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THE USE OF HYDROMETEOROLOGICAL DATA IN THE NWS EXTENDED STREAMFLOW PREDICTION PROGRAM

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1. INTRODUCTION

The National Weather Service River Forecast System (NWSRFS) provides the capabilities to produce both short-range and long-range streamflow forecasts. The NWSRFS operational forecast program generates short-range streamflow forecasts by inputting observed and forecast precipitation and temperature data to conceptual hydrologic and hydraulic models which simulate streamflow. Observed streamflow data are used to adjust the simulated streamflow to correct for errors which may have resulted from a combination of poor initial conditions, input errors (e.g., incorrect precipitation and temperature data), and model errors. The states of the models are updated and 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. The Extended Streamflow Prediction (ESP) procedure that has been developed by the National Weather Service (NWS) uses conceptual hydrologic and hydraulic models to simulate possible future streamflow using the current watershed conditions (e.g., snowpack, soil moisture, channel flow, and reservoir levels) with historical meteorological data as input (e.g., temperature and precipitation). The ESP procedure assumes that each year of historical meteorological data could occur in the future and simulates the future streamflow trace that would result from each, using the current watershed conditions. 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. Several programs that use the ESP procedure have been developed since that time. The California-Nevada RFC, the Colorado Basin RFC and the Alaska RFC are currently using the ESP procedure to help in forecasting water supply. The ESP program is being used in the Washington, D.C., metropolitan area by the Middle Atantic RFC and the Interstate Commission on the Potomac River Basin (ICPRB) to provide forecasts for water supply operations during droughts. (Smith et al., 1982)

The ESP program was developed originally to forecast water supply from snowmelt. Because of ESP's flexibility and conceptual basis, it has many additional applications. Its ability to analyze streamflow peaks as well as volumes make it suitable for issuing spring flood outlooks. ESP 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.

As demonstrated by the Washington, D.C. water supply project, ESP can be used as a drought analysis tool. The minimum streamflow or reservoir level can be shown at any desired exceedance probability value. By observing how many of the historical years' 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. In fact, the ICPRB operations are set up in this manner. 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 the risk of running out of water to an acceptable value.

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.

The probabilistic forecasts obtained with ESP should provide useful information to a wide range of users interested in extended forecasts

of streamflow and stage. The following sections discuss the development of the ESP program, its capabilities, and its hydrometeorological data requirements. Future research possibilities are also presented.

2. OPERATIONAL FORECAST SYSTEM

The NWSRFS comprises several large systems and programs including a Calibration System, the Operational Forecast System, and the ESP Program. The Operational Forecast System must be described in order for the basis of the ESP Program to be understood, since ESP has been designed as an integral part of the forecast system.

The Operational Forecast System is a complex software system that performs all the tasks needed for short-range river forecasting. A schematic of the system is shown in Figure 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 data from the Preprocessor Data Base, estimates missing data as required, and calculates mean areal time series of precipitation (MAP), temperature (MAT), and potential evapotranspiration (MAPE). The mean areal time series are then written to the Processed Data Base. The Forecast Component reads the necessary processed time series from the Processed Data Base, performs the requested hydrologic and hydraulic simulation, including model updating and display of results, and writes the simulated streamflow back to the Processed Data Base. Input to the Preprocessor and Forecast Components is provided through the Hydrologic Command Language (HCL). The command language 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.

Operations are the basic building blocks of the forecast program. Operations are computer algorithms that use time series data as input to perform further simulations and/or analyses. Hydrologic and hydraulic models, display procedures, analysis techniques, and arithmetic computations can all be programmed as operations. A list of the planned operations, along with a brief description of each, is shown in Table 1.

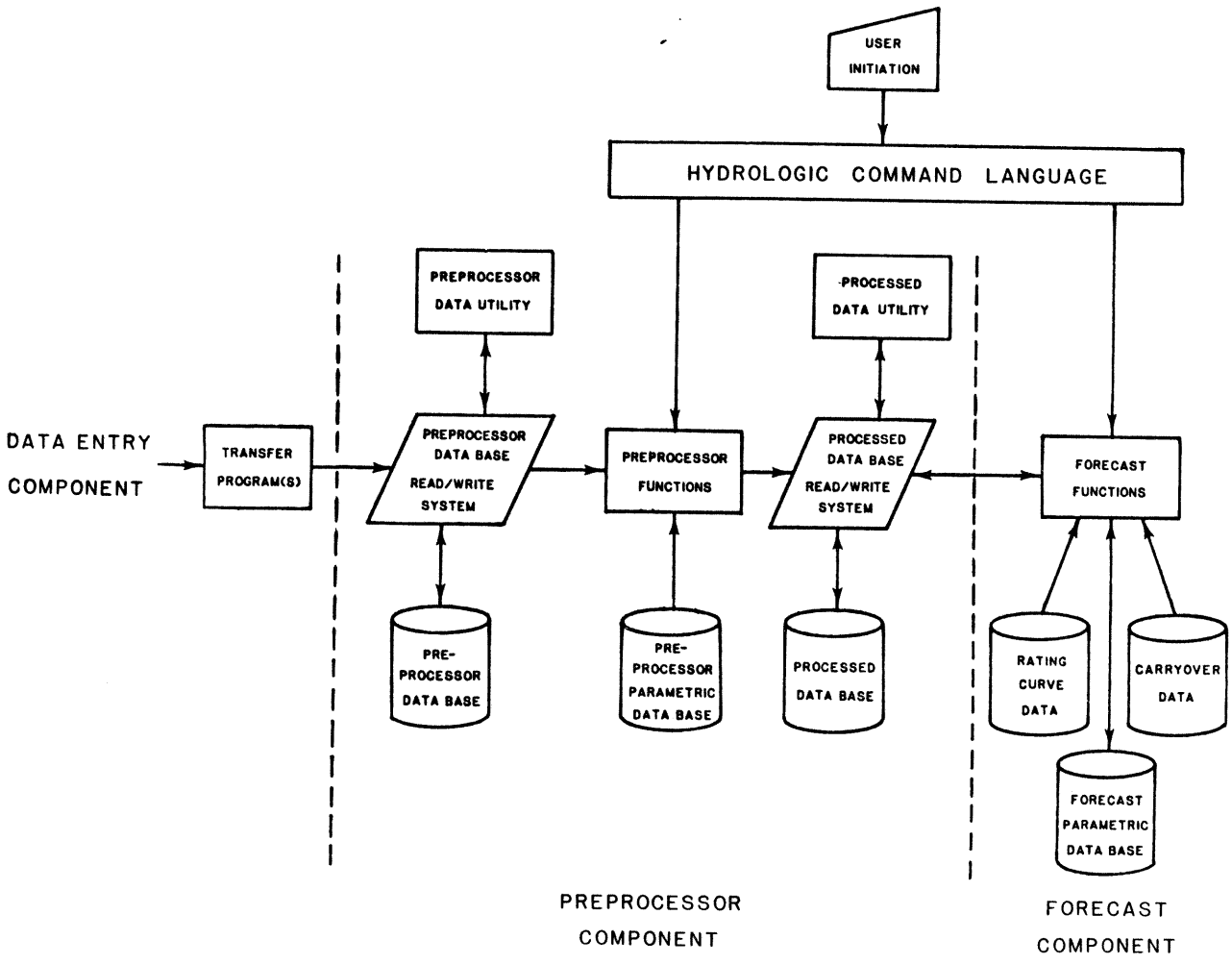

Figure 1. Operational Forecast System.

Table 1. Operations Planned for Forecast Component of NWSRFS Version 5.

HYDROLOGIC/HYDRAULIC MODELS

API/MKC	--	Antecedent Precipitation Index Rainfall-Runoff Model for the Missouri Basin and North Central RFC's
SAC-SMA	--	Sacramento Soil Moisture Accounting Model
UNIT-HG	--	Unit Hydrograph Operation
SNOW-17	--	HYDRO-17 Snow Accumulation and Ablation Model
LAG/K	--	Lag and K Routing
LAY-COEF	--	Layered Coefficient Routing
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

UPDATING AND VERIFICATION PROCEDURES

ADJUST-Q	--	Adjust Simulated to Observed Discharge and Blend into Future
CHAT	--	Computer Hydrograph Adjustment Technique
SACFIL1	--	Estimation Theory (Kalman Filter) Formulation of the SAC-SMA and UNIT-HG for Lumped, Non-Snow, Headwater Basins
STAT-OP	--	Statistical Package for Measuring NWSRFS Effectiveness

ARITHMETIC COMPUTATIONS

ADD/SUB	--	Add or Subtract Time Series
CLEAR-TS	--	Clear Time Series
WEIGH-TS	--	Weight Time Series
CHANGE-T	--	Change Time Interval of a Time Series
MEAN-Q	--	Computation of Mean Discharge for Specified Time Interval

DISPLAYS

INSQPLOT	--	Plots Instantaneous Discharge Time Series
WY-PLOT	--	Water Year Mean-Daily Flow Plot
SAC-PLOT	--	Sacramento Type Mean-Daily Flow Plot
PLOT-TS	--	General Time Series Plotting Utility
PLOT-TUL	--	Time-Series Plotting Routine Specifically Designed for Real-Time Operational Forecasting
STAT-QME	--	Computes Statistical Summary of Mean-Daily Discharge

NOTE: The 22 operations designated **in boldface** are complete as of this writing.

Any continuous hydrologic or hydraulic model can be programmed as an operation in NWSRFS. Currently, snow accumulation and ablation is calculated with a model developed within the Hydrologic Research Laboratory of the National Weather Service (Anderson, 1975). 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 (Burnash et al., 1972). 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 unit hydrograph operation is used to time distribute the runoff. Several operations are available that perform channel routing. 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. Figure 2 shows a typical sequence of operations that might be used to forecast streamflow at several points along a river. Segments use time series created by upstream segments as input, and they generate time series for use by downstream segments.

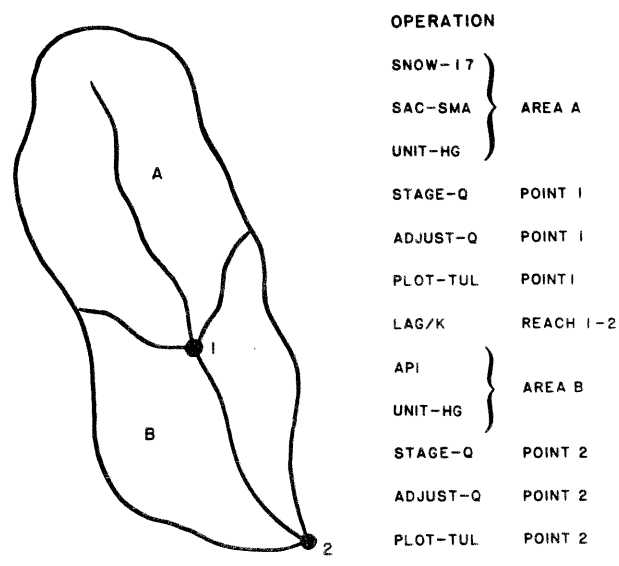

Figure 2. Streamflow Forecasting Using Operations

The ESP program takes advantage of the work that has been done by the forecast program. It uses the parametric information that was defined by the forecast program, e.g., segment definition, parameters needed for the operations, and the segment computational order. ESP gets the initial values of the states of the system from the forecast component carryover files which are kept up to date by the forecast program. (Carryover consists of the initial states of the variables of the NWSRFS models, i.e., all the nonparametric information that is needed to start up a forecast model.) ESP obtains its meteorological time series data from the historical data files and writes its output time series data to special ESP time series data files.

By linking ESP to the Operational Forecast System parameter and carryover files and to the HCL, the required input is kept to a minimum and ESP has access to the current states of the models in each segment.

3. ESP PROGRAM DESCRIPTION

A schematic of the ESP procedure is shown in Figure 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 conceptual hydrologic and hydraulic models along with the current conditions of the watershed (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. 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 can be simulated. The forecast period for each of these traces can be 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 modularity of the program allows additional output variables to be easily added.

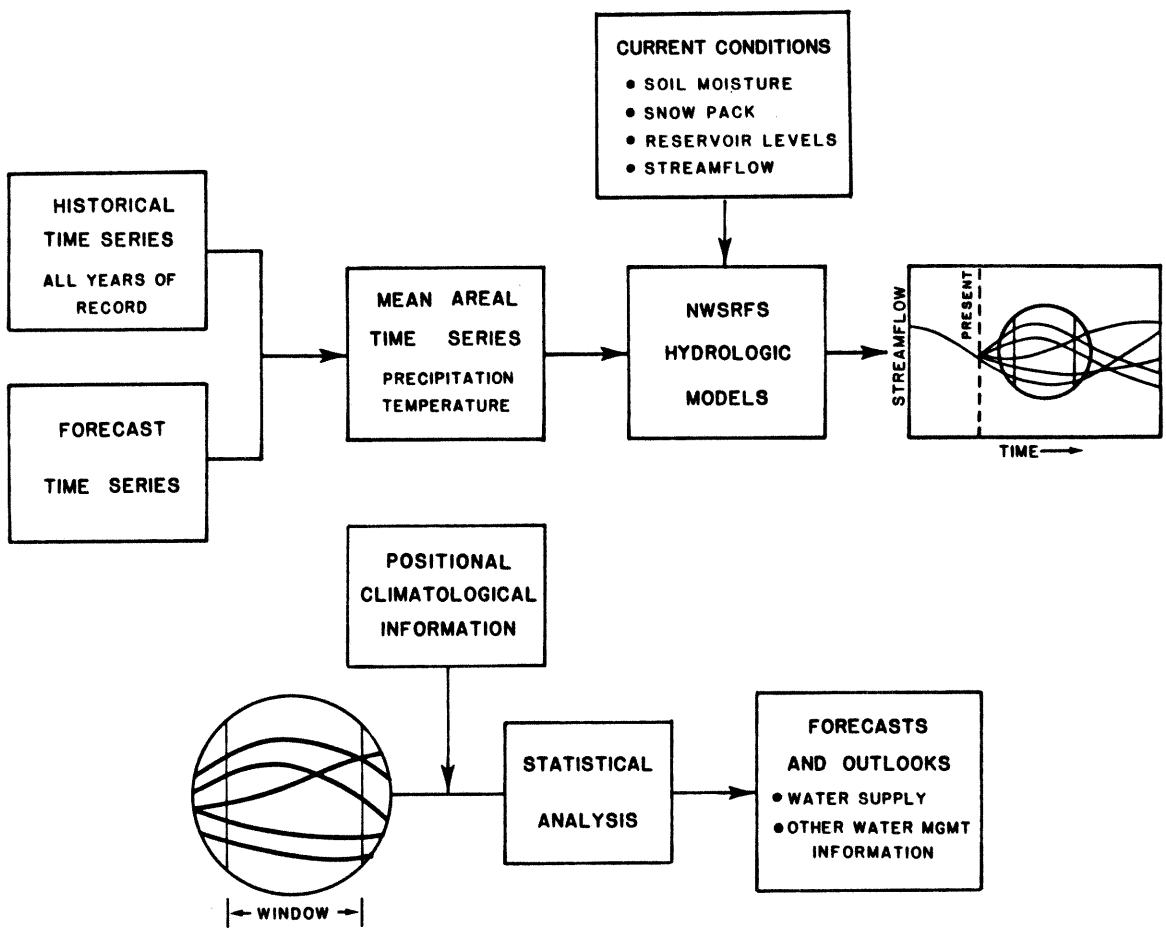

Figure 3. The ESP Procedure

Table 2. ESP Output Variables

1. MAXIMUM MEAN DAILY VALUE, AND NUMBER OF DAYS TO MAXIMUM MEAN DAILY VALUE. (MXMD)

2. MINIMUM MEAN DAILY VALUE, AND NUMBER OF DAYS TO MINIMUM MEAN DAILY VALUE. (MNMD)

3. MEAN DAILY VALUE. (MD)

4. CUMULATIVE VALUE (E.G., VOLUME). (SUM)

5. MAXIMUM INSTANTANEOUS VALUE, AND NUMBER OF DAYS TO MAXIMUM INSTANTANEOUS VALUE. (MXIN)

6. MINIMUM INSTANTANEOUS VALUE, AND NUMBER OF DAYS TO MINIMUM INSTANTANEOUS VALUE. (MNIN)

7. NUMBER OF DAYS UNTIL TIME SERIES GETS ABOVE A CRITERION, OR NUMBER OF DAYS UNTIL TIME SERIES GETS BELOW A CRITERION. (NDTO)

8. NUMBER OF DAYS TIME SERIES IS GREATER THAN A CRITERION, OR NUMBER OF DAYS TIME SERIES IS LESS THAN A CRITERION. (NDIS)

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 accumulated by scanning the N traces simulated. 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, log-normal, and empirical. The empirical distribution is produced by ranking the N values and calculating the associated probability for each: $p = m/(n + 1)$,

where p = probability, m = rank, and n = N (number of values).

ESP has the capability of analyzing several time series in addition to the conditional simulated time series. One of these is the time series of observed streamflow data. If nothing were known about the current watershed states, the best possible forecast would 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 initial watershed conditions different from one another and different from the current year's conditions. A forecast based only on the past observed data neglects information known about the current conditions. ESP uses conceptual 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: the mean areal precipitation and temperature time series used as input are estimates; 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 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 low flows and sometimes at high flows.

In order to give the user additional information needed to assess the magnitude of the bias in the conditional simulation, a historical simulated streamflow time series is included as an ESP option. ESP calculates the historical simulated time series by using 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 can be 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 would be due to biases in the input data, model formulation and calibration inaccuracies, and observed streamflow data errors. If the differences were significant, the user could subjectively, or objectively once a methodology is developed, adjust the conditional simulation to correct for the bias.

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 best define 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 the user is familiar with.

ESP results are presented in the form of several displays. An example of the summary table and frequency table displays is shown in Figure 4. Heading information is provided which describes the output variable and window being analyzed and the time series which were accumulated. The summary table shows the accumulated value for each year of historical data used for simulation along with the mean, standard deviation, minimum, and maximum for each time series type analyzed. The frequency table shows the value of the output variable for selected exceedance probability values. The frequency analysis has the options of providing an exceedance probability plot and including the output variable in a run summary table.

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

****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 SIMULATED		TIME SERIES 2 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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WATER YEAR	HISTORICAL SIMULATION VALUE IN CFSD	HISTORICAL SIMULATION DAYS TO VALUE	CONDITIONAL SIMULATION VALUE IN CFSD	CONDITIONAL SIMULATION DAYS TO VALUE	OBSERVED VALUE IN CFSD	OBSERVED 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.	5542.8	27.	3180.0	65.
1975	2742.3	64.	8594.8	64.	4090.0	65.
MEAN	6043.8	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

EXCEEDANCE PROBABILITY	HISTORICAL SIMULATION VALUE IN CFSD	HISTORICAL SIMULATION DAYS TO VALUE	CONDITIONAL SIMULATION VALUE IN CFSD	CONDITIONAL SIMULATION DAYS TO VALUE	OBSERVED VALUE IN CFSD	OBSERVED 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.

Figure 4. Sample ESP Summary and Frequency Tables.

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 level just as it does streamflow volume. Also, short-term forecasts of precipitation and temperature can be incorporated into ESP through a blend procedure that computes a linear weighting of the historical value and the forecast value. The user specifies a weighting period length along with the weights assigned to the forecast data at the beginning and end of the weighting period. A blending period length is also specified. The weight is gradually transferred to the historical data during the blending period. The ability to use short-term forecast temperature data should prove extremely useful, since the serial correlation and short-term forecast skill for temperature are rather high. Because of the lower skill associated with precipitation forecasts, less improvement would be expected for precipitation, except for cases in which the forecast precipitation in the near future is zero or insignificant.

4. FUTURE RESEARCH

The latest version of the ESP program is ready for operational use, but a number of possibilities exist for making future improvements. The possible improvements can be divided into five distinct categories: 1) improving the hydrologic and hydraulic models, 2) restructuring the program and/or data files to allow more efficient processing, 3) providing better estimates of the current watershed states, 4) reducing and/or defining the uncertainty of both the historical and forecast meteorological data, and 5) increasing the information content of the output. Since ESP has been designed as an integral part of the forecast system, research conducted in the Hydrologic Research Laboratory on other parts of the system benefits ESP.

The models used for streamflow simulation are approximations of the physical systems they represent. As more experience is obtained with these models, ideas for improvements and ideas for new models are generated. Before these models can be used operationally they must be calibrated with historical data. The data management tasks and parameter adjustment process that are part of the calibration procedure are time consuming and require a great deal of hydrologic knowledge on the part of the user. Research is being conducted that will make the calibration procedure more automated (Sorooshian, 1981 and Posada et al., 1982). The parts of the procedure (i.e., data analysis, etc.) that must be done manually can be streamlined by providing the user with additional information useful for analysis. The use of computer-generated graphics will play a major role in streamlining and improving the calibration procedure.

The ESP program has large computational demands. Input/output functions can be very time consuming when the program is processing 20 to 30 years of historical hydrometeorological data for each watershed in a large river system. Disk storage for these data could also become a problem with the current system constraints. A number of data compression techniques will be investigated in an attempt to reduce these demands.

ESP obtains the current states of the watershed from the forecast program. These states may be poor estimates due to errors in the input precipitation and temperature data and inaccuracies in the simulation models. The forecaster can subjectively adjust the Sacramento Soil Moisture Accounting Model states. Several research and development efforts for objective adjustment procedures are underway. One technique, the Computed Hydrograph Adjustment Technique (Sittner et al., 1979), automatically adjusts the precipitation and the unit hydrograph ordinates so that the simulated streamflow matches the observed streamflow more closely. The states of the soil moisture model are adjusted indirectly with this technique since the precipitation has been changed. Several researchers have applied estimation theory techniques which automatically and objectively provide optimal estimates of the states of the Sacramento Soil Moisture Model (Kitanidis et al., 1978 and TASC, 1980). A procedure has been developed that uses snow course data to update the snow water equivalent calculated by the model (Carroll, 1978). ESP will benefit from the improved estimates of the states that these procedures provide. Another factor which would indirectly provide better estimates of the models' states would be better estimates of the operational mean areal precipitation values. A project is currently underway to develop a procedure that will accept precipitation data from multiple sensors (gage, radar, and satellite) and objectively compute optimal estimates of mean areal precipitation (Greene et al., 1979).

The ESP procedure uses historical years of precipitation and temperature data to represent possible future occurrences. The program has the capability to blend available forecast data with the historical data. The weights are currently assigned to the historical and forecast data subjectively, but if the uncertainty of the forecast data could be defined, an objective procedure for weighting the two data types could be developed. As our ability to forecast precipitation and temperature increases, the uncertainty of the forecast data decreases. This should lead to more accurate and less variable ESP streamflow forecasts. Another possibility for incorporating current hydrometeorological information into the ESP program is through the weights assigned to the individual historical years. Currently each historical year is considered to be equally representative of what could occur this year. Studies are underway to investigate the feasibility and advantages of weighting historical years differently, based on knowledge of the current weather patterns and the similarity or dissimilarity to past years.

The last category of improvements to ESP deals with increasing the information content of the output. The historical simulation option was included in the ESP program to provide the information needed by the user to subjectively adjust for the simulation bias. A procedure is needed which would automatically adjust the conditional simulation for this bias.

Since a conceptual soil moisture accounting model is used in ESP, a lot of information is available that is not directly related to streamflow. ESP could be easily modified to perform statistical analyses on the various soil moisture states of the soil moisture accounting model just as it does on streamflow. By observing how these soil moisture states vary historically, additional insight might be gained as to what constitutes a drought. This insight could then be used to better define the severity of an existing or forecast drought.

Additional information that is not currently output by the soil moisture model is the actual evapotranspiration computed by the model. This information could be made available if there was a demand for it. As ESP use becomes more widespread, there will be demands for new products and ideas for improvements to existing products.

5. SUMMARY AND CONCLUSIONS

The NWS ESP program uses conceptual hydrologic and hydraulic models along with the current conditions, historical meteorological data, and forecast meteorological data to make extended probabilistic forecasts for a number of streamflow variables. 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. ESP products should be particularly useful to those involved in water management.

Several possibilities for improving the ESP program are presented. Some of the more significant possibilities are: compressing the data to allow more efficient processing, improving the forecast temperature and precipitation input to the model, defining the uncertainties of these input data so that an objective blend procedure

could be developed for merging the forecast and historical data, developing an objective procedure to correct for simulation bias, and developing a procedure that would enable historical years to be weighted based on their similarity to the current year.

Because of the conceptual basis of the models that are part of NWSRFS, several possibilities exist for taking advantage of improvements in forecast data and for providing more detailed information to interested users.

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