above discussions, it is clear that a class of modeling activity that should be given high priority for the future is employment of coupled approaches to real-time precipitation/streamflow forecasting. The authors are aware of only one such integrated modeling system, which was developed by Georgakakos and Bras (1982b). The Georgakakos and Bras work will be used as an example here, with the hope that more modelers in the future will begin to think in similar terms of hydrometeorological system integration. The Georgakakos and Bras (1982b) model is a physically based, nonlinear precipitation model compatible with hydrologic catchment models. Using as inputs the values of certain meteorological variables (temperature, pressure, and dewpoint temperature) from selected ground station(s), the model produces as an output the precipitation rate at a station location. The model also has the flexibility to incorporate upper air data where available operationally. The predicted precipitation values are assumed representative at the station or, because of the coarseness of the input data, actually representative of an area around the station. It may in fact be reasonable to assume that, to a first approximation, these values represent predictions of mean areal precipitation (MAP) for a watershed in proximity to the station. The state variable of this model is the liquid water content of the storm clouds at a certain time in an atmospheric column above the station location. The amounts of moisture flowing into and out of the cloud are computed, using simplified cloud microphysics. The precipitation model equations are coupled directly with the mathematical representation of the soil moisture accounting model of the NWSRFS (Peck, 1976), and with the nonlinear channel routing model of Georgakakos and Bras (1982a), thus forming an integrated hydrometeorological model. (See Fig. 2.) The generalized model uses, as input, forecasts and/or estimates of temperature, pressure, dewpoint temperature, and potential evapotranspiration rates, and produces mean areal precipitation and outflow discharge forecasts for the basin of interest. Georgakakos and Bras (1982b) explicitly account for errors in the input variables, initial conditions, model structure, and output variables through the use of an Extended Kalman Filter (Gelb, 1974) that, in real-time, compares the model forecasts with corresponding observations and makes the necessary corrections in the model states based on quadratic error criteria. This real-time updating capability helps to compensate for the fact that the operationally available surface data are not dense enough to accurately determine small area thermodynamic fields.

Tests of the Georgakakos and Bras model are in progress for various sizes of basins and forecast lead times. The results appear encouraging. Fig. 3 displays six-hour forecast time steps of instantaneous discharge (in mm/6-hr) indicated by a dashed line, with corresponding observations indicated by a solid line from data that were collected during the period from 1 May 1960 to 30 June 1960 in the Bird Creek drainage

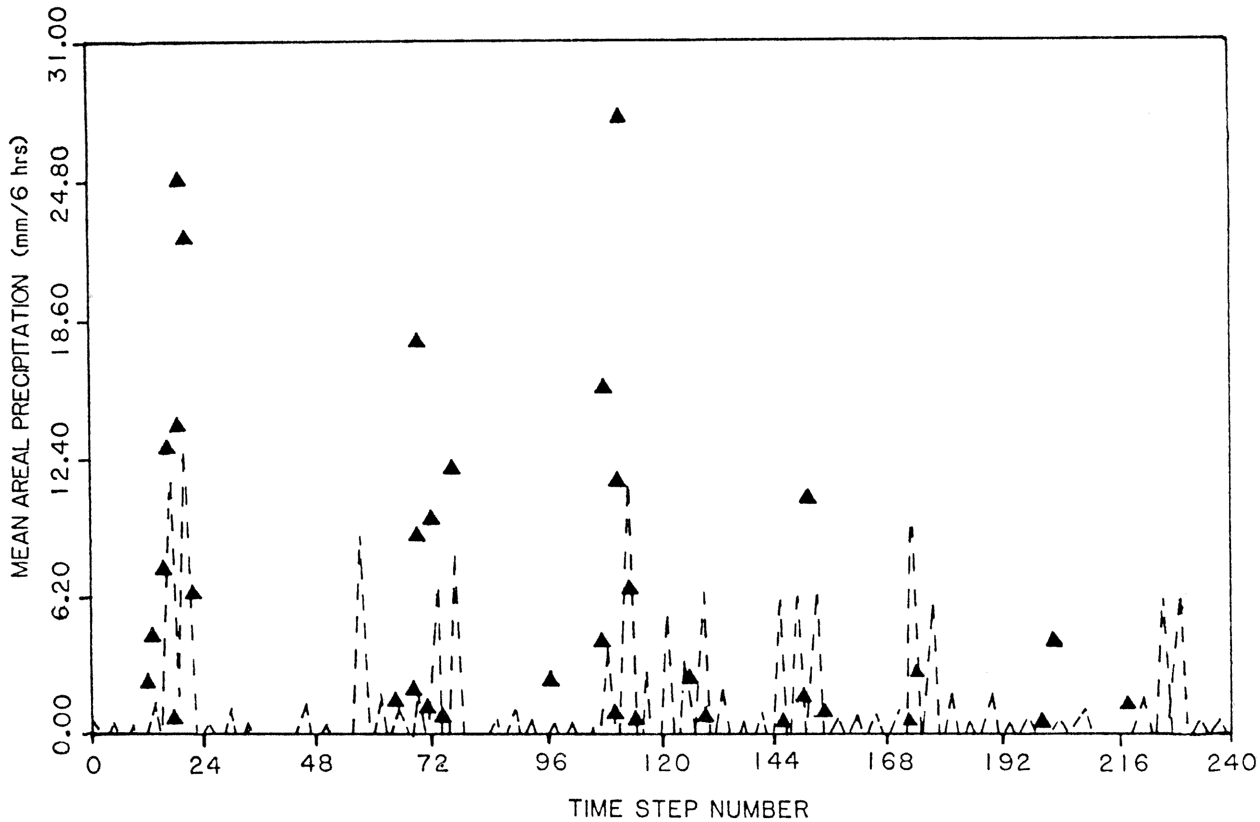


FIG. 4. Six-hour forecasts (dashed line) vs non-zero observations (black triangles) of mean areal precipitation rate for the Bird Creek basin, Oklahoma, for the period 1 May to 30 June 1960, based on the integrated hydrometeorological model of Georgakakos and Bras (1982b).

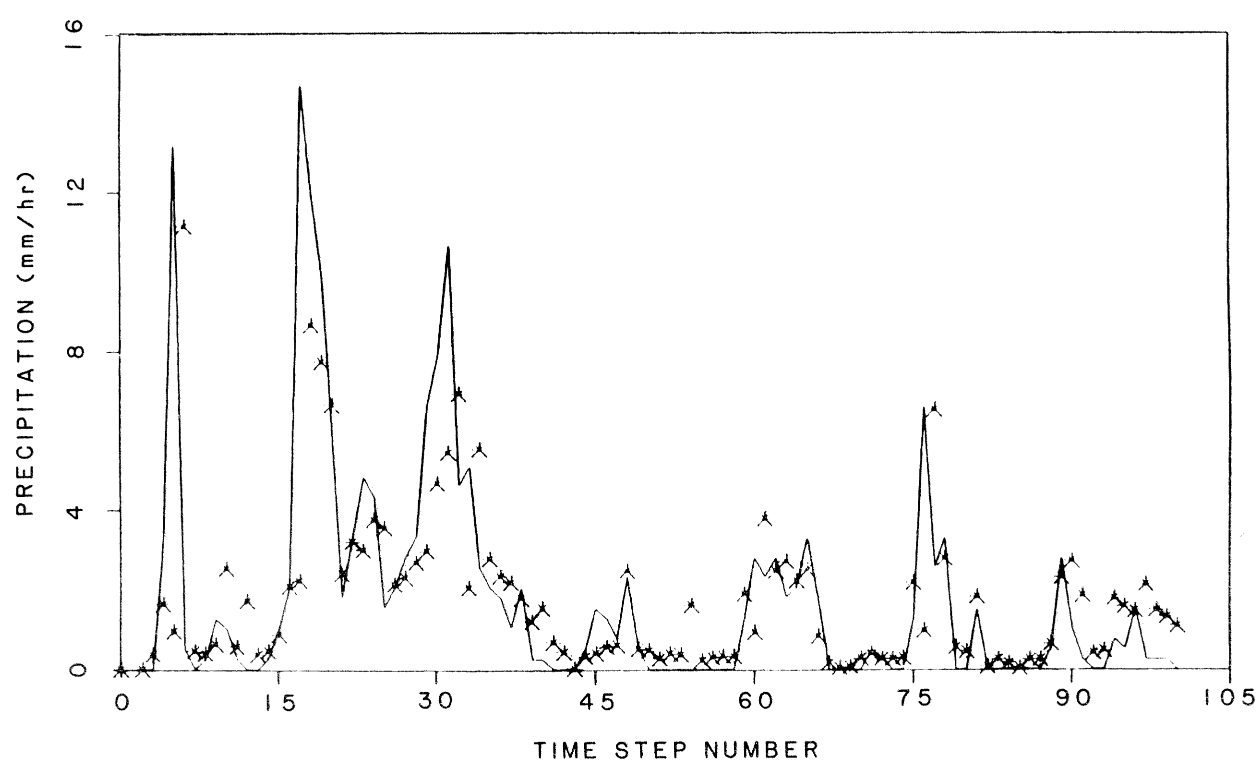


FIG. 5. One-hour forecasts (stars) vs observations (solid line) of the station precipitation rate at Tulsa International Airport, Oklahoma, based on the precipitation model of Georgakakos and Bras (1982b) in a stand-alone mode.

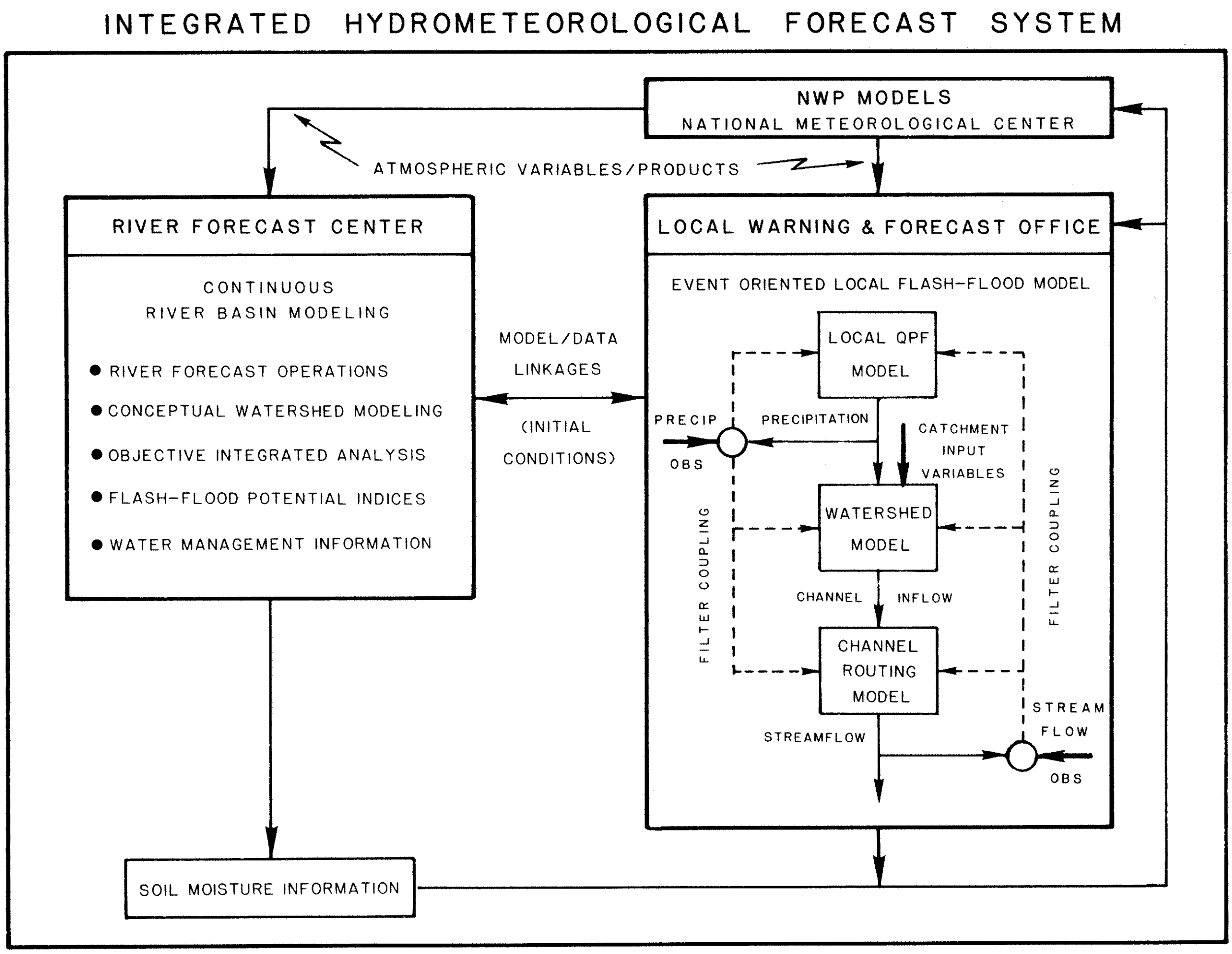


FIG. 6. Integrated Hydrometeorological Forecast System.

basin near Sperry, Oklahoma. Fig. 4 shows the model predictions of the mean areal precipitation rate (dashed line) corresponding to the forecasted discharge values of Fig. 3. It also shows the estimates (from rain-gage data) of the nonzero, concurrent mean areal precipitation (black triangles). The model inputs for these tests consisted of surface temperature, dew point temperature, and pressure data spatially interpolated from the data of the meteorological stations at Tulsa, Oklahoma; Wichita, Kansas; Springfield, Missouri; and Oklahoma City, Oklahoma.

Tests of the integrated model show skill in predicting the times of precipitation occurrence six hours ahead, and they show excellent performance in predicting discharge rates six hours in advance (up to 95% reduction in variance was obtained). The model tests also show the advantages of the feedback coupling through the Extended Kalman Filter. For example, in cases when the precipitation rate was erroneously over-forecasted, updating based on discharge prevented the hydrograph from rising excessively.

Considerable skill, both in timing and in magnitude of hourly precipitation forecasts, is noted in the results of Georgakakos and Bras (1982b). Fig. 5 is an example excerpted from their work and shows hourly precipitation forecasts (stars) for the station of Tulsa, Oklahoma, with the corresponding observations (solid line). This example is based on running the precipitation model in a stand-alone mode decoupled from the streamflow model. For the run shown in Fig. 5, a 30% reduction of variance resulted; i.e., the predictions explained 30% of the variance above the mean of the complete run. Even greater skill in hourly precipitation forecasts is expected when the precipitation model is coupled to a streamflow model and hourly discharge observations are available for updating. Then, accurate streamflow predictions are expected in flash-flood situations for which the time scales and the forecast lead times are relatively short.

The use of the precipitation model coupled with the catchment model also showed good skill for forecast lead times longer than six hours. An extended streamflow forecast run, for the same period and location as in Figs. 3 and 4, showed a reduction of variance of about 85% for a 12-hour forecast, about 75% for an 18-hour forecast, and about 58% for a 36-hour forecast. For all the extended forecast cases, the meteorological input was obtained from spatial interpolation of actual observed data. Of course, the streamflow forecast accuracies would decrease in a real-time operational mode unless the input meteorological forecasts were of good skill. An important aspect of these results is that given good performance for the longer forecast lead times, one can use the hydrometeorological model to arrive at efficient decomposition schemes for the simplification of updating computations in large basins with several tributary sub-basins (Georgakakos, 1983).

Details about the model formulation can be found in Georgakakos and Bras (1982b). The precipitation model parameter calibration issue is covered in detail in Georgakakos (1982). It is worthwhile to comment at this point that estimation of precipitation model parameters for various storm types, station locations, and estimation criteria gave similar optimal parameters. This exhibited robustness of the precipitation model and its compatibility with hydrologic models make it a particularly appealing approach for use in real-time river flow forecasting.

## 6. Concluding remarks and summary of future directions

As has been presented in the previous sections, there currently exist several QPF procedures that provide valuable guidance information over a broad geographic area, and to a lesser degree, guidance for localized areas. The literature review indicates, however, that while the currently available operational QPF information is useful in the planning of hydrologic forecasting operations, it falls short of meeting some of the requirements desired for real-time hydrologic forecasting applications. These desired requirements were specified in Section 3, and a summary of the currently available operational QPF approaches was presented in Section 4.

It appears that what is needed for the future is a hierarchical and more directly coupled approach to the problem. The guidance products produced by the NMC should improve in accuracy and geographic specificity in the future as finer resolution data from automatic/remote sensors and mesoscale modeling procedures are incorporated into the larger-scale numerical weather prediction modes. Similarly, the localized QPF products derived at the NWS field offices should improve as new data bases, such as the one that will be provided by the Next Generation Weather Radar (NEXRAD) program, become available and the meteorological forecasters are given interactive computer systems to expedite mesoscale analysis procedures like those presented by Maddox (1979).

Since numerical inputs of rainfall are desired in real time for many hydrologic forecasting applications, it is reasonable to conclude, at least conceptually, that more tightly coupled QPF and hydrologic prediction procedures are needed in the future. One such Integrated Hydrometeorological Forecast System (IHFS) was presented in Section 5 of this paper. This modeling system is based on the work of Georgakakos and Bras (1982b). We believe that work in this direction is one of the more important components to a desired hierarchical approach which directly incorporates QPF information from all levels into hydrometeorological modeling procedures.

Fig. 6 illustrates a proposed framework for model, data, and organizational interfaces for dynamic real-time coupling of meteorological and hydrological models and procedures (i.e., an IHFS) envisioned for the future. At the local site, the differential equations of a simplified QPF model are simultaneously solved with the differential equations of a soil moisture accounting model and a channel routing model. At the same time, a statistical/dynamical procedure (filtering algorithm) compares the hydrometeorological model predictions of precipitation and runoff to corresponding observations and corrects model state variables in real time. Estimates of the uncertainty in the model forecasts are generated by the filtering algorithm. The local hydrometeorological model is event-oriented. The necessary atmospheric input variables are provided by the grid-point NWP models covering a much larger area. The precipitation predictions from the hydrometeorological model complement other QPF information from the NMC and from analyses of the hydrometeorological situation by the local forecasters. Objective integrated analysis of radar/satellite and rain-gage data are performed to obtain MAP inputs for the IHFS.

Determination of areal flash-flood indices and of soil and channel model initial conditions at the onset of the event-oriented local hydrometeorological model operation, are provided by the continuously running hydrometeorological procedures at the RFC. Soil moisture information is fed from the RFC to the atmospheric models for the establishment of boundary conditions of soil moisture at ground level. Atmospheric input variables and regional QPF information are fed to the RFC level in support of the hydrological procedures, in continuous operation at the RFC.

In summary, a more tightly coupled hydrological forecasting system, providing the capability to share information between the larger and smaller scales of operational forecasting and more effectively incorporating meteorological forecast information, especially QPF products, is seen for the future. Hudlow and Brazil (1982) and Hudlow *et al.* (1981) discuss in greater detail the technological developments in hydrologic forecasting planned for the future by the National Weather Service.

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