NATIONAL WEATHER SERVICE

EXTENDED STREAMFLOW PREDICTION

By

T. M. Twedt 1/, J. C. Schaake, Jr., and E. L. Peck 2/

Introduction

Effective management of a water resource system is considerably enhanced by the provision of information pertaining to the expected state of the system in the future. In particular, long-term predictions of future streamflow are of extensive value to water users and other riverside interests, the value being dependent upon the accuracy and temporal structure of the predictions. The National Weather Service (NWS), through its network of River Forecast Centers, has traditionally provided such a service to a variety of users by means of an operational function known as water supply forecasting. A number of additional state and federal agencies also issue water supply forecasts with similar intent.

The general approach utilized for such forecasts has been some form of regression/correlation analysis between seasonal runoff and one or more types of hydrometeorological information such as snow course data, observed winter precipitation, past streamflow, or other measurements. Because of their mathematical structure and discontinuous operation, most of these methods are capable of providing only seasonal estimates of streamflow volume and do not associate their results with any chance of occurrence. Many irrigation interests, reservoir operators, and other water management agencies now possess sufficient sophistication to demand and efficiently utilize water supply forecasts of a probabilistic nature for a variety of time periods.

In response to these demands, a method of providing probabilistic streamflow predictions during any user-designated time period has been developed for headwater basins. The method to be described, known as the Extended Streamflow Prediction (ESP) model, is presently available as an experimental version, and subsequent modifications and improvements will be implemented as they develop. As an operational component of the National Weather Service River Forecast System (NWSRFS) currently under development (4), the ESP model will soon be expanded to provide operational water supply forecasts for entire river systems.

Theory of Prediction

Perfect prediction of the future state of a system is simply a matter of understanding the operation of the system perfectly and of knowing the future inputs to the system exactly. Any uncertainty in this knowledge would tend to decrease the accuracy of the prediction. In the particular case of water supply predictions, perfect mathematical representation of the hydrologic cycle within the basin and exact knowledge of the future meteorological inputs to the basin would produce completely accurate forecasts of future streamflow.

In actuality, these requirements can never be met; therefore, several simplifying assumptions must be made and the resultant loss of accuracy due to uncertainty accepted. The initial assumption implicit in the ESP method is that the hydrologic system of any catchment can be accurately represented by physically-based conceptual hydrologic models such that simulated streamflows from these models are equivalent to those produced by the real system under similar conditions. The general method does not preclude the use of less complex hydrologic models or even index-type forecast relationships if they can be accepted as sufficiently adequate representations of the system and can be operated on a continuous basis.

1/ Formerly, Research Hydrologist, Hydrologic Research Laboratory, NWS, Silver Spring, Maryland; presently, Hydrologist, River Forecast Center, Sacramento, California.

2/ Research Hydrologists, Hydrologic Research Laboaratory, NWS, Silver Spring, Maryland.

Since exact future inputs to the system can never be known, additional assumptions as the expected nature of the inputs and the subsequent system response must be made. Two alternative approaches to the problem are possible, the first being the synthetic generation of sets of input time series possessing the desired probabilities of occurrence, cross-time correlations, and internal sequencing for the type and length of prediction required. This set could then be input to the model and the resultant simulated streamflow taken as the prediction. However, due to the inherent nonlinearity of the hydrologic model of the system and the difficulties in dealing with jointly distributed random variables, considerable uncertainty would exist as to the actual probability of occurrence of these simulated streamflows.

A more appropriate, less complex, and more easily interpreted approach is utilized in the ESP model. A large number of years of actual historical data consisting of precipitation and temperature time series are utilized as model inputs. Separate simulations are run for each set of time series inputs, using in each run the current hydrologic conditions on the catchment as initial conditions for the model. The result is a set of possible streamflow regimes representing those which might be realistically expected from the catchment in the future and which are conditioned to the current state of the system at prediction time. This set of values is then analyzed to select the appropriate type of information (i.e., total volume, peak flow, etc.) for the time period of interest. A frequency, and hence probability, distribution is developed from these selections, enabling one to relate streamflow information to a desired chance of occurrence during this period. Thus, forecasts of predicted streamflow at user-selected levels of probability can be provided for any time period in the future.

Modeling Approach

Introduction

The water supply forecasting method described here is a dynamic entity in that it is continuously under modification and additional development both at the Hydrologic Research Laboratory and at a number of NWS River Forecast Centers. The process is expected to continue to evolve for some time, especially as it becomes operationally implemented and field usage provides further insights and needs. A number of items currently under consideration for modification or addition will be discussed later in this description.

Data Requirements

The ESP model requires three general types of data other than program control and option information: (1) hydrologic model parameters, (2) initial basin conditions, and (3) climatological time series inputs. The hydrologic model parameters are simply a set of values which act to fit the generalized conceptual models to the actual catchment under consideration. These values are determined by model calibration procedures and are assumed to be available at the time an extended streamflow prediction is requested. Initial watershed conditions are the set of values which represent the current state of the system in terms of moisture storage contents, snowpack water-equivalents, and other snow cover variables. The values are available to the model as carry-over from normal operational river forecast programs and are updated at the completion of every normal forecast. Use of these updated values as initial model conditions insures that the resultant simulated streamflows are "conditioned" to the actual state of the system at the time of prediction and are not simply marginal (climatic) normals.

The climatological time series required as input to the model must be in the form of areal means of precipitation and temperature over the basin. The model assumes that these time series have been transformed from point data previously and are accessible at the time of prediction. Several programs are available in the NWSRFS for the appropriate data manipulation and processing to provide excellent areal time series values, although more simplistic techniques producing less accurate values are also acceptable to the model. Time series representing a substantial period of record (at least 10-20 years) are required, since prediction accuracy improves with the utilization of a wide variety of climatic regimes, as represented by a long-term record.

Hydrologic Model

As indicated above, a wide variety of hydrologic models and other forecasting functions are compatible with the general approach of the method, their use restricted only by one's willingness to accept them as accurate representations of the system. However, the utilization of a continuous, physically-based, conceptual hydrologic model is very strongly recommended in order to fully exploit the capability of the method. Such a model should contain a soil moisture accounting procedure to describe the movements of water into and through the soil mantle, a method of representing snowpack accumulation and subsequent melt, and a technique for routing the flow of water through river channels. Inclusion of these model components permits the use of current watershed conditions as the initial state of the system, a vital component of the technique. The method currently includes a set of such routines from the NWSRFS consisting of a version of the Sacramento soil moisture accounting routine (2), an air temperature/energy index snow accumulation and ablation model (1), and a simple lag and K channel routing procedure (3). All are operated on a 6-hour computational time step and have been included in a modular form to permit easy modification or replacement as necessary.

Prediction Period

A primary objective during development of the ESP method was provision of the capability to produce predictions for a variety of time periods, rather than restricting them to a seasonal or even monthly basis. The approach taken allows the user to define a "window" which represents a period of interest in terms of starting date and length of prediction. This is accomplished in an analysis of the set of simulated streamflow regimes produced by the hydrologic model, where the ESP model selects from these regimes only those values which occur within the window. Periods beginning at any time in the future and extending any number of days can be defined, although those predictions initiated extremely far into the future and/or of excessive duration will contain substantially more uncertainty. Window definitions within which the amount of uncertainty introduced becomes unacceptable tend to be both basin and seasonally specific, as well as dependent upon the intended use of the prediction, the input data, and the hydrologic model used.

Statistical Analysis

The ESP model has the capability to produce predictions of the following properties derived from the simulated streamflows: total volume of flow, maximum mean daily flow, minimum mean daily flow, and average mean daily flow for the period of interest. For each year of record, these properties are derived from the streamflow regimes occurring within the period of interest and can be considered as sample values from the expected distribution of streamflow components given the current hydrologic conditions on the basin. The ESP method assumes that the statistical distribution of the flows is known or can be estimated. The current version assumes a lognormal distribution of flows for the following reasons: the distribution is appropriately asymmetrical, it possesses a lower bound of zero and no upper bound, and it is convenient and frequently used to describe hydrologic phenomena. Additional research is in progress to evaluate a variety of statistical distributions as to their value in representing streamflow regimes under varying conditions. Given the known probability distribution and its parameters, which are calculated from the set of sample values, the model determines expected values of the streamflow component at the probability levels of occurrence requested by the user.

Model Output

A number of optional types of output are available from the ESP model in addition to the actual streamflow predictions requested. Initially, information pertaining to the length and starting date of the prediction and the historical record utilized is displayed. The model then outputs information pertaining to the hydrologic characterization of and the initial conditions assumed for the watershed. For each streamflow property selected for analysis by the user, another set of displays is available. A listing of the values for both the conditionally simulated and actual observed streamflow properties for each year of record is provided, followed by a series of statistical parameters of both sets of values. The streamflow prediction itself follows, categorized by a user-provided classification (i.e., most probable, reasonable maximum, etc.) and its associated level of probability of exceedance. A plot of the conditional and marginal (climatic) probability distributions and the sample data points included in the analysis can be optionally displayed.

Application

The Extended Streamflow Prediction model has been experimentally applied to a typical Western United States snow basin, the Eagle River drainage in central Colorado. The catchment, comprising a drainage area of 2445 km^2(944 mi^1) with elevation ranging from 1913 m (6275 ft.) to 4266 m (13,966 ft.), normally begins accumulating a snowpack on its upper reaches in October and completes melt in July. Twenty years of historical precipitation and temperature data are available, and the catchment has been successfully calibrated to the NWSRFS.

Extended Streamflow Predictions of total volume of flow on the Eagle River drainage during the peak runoff months of May and June in Water Year 1971 were prepared as examples of ESP forecasts. The first example represents a prediction for these two months initiated on February 1, 1971, with the results given in Table 1. Table 2 provides the results of a prediction initiated as of May 1, 1971. The actual observed volume of flow during May and June 1971, was 239,316 acre-feet. Figure 1 is a plot of the conditional (computed by the ESP model) and marginal (actual observed) probability distributions for the second example.

Table 1. Eagle River, Colorado, total volume of flow prediction for May and June 1971, as of February 1, 1971.

CLASSIFICATION	EXCEEDANCE PROBABILITY	TOTAL VOLUME (Thousands Acre-Feet)	PERCENT NORMAL
Reasonable Max.	0.10	267.1	97.0
Most Reasonable	0.50	217.6	101.4
Reasonable Min.	0.90	177.3	106.5

Table 2. Eagle River, Colorado, total volume of flow prediction for May and June 1971, as of May 1, 1971.

CLASSIFICATION	EXCEEDANCE PROBABILITY	TOTAL VOLUME (Thousands Acre-Feet)	PERCENT NORMAL
Reasonable Max.	0.10	277.5	97.7
Most Reasonable	0.50	239.9	103.2
Reasonable Min.	0.90	207.3	109.7

Discussion

The ESP model produces streamflow predictions for user-designated time periods at any pre-selected probability levels of occurrence. The value of utilizing the current state of the watershed as initial conditions is indicated by the probability plots of Figure 1. The significantly flat slope of the conditional distribution relative to the marginal (historically observed) distribution indicates a lower level of uncertainty in the prediction than could be obtained from the use of historical normals alone.

This decreased uncertainty can be attributed to the inclusion of current knowledge regarding the contents and condition of the snowpack and soil moisture storages on the catchment. We would expect the uncertainty in the forecast to increase as the prediction period was extended further and further into the future, eventually increasing to the point where the marginal and conditional distributions are indistinguishable and the forecast would tend to be controlled by the historical record alone.

However, for prediction periods of reasonable length, especially during accumulation of the snowpack, the ESP model provides water supply forecasts which are appropriately accurate and probabilistically oriented. In addition, as indicated below, substantial

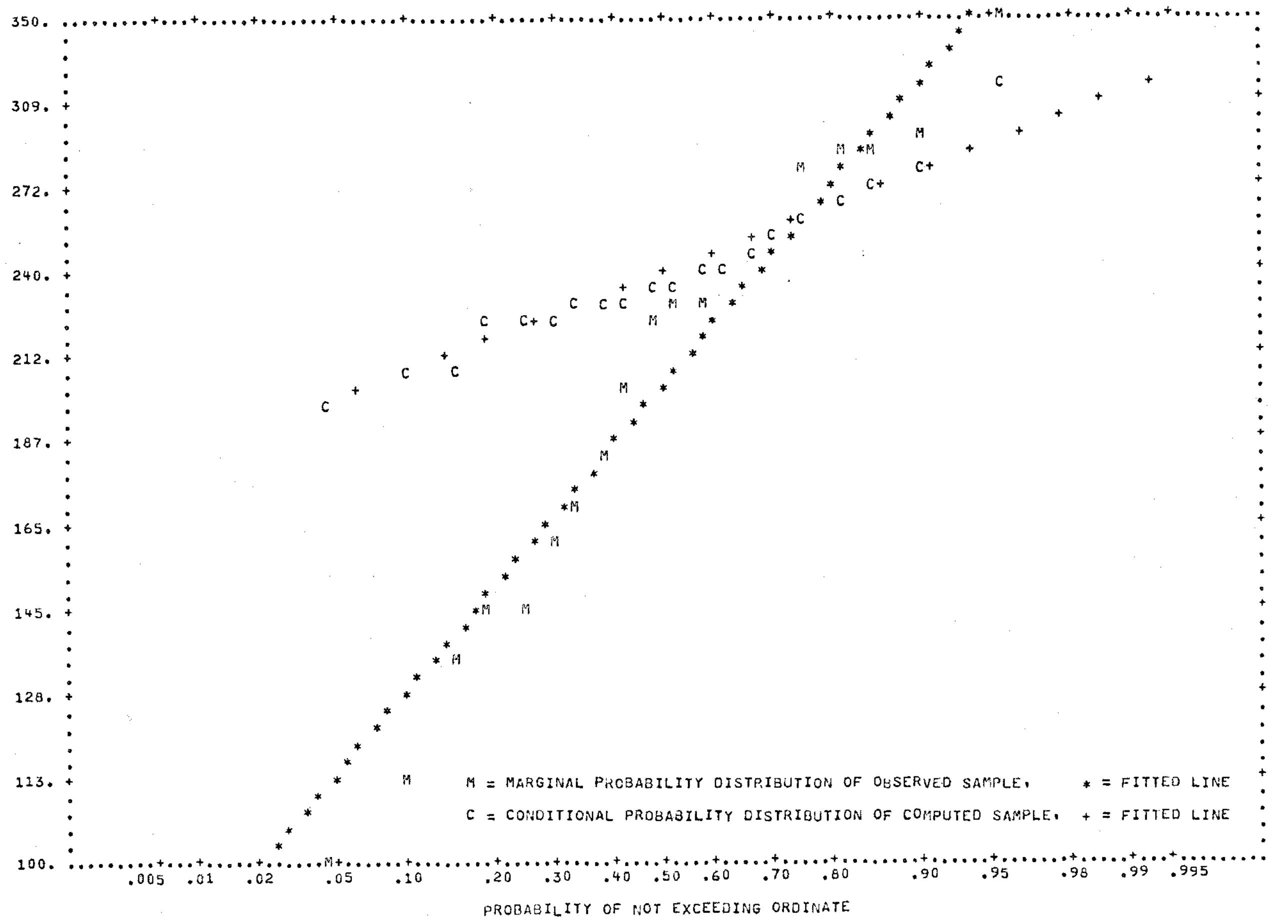

Figure 1. Marginal and conditional probability distribution plots for Eagle River total volume of flow (thousands acre-feet) during May and June 1971, predicted as of May 1, 1971.

further research and development is in progress at a number of National Weather Service installations to improve and modify the method as necessary.

Future Directions

The ESP model is continually being evaluated and modified via extensive testing and additional research. A number of items under consideration for inclusion into the model are briefly discussed here.

A major research effort in the near future is the development of procedures to permit the application of the ESP model to large river systems containing a number of catchments. The anticipated approach will involve a step-wise operation in which streamflow regimes for each catchment are simulated and routed into downstream catchments as upstream inflows. The usual analysis of the components and subsequent predictions would be available for any individual basin during the operation. A rather sophisticated data management system will be necessitated to provide efficient access to parameters, initial conditions, and input time series for each basin as the operation proceeds downstream.

Because the current method requires considerable amounts of historical data for input, computer storage needs tend to be fairly extensive. Use of the model to provide water supply forecasts for large river systems will necessitate even more storage space, perhaps requiring magnetic tape storage of input data or development of screening techniques for selecting only certain types or periods of data for analysis. Another approach might include the utilization of larger time steps in computation, eg. one day rather than six hours.

Another area under consideration is the development of techniques for automatically selecting property statistical distributions based on analysis of sample parameters. Such procedures would provide greater model flexibility and more accurate predictions from decidedly skewed distributions. An additional possible approach in modifying the form of predictions would involve the determination of confidence limits of property distributions and hence the presentation of ranges of values at selected levels of probability of occurrence.

Several final considerations involve the possible application of additional theoretical techniques such as quantitative precipitation forecasting (QPF) and state estimation theory to the ESP model. It is hoped that these applications would ultimately lead to a minimization of uncertainty in the approach. Certainly other possibilities will arise as the model receives operation use, and these will be evaluated and included where appropriate.

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