Extended Streamflow Forecasting Using NWSRFS[a]

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Abstract: Extended forecasting using the National Weather Service River Forecast System (NWSRFS) is done with the NWS Extended Streamflow Prediction (ESP) program. This paper examines the theory, capabilities, and potential applications of the ESP procedure. ESP uses conceptual hydrologic/hydraulic models to forecast future streamflow using the current snow, soil moisture, river, and reservoir conditions with historical meteorological data. The ESP procedure assumes that meteorological events that occurred in the past are representative of events that may occur in the future. Each year of historical meteorological data is assumed to be a possible representation of the future and is used to simulate a streamflow trace. The simulated streamflow traces can be scanned for maximum flow, minimum flow, volume of flow, reservoir stage, etc., for any period in the future. ESP produces a probabilistic forecast for each streamflow variable and period of interest. The procedure was originally developed for water supply forecasting in snowmelt areas, but it can also be used to produce spring flood outlooks, forecasts for navigation, inflow hydrographs for reservoir operation, and time series needed for risk analysis during droughts.

Introduction

The responsibility for water supply forecasting in the West is shared by the National Weather Service (NWS) and the Soil Conservation Service (SCS). Both of these agencies currently rely primarily on regression procedures to forecast seasonal water supply volumes. The regression procedures use a combination of monthly precipitation, first of the month snow water equivalent measurements, and past streamflow to predict streamflow volumes. The 10 and 90% exceedance probability levels are estimated from historical knowledge of how forecast accuracy varies throughout the forecast season. In most years, the regression procedures provide excellent forecasts of seasonal streamflow volumes; however, they sometimes fail to perform well in extreme years.

For some extended forecasts, e.g., spring flood outlooks, information is needed about the timing of the runoff. The NWS uses conceptual hydrologic and hydraulic models to melt the snowpack, calculate the runoff, and route it downstream in order to produce spring flood outlooks. For one current procedure, computer runs are made for the cases of zero future precipitation and normal future precipitation using several synthetic future temperature time series that create different snowmelt patterns. The forecaster compares the results from these different scenarios to develop a forecast. The value of this procedure is limited because of

[a]Presented at the March 14–16, 1983 ASCE National Specialty Conference, "Water Supply—The Management Challenge," held at Tampa, Fla.

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Note.—Discussion open until September 1, 1985. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 30, 1983. This paper is part of the *Journal of Water Resources Planning and Management,* Vol. 111, No. 2, April, 1985. ©ASCE, ISSN 0733-9496/85/0002-0157/$01.00. Paper No. 19684.

the subjectivity required, and the fact that the procedure does not provide any means for assessing the uncertainty of the forecast. Long-range forecasts contain useful information if the uncertainties can be quantified.

As the demand for water increases, the operating margin for making water management decisions will decrease. Water management decisions will require more detailed information in the future in order to maximize the benefit of existing resources. Some of the areas that can benefit from increased water management information are water supply, drought assessment, reservoir operation, and navigation. The NWS provides detailed river forecast information on a daily basis as part of its flood forecasting mission. Conceptual models, e.g., the ones used by the NWS to provide short-range forecasts, also have the capability to provide detailed long-range forecast information. An objective procedure for developing future time series data and for assessing forecast uncertainty is needed before optimum use can be made of conceptual models for long-range forecasting.

The National Weather Service River Forecast System (NWSRFS) Operational Forecast System generates short-range streamflow forecasts by inputting observed and forecast precipitation and temperature data into conceptual hydrologic and hydraulic models that simulate the snow accumulation and ablation, rainfall/runoff, watershed routing, and channel routing processes to produce simulated streamflow. Observed streamflow data are used to adjust the simulated streamflow to correct for errors that may have resulted from a combination of poor estimates of the initial conditions, errors in the inputs (e.g., incorrect precipitation and temperature data), and errors in the models and their parameters. The states of the models (e.g., snowpack, soil moisture, channel flow, and reservoir levels) are saved so that they can be used as initial conditions for subsequent simulations.

Because of the limited skill presently available in forecasting future meteorological conditions, it is not possible to develop quantitative estimates of future precipitation and temperature more than a few days into the future at the time scales needed for conceptual modeling. The Extended Streamflow Prediction (ESP) procedure provides an objective means of using conceptual models for long-range forecasting with the capability of assessing forecast uncertainty. ESP uses historical meteorological data and assumes that each year of historical data is a possible representation of the future. One streamflow trace is simulated for each historical year using the current watershed conditions as the initial conditions for each simulation. The simulated streamflow traces are analyzed statistically, so that probabilistic forecasts can be made.

The ESP procedure was first used in California in the early seventies by the NWS California-Nevada River Forecast Center (RFC) and the State of California. The Hydrologic Research Laboratory of the NWS began a project to develop an ESP program in 1975. The purpose of the project as stated in the project plan was "to develop and test an accurate and efficient procedure capable of predicting streamflow volume over both a long-term (seasonal) duration and a short-term (5–90 days) duration and providing associated probabilities of occurrence and statistical evaluation of the predictions." Since that first project plan for ESP was written, several programs that use the ESP procedure have been developed (6,12). The California-Nevada RFC, the Colorado Basin RFC, and the Alaska RFC are currently using the ESP procedure to help in forecasting water supply (11). The ESP procedure was also used successfully to assess the severity of the drought in the Washington, D.C., metropolitan area in 1977 (9). Initial versions of the ESP program demonstrated the value of the ESP procedure, but did not meet all of the requirements of an operational program from the standpoint of flexibility, efficiency, and ease of use. When a project to redesign NWSRFS began in 1979, it was decided to redesign the ESP program as an integral part of the new system. In addition to being completely compatible with the new NWSRFS operational program, the new ESP program was designed to eliminate many of the deficiencies of the previous programs. The new version of the ESP program has been completed and tested at several RFCs. It is being used operationally as part of a drought management system for the Potomac River Basin (10). The ESP program will be officially released with the rest of NWSRFS in the summer of 1984.

Program Development

The NWSRFS must be described, so that the basic framework of the ESP program can be understood. The NWSRFS consists of all the programs needed to generate streamflow forecasts. Included as part of NWSRFS are two systems of programs: a Calibration System and an Operational Forecast System. The Calibration System performs all the tasks needed to process historical hydrometeorological data and adjust model parameters so that simulated streamflow closely matches observed streamflow. The models are conceptual deterministic models and require mean areal precipitation (MAP), temperature (MAT), and evapotranspiration (MAPE) as inputs in order to simulate snow accumulation and ablation, calculate runoff, time distribute the runoff, and route the streamflow downstream. The simulated streamflow is analyzed statistically and visually compared to the observed streamflow to determine the necessary model parameter adjustments (2).

Once all the models have been calibrated for a watershed, the model parameters can be used operationally with real-time hydrometeorological data to forecast streamflow. The Operational Forecast System is a complex software system that performs all the tasks needed for operational river forecasting. A schematic of the system is shown in Fig. 1. The system includes three major components: Data Entry, Preprocessor, and Forecast. The Data Entry Component is a set of programs that transfer hydrometeorological data from a variety of sources to the Preprocessor Data Base. The Preprocessor Component reads the raw point data from the Preprocessor Data Base, estimates missing data as required, and calculates time series of MAP, MAT, and MAPE. The mean areal time series are written to the Processed Data Base for use by the Forecast Component. The Forecast Component reads the necessary processed time series from the Processed Data Base, performs the requested hydrologic and hydraulic simulations, including model updating and display of results, and writes the simulated streamflow back to the Processed Data

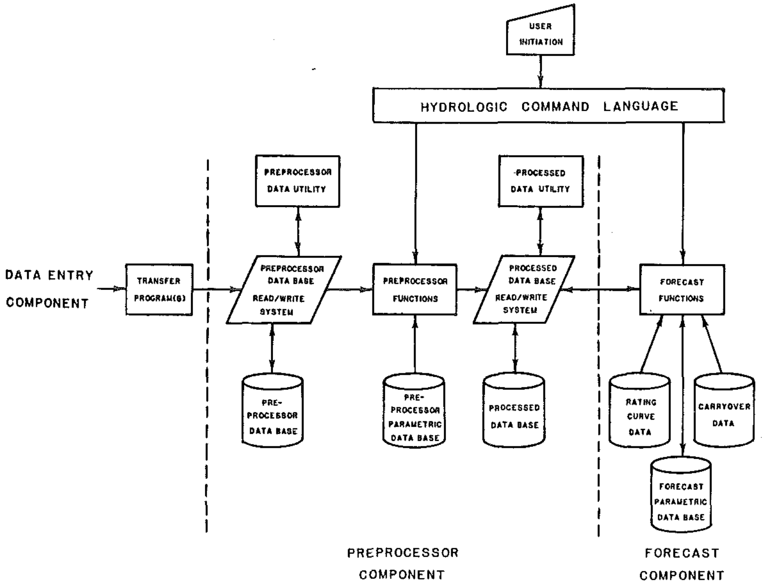

FIG. 1.—Operational Forecast System

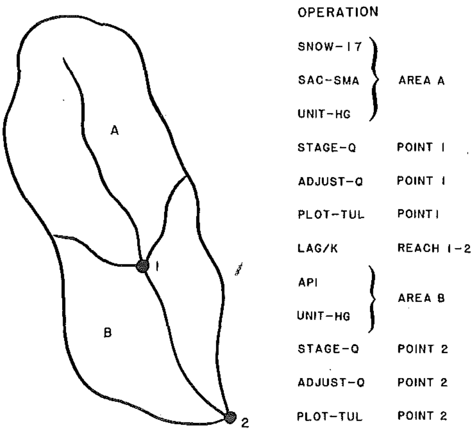

FIG. 2.—Streamflow Forecasting Using Operations

Base. These streamflow data can then be used as input to model a sub-watershed located downstream.

The Forecast Component is made up of computational modules called operations. Operations consist of a set of subroutines needed to perform some simulation or analysis, or both, using time series data. Hydrologic and hydraulic models, display procedures, analysis techniques, and arithmetic computations can all be programmed as operations. A list of

TABLE 1.—Operations Planned for Forecast Component of NWSRFS Version 5

Hydrologic/hydraulic models (1)	Arithmetic computations (2)	Updating and verification procedures (3)	Displays (4)
API/MKC—Antecedent precipitation index rainfall-runoff model for the Missouri Basin and north central RFC's	ADD/SUB—Add or subtract time series	ADJUST-Q—Adjust simulated to observed discharge and blend into future	INSQPLOT—Plots instantaneous discharge time series
SAC-SMA—Sacramento soil moisture accounting model	CLEAR-TS—Clear time series	CHAT—Computer hydrograph adjustment technique	WY-PLOT—Water year mean-daily flow plot
UNIT-HG—Unit hydrograph operation	WEIGH-TS—Weight time series	SACFIL1—Estimation theory (Kalman Filter) formulation of the SAC-SMA and UNIT-HG for lumped, non-snow headwater basins	SAC-PLOT—Sacramento type mean-daily flow plot
SNOW-17—HYDRO-17 snow accumulation and ablation model	CHANGE-T—Change time interval of a time series	STAT-OP—Statistical package for measuring NWSRFS effectiveness	PLOT-TS—General time series plotting utility
LAG/K—Lag and K routing	MEAN-Q—Computation of mean discharge for specified time interval		PLOT-TUL—Time-series plotting routine specifically designed for real-time operational forecasting
LAY-COEF—Layered coefficient routing			STAT-QME—Computes statistical summary of mean-daily discharge
MUSKROUT—Muskingum routing			
TATUM—Tatum routing			
DWOPER—Dynamic wave operational model			
CHANLOSS—Empirical channel-loss/gain routine			
CHANLEAK—Conceptual channel-loss/gain routine			
STAGE-Q—Converts river stage to discharge or vice-versa			
RES-SNGL—Single reservoir control operation			

Note: The 22 operations shown are complete as of this writing.

the planned operations, along with a brief description of each, is shown in Table 1. Operations are combined in a user-specified sequence to form a segment. A segment is usually comprised of all the operations needed to forecast the flow at a point. Segments use time series created by upstream segments as input, and they generate time series for use by downstream segments. Fig. 2 shows a typical sequence of operations that might be used to forecast streamflow at several points along a river. MAP and MAT time series for Area A are input to the SNOW-17 operation, which calculates snow accumulation and ablation (1). The SNOW-17 operation outputs a rain plus melt time series, which is input to the SAC-SMA operation. The rainfall-runoff modeling (4) operation, SAC-SMA, performs soil moisture accounting for Area A in order to calculate a runoff time series. The UNIT-HG operation performs the unit hydrograph calculations that time-distribute the runoff to produce a simulated streamflow time series for Forecast Point 1. Observed stage measurements are converted to observed discharge values using the STAGE-Q operation. The ADJUST-Q operation adjusts the simulated discharge time series to match the observed discharge values output by the STAGE-Q operation. The PLOT-TUL operation is used to display and plot the rain plus melt, simulated discharge, observed discharge, and adjusted discharge time series. The LAG/K operation is used to route the adjusted discharge time series at Forecast Point 1 to Forecast Point 2. The SNOW-17 operation is not needed for Area B, because there is no significant snow accumulation in this area. The MAP time series is input directly to the API operation, which is an antecedent precipitation index rainfall/runoff model. The UNIT-HG, STAGE-Q, ADJUST-Q, and PLOT-TUL are used just as they were for the upper area to produce an adjusted discharge time series for Forecast Point 2.

Both the Preprocessor and Forecast Components are separated into initialization and execution programs. Initialization programs are used to define, display, and change parametric information that can be stored on files. Examples of parametric information, which is defined at initialization time for the Preprocessor programs, include station location and identification information, the stations and weights used to estimate each station's missing data, the data correction factors for each station, and the stations and weights used to calculate mean areal time series. The Forecast Component requires the user to define the following at initialization time: (1) The operations in each segment; (2) the parametric information needed for each operation, e.g., melt factors, soil moisture storage capacities, recession constants, routing coefficients, etc.; (3) the time series needed for input and output from each operation; and (4) the order in which the segments should be executed.

Input to the execution programs is provided through the Hydrologic Command Language (HCL). This command language is the interface between the user and the Forecast and Preprocessor programs. It allows the user to easily execute a series of commands, providing some run-time information while allowing most run-time options to default to previously defined values. This allows the user the maximum amount of flexibility while keeping the required input to a minimum.

ESP, like the Preprocessor and Forecast Components, has been divided into initialization and execution programs. The initialization program allows the user to define which types of ESP analysis and displays are desired for each segment, print out the current ESP segment definition, change the current ESP segment definition, display the status of the ESP parameter file, and load the historical time series data into a form that allows more efficient execution. The HCL is used to provide input to the ESP execution program. Input that must be provided at run-time includes those segments that are to be executed and the historical data years to be used for the analysis. Other input options have default values that can be changed with the execution program if necessary.

The ESP program benefits from being designed as an integral part of the NWSRFS. The parametric information that was defined for the Operational Forecast System, e.g., segment definition, parameters needed for the operations, and the segment computational order, is also needed by the ESP program. The initial values of the states of the river system are obtained from the Forecast Component carryover files. The carryover files contain all the nonparametric information that is needed to describe the initial conditions of a model. The carryover files are kept up to date on a daily basis by the Forecast program. The input to the ESP initialization and execution programs is kept to a minimum, since the parametric and carryover information is obtained from the Operational Forecast System.

ESP Program Capabilities

A schematic of the ESP procedure is shown in Fig. 3. ESP assumes that past years of meteorological data represent possible future occurrences. Historical meteorological data are used to compute time series of mean areal precipitation and temperature. Each past year of mean areal precipitation and temperature is input to the conceptual hydrologic and hydraulic models along with the current conditions of the wa-

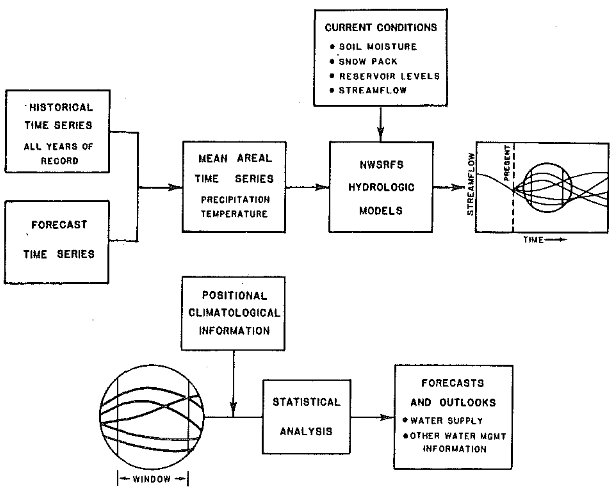

FIG. 3.—ESP Procedure

TABLE 2.—ESP Output Variables

Description (1)	Acronym (2)
Maximum mean daily value and number of days to maximum mean daily value	MXMD
Minimum mean daily value and number of days to minimum mean daily value	MNMD
Mean daily value	MD
Cumulative value (e.g., volume)	SUM
Maximum instantaneous value and number of days to maximum instantaneous value	MXIN
Minimum instantaneous value and number of days to minimum instantaneous value	MNIN
Number of days until time series gets above a criterion or number of days until time series gets below a criterion	NDTO
Number of days time series is greater than a criterion or number of days time series is less than a criterion	NDIS

tershed (e.g., snowpack, soil moisture, channel flow, and reservoir levels) to simulate possible future streamflow traces.

ESP is designed to accept any continuous procedure for snow modeling and rainfall-runoff modeling that has been programmed as an operation in NWSRFS and is currently being used in the Forecast program. Currently, snow accumulation and ablation is calculated with a model developed within the Hydrologic Research Laboratory of the National Weather Service (1). The model uses air temperature as an index to the snow cover energy exchange. Soil moisture accounting is typically performed with the Sacramento Soil Moisture Accounting model developed by personnel at the California-Nevada RFC (3,4). This is a lumped deterministic model, which continuously accounts for the movement of water throughout a number of soil zones and into the channel.

The simulation produced using the current watershed conditions with the historical meteorological data is called the conditional simulation. If N years of historical data are available, N traces of possible streamflow are simulated. The forecast period for each of these traces is scanned for the variable of interest, e.g., volume of streamflow, maximum streamflow, and minimum streamflow. A complete list of the output variables currently available in ESP is shown in Table 2. The forecast period scanned is called a window. Several windows can be analyzed in one execution. Windows can be of any length, with starting and ending dates anywhere within the simulated traces. N values of each output variable are obtained by scanning the N simulated traces. A frequency analysis can be performed on these values to produce a probabilistic forecast for each output variable of interest. ESP currently supports three probability distributions: normal, lognormal, and empirical. The empirical distribution is produced by ranking the N values and calculating the associated probability for each:

$$p = \frac{m}{(N + 1)} \qquad (1)$$

in which p = probability; and m = rank.

ESP also has the capability of analyzing the time series of observed streamflow data. In the absence of any particular knowledge about the current meteorologic and hydrologic conditions, the best possible streamflow forecast would probably be based on a frequency analysis of the observed streamflow data. The observed data represents what has occurred in the past and what might be expected to occur in the future with similar frequency. However, each year of observed streamflow occurred with its own set of initial conditions. A forecast based only on the past observed data neglects information known about the current watershed conditions. ESP uses conceptual watershed modeling to incorporate this knowledge of the current conditions into the forecast through the conditional simulation. The frequency analysis of the conditional simulated time series can be compared to the frequency analysis of the observed streamflow time series to determine the effect of the current conditions on the historical streamflow distribution.

The difference between the distributions of conditional simulated streamflow and the observed streamflow may be caused by more than the current conditions. The conditional simulation may be biased, because: (1) The mean areal precipitation and temperature time series used as input are estimates; (2) the conceptual models used to calculate snow accumulation and ablation, to convert rainfall to runoff, and to route streamflow are only approximations of the physical systems they represent; and (3) the models may not be perfectly calibrated. The observed streamflow data may also be biased, since the rating curves used to convert stages to streamflow values are often inaccurate at extreme flow levels.

In order to give the user additional information needed to assess the magnitude of the bias in the conditional simulation, a historical simulated time series is included as an ESP option. ESP calculates the historical simulated time series by using the past years of meteorological data continuously without resetting the initial conditions for each year to the current year's conditions. The historical simulated time series is also scanned for each output variable of interest and a frequency analysis performed. If no data or model errors exist, the analysis of the historical simulation should match that of the observed streamflow. Any differences between the two time series are due to the biases in the input data, model formulation and calibration inaccuracies, and observed streamflow data errors. If the differences are significant, the user can subjectively, or objectively once a methodology is developed, adjust the conditional simulation to correct for the bias.

The discussion thus far has been based on the analysis of time series of streamflow, but ESP has the ability to analyze other types of time series data. Other types of data which might be of interest include: reservoir level, reservoir volume, river stage, soil moisture, and snow water equivalent. ESP can provide probabilistic forecasts of minimum reservoir levels just as it does streamflow volumes. ESP also provides the option of analyzing observed streamflow data for a Base Period. Water supply forecasts are often issued as a percent of normal, where "normal" is the average of a certain historical period. An ESP analysis should be based on as many years as possible in order to define best the probability distributions of the output variables of interest. However, ESP provides the capability of analyzing the observed streamflow data for any base historical period, so that the forecast can still be compared to a normal base period with which the user is familiar.

A number of displays are produced by the ESP program to present the results. An example of the summary table and frequency table that can be produced by ESP is shown in Fig. 4. Heading information is provided which identifies the output variable, window, and the time series used for the analysis. The summary table shows for each time series the output variable value for each year of historical data along with the mean, standard deviation, minimum, and maximum for all the years. The frequency table shows the value of the output variable for each exceedance probability requested by the user. The frequency plot shown in Fig. 5 is an option included with the frequency analysis. ESP also produces the Run Summary Table shown in Fig. 6. The format used in the Run Summary Table is similar to the one used for forecast dissemination in the monthly publication "Water Supply Outlook for the Western United States" (8).

Simulated time series generated by ESP can be output to permanent files. These files can be used as input to later runs on downstream segments or they can be used as input to external programs with special

```
****BLUEERTH R NR RAPIDN****

SEGMENT               : BLUEERTH
OUTPUT ID             : NUMBER1
OUTPUT VARIABLE       : MAXIMUM MEAN DAILY VALUE
FORECAST PERIOD       :  2/ 8/1983 HR 24 TO  4/14/1983 HR 24   CST
FITTING DISTRIBUTION  : LOG NORMAL

      TIME SERIES 1                      TIME SERIES 2
        SIMULATED                          OBSERVED
      -------------                      -------------
        I.D.      : BLUEERTH               I.D.      : BLUEERTH
        DATA TYPE : QINE                   DATA TYPE : QME
        DELTA T   :  6 HRS                 DELTA T   : 24 HRS
```

SUMMARY TABLE
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	HISTORICAL SIMULATION		CONDITIONAL SIMULATION		OBSERVED	
WATER YEAR	VALUE IN CFSD	DAYS TO VALUE	VALUE IN CFSD	DAYS TO VALUE	VALUE IN CFSD	DAYS TO VALUE
1963	5153.8	48.	10537.2	48.	4100.0	46.
1964	776.7	65.	5472.8	27.	483.0	59.
1965	38469.1	61.	28871.4	64.	42500.3	60.
1966	3579.3	26.	6909.4	27.	4700.0	53.
1967	8085.5	56.	13667.2	56.	5300.0	56.
1968	310.3	2.	6735.2	32.	171.0	42.
1969	14925.3	62.	10375.5	62.	20900.2	61.
1970	2475.8	61.	8846.9	62.	2340.0	60.
1971	15873.3	41.	8835.7	42.	8210.1	41.
1972	4359.6	41.	7811.5	41.	3100.0	39.
1973	4114.8	37.	8361.8	37.	6940.1	36.
1974	3703.4	16.	5542.9	27.	3180.0	65.
1975	2742.3	64.	8594.9	64.	4090.0	65.
MEAN	8043.8	45.	10043.2	45.	8155.0	53.
ST DEV	9931.4	19.	5835.5	14.	11105.4	10.
MINIMUM	310.3	2.	5472.8	27.	171.0	36.
MAXIMUM	38469.1	65.	28871.4	64.	42500.3	65.

FREQUENCY TABLE
****
FITTING DISTRIBUTION: LOG-NORMAL

	HISTORICAL SIMULATION		CONDITIONAL SIMULATION		OBSERVED	
EXCEEDANCE PROBABILITY	VALUE IN CFSD	DAYS TO VALUE	VALUE IN CFSD	DAYS TO VALUE	VALUE IN CFSD	DAYS TO VALUE
.10	19926.7	65.	15386.4	64.	21975.0	65.
.50	4250.4	48.	9034.7	42.	3846.0	56.
.90	906.6	8.	5305.0	27.	673.1	37.

FIG. 4.—Sample ESP Summary and Frequency Tables

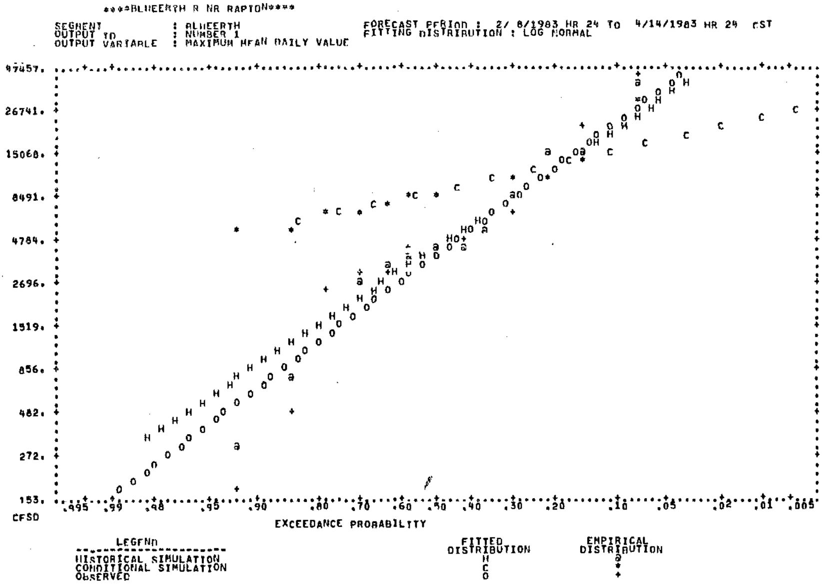

FIG. 5.—Sample ESP Frequency Plot

display or analysis capabilities. A reservoir optimization program is one example of an external program that might be used with these permanent files.

Although the skill in forecasting future precipitation and temperature is limited, some short-range forecast skill does exist. Temperature can

*** END OF RUN SUMMARY TABLE ***
FOR
SELECT OUTPUT VARIABLES

NOTE: OBSERVED AND BASE PERIOD VALUES SHOW THE MEAN AND 0.50 EXCEEDANCE PROBABILITY LEVEL
YEARS COVERED BY OBSERVED VALUE = 1962-1975

	OUTPUT VARIABLE			CONDITIONAL SIMULATED TIME SERIES AT 3 EXCEEDANCE PROBABILITY LEVELS				OBSERVED TIME SERIES	
SEGMENT	TYPE	I.D.	FORECAST PERIOD	UNITS	0.90	0.50	0.10	MEAN	.5 VALUE
GRANITEF	MXMD	GRANITEF	28FEB83-14APR83	CFSD	567.4	1351.8	3220.2	2264.6	582.0
GRANITEF	MXIN	GRANITEF	28FEB83-14APR83	CFS	585.2	1380.5	3256.8	MISSING	
GRANITEF	MNMD	GRANITEF	28FEB83-14APR83	CFSD	49.2	95.8	186.4	27.1	10.8
GRANITEF	SUM	GRANITEF	28FEB83-14APR83	ACFT	21884.5	42030.2	80720.9	27787.5	12499.0
GRANITEF	NDTO	GRANITEF	28FEB83-14APR83	CFS	37.9	9999.0	9999.0	MISSING	
GRANITEF	NDIS	GRANITEF	28FEB83-14APR83	CFSD	0.0	0.0	7.0	1.2	0.0
REDWOODF	MXMD	REDWOODF	28FEB83-14APR83	CFSD	582.7	1137.5	2220.6	2104.4	722.9
REDWOODF	MXIN	REDWOODF	28FEB83-14APR83	CFS	597.7	1157.5	2241.7	MISSING	
REDWOODF	MNMD	REDWOODF	28FEB83-14APR83	CFSD	83.5	135.4	219.6	20.2	9.2
REDWOODF	SUM	REDWOODF	28FEB83-14APR83	ACFT	25717.0	41186.3	65960.7	27881.0	14773.8
REDWOODF	NDTO	REDWOODF	28FEB83-14APR83	CFS	9999.0	9999.0	9999.0	MISSING	
REDWOODF	NDIS	REDWOODF	28FEB83-14APR83	CFSD	0.0	0.0	4.5	1.3	0.0
NEWULMMR	MXMD	NEWULMMR	28FEB83-14APR83	CFS	3005.3	6747.3	15148.6	MISSING	
NEWULMMR	MXIN	NEWULMMR	28FEB83-14APR83	CFS	3012.4	6924.9	15919.2	MISSING	
NEWULMMR	MNMD	NEWULMMR	28FEB83-14APR83	CFS	704.2	1353.5	2601.4	MISSING	
NEWULMMR	SUM	NEWULMMR	28FEB83-14APR83	CFS	84891.7	138129.5	224753.9	MISSING	
NEWULMMR	NDTO	NEWULMMR	28FEB83-14APR83	CFS	41.0	9999.0	9999.0	MISSING	
NEWULMMR	NDIS	NEWULMMR	28FEB83-14APR83	CFS	0.0	0.0	4.5	MISSING	

FIG. 6.—Sample ESP Run Summary Table

be forecast several days into the future with some confidence (7). Because of the high serial correlation in temperature data, abrupt changes between the current temperatures and the historical temperatures are not realistic. ESP allows a smooth transition from the forecast temperatures to the historical temperatures by providing the capability of specifying a weighting and blending period. The user specifies the length of a weighting period, a weight to be applied to the forecast data at the beginning of the weighting period (e.g., valid values of weights range from 0.0–1.0), a weight to be applied to the forecast data at the end of the weighting period, and a blending period length. Temperature values during the weighting period are calculated as a weighted combination of the historical value and the forecast value, where the weight of the historical value is one minus the weight of the forecast value. The weights of the forecast values vary linearly from the beginning to the end of the weighting period. Temperature values during the blending period are calculated as the sum of the historical value and some deviation, where the deviation varies linearly from the difference between the forecast value and the historical value at the beginning of the blending period to zero at end of the blending period.

Precipitation is more difficult to forecast than temperature, even on a short-range basis. Whether or not precipitation will occur can be forecast with some confidence, but it is extremely difficult to forecast precipitation amounts (5). It is even more difficult to localize quantitative precipitation forecasts so that they can be applied to individual watersheds. However, ESP also provides the capability to blend and weight precipitation data. Precipitation values during the weighting period are calculated using the same procedure used for temperature values. Precipitation values during the blending period are calculated as in the weighting period with the weight applied to the forecast data linearly decreasing to zero at the end of the blending period. As the ability to provide quantitative estimates of future precipitation and temperature increases, ESP will be able to take advantage of these forecast data.

One area of future research for ESP is the ability to incorporate knowledge of the current climatology into the procedure. Historical years of precipitation and temperature may or may not be equally representative of the current climatology. The Climate Analysis Center of the National Meteorological Center currently classifies each historical year (1948–1981) as an analogue, anti-analogue, or intermediate year. This classification is based on monthly average upper air data and reflects the similarity or dissimilarity of the historical year to the current year. If any skill exists in this classification scheme, it may be possible to develop an objective procedure for assigning weights to the historical years. These weights could be used within the ESP procedure to weight the output variable values obtained by scanning the streamflow traces. In one ESP study, years that were considered dissimilar to the current year were eliminated from the analysis without significantly affecting the results (9). The eliminated years had varying amounts of precipitation and negated one another. Research is needed to determine if this weighting scheme has any skill in relation to predicting streamflow, and if it does, an objective procedure for deriving these weights should be developed.

The National Weather Service Extended Streamflow Prediction (ESP) procedure uses conceptual hydrologic and hydraulic models, with the current watershed conditions, historical meteorological data, and forecast meteorological data to make extended probabilistic forecasts for a number of streamflow variables. Originally, the principal purpose in developing ESP was to provide an improved procedure for making water supply forecasts in snowmelt areas. ESP allows flexibility in the streamflow variables which can be analyzed, the capability to make forecasts over both short and long time periods, and the ability to incorporate forecast meteorological data into the procedure.

Because of ESP's flexibility and conceptual basis, it has many applications beyond forecasting water supply from snowmelt. Its ability to analyze peaks as well as volumes makes it suitable for issuing spring flood outlooks. The ESP program has the capability to show the peak flow at a range of exceedance probabilities, as well as to show how many historical years would have exceeded flood stage with the current conditions.

The ESP program can also be used as a drought analysis tool. The minimum streamflow, minimum reservoir level, or streamflow volume can be shown at any desired exceedance probability level. By observing how many of the historical year's simulations dip below critical levels, the user can define the risk of running short of water. If the risk exceeds an acceptable value, drought contingency measures can be taken. The streamflow time series generated by ESP could be input to other simulation models to investigate how water supply operations might be improved during a drought. These streamflow time series represent possible occurrences based on both the current conditions and forecast data. ESP provides water managers with information needed to quantitatively assess the severity of the drought, so that measures can be taken to reduce to an acceptable value the risk of running out of water.

Extended probabilistic forecasts of river stage should be beneficial to the navigation industry. Barge companies use extended forecasts for scheduling and in deciding how heavily to load their barges. The probabilistic information will give barge companies an idea of the risk involved, so that the expected profits can be maximized.

Recreation benefits of the ESP program include the capability to make a long-term forecast of when the river stage will get above or below certain levels. This is information that rafting enthusiasts, canoeists, and others are often interested in.

A final example of a way in which ESP should yield large economic savings is through the more accurate probabilistic forecast information that it can provide as input to multi-purpose reservoir operations, e.g., power generation, flood control, and water supply. As the management of our nation's water resources becomes more critical over the coming decades, the margin of error in making water management decisions must be reduced through the use of improved procedures such as ESP.

In summary, the probabilistic forecasts obtained with ESP should provide useful information to a wide range of users interested in extended forecasts of streamflow and streamflow-related variables. However, the largest single potential impact of ESP products is probably in the area of water supply. As more stress is put on the nation's water supply, the type of information that ESP can produce should prove to be very valuable to those involved in water management.

Acknowledgments

The writer would like to thank Mr. Edward J. VanBlargan (National Weather Service) and Dr. James A. Smith (Interstate Commission on the Potomac River Basin) for the excellent work they did in coding, debugging, and testing large portions of the ESP program. The writer would also like to thank Dr. Eric A. Anderson, Dr. George F. Smith, and Mr. Donald P. Laurine (National Weather Service) for their advice throughout the project.

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