JOURNAL OF THE
HYDRAULICS DIVISION

National Weather Service River Forecasting System[a]

By John C. Monro[1] and Eric A. Anderson[2]

Introduction

The hydrologic forecasting service of the National Weather Service, National Oceanic and Atmospheric Administration (NOAA), is undergoing a major change (10). Most forecast procedures currently used operationally in the field are based on index methods such as the Antecedent Precipitation Index (API) rainfall-runoff relationship (5). A few of the River Forecast Centers have developed or adapted conceptual models for local use, but no specific model has been adopted for general use. The term "conceptual model" refers to a synthetic model of the rainfall-runoff process. A synthetic model contains elements defined by explicit functions which are assumed to represent all significant physical components of the rainfall-runoff process. The parameters used in the functions are determined through the use of input/output data.

The Hydrologic Research Laboratory of the Office of Hydrology in Silver Spring, Md., is responsible for research and development support of the river forecasting service. Work on conceptual simulation models and studies of the physical processes of the hydrologic cycle has been in progress for several years. In 1971, the laboratory decided to publish descriptions of the necessary steps for developing operational river forecast procedures for continuous hydrologic forecasts, based on a conceptual hydrologic model, and digital computer programs needed for implementation (8). This paper presents the purpose, objectives, current components, and proposed additions to the National Weather Service River Forecast System (NWSRFS).

Note.—Discussion open until October 1, 1974. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 100, No. HY5, May, 1974. Manuscript was submitted for review for possible publication on July 6, 1973.

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Purpose

Comparison studies by the Hydrologic Research Laboratory, described later, show that some of the recent conceptual models have an accuracy advantage over the API technique. In addition, future hydrologic forecasts will extend beyond the forecasting of river stage and discharge to include such variables as water temperature, the amount of sediment transport, and the movement of pollutants. Conceptual models are much better suited for adaptation to those future forecasting problems than are index methods, e.g., API. It was decided that conceptual models should replace API as the basic tool for hydrologic forecasting as quickly as time and manpower permit. So an efficient means of applying conceptual models to a large number of forecast locations was needed. The National Weather Service currently issues river forecasts for approximately 2,500 points within the United States. Thus, the primary purpose of the NWSRFS is to provide the techniques needed for the efficient use of conceptual river forecasting models by field offices. The system also will serve as a base for further research on an improved model and other river forecasting techniques.

Objectives

To fulfill the primary purpose of the NWSRFS, the following basic objectives were established:

1. An efficient means of retrieving and processing basic data for model parameter calibration must be provided.
2. The soil-moisture accounting and channel-routing procedures must be applicable over the wide variety of hydrologic and climatic conditions found in the United States. In addition, the soil moisture accounting procedure must show a demonstrable accuracy advantage over API.
3. An efficient calibration procedure which would permit calibration of a large number of basins in a reasonable time is a necessity.

Data Retrieval and Processing.—Data requirements for the conceptual model differ from those for the API-type technique in two ways: (1) Data for parameter calibration purposes must be continuous; and (2) some form of potential evapotranspiration (PE) data may be required for both calibration and operational forecasting. All other data considerations are about the same as for conventional forecast procedures. Precipitation data (six hourly areal mean precipitation values are used) and streamflow data are needed. For calibration, mean daily discharge is required. Although the model simulates streamflow for a shorter time interval (currently 6 hr), model parameters are determined by comparing computed and observed mean daily discharge. This procedure yields reliable parameter values because storm periods occur at any time of the day. Since a calibration period will contain many storm periods, which are randomly distributed, any volume or timing error within a 24-hr period, due to incorrect parameter values, will be reflected in the sum total of errors between observed and simulated mean daily discharge. Instantaneous hydrographs for selected events also may be necessary to determine channel routing parameters. Operationally, no observed streamflow data are required, but the quality of the final product is improved if observed data are used periodically to update the model. Frequent observations of actual river discharge (six hourly values during storms, otherwise daily) could be routed downstream. Thus, errors in the upstream simulation from previous periods would not be propagated downstream. Actual observations could also be used to adjust variables in the model, for example, moisture storages, so that simulated and observed discharge would match. A set of decision rules would be necessary, to adjust the model variables or input data to improve real-time simulation. Objective updating of model performance is a subject for further research. If future studies show that the use of other hydrologic or meteorological data will improve the forecast, then those data will have to be obtained.

Vast amounts of data are required to implement the NWSRFS throughout the United States. Thus, it becomes necessary to have the means for efficient data retrieval and the use of computerized data manipulation and processing routines. A basic-tape format has been established for obtaining hourly precipitation and daily observations from the National Climatic Center, NOAA, in Asheville, N.C. This format provides for minimum conversion before the data are used for computation of areal means. Data are available by states. Hourly precipitation data for all states are currently on National Climatic Center (NCC) master magnetic tape; files start with January, 1948. Daily observations for all states are also available on the master files beginning with October, 1963. Data for periods other than those on master tape files can be obtained from NCC, but the cost of retrieval is much more expensive.

In addition to this new form of data retrieval, a digital computer program is provided to compute six hourly areal mean precipitation. The program estimates all missing data, converts daily observations into hourly observations, based on nearby recording precipitation gages, computes station weights, computes areal means, and prepares double-mass plots to check the consistency of the basic precipitation data. This program has proven efficient for processing precipitation data.

Soil-Moisture Accounting and Channel-Routing Procedures.—An extensive testing program was conducted within the Hydrologic Research Laboratory to evaluate three recently developed conceptual watershed models. A computerized model for simulating continuous streamflow based on the antecedent precipitation index (API) method was developed (11) as a basis for comparing the models. The conceptual watershed models considered were:

1. A slightly modified version of the Stanford Watershed Model IV(2).
2. The SSARR Model used by the River Forecast Center, Portland, Oreg. in conjunction with the Corps of Engineers (9,12).
3. The Sacramento River Forecast Center Hydrologic Model (2).

Simulation results from seven watersheds were used to evaluate the performance of the three models tested. Three factors were considered for selecting the watersheds: (1) Climate conditions; (2) drainage area; and (3) rain gage density. The watersheds were selected to represent humid and semiarid regions of the United States. Areas with uniform seasonal precipitation, as well as areas with wet and dry periods, were included. The drainage areas of the watersheds are representative of typical headwater basins currently in the operational forecasting program. The number of rain gages within and nearby the basins are such that reasonable areal and temporal definition of precipitation could be determined. The selected watersheds are believed to be representative of the hydrologic and climatic conditions found in most areas of the United States where snowmelt is not the major source of runoff. The seven watersheds and corresponding periods of record are:

1. Bird Creek near Sperry, Okla. 905 sq miles (2,344 km^2) (October, 1955–September, 1962).
2. French Broad River at Rosman, N.C., 68 sq miles (176 km^2) (October, 1953–September, 1958).
3. Leaf River near Collins, Miss., 752 sq miles (1,948 km^2) (October, 1951–September, 1969).
4. Mad River at Springfield, Ohio, 485 sq miles (1,256 km^2) (October, 1955–September, 1962).
5. Meramec River near Steelville, Mo., 781 sq miles (2,023 km^2) (October, 1954–September, 1962).
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7. South Yamhill River near Whiteson, Oreg., 502 sq miles (1,300 km^2) (October, 1957–September, 1967).

Several statistical measures based on observed and simulated mean daily discharge were used to evaluate model performance. Some of them were: (1) Annual and seasonal rms error of mean daily discharge; (2) annual and seasonal rms error of monthly maximum mean daily discharge; (3) seasonal and long-term flow bias; and (4) error frequency analyses. Additional information on the statistical techniques used is found in Ref. 11. All statistical measures of model performance were computed for the entire period of record for each basin. It is believed that the error analyses used gave a rather comprehensive evaluation of model accuracy. Based on these analyses of the model comparison test results of August, 1971, the modified Stanford Watershed Model IV was selected as the soil-moisture accounting procedure to use in the NWSRFS. This does not imply that the modified Stanford Model is the only acceptable model for use in the NWSRFS nor that it is the only soil-moisture accounting procedure that will be adopted for all future field use. Additional testing indicates there is no overall statistical difference in the accuracy of model output between the Sacramento River Forecast Center Hydrologic Model and the modified Stanford Model. Also note that these models show a very significant accuracy advantage over API only under one condition. This is in the modeling of river response after a long dry period. However, since long dry periods occur everywhere to some degree, the improved accuracy during these situations can be very important.

On the basis of these evaluations, it is concluded that the soil-moisture accounting portion of the basic hydrologic model is applicable over most of the United States. Other model studies within the Hydrologic Research Laboratory, involving basins with significant snow-melt contribution (1), have further substantiated this conclusion—with one exception. The exception is the situation in which the effects of cold temperature on the soil have a significant effect on river response. These effects include frozen soil, changes in moisture retention capacity, changes in infiltration rate, and movement of water within the soil by temperature gradients. Studies to incorporate the effects of cold temperature into the soil-moisture accounting procedure are in progress.

Lag and K channel routing (6) provide a very flexible hydrologic routing technique. For years this technique has been used successfully by River Forecast Centers throughout the United States. It is an adequate procedure for channel routing in a river forecasting model if there are discharge data (instantaneous hydrographs) to derive the routing parameters and if no variable backwater conditions exist.

Model Calibration.—To use the soil-moisture accounting and channel-routing model for river forecasting, the model must be calibrated for each watershed. The Hydrologic Research Laboratory has experimented with trial-and-error and automatic-parameter optimization techniques. Trial-and-error techniques involve subjective adjustments to parameters, based on specific characteristics of previous model output. Automatic techniques involve the use of direct-search optimization algorithms.

Model calibration can be accomplished by using a trial-and-error procedure, a direct search optimization procedure, or both. A combination of the two procedures is recommended for the NWSRFS. By combining the two procedures, it is possible to take advantage of the strengths of each procedure and minimize the weaknesses. A hydrologist experienced with the model can use trial-and-error analysis and arrive at a reasonably good set of parameter values. However, trial-and-error is a time-consuming process in terms of manpower. On the other hand, direct search optimization requires little more than the computer time to perform the analyses. While simple to use, direct search optimization has disadvantages. Some of these are: (1) Parameter adjustments are made based only on a single criterion of model performance; (2) a suboptimal set of parameter values can be calculated as a result of poorly selected starting values; and (3) the solution may converge slowly to the optimum because of the interrelationship between model parameters. In addition, since a large amount of computer time is required for direct search optimization, it is usually necessary to limit the period of record that is analyzed. By properly combining trial-and-error analyses with direct search optimization many of the disadvantages associated with direct search optimization can be overcome. Since the calibration procedure is so important to the effective use of conceptual models in river forecasting, the recommended procedure is described briefly.

NWSRFS Calibration Procedure

The automatic calibration method is the direct-search optimization technique known as Pattern Search (4,7), which has an advantage over most other direct search techniques in that its structure is simple. The Pattern Search algorithm sequentially adjusts parameter values by a rather simple strategy. The basic concept of this strategy is to increase the size of a parameter adjustment at each stage of optimization if a persistent direction (pattern) of adjustments has been established for the parameter. The success of a parameter adjustment is based on an improvement to model performance. Model performance is summarized by a single-valued objective function.

Objective Function.—The objective function which has been adopted is the sum of the squares of the errors between simulated and observed mean daily streamflow. Other objective functions (log differences, absolute differences, etc.) have been tried, but none gives overall results as good as those obtained with the quadratic function. The value of a quadratic function will tend to be influenced more by errors in high flows than by errors in low flows. However, calibration experience indicates that the use of this criterion of model performance results in parameter values that allow the model to simulate both high and low flows adequately. For comparative purposes, the results from Pattern-Search optimization were compared with parameter values obtained from an exhaustive trial-and-error analysis for two watersheds. The parameter values resulting from each procedure were essentially the same.

Calibration Period.—Two main factors should be considered when selecting the length of record for model calibration. First, a period of record should contain sufficient climatic and hydrologic variety (very dry to very wet conditions) so that each functional relationship in the model varies over as large a range as possible. Second, basin characteristics, such as land use, change with time. For forecasting, parameter values that express the present, not the past, are important. A suitable period of record appears to be the most recent 10 yr. The choice of a 10-yr calibration period, based on past experience, indicates that it is a realistic and adequate choice for calibrating most basins. In a humid climate, a shorter period may be adequate; conversely, in an arid climate, a longer period may be required. The length of record mentioned previously is for trial-and-error analysis; however, the length of record for automatic-parameter optimization is necessarily limited from a computer usage standpoint. The length of record should contain sufficient "hydrologic activity" and a population(s) of data errors with mean zero to insure the calculation of stable values for the parameters. Experience indicates that a 50-month record is generally sufficient for Pattern-Search optimization. This period includes 48 months for which the objective function is computed and a 2-month buffer period prior to the 48 months. The buffer period allows the assumed beginning of the period moisture conditions of the model to adjust to "actual" field conditions.

Computer Usage.—Pattern-Search optimization applied to a watershed model requires modest amounts of computer time. A typical optimization analysis may require 250 passes through a 50-month period, or, about 10 min of computation time on a CDC 6600 system. (Trade names are mentioned solely for purposes of identification. No endorsement by the National Weather Service, NOAA, or Department of Commerce, either implicitly or explicitly, is implied.)

Model Parameters.—To simulate watershed response, 20 moisture-accounting parameters and a channel-response function must be specified. Several model parameter values may be derived from observed precipitation and streamflow data. Some parameters may be treated as coefficients, with fixed values (based on a knowledge of the area). A good first guess for the channel-response function can be derived from streamflow data in a manner similar to unit hydrograph analysis. There are, however, about 12 to 14 parameter values that must be determined by the combined Pattern-Search/trial-and-error optimization procedure.

Recommended Procedure.—There are advantages and disadvantages to both

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Model calibration can be accomplished by using a trial-and-error procedure, a direct search optimization procedure, or both. A combination of the two procedures is recommended for the NWSRFS. By combining the two procedures, it is possible to take advantage of the strengths of each procedure and minimize the weaknesses. A hydrologist experienced with the model can use trial-and-error analysis and arrive at a reasonably good set of parameter values. However, trial-and-error is a time-consuming process in terms of manpower. On the other hand, direct search optimization requires little more than the computer time to perform the analyses. While simple to use, direct search optimization has disadvantages. Some of these are: (1) Parameter adjustments are made based only on a single criterion of model performance; (2) a suboptimal set of parameter values can be calculated as a result of poorly selected starting values; and (3) the solution may converge slowly to the optimum because of the interrelationship between model parameters. In addition, since a large amount of computer time is required for direct search optimization, it is usually necessary to limit the period of record that is analyzed. By properly combining trial-and-error analyses with direct search optimization many of the disadvantages associated with direct search optimization can be overcome. Since the calibration procedure is so important to the effective use of conceptual models in river forecasting, the recommended procedure is described briefly.

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Objective Function.—The objective function which has been adopted is the sum of the squares of the errors between simulated and observed mean daily streamflow. Other objective functions (log differences, absolute differences, etc.) have been tried, but none gives overall results as good as those obtained with the quadratic function. The value of a quadratic function will tend to be influenced more by errors in high flows than by errors in low flows. However, calibration experience indicates that the use of this criterion of model performance results in parameter values that allow the model to simulate both high and low flows adequately. For comparative purposes, the results from Pattern-Search optimization were compared with parameter values obtained from an exhaustive trial-and-error analysis for two watersheds. The parameter values resulting from each procedure were essentially the same.

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Recommended Procedure.—There are advantages and disadvantages to both trial-and-error and Pattern-Search optimization for deriving model parameter values as described previously. Trial-and-error analysis is more beneficial at the initial and final stages of calibration, and Pattern-Search, during the intermediate stage of calibation.

Initial Stage.—Initial values for all parameters are selected and streamflow is simulated for the entire calibration period. The initial value for unknown parameters may be selected from a nearby calibrated basin or may be based on the experience of the hydrologist. Ref. 8 gives some guidance on typical ranges for parameter values. Simulation should reveal gross errors in the data, and the adequacy of the channel routing function and initial values for the parameters. If the initial simulation is inadequate, which is likely, trial-and-error is used to adjust parameter values. Trial-and-error calibration should be continued until a set of parameter values is obtained which will produce a simulated mean daily discharge plot resembling the actual mean daily discharge plot. This set of parameter values will provide good starting values for Pattern-Search optimization. Trial-and-error calibration should also be used to minimize the number of parameters included in Pattern-Search optimization. Especially, the values of parameters which have a small effect on the objective function should be determined prior to Pattern-Search optimization. Trial-and-error analysis proves more effective as the hydrologist gains experience with the hydrograph-simulation model.

Intermediate Stage.—Based on the trial-and-error analysis, an appropriate data period and an appropriate set of initial parameter values are selected for Pattern-Search optimization. The results of using Pattern-Search optimization on many watersheds indicate that with few exceptions: (1) Realistic parameter values are obtained; (2) simulation accuracy is improved substantially by using these parameter values; and (3) improvement in simulation accuracy is about the same for the 50-month period used for direct-search optimization and for the remaining period of record used in calibration.

Direct-search optimization has been shown to be a good objective watershed-parameterization technique. The "optimal" parameter values, however, are not necessarily unique but may be just a good set of values among other possible sets.

Final Stage.—The observed and simulated streamflow (using parameter values obtained by Pattern Search) are compared for the entire period of record. If bias is absent at low, median, and high flows, the calibration of the basin is considered complete. If, however, bias is present, trial-and-error or possibly further Pattern-Search optimization is used to correct the deficiency.

Operational River Forecasting Program

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Future Additions to System

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10549 NATIONAL WEATHER SERVICE FORECASTING

KEY WORDS: Data processing; **Forecasting; Hydraulics; Hydrologic models;** Optimization; **Precipitation (atmospheric); Rivers**

ABSTRACT: The National Weather Service River Forecast System describes a method and details computer programs for efficient operational use of a conceptual hydrologic model for river forecasting. A new format has been established for the retrieval of hourly precipitation data and daily observations (from the National Climatic Center, NOAA). A computer program is provided to perform all steps to convert the basic precipitation data to areal means. A procedure and computer programs needed for calibrating the basic conceptual model to a large number of basins in a reasonable time are described. The basic conceptual model has wide applicability. The inclusion of a snow-pack model and additions to the channel-routing procedure planned for the near future will make the model applicable over nearly all of the United States.

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trial-and-error and Pattern-Search optimization for deriving model parameter values as described previously. Trial-and-error analysis is more beneficial at the initial and final stages of calibration, and Pattern-Search, during the intermediate stage of calibation.

Initial Stage.—Initial values for all parameters are selected and streamflow is simulated for the entire calibration period. The initial value for unknown parameters may be selected from a nearby calibrated basin or may be based on the experience of the hydrologist. Ref. 8 gives some guidance on typical ranges for parameter values. Simulation should reveal gross errors in the data, and the adequacy of the channel routing function and initial values for the parameters. If the initial simulation is inadequate, which is likely, trial-and-error is used to adjust parameter values. Trial-and-error calibration should be continued until a set of parameter values is obtained which will produce a simulated mean daily discharge plot resembling the actual mean daily discharge plot. This set of parameter values will provide good starting values for Pattern-Search optimization. Trial-and-error calibration should also be used to minimize the number of parameters included in Pattern-Search optimization. Especially, the values of parameters which have a small effect on the objective function should be determined prior to Pattern-Search optimization. Trial-and-error analysis proves more effective as the hydrologist gains experience with the hydrograph-simulation model.

Intermediate Stage.—Based on the trial-and-error analysis, an appropriate data period and an appropriate set of initial parameter values are selected for Pattern-Search optimization. The results of using Pattern-Search optimization on many watersheds indicate that with few exceptions: (1) Realistic parameter values are obtained; (2) simulation accuracy is improved substantially by using these parameter values; and (3) improvement in simulation accuracy is about the same for the 50-month period used for direct-search optimization and for the remaining period of record used in calibration.

Direct-search optimization has been shown to be a good objective watershed-parameterization technique. The "optimal" parameter values, however, are not necessarily unique but may be just a good set of values among other possible sets.

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