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A PROCEDURE TO INCORPORATE SNOW COURSE DATA INTO THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

Thomas R. Carroll
Hydrologic Research Laboratory (W23)
National Weather Service, NOAA
Silver Spring, Maryland 20910

ABSTRACT. The National Weather Service River Forecast System uses estimates of mean areal precipitation and temperature as model input for forecasting river discharge. Errors in the mean areal precipitation estimate can generate errors in the monthly streams discharge volume estimate. Snow course data offer an additional precipitation index which can be used to update the simulated snow water equivalent calculated by the snow accumulation and ablation model. When snow course observations are available, the simulated snow water equivalent may be modified to reflect more closely the true mean areal snow water equivalent over the basin. In this way, an empirical estimate of snow water equivalent can be incorporated into the conceptual river forecast model. The snow course update procedure is tested on three high elevation basins in the western U.S. using a 20-year period of record and is capable of reducing the mean monthly simulated volume errors by as much as 40 percent.

INTRODUCTION

The National Weather Service River Forecast System (NWSRFS) is a set of conceptual techniques and computer programs used to produce river forecasts in the United States (Monro and Anderson, 1974; Curtis and Smith, 1976). Included are programs to manage the large volumes of data associated with a national forecasting system and programs to perform the hydrologic and hydraulic computations necessary to forecast river system response. Central to the NWSRFS are the soil moisture accounting model (Burnash, et al., 1973) used to simulate the movement of water through the soil profile and the snow accumulation and ablation model (Anderson, 1973) used to describe the buildup and subsequent melt of the snowpack. The models are driven by precipitation and temperature data. A series of computer routines is used to calculate mean areal precipitation and mean areal temperature from point observations.

NWSRFS can provide accurate and timely hydrologic information to users with interests in flood forecasts, irrigation, navigation, power, reservoir operation, recreation, or water supply forecasts. In the western United States 80 percent of the water supply comes from the winter snowpack; consequently, accurate and timely water supply forecasts are useful when seasonal water supply allocations are made. Water supply forecasts are generated by the NWSRFS using the Extended Streamflow Prediction (ESP) technique described by Twedt, et al. (1977). The Soil Conservation Service has collected snow course data in the western U.S. in excess of forty years. These data give the snowpack depth and density at each snow course site four to six times a year. The data are generally used in much of the West when water supply forecasts are made in the spring. This paper describes a technique developed to incorporate the snow course data into the NWSRFS.

PROBLEM

The snow accumulation and ablation model is a conceptual model that describes the important physical processes taking place during the accumulation and ablation of the snow cover. The model first determines the form of precipitation input based on a reference air temperature. Precipitation falling as snow is accumulated by the model as simulated water equivalent (SWE). Accurate and sufficient precipitation and temperature data are needed to generate representative mean areal temperature and precipitation patterns used to simulate snowpack accumulation.

Errors in simulated runoff may often be described as (1) errors in the timing of simulated discharge, or (2) errors in the volume of simulated discharge. Timing errors are related to the timing of snowpack release. Heat exchange at the air-snow interface is the critical factor in controlling snowpack ablation. Air temperature is the only index used to calculate surface melt. Errors in the simulated melt rate may be introduced because (1) ambient air temperature is not a perfect index of heat exchange, (2) error in the areal extent of snow cover may occur, and (3) errors may exist in the estimate of mean areal temperature. As a result, the timing of simulated stream discharge may be earlier or later than observed discharge while the total simulated and observed discharge volumes may be equal (Fig. 1a). However, volume errors in simulated discharge are likely to result if the estimate of mean areal precipitation is in error (Fig. 1b). The aim of this study is to reduce stream discharge monthly volume errors using snow course data.

Snow course data integrate the many physical processes which lead to seasonal snow accumulation. Consequently, they offer a check on the accumulated water equivalent simulated by the snow model. When the simulated snow water equivalent significantly differs from an index based on the observed snow water equivalent, the snow course data offer an empirical basis to modify the simulated water equivalent generated by the snow model. In this fashion, it is possible to reduce stream discharge volume errors based on monthly snow course measurements.

TECHNIQUE

A basin with a satisfactory calibration and period of record is selected for snow course updating and the simulated water equivalents are calculated by the snow model using mean areal precipitation and temperature. Appropriate snow courses are selected and the simulated water equivalents are regressed on the snow course data for the period of record. The dependent variable estimated by multiple regression is the regression water equivalent (RWE) and is an estimate of the mean areal snow water equivalent based on point snow course observations. Certain physical processes taking place during snow accumulation (e.g., sublimation, redistribution, mid-winter melt, etc.) are accounted for by the regression equation and are reflected in the regression water equivalent estimate.

Weighting Function

The update procedure calculates an estimated water equivalent (EWE) which is a weighted value based on the simulated water equivalent (based primarily on precipitation data occurring during accumulation) and the regression water equivalent (based on snow course data). The value of the simulated water equivalent calculated by the snow model is subsequently replaced by that of the estimated water equivalent derived by the update procedure. In this fashion, an empirically derived estimate of areal snow water equivalent is incorporated into the snow accumulation and ablation model.

The series of estimated water equivalents, when substituted for the simulated water equivalents, should improve the stream discharge prediction in years with a poor fit while allowing the stream discharge prediction in years with a good fit to remain essentially unchanged. Figure 2 describes the three parameter weighting function from which the estimated water equivalent is calculated using the simulated and regression water equivalents. Two parameters define the shape and location of the curve; the third parameter is calculated from the snow course data and selects the point on the curve defining the estimated water equivalent. The adjustment parameter (ADJ) determines the relative weight placed on the simulated and regression water equivalents in a month with near normal snow accumulation. This parameter value may range from 0 to 1 where 0 places total weight on the simulated water equivalent (the

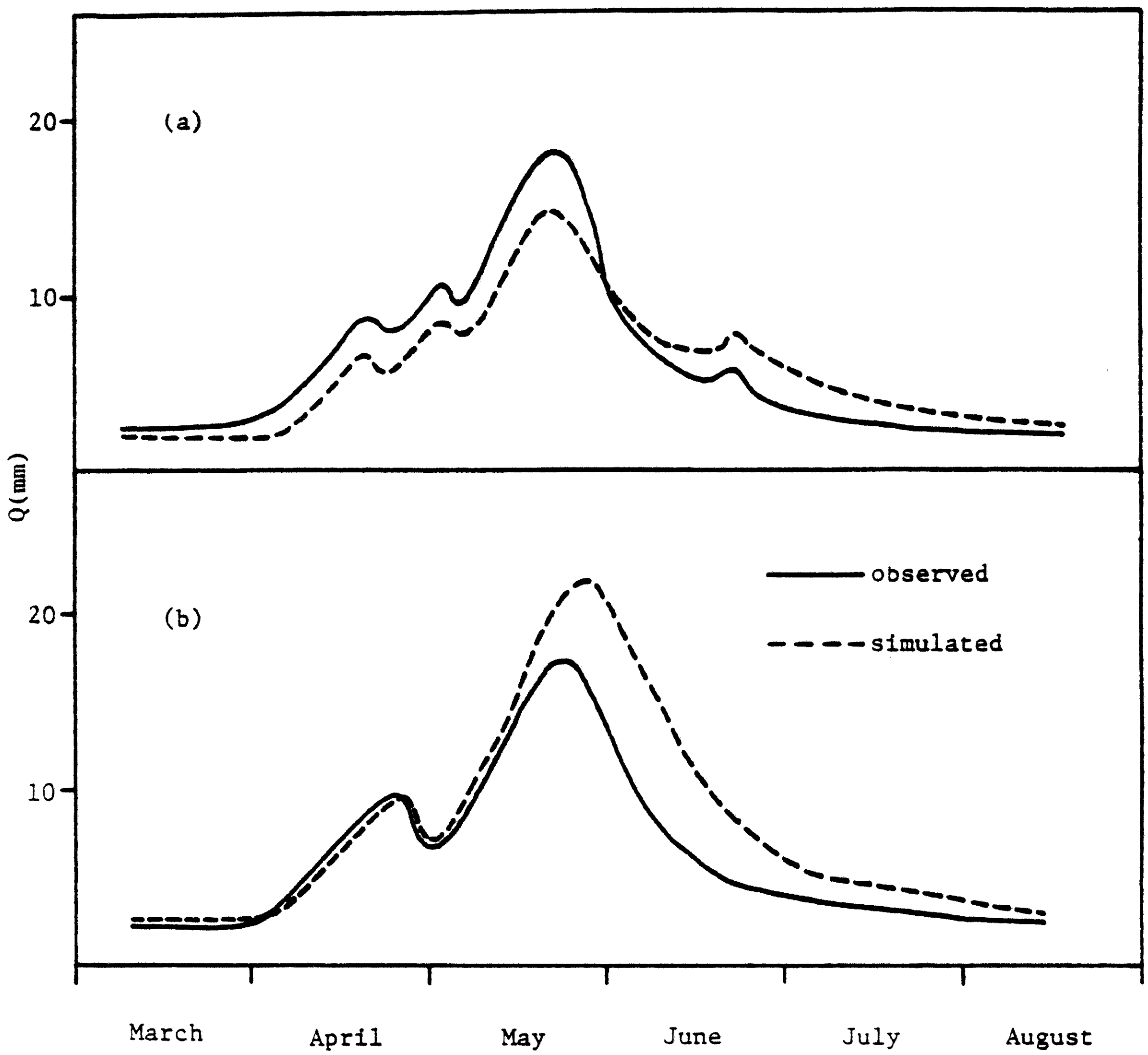

Figure 1. Timing errors in simulated discharge (a) are generated when the snowpack energy balance is inaccurately estimated. Volume errors in simulated discharge (b) occur if the simulated water equivalent is over or underestimated.

precipitation data) and 1 places total weight on the regression water equivalent (the snow course data). The shape parameter (S) controls the shape of the curve and ranges from 0 to 1; a value of 0 maps a cubic function while a value of 1 maps a linear function (Fig. 2). The third parameter is calculated from the snow course data and is an estimate of how normal or abnormal the observed snow accumulation is for each month for the period of record. The reliance parameter (R) is used to quantify the normality of the monthly snow accumulation pattern and to give some measure of the reliance that should be placed on the simulated and regression water equivalents. Normality here is based on two factors: (1) the deviation of the monthly snow course water equivalent from normal, and (2) the deviation of the monthly rate of snow accumulation from normal. An R-value near -1 indicates that both the rate and depth of snow accumulation are near normal, while a value near 1 indicates that both the rate and depth are much above or below normal. During months of near normal snow accumulation, the use of snow course data (regression water equivalent) tends to generate a better fit while the simulated water equivalent (precipitation data) tends to generate a better fit when snow accumulation is abnormal.

Both the shape and adjustment parameters may be mathematically

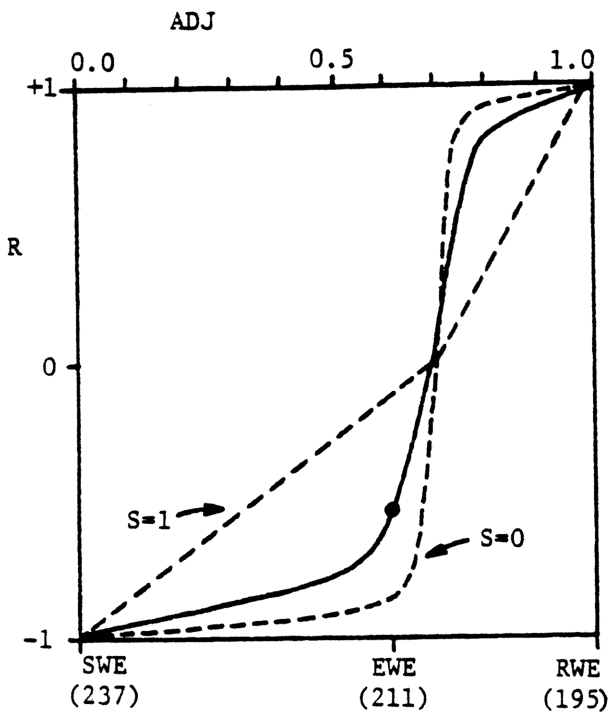

Figure 2. With ADJ, R, and S equal to .7, -.55, and .2, respectively, the estimated water equivalent equals 211 mm.

optimized to minimize the total monthly volume error. The optimum value of these parameters should reflect the physical relationship of the precipitation data to the snow course data and consequently vary from one basin to another.

The estimated water equivalent can be calculated after the three parameters have been determined. For example, figure 2 indicates that with SWE, RWE, S, ADJ, and R equal to 237 mm, 195 mm, .2, .7, and -.55, respectively, the estimated water equivalent becomes 211 mm. This value then replaces the simulated water equivalent generated by the ablation model.

Criteria to Evaluate Results

The update procedure is intended to reduce monthly volume errors in stream discharge and provide a set of statistics with which to evaluate the results. The statistics include three sets of monthly discharge values for the entire period of record: (1) observed discharge, (2) simulated discharge generated without using the update procedure, and (3) simulated discharge generated using the update procedure. With these data, it is possible to determine the degree to which the update procedure reduces or increases the discharge volume error associated with (1) each month, (2) each year, and (3) the period of record. The principal criterion to evaluate the update results represents the increase or decrease of volume errors. This criterion is expressed as

$$C = \left| \sum_{i=j}^{k} (sim_i - obs_i) \right| - \left| \sum_{i=j}^{k} (simu_i - obs_i) \right|$$

where

sim = simulated monthly discharge before update (mm)
simu = simulated monthly discharge after update (mm)
obs = observed monthly discharge (mm)
j = first month
k = last month.

In this way, it is possible to evaluate the update results for any duration during the period of record. Typically, criteria are calculated for each water year, C_t, and for a subset of each water year based on data from April to September, C_s. Peak snow accumulation generally occurs between mid-March and May 1 in the high elevations of the western U.S.; consequently, the most important water supply forecasts are made typically after the April 1 snow course data are available. It is possible to update the simulated water equivalent based on the February, March, and April 1 snow course data and use the criterion based on the April to September discharge data to indicate the improvement generated by the update procedure for the water supply forecast period.

A second statistic which is calculated by the update procedure is simply the criteria (C) weighted for observed discharge:

$$P = \frac{-C}{\sum_{i=j}^{k} obs_i} \cdot 100.$$

P indicates the change in simulated discharge error as a percentage of observed discharge; P can also be calculated for the total water year or any subset. C_t, C_s, P_t, and P_s are calculated for each water year and also for the period of record. The P_t and P_s values for the period of record indicate the percentage the total monthly volume error is reduced when snow course data is used to update the simulated water equivalent.

RESULTS

The update procedure has been applied to three basins in the West: (1) Sevier River at Hatch in south-central Utah, (2) Dolores River at Dolores in south-western Colorado, and (3) the Eagle River in central Colorado. These basins have an NWSRFS calibration, much of their stream discharge originates from the snowpack, and Soil Conservation Service snow course data are readily available.

Sevier River

The update procedure was tested using two different model calibration for the Sevier River basin (881 km^2). The first calibration used an isohyetal analysis to assign precipitation to two physically identifiable subareas. The upper area represents the primary region of snow accumulation and generates 80 to 90 percent of the runoff; consequently, only the simulated water equivalent of the upper area is updated using the snow course data. The simulated water equivalents are regressed on thirteen snow course variables using January to April 1 data from 1952 to 1971. The regression equation estimates the regression water equivalent and has a significant F - value (.01 level) of 29.9, correlation coefficient of .972, and a ratio of the residual range to the standard error of the estimate of 3.9. For example, without benefit of the snow course data, the model over-simulates stream discharge for the 1963 water year by 7.4 mm (Table 1a). However, the update procedure reduces the simulated water equivalent by 10 mm on December 28, by 9 mm on January 29, by 14 mm on February 26, and 33 mm on March 28. Table 1a shows that the over-simulation for May, June, July, and August has been reduced along with the total error which is reduced by 6.7 mm or 10.6 percent of total discharge. Table 1b gives the results from 1952 to 1971; the mean yearly total error is reduced by 20.4 percent from 12.84 to 10.23 mm while the mean yearly subset error (based on April to September data) is reduced by 27.3 percent from 9.88 to 7.19 mm. This suggests that, on the average, the update procedure is capable of reducing monthly stream discharge volume errors by 27 percent during the critical April to September water supply forecast period for the Sevier River.

The update procedure was also tested using a different calibration for the same basin and period of record. The second calibration uses two pseudosubareas which do not correspond to physical parts of the basin. Weights were assigned to precipitation stations such that mean precipitation for each area corresponded roughly to the mean for the basin. The two areas were assigned a different elevation and consequently responded at different times during the melt season. The input parameters for each area were adjusted so simulated discharge reasonably corresponds to observed. This approach is computationally adequate (even though physically unrealistic) when no snow updating procedure is employed. Because neither of the pseudosubareas correspond to a physical position in the basin and both generate significant runoff, it is necessary to update both subareas. The simulated water equivalents calculated for each subarea are regressed on the snow course data. The equations used to estimate the regression water equivalents for the two subareas have significant F-values (.01 level) of 32.9 and 31.3, correlation coefficients of .975 and .974, and a ratio of the residual range to the standard error of the estimate of 3.9 and 4.5, respectively.

Table 1c summarizes the results from 1952 to 1971; the mean yearly total error is reduced by 3.8 percent from 11.15 to 10.72 mm while the mean yearly subset error (based on April to September data) is reduced by 6.2 percent from 9.57 to 8.98 mm.

The first calibration generates a lower error term than the second which suggests a physically realistic estimate of mean areal precipitation is necessary to obtain maximum benefit from a physically based snowpack update procedure.

Dolores River

The update procedure was tested

TABLE 1

UPDATE PROCEDURE RESULTS (mm)

(a) SEVIER RIVER - 1963

MONTH	OCT	NOV	DEC	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	TOTAL
OBS	5.0	5.0	4.8	4.3	4.4	4.5	4.7	13.1	4.9	3.8	4.4	4.2	63.1
SIM	6.1	5.1	4.5	4.1	4.1	4.5	5.6	14.2	7.8	4.7	4.9	4.9	70.5
SIMU	5.9	4.9	4.3	3.9	4.0	4.4	5.4	11.5	5.4	3.9	4.4	4.4	62.4

C_T = 6.7 C_S = 7.0

(b) SEVIER RIVER - Calibration One - 1952 to 1971

YEAR	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
OBS	165.2	68.7	85.4	61.4	58.9	87.5	164.4	64.2	53.0	58.8	120.0	63.1	71.9	108.6	103.7	131.6	131.7	209.4	87.5	72.6
SIM	170.1	83.1	85.2	53.6	42.0	75.0	192.7	94.6	65.5	83.4	102.6	70.5	64.7	101.8	127.2	135.7	121.3	198.7	98.5	78.4
SIMU	163.8	80.7	83.3	53.0	48.2	79.0	182.6	90.3	69.9	76.8	96.9	62.4	64.9	105.7	122.5	131.7	124.7	201.4	98.5	79.0
C_S	6.2	1.1	1.3	-0.2	6.3	2.4	10.8	2.2	-5.3	7.7	-3.9	7.0	2.3	3.5	5.5	4.0	6.8	1.4	0.4	-0.7

MTE = 12.84, MTUE = 10.23, 20.4% Reduction; MSE = 9.88, MSUE = 7.19, 27.3% Reduction

(c) SEVIER RIVER - Calibration Two - 1952 to 1971

YEAR	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
OBS	165.2	68.7	85.4	61.4	58.9	87.5	164.4	64.2	53.0	58.8	120.0	63.1	71.9	108.6	103.7	131.6	131.7	209.4	87.5	72.6
SIM	168.3	91.0	84.9	57.4	47.3	82.1	167.6	91.9	67.5	80.2	104.0	73.9	63.1	113.7	117.5	133.5	126.5	180.9	102.4	76.6
SIMU	163.5	86.9	90.1	58.4	52.2	93.0	160.3	86.2	71.3	76.3	92.4	63.5	61.7	117.9	110.5	122.6	131.5	181.3	102.4	78.9
C_S	5.0	2.9	-6.0	0.6	4.7	-9.6	8.3	3.5	-5.1	4.9	-10.5	6.5	1.8	-4.3	8.4	-2.9	7.7	-1.2	-0.3	-1.9

MTE = 11.15, MTUE = 10.72, 3.8% Reduction; MSE = 9.57, MSUE = 8.98, 6.23% Reduction

(d) DOLORES RIVER - 1957 to 1973

YEAR	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
OBS	477.3	401.0	110.2	268.5	218.2	294.2	164.3	184.6	377.8	254.3	168.0	278.9	295.0	276.4	250.0	169.1	476.7
SIM	467.9	391.3	148.8	309.9	238.1	248.9	171.6	165.3	407.2	260.7	180.5	218.1	285.8	259.8	236.4	183.6	525.0
SIMU	465.7	399.7	154.4	303.6	229.4	263.8	176.8	171.6	373.4	246.9	176.8	251.9	300.9	267.7	237.4	178.0	485.5
C_S	-2.2	8.5	-5.2	6.4	-2.3	15.4	-3.0	6.0	34.2	3.9	3.7	33.7	-8.3	7.1	-0.3	5.8	39.1

MTE = 23.66, MTUE = 14.84, 37.3% Reduction; MSE = 20.97, MSUE = 12.59, 40.0% Reduction

(e) EAGLE RIVER - 1949 to 1972

YEAR	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
OBS	234.5	202.6	237.6	296.3	205.7	112.8	149.2	200.4	317.2	219.1	187.1	208.3	151.0	287.8	131.7	158.7	267.6	145.5	163.8	199.2	200.9	256.3	256.2	195.7
SIM	239.1	162.6	246.7	288.4	178.3	114.9	130.8	213.6	337.4	209.4	208.1	235.5	160.7	303.2	162.7	117.7	235.9	147.6	152.8	134.3	191.5	249.8	213.7	148.6
SIMU	240.8	166.6	255.6	283.4	180.9	120.9	131.5	220.6	326.8	202.7	189.4	228.1	156.8	292.8	139.7	117.4	221.0	144.2	161.9	149.6	181.8	233.9	225.5	164.9
C_S	-1.6	4.1	-8.6	-5.4	2.9	-5.8	-0.1	-7.0	11.0	-6.4	18.4	6.2	3.9	10.0	22.6	1.9	-15.0	2.7	8.9	14.4	11.3	-2.9	12.5	15.6

MTE = 21.38, MTUE = 18.92, 11.15% Reduction; MSE = 19.27, MSUE = 15.73, 18.4% Reduction

NOTE: OBS = observed discharge
SIM = simulated discharge before update
SIMU = simulated discharge after update
C_T = total error improvement
C_S = subset error improvement (April-Sept data)
MTE = mean total error
MTUE = mean total update error
MSE = mean subset error (April-Sept data)
MSUE = mean subset update error (April-Sept data)

also on the Dolores River at Dolores ($1305\ km^2$) in southwestern Colorado from 1956 to 1973. The upper subarea is $522\ km^2$ with a mean elevation of 3335 m while the lower subarea is $783\ km^2$ with a mean elevation of 2650 m. Both subareas are updated using data through the April 1 observation from eleven snow courses. The regression equations for the upper and lower subareas have significant F-values (.01 level) of 13.5 and 13.7, correlation coefficients of .962 and .963, and a ratio of the residual range to the standard error of the estimate of 3.5 and 4.1, respectively.

The update procedure reduces the total yearly simulation error for thirteen of the seventeen years. Table 1d gives the results from 1956 to 1973; the mean yearly total error is reduced by 37.3 percent from 23.7 to 14.8 mm while the mean yearly subset error (based on April to September data) is reduced by 40.0 percent from 30.0 to 12.6 mm.

The update procedure is based on April 1 snow course data; however, snow course observations are made on May 1 and, in a few cases, June 1. When Dolores River was updated using data through May 1; the mean yearly total volume error was reduced from 23.66 mm to 19.83 mm, an improvement of 16.2 percent. However, when data through only April 1 are used, the same error is reduced to 14.8 mm, a 37.3 percent improvement (Table 1d). Variation of slope and aspect cause differential melt of the snowpack; consequently, snow course measurements taken near maximum accumulation tend to be a better index of mean areal snow cover than those taken during the ablation season (Hannaford, 1956).

Eleven snow courses were used to derive the regression equations for the April 1 and May 1 update procedures on the Dolores River. However, only two snow courses are in the Dolores watershed; two are located 5 to 10 km north in the San Miguel watershed; the remainder are in the Animas watershed to the east and separated by a 4000 m massif running north and south. The Dolores River was updated using May 1 data and only the four snow courses west of the massif to check if the seven courses to the east were unrepresentative. The correlation coefficients for the upper and lower areas are .89 and .93 in contrast to .95 and .97 when all eleven snow courses are used; the regression water equivalent is not as accurately estimated when using data from only four courses. Consequently, the update procedure <u>increases</u> the mean yearly total error by 10.6 percent when using four courses, in contrast to the reduction of 16.6 percent when eleven snow courses are used to calculate the regression water equivalent. The success of the update procedure is consistently proportional to the explanation of the regression equations for all basins.

Eagle River

The update procedure was tested on the larger Eagle River at Gypsum ($2445\ km^2$) in central Colorado for 1949 to 1972. The Eagle basin is divided into an upper ($1222\ km^2$, 2600 m) subarea. Only the upper subarea is updated using data from six snow courses through the April 1 observation. The regression equation has a significant F-value (.01 level) of 66.1, correlation coefficient of .966, and a ratio of the residual range to the standard error of the estimate of 5.0.

Table 1e summarizes the results from 1949 to 1972; the mean yearly total error is reduced by 11.5 percent from 21.38 to 18.92 mm while the mean yearly subset error (April to September) is reduced by 18.4 percent from 19.3 to 15.7 mm. The update procedure generates a greater improvement in the monthly volume errors for the Sevier and Dolores Rivers than for the Eagle River. The precipitation stations and the snow course sites used for the Eagle River simulation are in close proximity in the south-eastern section of the basin. Consequently, only limited information is added by the use of the snow course data.

DISCUSSION

The most critical aspect of the update procedure is the algorithm which selects the estimated water equivalent from the range of the simulated and regression water equivalents. The selection is controlled by the two input parameters and the reliance parameter (R) calculated from the snow course data. Currently, the algorithm which calculates the R-value does not directly incorporate the physical characteristics of the snow courses. Perhaps the additional consideration of slope, aspect, elevation, and proximity to the basin may lead to a physically more justifiable R-value with which to select the estimated water equivalent. A second possible approach would consider only the error properties of both the simulated and regression water equivalents in selecting the optimum estimated water equivalent. The most effective use of snow course data to update the simulated water equivalent should tend to minimize the mean yearly total error of monthly stream discharge volume.

CONCLUSION

Both timing and volume errors can occur in stream discharge simulation of a snow-covered watershed. Snow course data offer an index of winter precipitation which integrates the many physical processes contributing to snowpack accumulation. As a result, snow course data can be used to reduce volume errors in simulated discharge. This is accomplished by weighting a regression estimate of water equivalent based on snow course measurements along with the mean areal simulated water equivalent generated by the snow accumulation and ablation model to determine a revised estimate of water equivalent. The snow course data represent a physical basis for modifying the simulated water equivalent to reflect more accurately the true snow cover of the basin. Snow course data collected on April 1 generally represent a good estimate of peak snow accumulation and can be successfully used to update the simulated water equivalent generated by the snow accumulation model. However, snow course observations made during the melt season are not as representative of basin wide snow cover and consequently do not lead to an accurate estimate of mean areal water equivalent.

Monthly volume errors in stream discharge simulations were reduced by 40, 28, and 18 percent on the Dolores, Sevier, and Eagle Rivers, respectively, using the April 1 snow course observations to update the mean areal snow water equivalent. The results demonstrate that snow course data can be used to significantly reduce volume errors in conceptual streamflow simulation models.

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