SNOWMELT MODELING OF UPPER MISSOURI RIVER WATERSHEDS WITH SSARR

by

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Introduction

Estimates of snowmelt runoff from high elevation watersheds are needed to properly regulate six multipurpose reservoirs on the main stem of the Missouri River. The Missouri River Division (MRD), Corps of Engineers schedules reservoir operations to provide for flood control, hydroelectric power generation, navigation, and irrigation. The operating capacity of this reservoir system varies from 36 to 145 percent of observed annual streamflow. Weekly or monthly streamflow volume estimates are adequate to regulate conservation storage during years with low precipitation and runoff. During periods of high runoff, and thus flood potential, daily streamflow estimates are needed. A continuous simulation model which is capable of using SNOTEL (Barton and Burke 1977) and other available data was considered to be appropriate for these purposes.

Initially, the Missouri River Division considered several models and modeling approaches. The Streamflow Synthesis and Reservoir Regulation (SSARR) model was selected to be tested because of its realistic data input requirements, its snowmelt options, and its demonstrated capability to provide real-time streamflow forecasts in the Columbia River system (U.S. Corps of Engineers 1972). In addition, the model can be used to simulate reservoir operations, streamflow depletions, and return flows.

Basin Descriptions

The Gallatin and Madison River Basins were selected as test basins for the SSARR model. Snowmelt is the primary source of streamflow in both rivers. Each basin was subdivided according to the locations where streamflow data were available. The Madison Basin included the area above Ennis Lake, near McAllister, Montana. The 924-square mile area above Hebgen Lake was modeled separately from that between Hebgen Lake and Ennis Lake (area = 1,276 sq. mi.). The Gallatin Basin was modeled above Gateway (area = 821 sq. mi.).

Groundwater inflow to both rivers results in high baseflow throughout the year, particularly in the Madison. The groundwater influence in the Madison is evident when water budgets are examined (Table 1). Streamflow represents a high percentage of annual precipitation and runoff volume is relatively constant from year to year. Much of this baseflow originates from springs and thermal activity in or near Yellowstone National Park (USDA 1976).

Soils may be considered shallow from a soil scientist's viewpoint, but the deep, weathered parent material provides for substantial storage of rainfall and snowmelt. Soils in the Madison Basin range from loamy sand to sand with reported available water capacities of 3 to 5 inches (USDA 1978). Soils in the Gallatin Basin range from clay to loam with available water capacities of 4 to 12 inches (USDA 1978).

Lodgepole pine (*Pinus contorta* Dougl.) is the predominant forest type in the upper elevations of both basins. At lower elevations, open wet meadows contain willow (*Salix* spp.) and cattails (*Typha* spp.). In the drier areas, sagebrush (*Artemisia* spp.) and perennial grasses are most common.

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Table 1. Upper Madison annual water budget.

Water Year	Precipitation[a]	Runoff	Δ Soil Moisture[b]	Et[c]	PET[d]
1964	24.76	14.74	+2.05	7.97	17.23
1965	31.68	17.21	+3.53	10.94	17.51
1966	18.06	13.42	-2.33	6.97	18.72
1967	26.47	17.08	- .82	10.21	17.46
1968	28.87	16.85	+3.60	8.42	17.49
1969	20.47	18.23	-1.50	3.74	18.90
1970	23.35	16.47	+1.38	5.50	16.85
1971	27.50	19.87	+ .42	7.21	16.77
1972	25.49	20.05	-2.35	7.79	17.32
1973	22.09	16.23	+ .27	5.59	17.37
1974	20.80	18.57	- .67	2.90	18.40
1975	21.36	17.45	-1.92	5.83	17.23
1976	26.04	17.87	+2.14	6.03	18.14
1977	16.02	12.87	not available	--	18.64

[a] Precipitation determined by Thiessen Polygon Method.

[b] Soil Moisture change calculated using SCS data (USDA 1978).

[c] Et calculated as residual.

[d] Thornthwaite PET.

Methods

The study was conceived and carried out with the understanding that data and methods would be compatible with operational streamflow forecasting and reservoir operation. Thus, only climatologic and hydrologic data which would be available to MRD personnel were used. Likewise, a straight-forward model calibration procedure has been developed to facilitate model application to other basins. To the extent possible, relationships were developed from physical watershed characteristics.

The snow-band option, as described by the U.S. Corps of Engineers (1972), was used to model both basins. Snowmelt was computed using the temperature-index method with maximum daily temperature.

Data Base

Streamflow, maximum daily temperature, precipitation, and snow-course data for water years 1964-1977 were used in this study. Eight of these years were chosen for calibration and the remaining six years were set aside to verify the model. The fourteen water years were initially grouped according to whether they exhibited higher or lower than average streamflow. Years were randomly selected from each category to assure that the calibration data set contained high and low flow years.

Precipitation and temperature stations in each sub-basin are given in Table 2. Precipitation weightings were determined by the Thiessen polygon method (Linsley *et al.* 1975). The single temperature station which was most centrally located in each sub-basin was selected and given a weighting of 1.00.

Overview of snowmelt simulation

Simulation of snowmelt-runoff with the SSARR model involves several parameters and relationships (U.S. Corps of Engineers 1972). In order to correctly simulate the timing and magnitude of snowmelt, the following information was needed:

1. Area - elevation relationship of each basin
2. Rain - freeze temperature
3. Lapse rate

4. Base temperature for temperature index method

5. Melt rate(s)

6. Snow water equivalent distribution over the basins

Area - elevation relationships

The area - elevation relationship for each sub-basin was determined by planimetry (Figure 1). The snowbands were specified in 1000-foot intervals. Some bands had a very low percentage of the total area. For practical application a snowband should not represent less than 5 percent of the basin area.

Rain - Freeze Temperature

The rain - freeze temperature determines whether precipitation falls as rain or snow. Initially, the simulated streamflow was sensitive to precipitation early in the melt period while the observed streamflow was not. The model was treating precipitation as rainfall when it actually was snowfall. To correct this problem the rain - freeze temperature was changed from the default value of 35°F to 40°F.

Lapse Rate

The lapse rate is a critical parameter for snowmelt simulation. It extends air temperature from observed elevations to the entire basin. The lapse rate determines the elevation at which snowmelt occurs and the elevation at which rainfall changes to snowfall. Consequently, the lapse rate affects the timing of runoff from rainfall and snowmelt for the snowbands.

Using the default value of 3.3°F per 1000 feet, the snowbands became snowfree approximately 6 days apart. By examining plots of temperature versus discharge, actual snowmelt was contributing to runoff well after the highest elevation bands in the model were snowfree. To correct this, the lapse rate was increased to 4.0°F per 1000 feet.

Base Temperature

The base temperature for the temperature-index method affects both the timing and magnitude of melt. The base temperature for each sub-basin was determined using plots of temperature and discharge. These plots indicated that a temperature of approximately 50°F must be reached before the streams responded significantly. A base temperature of 47°F was selected, taking into consideration that melt was likely occurring at lower temperatures before the streams showed a significant response.

Table 2. Hydromet Stations Summary.

Station	Number	Elev. (ft.)	Precip. Weighting	Temp. Weighting
		UPPER MADISON		
Hebgen Dam	4038	6,489	.17	.00
West Yellowstone	8857	6,600	.83	1.00
		LOWER MADISON		
Ennis	2793	4,950	.52	1.00
Hebgen Dam	4038	6,489	.48	.00
		UPPER GALLATIN		
Bozeman St. Univ.	1044	4,850	.12	.00
Bozeman 12 NE	1050	4,850	.12	.00
Ennis	2793	4,950	.24	1.00
Hebgen Dam	4038	6,489	.52	.00

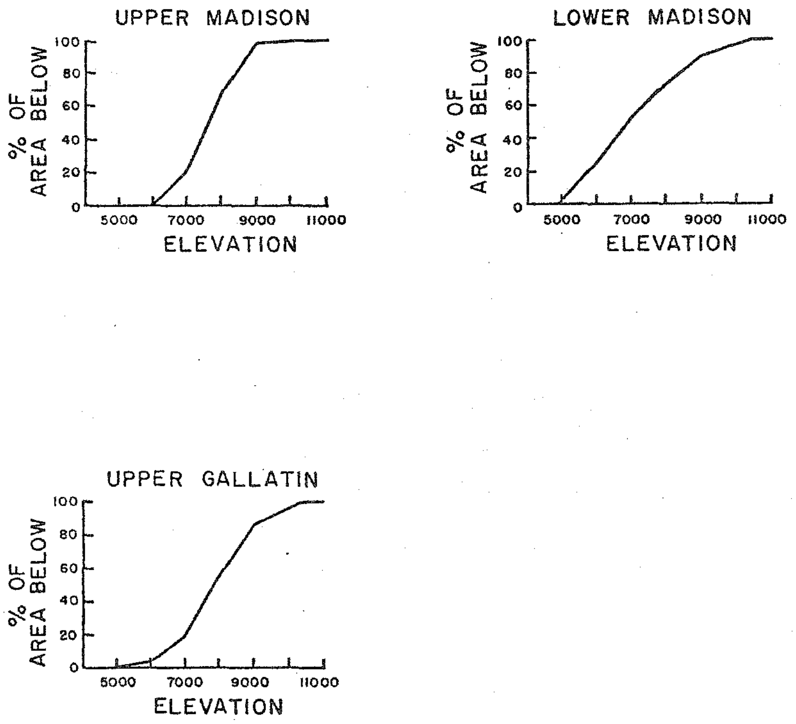


Figure 1. Area-elevation relationships for the sub-basins of the Madison and Gallatin Rivers.

Melt-rate Function

The melt-rate function or degree-day factor (U.S. Corps of Engineers 1956) affects the timing and magnitude of snowmelt and hence, runoff. Melt-rate functions in inches per degree-day were developed on the basis of accumulated degree-days above 47°F. Degree-days were accumulated from April 1 for the upper basins and April 15 for the lower basin. These dates were selected because they coincided with the approximate starting dates for snowmelt simulations and adequate results were obtained with these dates. By considering the degree-days before the selected starting points the melt-rate functions were not improved.

The magnitude of the melt-rate was changed after a specified number of degree-days. The amount of each change was determined subjectively. The melt-rate was increased stepwise so that on the average, the simulated hydrograph followed the observed hydrograph as illustrated in Figure 2. The final melt-rate functions for each sub-basin are illustrated in Figure 3. The melt-rate functions determined by this method may be improved with the analysis of SCS snow-pillow data.

Snow Water Equivalent Initial Condition

Soil Conservation Service snowcourse data were used to estimate the basin snow water equivalent (SWE) for the beginning of each simulation. Snowcourses were selected on the basis of proximity to each sub-basin. Ten snowcourses were used in the Upper Madison ranging in elevation from 6550 to 9000 feet. In the Lower Madison 12 courses were used, ranging in elevation from 6100 to 8850 feet. Finally, in the Upper Gallatin, 15 courses were used ranging in elevation from 6300 to 9000 feet.

A relationship between SWE and elevation was needed to allocate initial SWE values into the respective elevation bands. The regression of SWE on elevation was unsatisfactory; therefore, the arithmetic mean of the reporting stations for each basin was used. The mean SWE was then distributed over the elevation bands proportional to previously determined SWE values obtained from the SSARR model. This distribution of SWE, which was dependent upon rain-freeze temperature, lapse rate, and snowmelt computations by the model, indicated a snow wedge effect.

Early computer runs indicated that simulated streamflow was quite sensitive to the initial SWE values. Since the Soil Conservation Service snowcourses are, by design, located in areas of high accumulation which contain snow late into the melt season, snowmelt volumes were over-estimated considerably. The average SWE values were subsequently reduced by a fixed percentage until, on the average, the calculated and observed runoff volumes were equal. The SWE for the basins ranged from .28 to .53 of SCS snowcourse average values. These same weighting factors were applied without modification for the verification years.

Evaluation

The SSARR model simulations were evaluated only during the period of snowmelt runoff. For each year the evaluation period began five days before the initial rise of the snowmelt hydrograph and ended five days after the recession flow became constant.

Evaluating the SSARR model simulations is extremely difficult because an optimal set of parameters and relationships cannot be readily developed. The "fitted-parameter" approach requires that relationships be adjusted until simulated streamflow approximates observed streamflow. The key to determining when the model has been satisfactorily fitted, depends on the purposes of the simulation. In this case, streamflow volumes were of primary importance; therefore, the basins were considered sufficiently modeled when the simulated volumes were within 15 percent of observed. This accuracy seems reasonable since gaged streamflow that is within 10 percent error is considered good (Linsley and Franzini 1979).

The comparison of volume estimates is a simple matter with SSARR. A synthetic reservoir is defined into which computed flow is an input and observed flow is changed into negative flows which are likewise an input (U.S. Corps of Engineers 1972). The reservoir storage-elevation relationship is specified such that one foot is equal to runoff of one area inch. Streamflow volumes can be compared over time to within .01 area-inch with this technique.

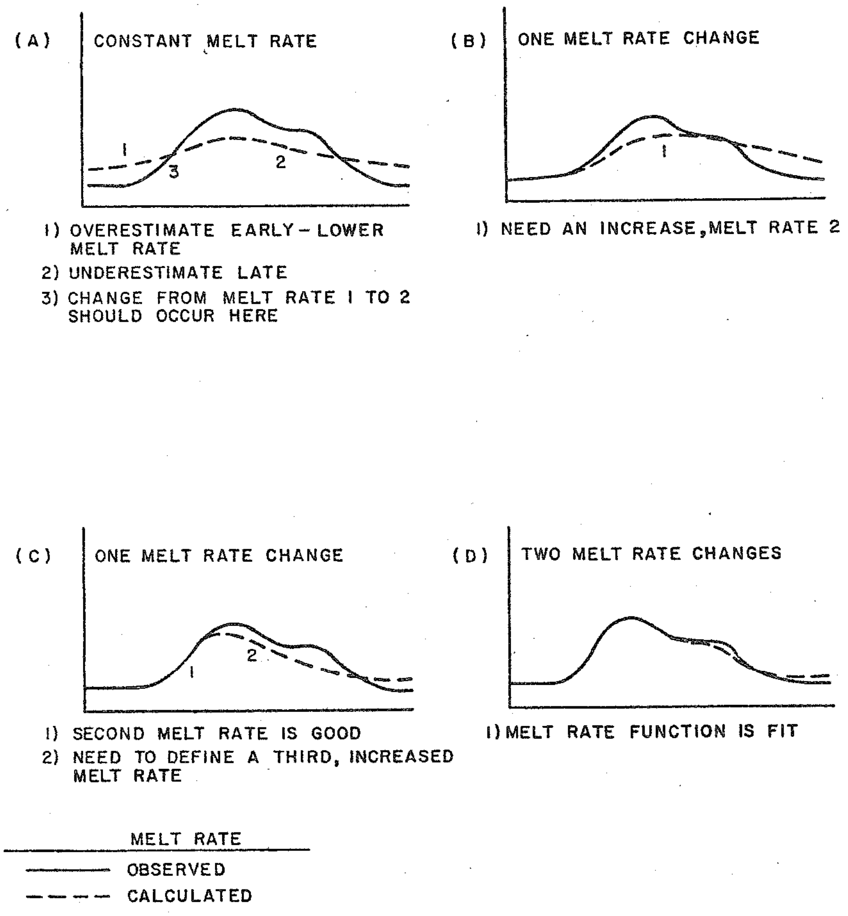


Figure 2. Melt-rate function development; the abscissa represents time and the ordinate represents discharge in cubic feet per second.

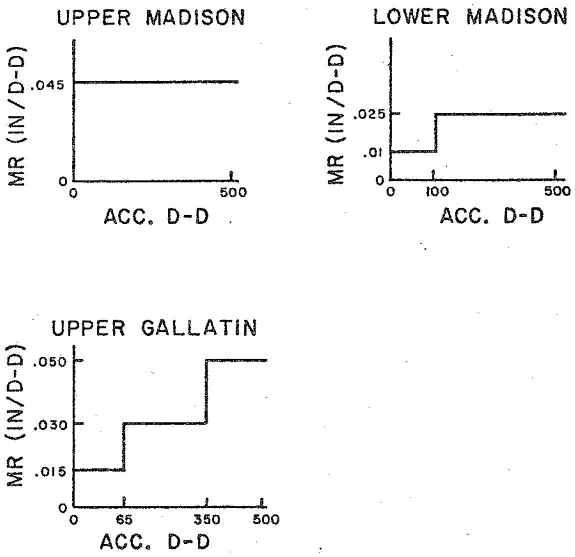


Figure 3. Melt-rate functions for Madison and Gallatin sub-basins using maximum daily temperature and base temperature of 47°F.

In this study, the comparison of parameter sets was based on the average and standard deviation of the ratio R, where R is the simulated value divided by the observed value. Using this ratio, a perfect fit on every year would yield $\bar{R} = 1.00$, S.D. = .00. The R statistic was determined for snowmelt peak magnitude and timing of the peak although the hydrograph shape was of secondary concern. Timing of the peak was measured in days following the initial rise in snowmelt streamflow.

A major strength of the R statistic is that it is dimensionless. Thus, in a case where volume, magnitude, and timing of peak are all of interest, the R and standard deviation of R for each component can be calculated, weighted as desired, and combined to give representative numbers for comparison of parameter sets. Other possible methods include Chi-Square goodness-of-fit, and time-series analysis. Both of these methods are difficult to interpret and time consuming, and therefore were not used in this analysis.

Results and Discussion

Snowmelt-runoff volumes were simulated within the acceptable limits for all three sub-basins (Table 3). The calculated volumes are contrasted to observed volumes in Figure 4. The best results in terms of the R statistic were obtained for the Upper Madison. Streamflow simulations of the Upper Madison River for one calibration year and one verification year are illustrated in Figure 5.

Peak flows were generally underestimated and were later than the observed (Table 3). A lack of precipitation and temperature stations within the Upper Gallatin may explain the lack of precision with respect to timing and magnitude of the peak for this basin.

Snowmelt-streamflow simulation for forecasts in the Upper Missouri River may be further enhanced by using SNOTEL data (Barton and Burke 1977). Better estimates of melt-rate coefficients should be obtained using these data. Recent modifications to the SSARR model described by Speers *et al.* (1978) and Kuehl (1979) may also improve real-time forecasting capabilities using the snow-band method. The basic snowmelt relationships and watershed parameters developed in this study could be easily incorporated into the latest version of SSARR.

Table 3. Calibration and verification results of SSARR simulations for three sub-basins to the upper Missouri River.

	Calibration of Snowmelt Runoff					
	Volume		Peak		Timing of Peak	
Basins	$\bar{R}$[a]	S.D.[b]	$\bar{R}$	S.D.	$\bar{R}$	S.D.
Upper Madison	1.00	.08	.98	.16	1.02	.10
Lower Madison	.98	.15	.91	.28	1.06	.05
Upper Gallatin	.99	.08	.81	.13	1.04	.08

	Verification of Snowmelt Runoff					
	Volume		Peak		Timing of Peak	
Basins	$\bar{R}$	S.D.	$\bar{R}$	S.D.	$\bar{R}$	S.D.
Upper Madison	1.02	.12	.90	.10	.98	.11
Lower Madison	.96	.19	.81	.31	1.01	.06
Upper Gallatin	.95	.24	.77	.19	1.02	.04

[a] $\bar{R}$ = ratio of simulated to observed.

[b] S.D. = standard deviation.

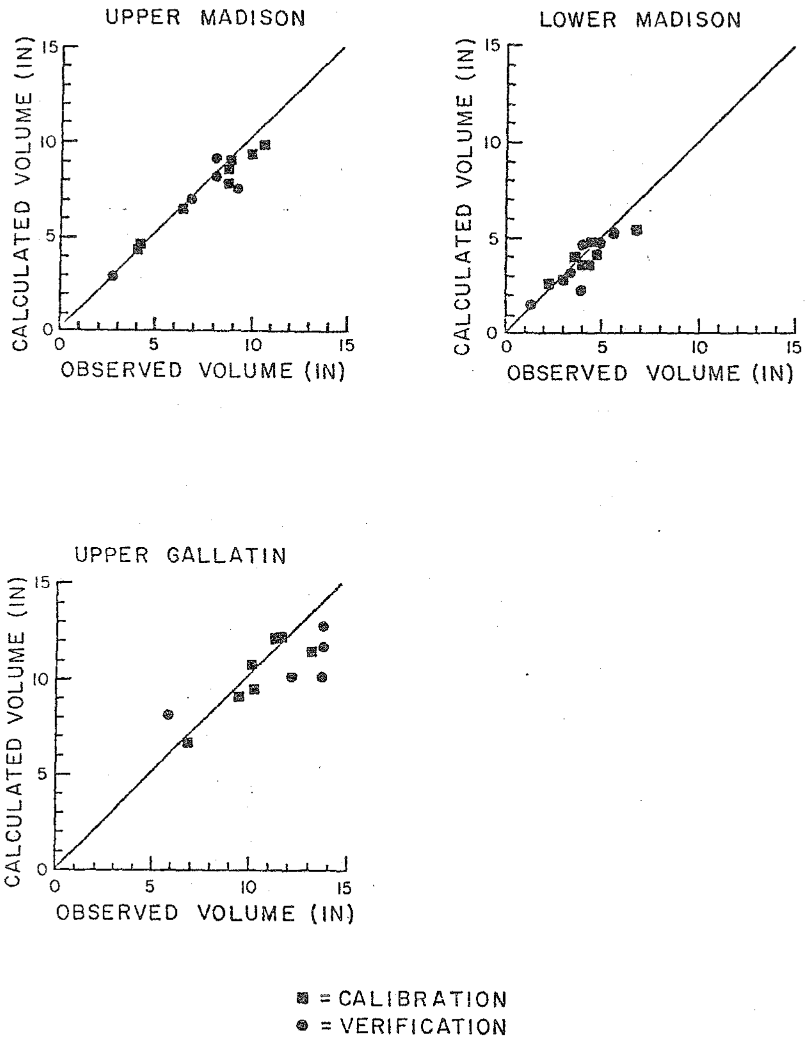
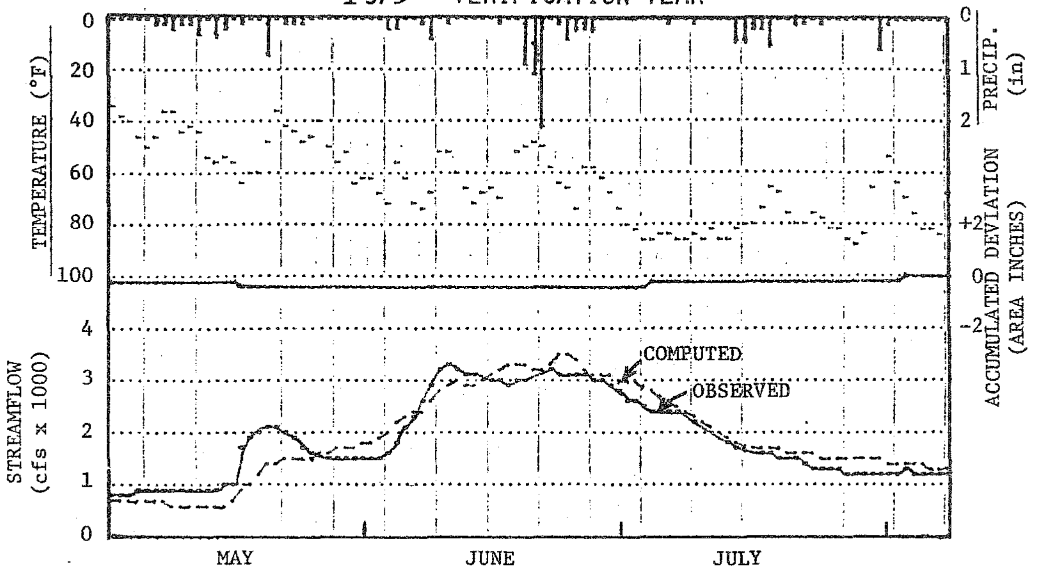


Figure 4. Calculated vs. observed streamflow volumes for SSARR model calibration and verification years.

1975 - VERIFICATION YEAR



1967 - CALIBRATION YEAR

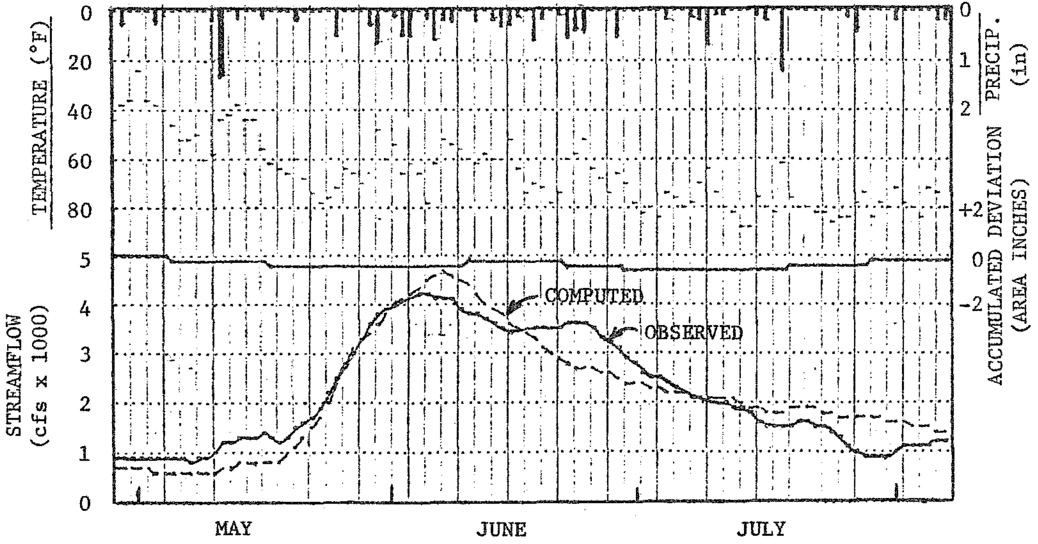


Figure 5. Computed and observed streamflow for the Upper Madison River.

Summary and Conclusions

In order to improve snowmelt-runoff forecasts and thus reservoir operations, the SSARR model was calibrated and tested on Madison and Gallatin sub-basins of the Upper Missouri River. The snow-elevation band option was used and snowmelt was computed by the temperature index method. The model was calibrated on 8 years of daily streamflow data, selected randomly from a 14-year record. The remaining years were used for model verification. Procedures for the parameter fitting process were developed which rely on basin characteristics and readily available data. For the snowmelt-runoff periods, streamflow volumes and peaks were simulated well within acceptable limits. The SSARR model can, therefore, be used in the Upper Missouri River Basin to simulate snowmelt runoff, which should improve streamflow forecasts and downstream reservoir operations.

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