THE NWS EXTENDED STREAMFLOW PREDICTION TECHNIQUE

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1.0 INTRODUCTION

As the utilization of our nation's water resources becomes more intense, water management decisions may often be improved by including information regarding future values of a variety of streamflow properties in the decision process. Forecasts of daily streamflows, maximum flows, minimum flows, flow volumes, etc. may be of use to many different users. Industrial discharges and, therefore, production schedules may be tied directly to river flows. Thus, a knowledge of future minimum streamflows may help reduce uncertainty in planning plant production. Reservoir operators may use estimates of future inflows to update operating policies. Users of navigable waters, for example, may more effectively plan shipping schedules with a better understanding of future river stages, and water supply managers may make more efficient use of limited supplies by having better information about future storm or precipitation prospects.

Traditionally, the National Weather Service has provided a product for water managers to help reduce the uncertainty in anticipating future water availability. Water supply forecasts for October through September are issued by NWS river forecast centers for about 600 locations in the U.S., mostly associated with areas of significant snow accumulation and melt. These forecasts are generally presented as annual volumes for given levels of probability: most probable (i.e., 50% exceedance), most probable maximum (i.e., 10% exceedance), and most probable minimum (i.e., 90% exceedance).

The newest tool developed by the NWS for water supply forecasting and for long-range streamflow forecasting in general is the subject of this paper. The tool is called the NWS Extended Streamflow Prediction model or, in a more appropriately cryptic vernacular, ESP. The basic composition of the model, its accompanying methodology, example applications, and prospects for research and improvement will be presented.

There are a variety of ways to forecast future streamflows. The most common methods have centered on regression formulas where the independent variable, streamflow, is a function of watershed indicators such as snow course measurements and future values of precipitation and temperature at specific probability levels. Regression techniques, although quite simple and straightforward, have a number of crucial shortcomings. They are least reliable during extreme events. This is particularly true for low flows where the probability distribution often

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has a flat tail which may not be represented very well by regression. The physical structure may not be adequately represented by the regression techniques. When conditions arise that did not occur in the sample of data used to fit the regression, estimates of streamflow given by the regression may not be reliable. Also, the lowest values of streamflow depend upon the nature of a nonlinear ground water system whose performance may not be well represented by regression.

The NWS ESP technique follows a more physically based approach through the use of a conceptual hydrologic model. Through an appropriate selection of future precipitation and temperature values, a more complete description of watershed physics and a probabilistic analysis of model outputs, a better representation of major causes of uncertainty in future streamflows is possible. The ESP technique overcomes many of the inherent weaknesses of a regression analysis and is more flexible as well. For example, with each new flow property needed to be analyzed, a new regression formula is required. Such procedure development is avoided by the ESP model which would only require a few extra lines of code in the statistical analysis routine. Thus, requests for new information can be handled expeditiously.

2.0 EXTENDED STREAMFLOW PREDICTION MODEL

The Extended Streamflow Prediction technique utilizes a subset of the collection of hydrologic, hydraulic, and data processing functions known as the National Weather Service River Forecast System (NWSRFS) (Ostrowski, 1979; Curtis and Smith, 1976).

The meteorological data processing routines of the NWSRFS that are needed by ESP include:

a. Mean Areal Precipitation -- Routines that transform point estimates of precipitation into areal averages.

b. Mean Areal Temperature -- Routines to convert point temperature estimates to areal averages.

c. Mean Areal Evapotranspiration -- Routines to compute mean areal evapotranspiration.

The major hydrologic and hydraulic computational elements that form the core of ESP are:

a. Soil Moisture Accounting -- Routines to simulate the distribution and movement of moisture through the soil profile.

b. Snow Accumulation and Ablation -- Routines to simulate the buildup and subsequent melt of snow cover.

c. Channel Routing -- Various hydrologic and hydraulic methods used for describing the movement of water through stream channels.

ESP as developed by the NWS is a stochastic dynamic model that utilizes these conceptualizations of catchment hydrology in conjunction with available historical data to produce probabilistic estimates of future streamflows. The following paragraphs briefly detail the technical aspects of the ESP procedure. More complete descriptions can be found in Twedt, et al., (1977), and Twedt, et al., (1978).

2.1 Conceptual Models

Soil Moisture Accounting

The model used for runoff computations in the NWSRFS is the Sacramento soil moisture accounting model (Figure 1) (Burnash, et al., 1973). It can be classified as a quasi-distributed deterministic model. With respect to each soil moisture accounting area, the model is a lumped parameter, lumped input type. The variability of conditions within a watershed can be represented by multiple soil moisture accounting areas.

Vertically, the model divides the soil into two soil moisture accounting zones: an upper zone defining the upper soil layer and interception storage, and a lower zone representing the bulk of the soil moisture and ground water storage.

The two zones are viewed as storing both "tension" and "free" water. Tension water is that water which is held tightly to the soil particles, whereas free water constitutes the portion available for movement within the soil layer. Moisture entering the upper zone must first fulfill tension water requirements before water can move to free water storage. Free water quantities are reduced through percolation, horizontal interflow, evapotranspiration, or tension water replenishment. Tension water can only be depleted by evapotranspiration. The model recognizes and generates five components of flow to the channel:

1. Direct runoff, resulting from moisture applied to impervious areas.
2. Surface runoff, resulting when rainfall and melt rates are greater than the upper zone intake.
3. Interflow, lateral drainage from upper zone free water.
4. Primary base flow, lateral flow from lower zone primary storage.
5. Supplementary base flow, lateral flow from lower zone supplementary storage.

Snow Accumulation and Ablation

The snow accumulation and ablation model (Figure 2) is a conceptual model that describes the important physical processes occurring during buildup and decay of the snow cover. Output from the snow model, which becomes input to the soil moisture accounting model, is snow cover outflow (melt plus rain exiting the snow pack) plus rain that fell on bare ground.

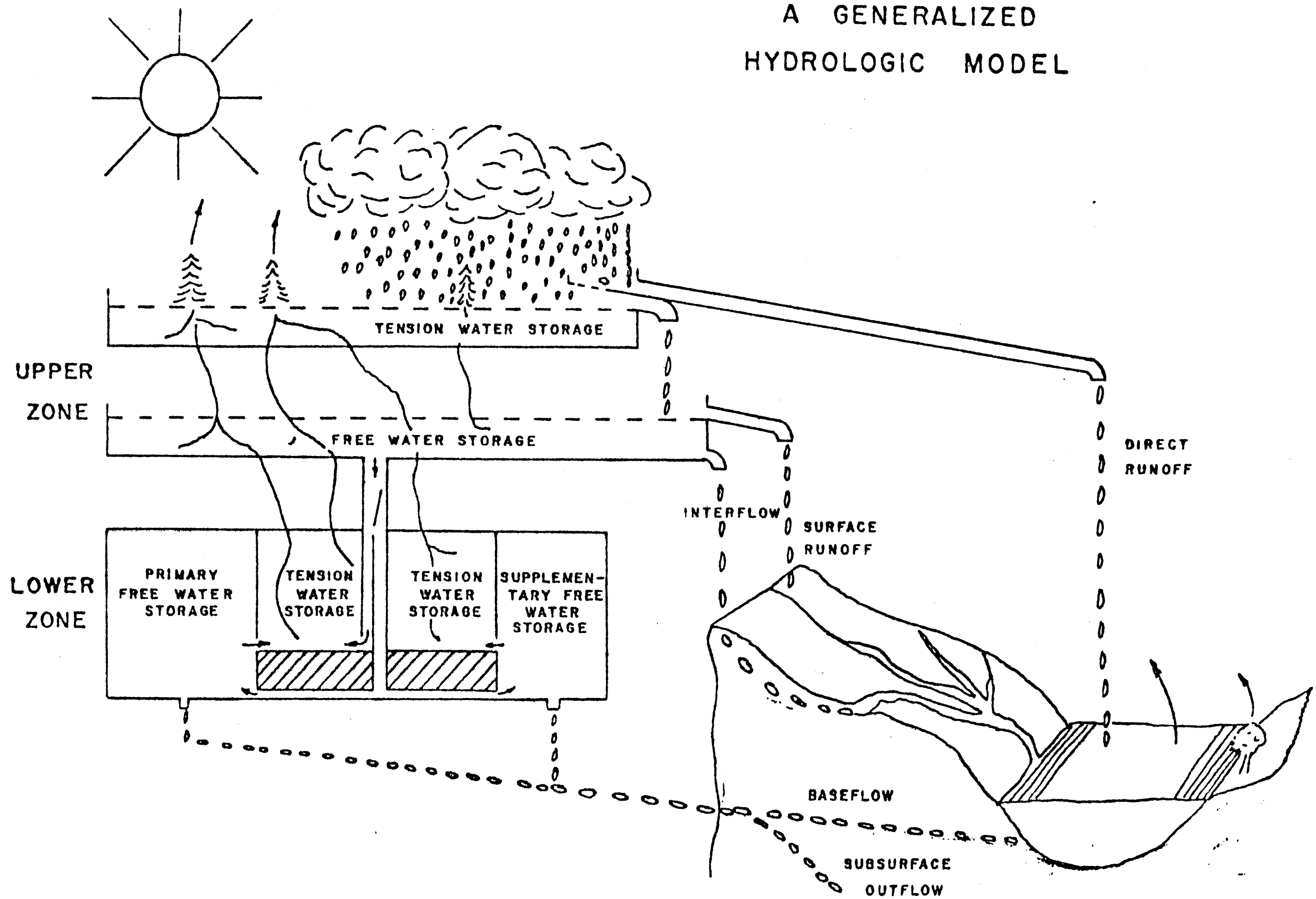
The current version of the NWSRFS snow model uses air temperature as the only index to energy exchange across the air-snow boundary (Anderson, 1973). The air temperature controlled snow model is used because air temperature data are readily available in a real-time forecasting environment, and close agreement has been exhibited between the air temperature index model and a more detailed energy balance snow cover model in simulating runoff in a limited number of test cases.

2.2 Methodology

The general approach to ESP assumes that the conceptual models are reasonable representations of catchment hydrology, and that the set of historical time series of temperature and precipitation represents an ensemble of equally likely sequences of model inputs. Separate simulations of catchment response are produced for each set of input time series, using in each run the current catchment conditions. The

Figure 1

A GENERALIZED HYDROLOGIC MODEL



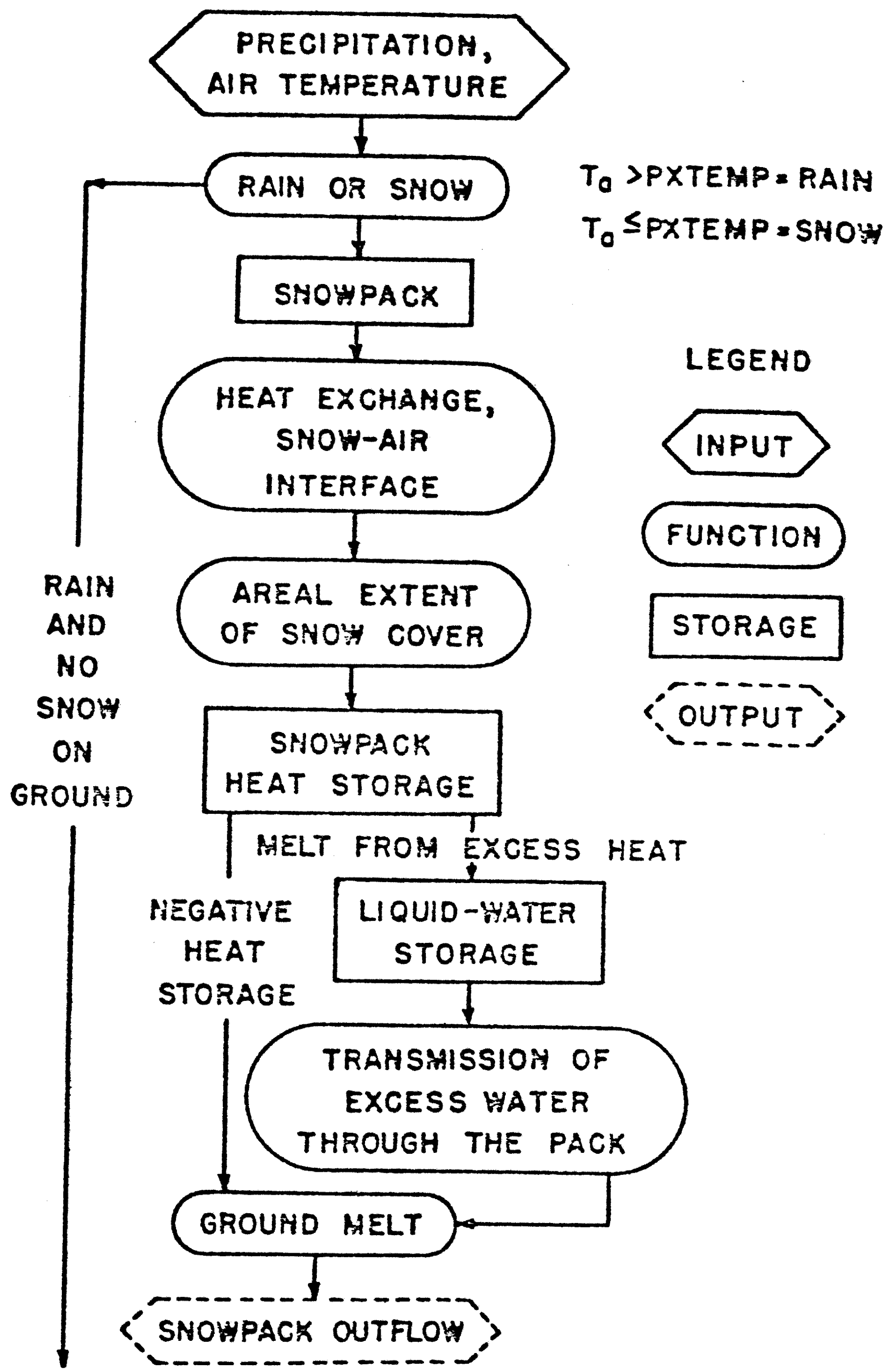


FIGURE 2.-FLOW CHART OF SNOW ACCUMULATION AND ABLATION MODEL.

resulting collection of streamflows is assumed to be representative of the possible future outflows that might be expected, given the current catchment conditions. Frequency distributions can be developed for selected characteristics of the future streamflows (i.e., total volume, peak flow, etc.). From the frequency distributions, parameters can be estimated for supposed underlying probability distributions, enabling one to relate streamflow information to a chance of occurrence. Forecasts of streamflow at user-selected levels of probability can then be provided for any time period in the future.

Historical time series are currently used as future inputs rather than other alternatives such as data synthesized by stochastic generation procedures. In making this decision, certain tradeoffs between the advantages and disadvantages of each technique must be considered. Historical data sequences contain more information since stochastic processes are capable only of mimicking reality, mostly by attempting to preserve the lower moments of an assumed probability distribution. Additional difficulties with stochastic generation arise from defining the appropriate probability distributions, and from the preservation of observed time and space correlation structures. However, as the ESP technique gets implemented nationally, the large computer storage requirements associated with the historical data must be considered carefully against the minimal storage requirements of stochastic generation techniques which need only store a small number of parameter values.

2.3 Data Requirements

The ESP model requires three general types of data other than program control and option information: (1) hydrological model parameters, (2) initial basin conditions, and (3) representative future 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, snow pack water-equivalents, and other snow cover variables. The values are available to the model as carryover 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 representative future 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. 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.

2.4 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 in the basin. The ESP method assumes that the statistical distribution of the flow property of interest is known. Given the known probability distribution, and its parameters which are calculated from the set of sample values, the model determines expected values of streamflow properties at the probability levels of occurrence requested by the user.

The differences between the forecast distribution of streamflows derived by ESP and the climatological distribution are a function of two things: (1) the information content of initial snow and soil moisture conditions; and (2) the information (if any) regarding future weather scenarios that has been incorporated into the data input sequence.

The influence of both types of information on extended streamflow predictions decay with time. Thus, as the range of the forecast period increases, streamflow predictions converge to the climatic or marginal values.

3.0 ESP EXAMPLES

Although Extended Streamflow Prediction can apply to just about any future streamflow situation, one major application of the ESP model described here is seasonal water supply forecasting. Currently, one version of ESP is being used routinely by the California-Nevada River Forecast Center to provide water supply outlooks for the Sierra-Nevada mountain region. A second version is being operated by the Salt Lake City River Forecast Center for the central Rocky Mountain area. The Hydrologic Research Laboratory of the NWS Office of Hydrology maintains a version for development purposes.

Two examples of the use of ESP for water supply forecasts will be presented here. One example pertains to the drought situation that existed in California during water years 1976-77. A second example will exhibit water supply forecasts in the metropolitan Washington, D. C. area during the northern Virginia drought of fall of 1977.

3.1 California Drought

The period during water years 1976-77 was one of record low precipitation patterns in California. Lacking sufficient amounts of runoff from melting snow packs, reservoir levels fell to record lows and regional water shortages were experienced.

Effects of precipitation shortfalls on the successive water supply forecasts can be seen in Table 1. At the beginning of the 1976 water supply forecasting season, there was still a reasonable chance that, if normal precipitation patterns reappeared, water shortages would not be severe. However, as the season progressed, it became obvious to the forecasters that even the return of normal precipitation regimes would

TABLE 1

WATER SUPPLY FORECASTS

SAN JOAQUIN BASIN

MOST PROBABLE WATER YEAR FLOWS
(% of 1958 - 1972 Average)

	1976	1977	1978
JAN 1	75	60	103
FEB 1	51	42	130
MAR 1	45	23	150
APR 1	37	20	179
MAY 1	33	16	189

not be sufficient to prevent shortages. Fortunately for many Californians, 1976 followed seasons of normal or above normal precipitation, and water carried over in storage facilities served to buffer the shortage situation.

During water year 1977, precipitation-producing storms were again bypassing the region. By January 1977, computed soil moisture deficits were so large that even the return of higher than normal rainfalls would not totally alleviate the drought condition. In addition, meteorological analyses indicated that storm patterns similar to those experienced the previous season were present. A return to normal precipitation was, at the time, judged unlikely to occur. To emphasize the gravity of these conclusions, a special press release was prepared and released by the California-Nevada River Forecast Center providing warnings of these conditions at a time when the state was only 25% into its normal precipitation year (Twedt, 1978).

Wet conditions fortunately returned to California during the fall of 1977. Precipitation was so heavy that by the beginning of the water forecast season in 1978, the drought appeared to finally be over. Again, special press releases were in order, but this time a return to normal conditions was indicated by the River Forecast Center in January 1978. The wet conditions persisted and soon Californians had to face a problem which they had not faced in years -- too much water!

3.2 Northern Virginia Drought

In late 1977 a drought of limited spatial scale was in progress in northern Virginia and the water supply for parts of the metropolitan Washington, D. C. area was severely threatened. This was the driest year in the previous 27 years. The ESP model was used to assess the situation and to analyze alternative water conservation measures that would bring the risk of experiencing specific water shortage conditions to within acceptable levels. The ESP application by the NWS began late in September 1977.

One of the significant problems in the northern Virginia case was the tremendous uncertainty in the future quantities of streamflow to be expected. The Occoquan Reservoir serving northern Virginia was almost empty. Inflow to the reservoir from natural ground water seepage was less than the rate water was being taken from the reservoir. Before runoff could occur from the land surface, it was necessary for the soil moisture and ground water systems to be replenished by rainfall. At the same time, natural evapotranspiration was continuing to deplete the water remaining in the soil moisture and ground water systems. The soil moisture and ground water deficiencies were estimated to total about 5.5 inches. This was of considerable concern because the mean October rainfall of 2.83 inches is much less than this moisture deficit. Preliminary studies had shown that the historical streamflow during the driest years in the past, when combined with the depleted contents of the Occoquan Reservoir, would not suffice to meet the needs for water at the current demand rate.

Applying the ESP technique to the northern Virginia case, it was important to consider if the future precipitation series was adequately represented by the historical series, or if there was some information available in this particular year that would indicate the forthcoming October would be wetter or drier than normal. Therefore, we looked very carefully at the forecast information available from the National Weather Service long range prediction unit for October. Dr. Donald L. Gilman, Chief of the NWS Long Range Prediction Group, did not believe that a very accurate quantitative precipitation forecast could be made for the month of October, but he did believe that the best possible way to use the available data was through an "anti-analog" approach. According to this approach, it would be possible to judge that certain of the historical years were not representative of the current year because the forecast of upper air circulation pattern for October was vastly different, in a sense opposite, from the historical upper air circulation patterns for October. A total of 5 years was excluded from the historical record, and the remaining record was judged to be representative of the type of precipitation pattern that might be expected in the current year. The mean of this conditional distribution was only about a tenth of an inch above the mean for the climatic distribution for October, and the standard deviation of the conditional distribution was about 7% greater than the climatic distribution. The similarity of the statistics of the conditioned data set and the complete historical set indicated that use of the historical record was, for this particular case, a reasonable representation of future inputs.

The ESP technique was applied in northern Virginia, using the complete historical precipitation series. It was found there was about a 10% chance that reservoir levels in the Occoquan Reservoir would fall below the threshold that would require the water authorities to declare a so-called stage three emergency which would prohibit all water use not essential for maintaining the health and safety of the community. Conversely there was a 90% chance of avoiding a stage three emergency, and there was a considerable chance that the reservoir would refill before the end of the 1977 calendar year. But still, there was the 10% risk of reaching a stage three emergency. This was judged by the community to be unacceptable. Therefore, additional studies were made with the ESP technique to determine what conservation measures were required to reduce the risk to a more acceptable level. Although political representatives of the community were unable to define an unacceptable risk level, it was judged that a 20% reduction in withdrawal from the reservoir would reduce the risk level to about 2% or 3%. Plans were made, therefore, to reduce withdrawals until the reservoir had recovered to a normal level. Heavy rains began to occur in October and lasted through November. By mid-November the reservoir had refilled and the emergency was over. Analysis of the precipitation for October and November showed that there was only a 5% chance of having such a wet fall. Northern Virginia was indeed very lucky.

4.0 AREAS FOR FUTURE RESEARCH

Fertile areas of research that will provide significant improvements in the performance and utility of Extended Streamflow Prediction include: (1) optimal state estimation; (2) short and long term weather forecasts; (3) model error analysis; (4) model output analysis; and (5) analysis of economic impacts.

4.1 Optimal State Estimation

One of the important aspects of Extended Streamflow Prediction is the representation of the initial conditions of the system. This is true because all of the simulations are conditioned by the same initial state. Conditioning simulations by the current state of the system is what contributes the reduction of variance gained in ESP forecast over forecasts made by assuming climatological mean flows.

One of the main contributions to uncertainty in the Occoquan analysis was the fact that initial soil moisture levels were not well defined. Uncertainty in knowledge of soil moisture levels translated to uncertainty in the amount of rainfall needed to produce runoff. Therefore, it was unclear how much rainfall was needed to alleviate the drought and the utility of the streamflow forecast was reduced.

Current research projects being conducted by the Hydrologic Research Laboratory of the NWS are studying ways to utilize the techniques of estimation theory to provide optimal estimates of the states of the simulation models. The idea is to mathematically combine information that we know about the structure of the simulation models, the error characteristics of the models, the data observations and their error properties in such a manner that state variables (e.g., computed soil moisture levels) are optimally estimated at each computational time step. In this fashion, the simulation models are in the best possible position to make a forecast, given the information we know now and how certain we are about it.

4.2 Short and Long Term Weather Forecasts

Knowledge of future weather systems is of obvious importance to ESP. If future sequences of precipitation, temperature, etc. are known with certainty, our experience with streamflow simulation models tells us that we could forecast streamflows with little uncertainty. However, we don't know how future weather systems will evolve exactly. To appreciate this fact, just remember the last time you listened to a forecast of fair weather and later got caught without an umbrella.

Weather forecasters do exhibit some skill in understanding how meteorological systems will evolve during time periods of a week or so, and also exhibit some skill in predicting long term trends (e.g., monthly). This information is not currently incorporated formally in the ESP technique; thus, the inertia of the existing weather condition is neglected.

It should be obvious, at this juncture, to expect that significantly improved extended streamflow predictions could be realized through improved weather forecasts. This thought, however, begs the question, "How predictable is the weather?" The answer to this question will give an idea of how much to expect in terms of improved streamflow forecasts, at least in the forseeable future.

Prospects of greatly improved weather forecasts are tempered by the notion that there exists theoretical and experimental evidence that the limit of the range of predictability of instantaneous weather conditions is on the order of 2 to 3 weeks (Schneider and Dickenson, 1974; Lorenz, 1975; Leith, 1978). Beyond this period, forecasts would be no better than randomly picking a set of instantaneous weather conditions. Present skills, however, are nowhere near the theoretical limit as forecasts beyond a couple of days are not entirely reliable.

Much of the reasoning behind this notion centers on the inherently nonlinear and unstable nature of the atmosphere. Two or more nearly identical states, obeying the same atmospheric laws, will eventually evolve into widely differing states as time continues to advance. Numerical studies have indicated that small errors in representing the state of the atmosphere would tend to double every 2 to 4 days (Lorenz, 1975).

Errors in forecasts are introduced in several ways. The most significant errors involve the specification of initial conditions and in the numerical representation of the atmosphere. Even if the perfect model of the atmosphere existed, so little is known about the instantaneous state of the atmosphere, a perfect forecast is not possible.

Currently, there are only about 100 observing stations in the U.S. that collect information regarding the three-dimensional structure of the atmosphere. Observations of vertical profiles are only made routinely once in 12 hours. Measurements taken at this scale are adequate for identifying large scale weather features, but contribute little to identifying mesoscale and smaller levels of atmospheric activity. Large and small-scale processes are intimately related through the dynamic transfers of mass, energy, and momentum. Much of the atmospheric information content is not resolved by current observation networks and is, therefore, unavailable for use in numerical models.

In addition, as the range of predication increases, the zone of atmospheric interest increases rapidly, meaning that more and more information about weather systems outside the U.S. is required to make extended period forecasts. As sparse as the U.S. observing network is, networks over the oceans and in many other countries are at least an order of magnitude less dense. Thus, even less is known about the instantaneous hemispheric or global atmospheric condition, making extended forecasting extremely difficult.

Even though conventional numerical models of the atmosphere appear to have restricted abilities for extended weather forecasts, all hope is not lost for improvement in ESP. It may not be possible to predict the exact chronology of weather events beyond a couple of weeks, but it is possible to project general trends for longer periods in terms of statistical averages. Current technology exhibits some skill in creating 30-day outlooks that are better than randomly selecting weather patterns, but much needs to be done. It is expected that with an appropriate international effort in the next decade, we could learn whether usefully skillful weather predictions extending out to months and seasons are feasible (Climate Research Board, 1978). In concert with this effort, techniques are needed to incorporate the information contained in these extended weather forecasts to properly condition the input time series for the ESP models. In this fashion, the ESP input data would better represent the set of weather conditions likely to evolve from the meteorological situation at the time of forecast.

4.3 Model Error Analysis

Of particular importance to the utility of extended streamflow prediction is the performance of the streamflow model during conditions of extreme low flows. Model errors that are insignificant during periods of high flows can become highly significant with respect to low flows. Such behavior can decrease forecast reliability at a time when risks associated with making wrong water management decisions are high. The effect of model errors under low flow conditions is to bias the mean and higher moments of the forecast distribution of streamflow values. This bias can be corrected if the nature of the model errors is understood.

Biases in the forecast distributions also result from the basin calibration process. Improved parameter estimation techniques will help avoid built-in bias, but procedures to recognize and correct this bias are needed as well.

4.4 Model Output Analysis

Probabilistic analyses of streamflow properties turn on the character of the probability distributions assumed to represent the natural processes. Skillful selection of the proper theoretical distribution will enhance forecast reliability. More comprehensive probabilistic routines need to be developed to allow more user flexibility in choosing representative probability distributions. Because of the large number of possible forecast points, automation of the selection process would greatly benefit the NWS in terms of decreased manual intervention.

4.5 Analysis of Economic Impact

Predictions of future streamflows are not solely the variables upon which decisions are made. More often than not, levels of future streamflow are transformed into some monetary measure of system performance. The system may be an individual farm, private corporation, or governmental entity. Sometimes the transformation may be done explicitly. Other times the transformation is implied or done intuitively based on past experiences. Decisions are thus made based on the impact of a possible future flow, not on the flow itself.

The nature of potential impacts may not be readily identifiable, particularly in regard to, say, national or regional economies. Extended streamflow predictions will achieve greater utility as the complexities of our economic system and decision-making processes are better understood.

There are also some important "feedbacks" relating to the ESP technique itself as more is understood about the response of economic systems to streamflow forecasts. By knowing how an economic system responds to a forecast, response sensitivity and hence the response to forecast errors can be assessed. The response to forecast errors can be translated into economic terms, and a measure is obtained for the profitability of allocating resources committed to forecast improvements. In this way, improved utilization of model development funds will result.

5.0 SUMMARY

The National Weather Service Extended Streamflow Prediction model has been presented. Examples were given to show how the ESP technique has been applied to water supply forecasting and particularly fertile areas of ESP research have been discussed. ESP is a potentially powerful tool for use by a variety of water managers to address uncertain future inflows.

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