A REVIEW OF OPERATIONAL WATER SUPPLY FORECASTING TECHNIQUES IN AREAS OF SEASONAL SNOWCOVER [1]

645-78

By

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Introduction

The continuing need for improved forecasts is accentuated by the recent number of technical papers appearing in the literature. For example, the Banff Symposium Proceedings on the Role of Snow and Ice in Hydrology (1972) contained 22 papers directly addressing the forecast problem. In 1975, the Agricultural Research Service (ARS) and the Soil Conservation Service (SCS) sponsored a water-supply forecasting workshop in Boise, Idaho. Federal and State agencies involved in forecasting activities and responsible for water-supply forecasts in various Western States were represented. One of the work groups pointed out the objectives of streamflow forecasting: "The long-term objective of forecasting should be to forecast the complete hydrograph, or at least the significant hydrograph characteristics. As a first priority, or at least concurrent to the perfection of the long-term objective, efforts should be directed toward the potential for improving the seasonal volume forecast accuracy." Attendees also agreed on recommendations for improving water-supply forecasts. These recommendations were:

(1) Research is needed that applies to both long- and short-term forecasts; i.e., to test the model's sensitivity to various input parameters and to rank these parameters according to their relative importance and accuracy requirements.

(2) Snowpack, precipitation, and other meteorological sensors, like humidity, must be improved.

(3) Evaluation of sensors should be published and made available for use.

(4) The potential for increased accuracy through better snow course network design should be investigated.

(5) The limits of accuracy obtainable from regression equations as affected by the quantity of available data should be tested.

(6) The potential for increased accuracy in water-supply forecasts due to increased accuracy in weather forecasting (both long- and short-range) should be investigated.

(7) An objective process for ranking data sites according to their impact on water-supply forecast accuracy should be formulated. Full consideration must be given to site importance under present forecast procedures, as well as under future situations when different forecast models may be used.

(8) Interagency coordination in the selection of sites to be automated should be encouraged.

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The reason for this continuing search for better, more accurate water-supply forecasts is optimum management of the water resource. Planning for agriculture, municipal water supply, energy generation, recreation, navigation, flood and pollution control, all benefit from an accurate forecast.

The actual relationships between forecast accuracy and monetary benefits have not yet been precisely defined, due to the complexity and interactions of various water uses. However, attempts have been made to relate the value of water-supply forecasts in terms of dollars (Clyde and Howton, 1951; Nelson, 1969; Hamon, 1972). Recently, Schramm et al. (1974), using a probabilistic Linear Programming model, generated gross benefits ranging from a few cents up to $6.00/acre, depending on the economic values in the use area. Elliott (1977), who compared the benefits to irrigated agriculture of a perfect vs. an actual forecast for 10 Western states, estimated it to be greater than $22 million/year.

Seasonal Water Supply Forecasts

The most widely used approach to seasonal water supply forecasting is the linear model

$$Y = a + B_1X_1 + B_2X_2 \; . \; . \; . \; . \; B_nX_n \qquad [1]$$

where Y is the runoff volume for a specific forecast period; X_1 through X_n are runoff index variables; a is a fitting coefficient; and B_1 through B_n are weighting factors for each runoff-index variable. Basically, the procedure involves the correlation of the historical runoff record with the index variables.

According to the SCS National Engineering Handbook (1970), the index variables used or suggested as potentially important forecast parameters are: snow water equivalent, antecedent streamflow, baseflow, soil moisture, precipitation, temperature, wind, solar radiation, and relative humidity. This agrees in general with a similar list published by the U. S. Army Corps of Engineers (1956). In both publications, the suggested method of calculating weights to apply to the index variables and of determining the fitting coefficient is the use of multiple-linear-regression techniques. In actual practice, weights for the index variables are often determined subjectively or through trial and error, although the current trend is to use statistical methods (Coulson, 1970; Schermerhorn and Barton, 1968). Marsden and Davis (1968) used principal components regression to calculate weights and demonstrated an improved accuracy in the forecast when the method was applied to the Yakima Basin in Washington. A pattern-search optimization technique was used by Zuzel et al. (1975) and Zuzel and Ondrechen (1975), which more accurately forecasts water supply than the methods currently in use for the Boise River in Idaho.

The question of which variables to use in any forecast model has been a subject of much discussion, but in the final analysis, is probably dependent on the topographic, climatic, geologic, soils, and vegetative characteristics of each basin. The most commonly employed runoff-index variables are snow water equivalent, measured at a snow course site, and precipitation, measured at a snow course site or at a valley station.

Although not a recent innovation, the use of aerial photography to estimate snow cover has become more important since the advent of satellite photography. Rango and Salomonson (1975), used LANDSAT-I imagery to determine snow cover over the upper Indus Basin of Pakistan, and the Wind River Mountains of Wyoming. Using this data and seasonal streamflow, they developed regression equations that produced remarkably high correlation coefficients between snow cover and seasonal runoff.

The evaluation of aerial photography by image-analyzing computer has been explored by Martinec (1973). Leaf (1969) developed a depletion-runoff relationship, based on snow cover, calculated from aerial photographs. The major objections to either satellite or aircraft photography are the excessive turn-around time for photo processing, the large number of cloud-covered days, and the inability of photointerpreters and image analyzing computers to definitely distinguish between clouds and snow.

Fletcher (1966) discussed the importance of soil moisture data for inclusion among the index variables. However, the difficulties of obtaining routine soil moisture measurements have never really been overcome. Resistance and capacitance measurements have a tendency to change calibration with time and neutron moderation equipment is simply too expensive and delicate for routine over-snow use.

A procedure for correcting snow-water-equivalent measurements for evaposublimation was introduced by Peak (1969). Using wind, solar radiation, and temperature data, he succeeded in reducing the forecast error for several Wyoming watersheds. However, during the same year, Doty and Johnston (1969), in a research study conducted in Utah, reported that the amount of winter evaposublimation was compensated for by the amount of condensation and that the net effect of the two processes was essentially zero. Also, while temperature measurements are collected routinely at most remote sites, wind and solar radiation are not, and valley stations must be used to obtain these variables.

Antecedent streamflow and/or baseflow are incorporated into forecast models much more frequently since streamflow does effectively index the soil moisture and groundwater conditions on some watersheds (U.S. Army Corps of Engineers, 1956; George, 1970; Warnick and Brockway, 1974).

Another index method, the coastal stream index, relates the winter runoff of low elevation streams to the spring snowmelt runoff.

The method is reported to be as accurate as those that use snow water equivalent and precipitation data. A recent modification of this method and application to some western Washington watersheds is described by Tangborn and Rasmussen (1976).

Index-forecasting methods have probably reached the point where large increases in accuracy are not possible through manipulation of data inputs. Slight improvements in accuracy can be obtained, however. Wilson (1966) suggested that more accurate forecasts can be obtained by using only point samples of snow water equivalent, which are highly correlated with runoff, rather than snow course average, snow water equivalent. Accuracy can be improved by adjusting the calculated forecast on the basis of "feel," since the forecaster knows certain facts, like "no snow on south slopes" or "snow line elevation higher than other years" (Malsor, 1967).

The success or failure of computer-based watershed models is not readily apparent from the literature. Pearson (1974) used the Streamflow Synthesis and Reservoir Regulation (SSARR) model developed by the U.S. Army Corps of Engineers to simulate inflows to Hungry Horse Reservoir in Montana. He stated that the model could be used in volumetric forecasting based on the agreement between cumulative values of simulated vs. actual inflows over the forecast period. A computer-based water-budget model, reported by Quick and Pipes (1973), has been successfully used in forecasting both daily and seasonal runoff volumes. A desirable feature of this model is its ability to input weather data from previous years and create various scenarios so that upper and lower bounds can be attached to the snowmelt runoff forecast.

Many references to snowmelt runoff simulation can be found in the literature (Riley et al, 1969; Rockwood and Anderson, 1970; Pipes et al, 1970; Willen et al., 1971; Anderson, 1973), but reports on the operational use of these models are almost completely lacking.

From this review and also based on the current practices of the agencies responsible for seasonal streamflow forecasts, one can conclude that the index method, with all its variations and shortcomings, has not yet been replaced by simulation models operated in the forecast mode. These models can provide the timing, as well as the volume of snowmelt runoff, although most would require accurate long-term weather forecasts, as well as continuously reporting data networks.

Comparison of Long-Term Volume Forecast Models

Comparison of forecast accuracy are difficult to obtain, since most basin forecasts are made using one model and, except for SCS and the National Weather Service, forecasts are not published. However, in a study conducted by the Idaho Department of Water Resources (1974), the forecasts made by the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers were examined for the Boise River in Idaho. Both agencies prepare forecasts on the first of the month from January through April. The difference in accuracy of the two forecasts was not really significant. Both methods underestimated runoff in the lowest runoff years and overestimated runoff in the highest runoff years. Zuzel and Ondrechen

(1975) also compared these models with the pattern-search optimization technique. Pattern-search optimization produced a more accurate forecast, especially in low and high runoff years, although data from several more snow courses was required.

Apparently, presently used forecast models can be improved by the application of new techniques. Any improvements in forecast accuracy imply testing of various models and the establishment of comparison criteria to determine the best model for a particular basin.

In an effort to determine the most accurate forecast model for the Middle Fork of the Boise River in southwestern Idaho, five models were tested and comparisons were made using the correlation coefficients and standard errors as the accuracy criteria.

The Middle Fork of the Boise River has a drainage area of 2150 square kilometers and ranges in elevation from 993 meters at the gaging station at Twin Springs to 2947 meters at the headwaters, with a mean elevation of 1936 meters. The average yearly discharge is 496 millimeters, about 80 percent of which is the result of snowmelt during March through July.

On the Middle Fork of the Boise River, complete, comparable records exist for the Arrowrock Dam precipitation gage, the Twin Springs streamflow station, and Mores Creek, Trinity, Atlanta, and Bad Bear snow courses for a 15-year period (1959 to 1973). This period was, therefore, selected for analysis on the basis of length, completeness, and comparability of the streamflow record, precipitation record, and snow course records.

Using these data, the precipitation index, water balance, pattern search, multiple linear regression, and the Tangborn-Rasmussen (1976) seasonal forecast models were tested and the results compared. Correlation coefficients, standard errors, and data requirements were assumed to be indicative of the relative accuracy and cost of each model. Therefore, these parameters were used to compare model performance.

Precipitation Index Model.--The precipitation index model tested is a two-variable linear regression of the form

$$Q_s = ap_w + b \qquad [2]$$

where Q_s is the seasonal runoff in millimeters at Twin Springs from the forecast data through July, p_w is the cumulative winter precipitation from October 1 through the forecast data from the Arrowrock gage, and a and b are the regression coefficients.

Water-Balance Model.--The water-balance method assumes that the difference between cumulative winter precipitation and cumulative winter runoff is an estimate of total basin storage. The relationship used is

$$Q_s = a(p_w - Q_w) + b \qquad [3]$$

where Q_w is the cumulative winter runoff from October 1 through the forecast date at Twin Springs, and all other variables are as previously defined. The quantity $(p_w - Q_w)$ is, therefore, the estimate of total basin storage including snow, groundwater, and soil-moisture storages.

Pattern Search Model.--The pattern search technique (Zuzel and Ondrechen, 1975) is currently being used by SCS and the Idaho Department of Water Resources to forecast flows of the Boise River at Lucky Peak Dam. The version used in this study is

$$Q_s = b + a_1p_w + a_2s_1 + a_3s_2 + a_4s_3 + a_5s_4 \qquad [4]$$

where s_1 through s_4 is the snow water equivalent at Mores Creek, Trinity, Atlanta, and Bad Bear; a_1 through a_5 are coefficients; p_w is as previously defined; and b is a constant. The pattern-search model differs from a multiple linear regression in that the technique does not rely on lease squares methods and the restriction $a_i \geq 0$ can be imposed. When this restriction is imposed, the result is a water-balance model, since each independent variable is now expressed as a depth-area function, and the sum of the independent variables is an estimate of basin snow water storage.

Multiple Linear Regression Model.--The multiple linear regression model used in this study is identical to equation [3]. However, no restrictions on the coefficients are possible and the method is an index rather than water balance method.

Tangborn-Rasmussen Model.--The Tanborn-Rasmussen approach makes use of the fact that winter precipitation is a good indicator of annual runoff on many watersheds. The formulation used is a two-variable linear regression of the form

$$Q_y = ap_w + b \qquad [5]$$

where Q_y is the yearly runoff at Twin Springs, and a, p_w, and b are as defined previously. Regression coefficients for equation [4] were determined from the 15-year record of streamflow at Twin Springs and winter precipitation at Arrowrock. Further, if the runoff, Q_y, is separated into seasons

$$Q_y = Q_s + Q_w \qquad [6]$$

substituting into equation [5] yields

$$Q_s = ap_w + b - Q_w \qquad [7]$$

since a and b were determined for equation [5] and Q_s and Q_w are known on the forecast date, equation [7] was used to generate the seasonal forecasts for Twin Springs. The model is another water-balance form and it is strongly dependent on an acceptable correlation between winter precipitation and yearly runoff.

The results of the analyses performed are listed in Table 1. The correlation coefficients and standard errors indicated that the pattern search and multiple linear regression models, on the average, yield more accurate seasonal forecasts than the other models tested. Although we did not use a test season, as suggested by Tangborn and Rasmussen (1976), in this study, their results did not indicate significant improvement in the accuracy of the early forecasts (January 1 and February 1).

The accuracy of the early forecasts cannot be overemphasized, particularly on multipurpose reservoir systems where the flood-space evacuation period is limited in time as well as allowable releases. In their recent study, the Idaho Department of Water Resources (1974) concluded that because of the inaccuracy of early forecasts, there is a reluctance to make required releases early.

Another important consideration in selecting an operational forecast model is the cost of data acquisition. Significant predictor variables for each model are also shown in Table 1. Acquisition costs for the precipitation index, Tangborn-Rasmussen, and water balance models are insignificant, particularly since Twin Springs is an automated station and transmits flows directly to Boise each day. However, the cost of obtaining data from five snow courses every 2 weeks is about $6,500 for a 6-month snow season (J. Wilson, personal communication, 1977).

The results of this analysis indicated that the combined use of the pattern search and multiple linear regression models most accurately forecasts runoff for all forecast dates. The improved resource management potential, as well as the increased forecast accuracy, should return much more than the cost of additional data acquisition associated with the pattern search and multiple linear regression models.

Short-term Snowmelt Runoff Forecasting

Most of the work in this area (predictions of daily, weekly or monthly streamflow volume) has again involved the use of index variables, most frequently air temperature. The usual procedure is to relate air temperature of an index site to daily streamflow and, from this relationship, predict daily streamflow volumes one to several days in advance (Zimmerman, 1972). The objection to this procedure is that, while temperature is the best single index to snowmelt and thus runoff, it largely ignores the energy inputs required for the melting of the snowpack

In a 1975 study, Zuzel and Cox (1975) found that in a 100 percent snow cover situation, more than 60 percent of the snowmelt is the direct result of net allwave radiation. Further studies in 1976 confirmed these results. These data also substantiate the work of

Dewalle and Meiman (1971), who obtained similar values, although their data were collected over only a 2-day period.

TABLE 1.--Correlation coefficient (r), standard error in millimeters (S.E.), standard error as percent of mean flow (%S.E.), and significant forecast variables from the forecast date through July for Twin Springs Gaging Station, Middle Fork of the Boise River, Idaho.

		Forecast Model				
Forecast Date		Precipitation Index	Tangborn-Rasmussen	Water Balance	Pattern Search	Multiple Regression
JAN. 1	r	0.828	0.812	0.787	0.924	0.828
	S.E.	77	81	85	57	78
	%S.E.	18	19	20	13	18
	Variables	1	1,2	1,2	1,4,6	1
FEB. 1	r	0.917	0.893	0.880	0.969	0.917
	S.E.	52	59	63	35	52
	%S.E.	13	14	15	8	13
	Variables	1	1,2	1,2	1,3	1
MAR. 1	r	0.974	0.953	0.921	0.969	0.988
	S.E.	29	39	50	34	24
	%S.E.	7	10	13	8	6
	Variables	1	1,2	1,2	1,3	1,3,5
APR. 1	r	0.931	0.833	0.833	0.975	0.985
	S.E.	44	56	67	29	25
	%S.E.	12	15	18	8	7
	Variables	1	1,2	1,2	1,3	1,3,5
MAY 1	r	0.928	0.915	0.835	0.978	0.977
	S.E.	38	41	56	23	26
	%S.E.	13	14	19	8	9
	Variables	1	1,2	1,2	1,3,4,6	1,4,5,6
JUN. 1	r	0.899	0.719	0.360	*	*
	S.E.	29	46	62	*	*
	%S.E.	17	27	37	*	*
	Variables	1	1,2	1,2	*	*

Variables: 1. Arrowrock Precipitation
2. Twin Springs Runoff
3. Atlanta Summit Snow Water Equivalent
4. Bad Bear Snow Water Equivalent
5. Mores Creek Snow Water Equivalent
6. Trinity Snow Water Equivalent

*Insufficient June 1 Data

As the melt-season progresses and more soil and vegetative surfaces become exposed, advected sensible heat contributes more to the melt process and may become the dominant heat source (Gray and O'Neill, 1974; Cox and Zuzel, 1976). The relationship between the various heat sources and snowmelt is, therefore, constantly changing, and snowmelt can only be precisely calculated by approximating these heat sources for varying situations. Anderson (1976), in comparing the energy-balance approach with the temperature-index method, concluded that the energy-balance method does enable one to calculate snowmelt more precisely.

Snowmelt can also be measured at several index sites on a watershed by using snow pillows, isotopic snow gages, or snowmelt lysimeters, in conjunction with a telemetry system. Pysklywec et al. (1968) and Haupt (1969) both suggested that melt plots and/or lysimeters are efficient methods of measuring point snowmelt at index sites. Cox and Zuzel (1973) successfully used daily snowmelt data from snowmelt collectors to forecast basin runoff during peak snowmelt events. However, further experience has shown that snow pillows and snowmelt collectors can be unreliable for measuring diurnal changes in snow water equivalent (Cox, 1971).

Considering the above arguments, the present advantage of watershed models for short-term forecasting becomes apparent. Varied climatological sequences can be used as input, along with known snow water equivalent and other antecedent variables. From this, short-term forecasts can be stated probabilistically rather than deterministically.

Summary and Conclusions

The forecast models briefly discussed in the preceding sections use basic inputs of snow water equivalent and precipitation. They can be classified as regression methods, pseudo-water-balance methods (pattern search optimization and coastal index), water balance methods, and simulation methods. Data requirements necessary to reasonably estimate streamflow volume increase as one proceeds from the simple linear regression to the complete watershed model.

The comparison of five streamflow models for six forecast periods on the Middle Fork of the Boise River in southwest Idaho indicates that the multiple linear regression and pattern search models produce the most accurate forecasts for this basin. However, data requirements are greater than the other models tested.

The accuracy of computer-based watershed models operated in the forecast mode versus index methods is difficult to determine from the literature. However, computer-based watershed models have the potential to provide the timing as well as the volume of snow melt runoff. Since varied climatological sequences can be used as input to these models, forecasts can be stated probabilistically.

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