# A MODEL FOR UPDATING STREAMFLOW FORECASTS BASED ON AREAL SNOW COVER AND A PRECIPITATION INDEX[1/]

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By

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## Introduction

Efficient operation of water projects depends on the accuracy of streamflow forecasts. Forecasts are required to: (1) determine permissible releases from reservoirs for power, irrigation, or municipal uses with assured refill, and (2) meet mandatory release and storage requirements for recreation, pollution abatement, and flood control. Where multi-purpose projects are involved, operations must be scheduled on a short-term basis.

In the Rocky Mountain West, virtually all streamflow results from snowmelt; hence, forecasting procedures depend on snowpack measurements. Seasonal or total flow forecasts are generally based on surveys of peak snowpack water equivalent. Extensions of these early-spring forecasts to a short-term basis may not be reliable, however, since they assume that precipitation and meteorological conditions during the ensuing melt season will be normal.

One index of runoff, which is useful for improving forecasts of residual runoff during the snowmelt season, is areal snow cover. In the United States, surveillance of the snow cover was proposed more than 25 years ago by Gross (1937), Parshall (1941), and Potts (1944). These investigators obtained index observations of snow cover by ground photographic methods. Since the late forties, several workers have estimated total snow coverage on drainage basins (Daniels 1949, Miller 1953, Brown and Dunford 1956, U. S. Army 1956, Garstka et al. 1958, Parsons and Castle 1959, Thoms 1961, Ffolliott and Hansen 1968, Thoms 1969, Thoms and Wang 1969, Leaf 1969).

Empirical correlations between snow cover and runoff developed from this type of work have been incorporated into modern computerized simulation models. A notable example is the "SSARR" hydrologic model (Rockwood 1961, Rockwood 1964, Schermerhorn and Kuehl 1968, and Anderson and Rockwood 1970). This model utilizes cover-runoff relationships to calculate the area of snow cover on the basis of accumulated generated runoff.

In addition to their application in continuous simulation of streamflow, depletion-runoff relationships are effectively used to forecast residual flows during the snowmelt runoff season (U.S. Army 1956, Parsons and Castle 1959, Thoms 1961, Thoms 1969). In these procedures, estimates of snow coverage during the melt season provide the means for forecasting subsequent runoff. These forecasts can be continuously revised by repeated observations of the decrease in horizontal extent (depletion) of the snow cover.

The areal extent of snow is becoming an important parameter in the growing emphasis on application of remote sensing in the water resource field. Several remote sensing techniques appear promising for snow cover measurement (Barnes and Bowley 1968, Popham 1968, Waite and Macdonald 1970). For large basins, satellite sensing appears most feasible. Effective practical application of these methods in streamflow forecasting will depend, however, on further development of the actual forecasting relationships on a smaller scale.

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Recognizing the need to develop snow cover-runoff relationships, the Forest Service initiated a program in 1964 to measure the areal extent of snow cover in Colorado. Since 1965, we have cooperated with the Office of Atmospheric Water Resources, Bureau of Reclamation, in photographing snow cover during each snowmelt season at the Fraser Experimental Forest and in the Park Range near Steamboat Springs, Colorado (Leaf, 1967, 1969). Aerial photographs are taken by a private contractor.

This report describes a procedure we have developed for updating streamflow forecasts based on the areal extent of snow cover.

## Experimental Watersheds

Three forested experimental watersheds in the Fraser Experimental Forest (East St. Louis, Deadhorse, and Lexen), with drainage areas of 1,984, 667, and 306 acres, respectively, were selected for study. They are typical of headwater streams which contribute to the flow in the Upper Colorado River Basin. Annual precipitation of 28 inches results in 12 inches of streamflow. Detailed discussions of forest cover, geology, climate, and water yield are found in: Garstka et al. (1958), Retzer (1962), Leaf (1966), Hoover (1967), and Leaf (1969).

## Observations

### Snowpack depletion

Aerial photographs with a photo scale of approximately 1:6,000 were used to observe the amount of snow cover at about 10-day intervals after snowmelt began. The extent of snow cover on the photographs was estimated visually with the aid of a folding stereoscope; these estimates were transposed to subdivided base maps of each watershed (Leaf 1969). Subareas within each watershed were delimited on the basis of forest cover, orientation, and slope steepness. Total snow cover was determined by computing a weighted average based on the area and extent of snow cover in the various watershed units.

### Runoff and precipitation

Streamflow from the three watersheds is gaged by weirs. Measurements of winter precipitation in 100-inch Sacramento storage gages at the stream-gaging stations were converted to an index of April 30 water equivalent. These indices of peak snowpack are contingent on snow course measurements made each spring on the watersheds. The storage gages correlate well with these snow course surveys, and are presumed to be reliable. Precipitation during snowmelt was measured in standard 8-inch recorders at the Fraser Experimental Forest Headquarters site.

## Snow-Cover Depletion in Relation to Streamflow

The first step in developing runoff forecast curves for the Fraser watersheds was to plot percentages of snowpack depletion and runoff for the 1964-1968 record period (fig. 1). Note that each watershed has its own characteristic relationship between snowpack depletion and runoff that does not change appreciably, even though the amount of snowpack and weather conditions which produce runoff each year vary considerably. The scatter around the mean curves may be the result of annual differences in initial snowpack water equivalent, recharge requirements, and meteorological conditions during snowmelt. Also, subjective interpretation of the photos may account for a large portion of the variation.

Shown in figure 1 are relationships between snow-cover depletion and observed and generated runoff. Generated runoff includes water still in storage on the watershed, and is defined as that quantity of snowmelt during a given time interval which results as streamflow. Generated flows were isolated on the discharge hydrograph by means of the recession curve (U.S. Army 1956, Garstka et al. 1958, Leaf 1969). Both relationships were plotted to show the significant displacement caused by natural regulation within these watersheds. Generated flows were also computed in order to: (1) correct for antecedent winter runoff, and (2) obtain an accurate estimate of runoff produced during the snowmelt season.

Miller (1953) and Parsons and Castle (1959) have pointed out that the primary difference in runoff volume between years is due to the initial amount of snowpack. Thus, when areal snow cover is plotted as a function of residual or "future runoff" (Miller 1953), a family of curves necessarily results, which accounts for both "high" and "low" snow years. Such curves for the Fraser watersheds are plotted in figure 2. They were developed from the dimensionless relationships (for observed runoff) in figure 1. In practice, these curves would be used in conjunction with total flow forecasts at the time of peak snowpack accumulation.

In addition to peak snowpack accumulation (assumed here as the April 30 storage gage measurements), subsequent precipitation during snowmelt can considerably influence stream runoff. Thus, it is desirable to revise residual forecasts during the melt season to reflect this additional input. Parsons and Castle (1959) have developed a method for making appropriate revisions by means of an "adjusted snow index". We developed a similar procedure.

## Snow Cover-Precipitation Index Forecast Curves

### Precipitation index

At the Fraser Experimental Forest, the average annual precipitation is approximately 28 inches. Of this amount, about 15 inches results as snow accumulation prior to May 1. Average precipitation is 2 inches during May and 3 inches during June. Although the snowmelt runoff season generally ends around June 30, recession flows continue until late summer.

Table 1 is a summary of measured precipitation for May and June, plus peak accumulation on April 30. In our forecasting procedure, the values summarized in table 1 are given a value of 100. Thus, above-normal precipitation amounts would receive values greater than 100, and below-normal amounts less. With normals fixed for May and June inputs, the precipitation index derived from the April 30 measurements can be adjusted for later dates in the melt season. These adjustments would normally be made around May 31 and June 30. Weight factors for each of the three intervals are summarized in table 2.

Table 1.--Precipitation summary[1]

| Watershed | Peak (April 30) | May | June | Total |
|---|---|---|---|---|
| | Inches | | | |
| Deadhorse | 17.6 | 1.8 | 2.4 | 21.8 |
| Lexen | 18.9 | 2.2 | 2.9 | 24.0 |
| E. St. Louis | 13.9 | 1.9 | 2.4 | 18.2 |

[1] Based on 1963-68 observations at 100-inch Sacramento storage gage adjusted to 1940-70 record period at Fraser Experimental Forest Headquarters site.

Table 2.--Index Weight factors

| Watershed | Peak (April 30) | May | June |
|---|---|---|---|
| Deadhorse | 0.81 | 0.08 | 0.11 |
| Lexen | .79 | .09 | .12 |
| E. St. Louis | .76 | .11 | .13 |

Precipitation indices are derived by means of the equation:

$$I_p = 100 [W_a i_a + W_m i_m + W_j i_j] \quad (1)$$

where

$I_p$ is the weighted precipitation index,

$W_a$ is the weight factor for seasonal snow accumulation through April 30,

$i_a$ is the snow accumulation index through April 30,

$W_m$ is the weight factor for May,

$i_m$ is the precipitation index for May,

$W_j$ is the weight factor for June, and

$i_j$ is the precipitation index for June.

To illustrate the application of equation (1), assume that on East St. Louis Creek, the April 30 measurement is 19.2 inches. The appropriate index for April 30, from tables 1 and 2, is

$$100[(19.2/13.9)0.76 + 0.11 \times 1.00 + 0.13 \times 1.00] = 128.9$$

If the precipitation during May was only 0.9 inch, the new index would be revised downward as follows:

$$100[(19.2/13.9)0.76 + (0.9/1.9)0.11 + 0.13 \times 1.00] = 123.2$$

Similarly, if precipitation during June was a normal 2.4 inches, the June 30 index would remain at 123.2.

### Forecast curves

Having determined a procedure for computing precipitation indices, we then developed a simple graphical method to forecast residual streamflow volumes, based primarily on snow-cover data obtained from aerial photographs (fig. 3). Note that the residual volume forecast curves for 100 percent snow cover are precipitation-runoff relationships derived from the April 30 storage gage measurements (Leaf 1969).

## Model Verification - 1969 Snowmelt Season

Trial forecasts were made during the 1969 runoff season to test the accuracy of the forecast method. The year 1969 proved to be a good year to verify the model because precipitation during May and June was abnormally high (table 3). Adjustment of the precipitation indices significantly improved the residual flow forecasts as the melt season progressed.

Trial forecasts are compared with observed flows in table 4. The snowmelt runoff season lasted until July 4 on East St. Louis Creek, and until June 11 and June 12 on Deadhorse and Lexen, respectively. The precipitation indices were adjusted upward on May 25 and July 2 to account for additional input. The index for May 15 could also have been adjusted upward since unusually high precipitation occurred during the first week in May. Residual volumes corresponding to snow cover amounts not plotted in figure 3 were determined by interpolation.

Figure 4 shows forecast error as a function of snow-cover depletion or percent residual flow volume. These are average relationships computed from the summary in table 4. From an initial average error of approximately 20 percent, forecasts were successively improved to within 10 percent of observed flows. This accuracy was attained when residual flow was about 80 percent of the seasonal total. Also plotted in figure 4 is average forecast error, if no adjustment were made for precipitation during May and June (i.e., if only snow-covered area were used in predicting flows). Comparison shows that forecasts were improved about 10 percent through adjustment of precipitation indices.

## Conclusions

Extensions of water supply forecasts based on early spring snow surveys become less reliable when precipitation input and meteorological conditions during the ensuing melt season deviate appreciably from normal. The simple model described here has enough flexibility to account for unusual hydrologic conditions. Moreover, it appears that, with additional records, the method will provide accurate residual flow forecasts during the critical high-flow period on the small Fraser watersheds.

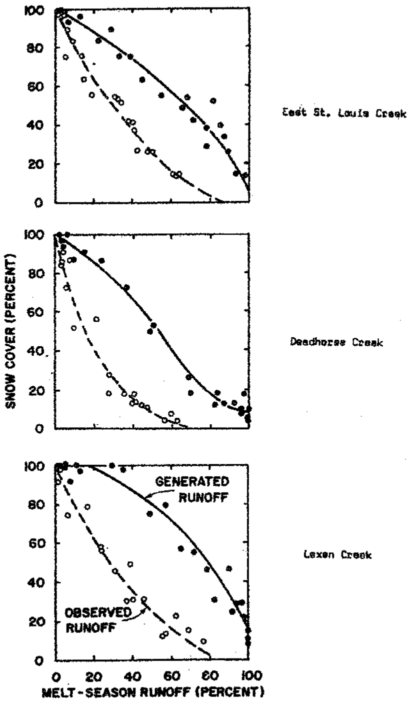

Figure 1--Snow-cover depletion as a function of accumulated runoff, 1964-68.

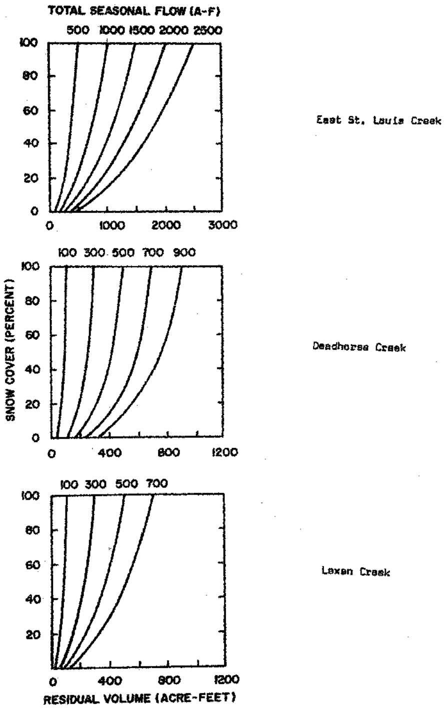

Figure 2--Snow-cover depletion as a function of residual flow.

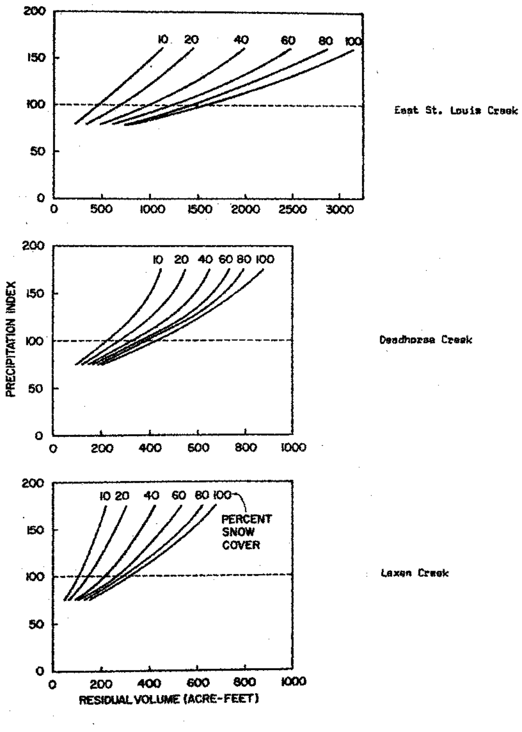

Figure 3--Snow Cover precipitation Index forecast curves.

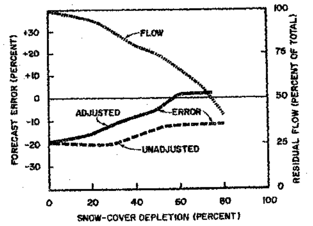

Figure 4--Average adjusted and unadjusted forecast error as a function of snow-cover depletion or residual flow in 1969.

Table 3.--Precipitation input[1] for 1969

| Watershed | Peak (April 30) | May | June | Total |
|---|---|---|---|---|
| | Inches | | | |
| Deadhorse | 15.0 | 3.1 | 4.5 | 22.6 |
| Lexen | 16.6 | 3.1 | 4.5 | 24.2 |
| E. St. Louis | 13.6 | 3.1 | 4.5 | 21.2 |

[1] May and June measurements made at Fraser Experimental Forest Headquarters site.

Table 4.--Trial residual volume forecasts, 1969

| Stream | Date of aerial survey | Estimated snow cover | Precipitation index | Residual volume | |
|---|---|---|---|---|---|
| | | | | Forecast | Observed |
| | | Percent | | Acre-feet | |
| Deadhorse | April 30 | 100 | 88 | 320 | 428(to 6/1) |
| | May 15 | 82 | 88 | 280 | 399 |
| | May 25 | 54 | 94 | 320 | 344 |
| | June 4 | 19 | 94 | 220 | 238 |
| Lexen | April 30 | 100 | 90 | 260 | 297(to 6/1) |
| | May 15 | 93 | 90 | 250 | 283 |
| | May 25 | 76 | 94 | 260 | 230 |
| | June 4 | 40 | 94 | 190 | 170 |
| E. St. Louis | April 30 | 100 | 98 | 1600 | 1950(to 7/4) |
| | May 15 | 94 | 98 | 1550 | 1905 |
| | May 25 | 75 | 105 | 1525 | 1797 |
| | June 4 | 51 | 105 | 1225 | 1357 |
| | July 2 | 11 | 117 | 650 | 568 |

One shortcoming in this study is in the subjective interpretation of the aerial photographs. We are trying to overcome this problem through photogrammetric measurements of snow cover on small index areas in and near the study basins (Barnes 1970). These index areas are visible on the photographs and sensitive enough to monitor watershed depletion patterns. Index-area measurements will not only save time in mapping, but will also reduce the cost of flights while enabling the hydrologist to obtain precise estimates of the extent of snow cover. In addition to improving precision, index-area mapping should make the model useful for forecasting residual flows on larger drainage basins in the Colorado snow zone.

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