

BY

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INTRODUCTION

Improved forecasts of snowmelt streamflow in the western United States could have a significant impact on management options and economic returns, since most of the annual streamflow occurs during the April-July period. Better forecasts would allow reservoir managers to more nearly optimize storage-release relationships, thereby allowing the multitude of competing water users to maximize returns.

Traditionally streamflow forecasts have been based on regression techniques, which have provided good estimates of seasonal streamflow volume, except in extreme years. Mathematical simulation models designed to represent snow accumulation and melt, rainfall, runoff, and watershed and channel routing processes offer the potential of improved streamflow forecasts. These models provide estimates of both seasonal volume, and the timing of runoff, which is especially important to flood stage prediction and reservoir operation. The possibility of using real-time snowpack information such as that provided by the Soil Conservation Service (SCS) SNOW TELemetry (SNOTEL) system also offers the potential of improved and more timely forecasts from simulation models which can be updated as data becomes available. Models also provide the opportunity for analyzing any given event during the season.

The objectives of this paper were to: 1) evaluate the snow accumulation and melt model HYDRO-17, which is a component of the National Weather Service River Forecast System (NWSRFS) model, as a possible replacement for more simplified snow models presently used in several hydrologic models; and 2) evaluate the NWSRFS model using data from a Montana watershed with respect to simulating streamflow and future forecast applications using real-time data.

Description of the Study Site.

The Lower Willow Creek basin is located near Hall, Montana, and encompasses an area of 190 square kilometers above the dam (Figure 1). Elevation ranges from 1430 m above sea level at the dam to over 2400 m at the highest point. Average annual precipitation varies from 350 mm at the lower elevations to more than 760 mm at the higher elevations. Streamflow records are available for most of the spring, summer, and fall months of each year from 1967 through 1984.

Two SCS SNOTEL sites, each consisting of a snow pillow, precipitation gage, and radio transmitter, are located on the Lower Willow Creek Watershed. The Combination data site is located near a main tributary in the southerly part of the basin at an elevation of 1700 meters. Average annual precipitation at the site is about 538 mm. Daily snow water equivalent (SWE) data are available for the 1973-1985 period, and daily precipitation data are available for the 1979-1985 period. The Combination site represents the lower end of a conifer forest.

The Black Pine data site is located at an elevation of 2164 m on the southerly upper end of the Lower Willow Creek basin. Average annual precipitation is about 726 mm. Records of SWE are available for the 1966-1985 period. The Black Pine site is located in a dense conifer setting and represents a continuous conifer forest.

Long-term climatological records are available for three stations within the general area of Lower Willow Creek. The stations, Drummond, Philipsburg, and Silver Lake, all lie outside of the watershed boundaries. Records from the Drummond weather station were

^{1/} Presented at the Western Snow Conference, April 15-17, 1986; Phoenix, Arizona.
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"Reprinted Western Snow Conference, 1986"

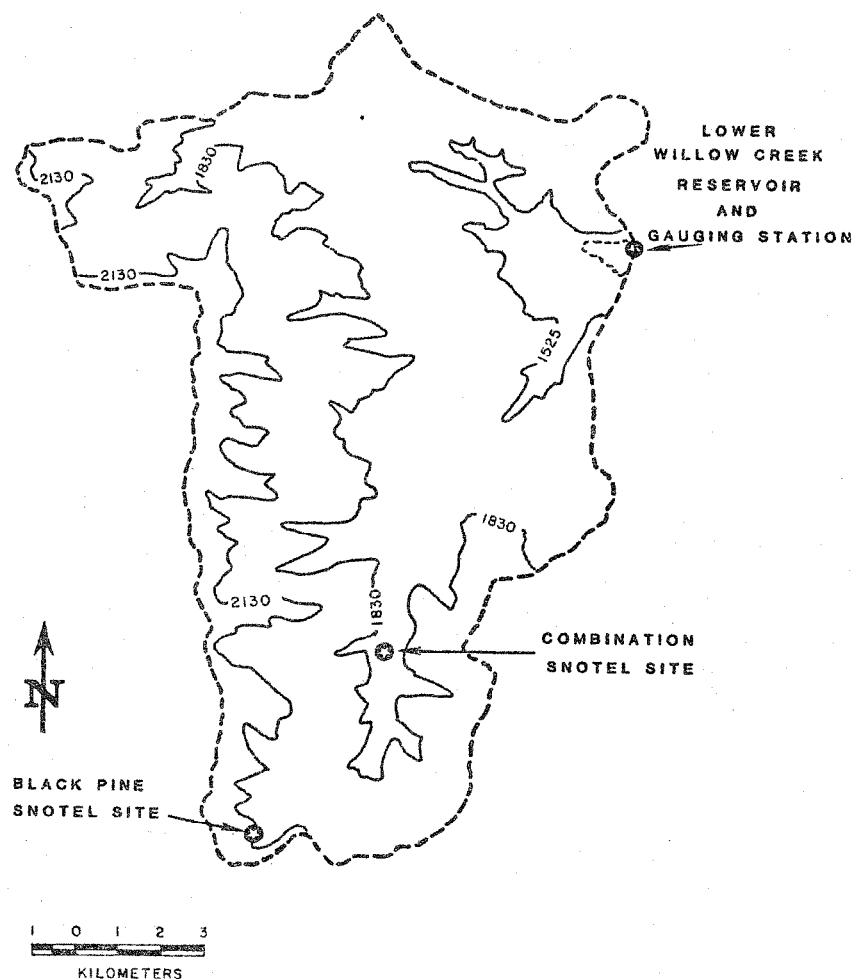


Figure 1. Lower Willow Creek Watershed near Hall, Montana.

the most complete and produced the best overall results in preliminary tests. Therefore, Drummond daily air temperature and precipitation records were used whenever needed as input to the models. Drummond is located approximately 16 km northeast of the basin at an elevation of 1202 m.

PROCEDURES AND RESULTS

Establishing Parameter Values.

The difficulty associated with running a model the first time, or at a new location, is reduced when a suggested range of parameter values is provided, as is the case with the NWSRFS snowmelt model (Anderson, 1973). Still, the range of suggested values is wide enough, and the possible combinations of parameter values which will minimize objective functions based on snow water equivalent are great enough that selecting the best set of parameter values can take considerable effort. If initial values of the parameters could be obtained from relatively simple analysis of the precipitation data, it would expedite the application of the model at new sites. Two analyses of the precipitation data were performed in an attempt to determine initial parameter values.

The first consisted of a standard regression analysis between daily precipitation at the snow pillow sites and the climatological stations. The regression analysis was performed for all combinations of precipitation data from the three stations near the Lower Willow Creek watershed and precipitation at the two snow pillow sites on the watershed for the February 1979 to August 1983 period. Results of the regression analysis are presented in Figure 2 for Drummond and the Black Pine pillow site, using daily values on days when either one or both of the stations being compared recorded precipitation. Correlations for the other climatological stations were also run, but none of the comparisons produced good

relationships; those for Drummond were the best. The low correlations may be partly due to differences in the time of reading of daily totals, and partly due to differences in meteorological conditions at the various locations. In this case, even if the correlations had been good (high r^2), the coefficients produced during the analysis do not relate to model parameter values, and are therefore of little value in choosing initial parameter estimates. Correlations considering only days when both sites recorded precipitation (eliminate zero values) may produce better results which could aid in parameter selection, although the number of data pairs (n) would be reduced greatly, thus reducing confidence in the results.

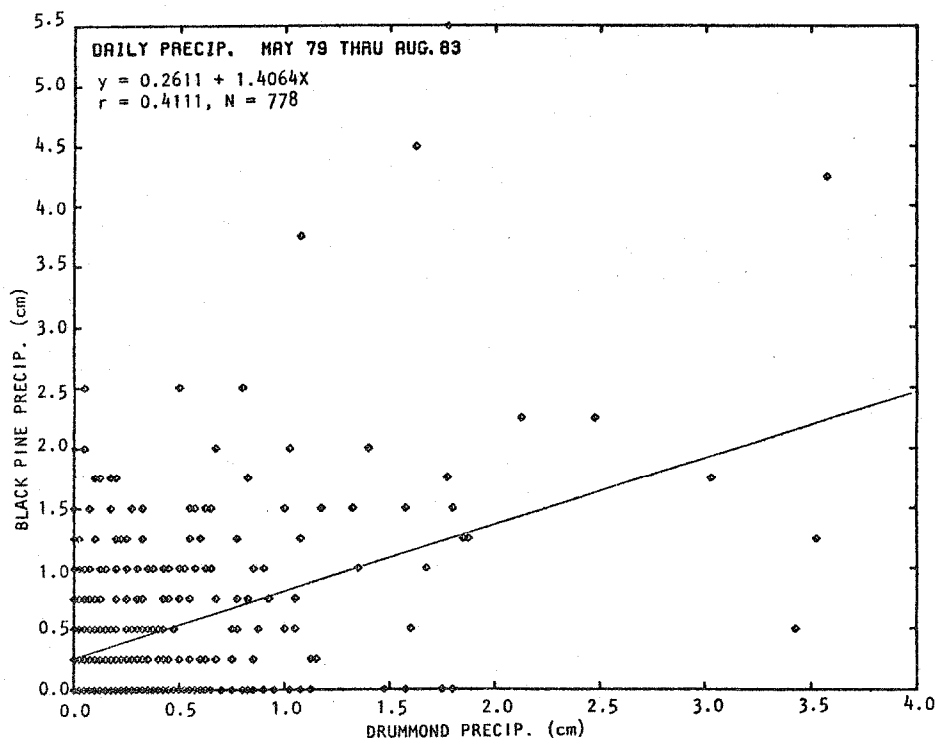


Figure 2. Relationship of daily precipitation at the Black Pine snow pillow site to daily precipitation at the Drummond weather station.

The second analysis consisted of determining monthly, seasonal, and annual ratios between snow pillow site precipitation and Drummond precipitation. The average monthly precipitation at Drummond weather station and the ratios are presented in Table 1. The periods selected to represent the summer and winter seasons were May through October and November through April, respectively.

The ratios in Table 1 indicate that precipitation at the pillow sites is 1.6 to 2.1 times that recorded at Drummond. The model parameter normally used to account for these differences in precipitation volume is PXADJ. PXADJ is a multiplier that is applied to all precipitation in the snow model. However, in this case the monthly ratios vary considerably during the year, and a constant multiplier would not provide the proper amount of precipitation at the right times. It is not possible to use monthly values of PXADJ at this time without stopping a model run at the end of the month, changing PXADJ, and starting the model run again for the next month. Therefore, the seasonal ratios were used to help account for the variability noted. First, PXADJ was set at the value of the summer ratio; then, in order to account for the greater difference observed during the winter, the snow correction factor SCF was set at a value near the winter ratio. The SCF multiplier is applied only when the precipitation occurs as snow (i.e., the air temperature is less than a threshold temperature which delineates rain from snow) and thus helps to properly accumulate the snowpack. This use of SCF is not part of the standard NWS procedure in that SCF generally represents an adjustment to account for snowfall loss from unshielded gages (Anderson, 1973). The values of SCF used in this study are therefore considerably greater than those suggested in NWSRFS documentation.

Using the seasonal ratios to represent PXADJ and SCF provided better simulations of snow water equivalent (SWE) at the two pillow sites than results obtained using only the annual ratio to represent PXADJ and a normal NWSRFS value of SCF. If precipitation records were not available at the snow pillow sites, precipitation-elevation relationships could be used to provide first estimates of PXADJ and SCF (Hanson, 1982).

Table 1. Average monthly precipitation at Drummond, Montana weather station and ratios of Combination and Black Pine snow pillow site precipitation to that at Drummond.

	Average monthly ^{1/} precipitation at Drummond (mm)	Ratio of Combination ^{2/} precipitation to Drummond precipitation	Ratio of Black Pine ^{2/} precipitation to Drummond precipitation
J	21.3	1.88	2.90
F	16.5	1.58	3.20
M	23.9	1.88	3.34
A	26.7	1.79	2.46
M	49.3	1.60	2.14
J	45.2	1.67	1.87
J	31.8	0.98	0.90
A	35.8	0.87	1.09
S	28.2	2.12	1.62
O	23.9	1.70	2.23
N	19.3	2.03	2.03
D	25.7	1.80	2.61
Annual	349.5	1.61	2.07
Summer			
May-Oct		1.50	1.64
Winter			
Nov-Apr		1.83	2.76

^{1/} Based on Jan 1973 - Sep 1984 period.

^{2/} Average monthly precipitation based on Feb or Apr 1979 - Sep 1984 periods. Ratios were also calculated using matching periods (1979-1984) for Drummond, and results were similar to those shown for seasonal and annual ratios, but monthly ratios were slightly more variable.

Snowpack Simulations

One of the objectives of this study was to locate or develop a more general and improved snow accumulation and melt algorithm than presently used in hydrologic models such as CREAMS (Knisel, 1980) and EPIC (Williams et al., 1984). These models use different methods of dividing basins into zones or fields, and water balance accounting than the NWSRFS model. Therefore, a different method of calibration was employed. Whereas the NWSRFS documentation recommends the various submodels selected be calibrated as a whole against streamflow (Brazil and Hudlow, 1981), in this study the snow accumulation and melt submodel was calibrated separately against snow water equivalent as recorded at the snow pillow sites.

Simulated and observed SWE at the Combination snow pillow are presented in Figure 3 for the 1974-1978 water years. Similar results were obtained for the Black Pine snow pillow site. In both cases Drummond temperature and precipitation data were used as inputs for the simulations. Because of the difference in elevation between the snow pillow sites and Drummond, the temperatures were adjusted using a standard lapse rate, and precipitation was adjusted by the ratios as previously explained. The results obtained here are similar to those described by Huber (1983) using data from a snow pillow in Idaho. He found that simulated SWE values could be made to essentially duplicate observed values for a given

year. However, when the same parameter values were used for simulations in other years, results did not match as well. Even so, the NWSRFS snow model produced better results than four other models tested on the same data set (Huber, 1983). These results suggest that when one set of parameter values is used for several years, simulated values will be high some years, low some years, and about the same as observed other years. Under certain conditions the ambient temperature appears to fail as an index of the physical processes that cause the snow to accumulate and melt. The inclusion of additional variables such as solar radiation, wind run, and vapor pressure may be necessary to improve the model. Since these data are seldom available at the sites requiring simulation, the temperature data must suffice and this limitation of the model must be recognized.

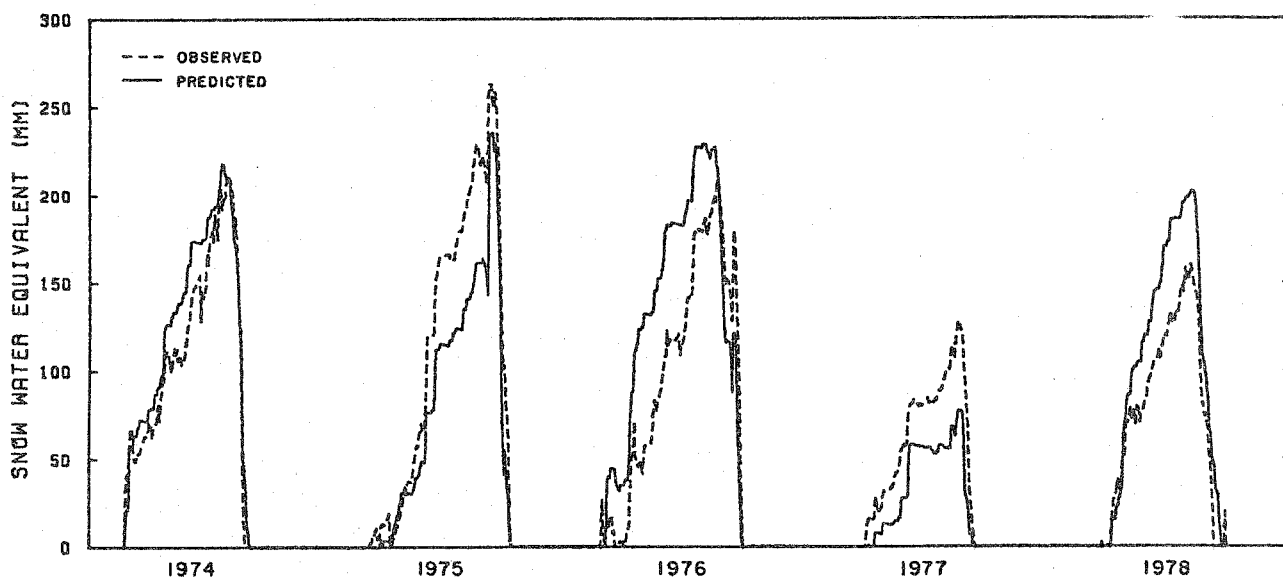


Figure 3. Simulated snow water equivalent at Combination snow pillow using Drummond weather station precipitation and temperature data, compared to observed snow water equivalent (----- observed; ——— simulated).

While other models were not evaluated, in this case, the results obtained indicate that HYDRO-17 provided adequate simulations of the snow water equivalent and good duplication of the initiation and depletion of the snowpack. The fact that HYDRO-17 is physically based, and considers melt under rain and non-rain conditions, suggests that better results should be produced. This is particularly true for areas where snow is a significant portion of the annual precipitation, such as the northern states and higher elevations. The results of this study and those presented by Huber (1983) indicate that HYDRO-17 may indeed be a more general model which will provide improved results over a wider range of climatic conditions.

Simulating Runoff.

The second objective of this study was to evaluate methods of improving water supply forecasts. The use of simulation models offers possibilities for improvement over results provided by traditional regression techniques, and a way of using real-time snowpack data. A twelve-year record (1973-1984) of daily snow pillow and streamflow data at Lower Willow Creek, and corresponding temperature and precipitation data at Drummond were available for evaluating the NWSRFS model. In this study, a six-year (1973-1978) calibration and a six-year (1979-1984) test period were selected. Both six-year periods contained high, low, and average years of streamflow.

The normal NWSRFS calibration procedure was followed for the 1973-1978 period. That is, parameters in the snow model (HYDRO-17), the soil moisture accounting model (SAC-SMA), and the unit hydrograph model (UNIT-HG) were all adjusted until the best fit streamflow trace was produced. However, because continuous streamflow records were not available (flow measurements were not normally made from November through March), it was difficult to calibrate on base flow or partial year volumes. Therefore, more emphasis was

placed on matching spring (Apr-Jul) streamflow hydrographs and volumes. Where possible, initial parameter values used in the model were based on actual data, i.e., potential evapotranspiration was based on data from Bozeman, Montana.

The observed and model simulated streamflow traces for the 1973-1978 calibration and the 1979-1984 test years are presented in Figures 4 and 5, respectively. In general, simulated values of streamflow match observed values better during the calibration period than during the test period. Simulated runoff volume was greater than observed runoff volume during most of the test years (Table 2). The magnitude of the overprediction during the test period tended to be greater than the differences noted for the calibration period. These differences could be due in part to a change in the relationships between precipitation on the basin and that at Drummond during the two six year periods because of changes in storm tracks, etc. Unfortunately, data is not available prior to 1979 to provide verification.

Although differences between observed and simulated runoff volume are rather large some years, the timing of major events (peaks) normally produced by spring snowmelt is in quite close agreement (Figs. 4 and 5). One problem noted several times during the summer or fall (late June through September) was the appearance of a simulated runoff event when there was no indication of a change in observed runoff. These simulated events seem to be produced by thunderstorm rainfall recorded at Drummond and simulated by the model (when adjusted by PXADJ) to be significant enough to produce runoff from rainfall. Since there is no indication of an observed event, the storms either did not occur on the watershed or they were not of sufficient magnitude to produce overland flow and a change in streamflow because soils on the watershed were dry enough to absorb the rainfall. These discrepancies serve to emphasize the need for on-site precipitation data to improve model results.

Implications for Using Real-Time Data.

In addition to the calibration procedure described previously in which the values of SCF and PXADJ were related to seasonal precipitation ratios in order to produce proper streamflow volume, an earlier calibration was conducted immediately after obtaining the model as a means of becoming familiar with model operations and capabilities. In contrast to the second calibration where parameter values were based on data where possible, parameter values during the first calibration were adjusted somewhat arbitrarily (but within suggested limits) to obtain desired results. Also, only SCF was adjusted (increased) to account for the greater volume of water needed to supply runoff. The parameter values used during the two calibrations for both the HYDRO-17 (SWE) and the NWSRFS streamflow (Q) evaluations are shown in Table 3.

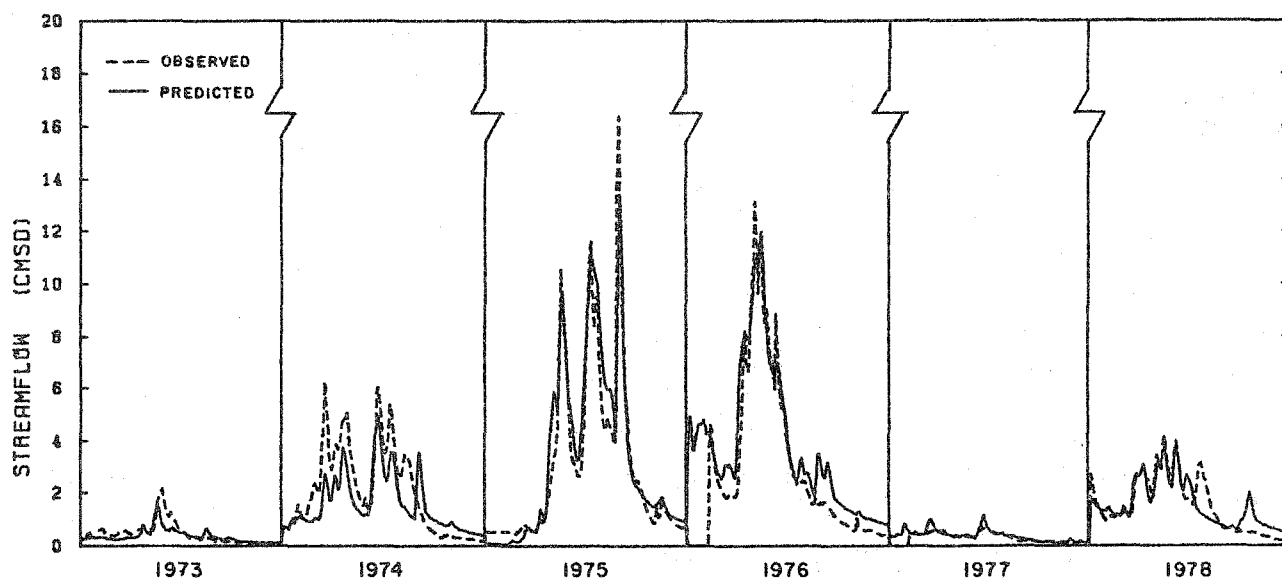


Figure 4. April through July observed and simulated streamflow at Lower Willow Creek, Montana for the 1973-1978 calibration period.

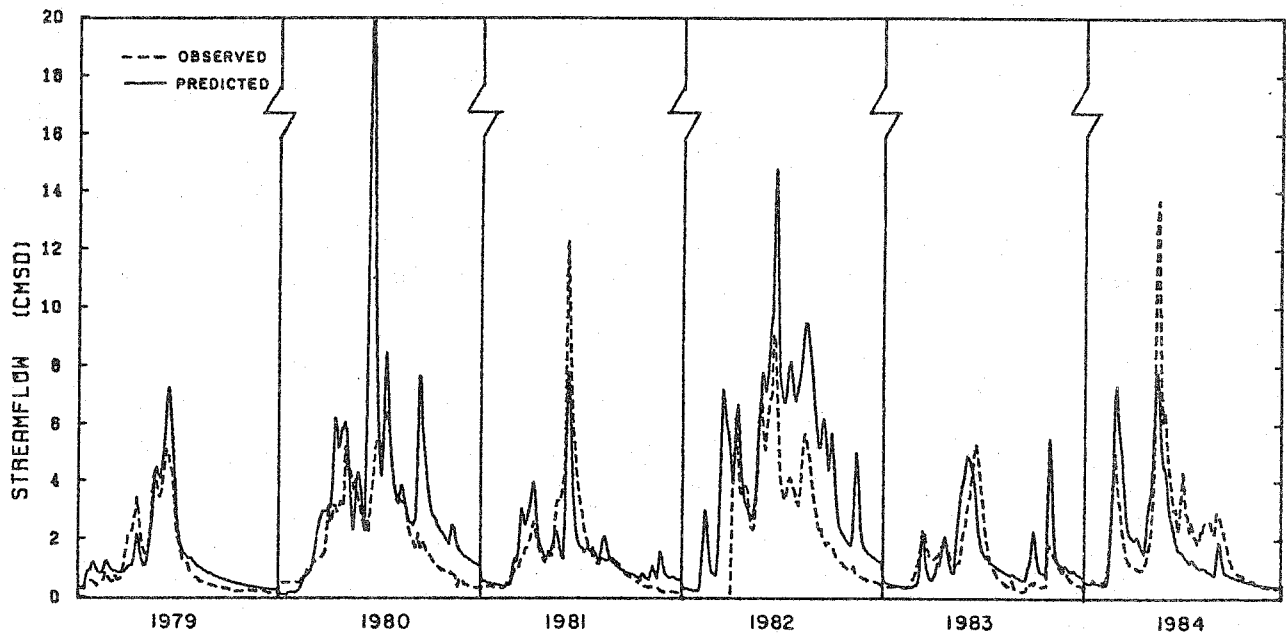


Figure 5. April through July observed and simulated streamflow at Lower Willow Creek, Montana for the 1979-1984 test period.

Table 2. Simulated and observed annual and spring (Apr-Jul) streamflow (in mm) for Lower Willow Creek, Montana. Simulated values produced by the NWSRFS model calibrated on snow water equivalent and streamflow (SWE+Q) or streamflow (Q) only.

	Annual Streamflow			Spring Streamflow (Apr-Jul)		
	Observed	Simulated (SWE+Q)	Simulated (Q)	Observed	Simulated (SWE+Q)	Simulated (Q)
1973	29	32	31.6	25.7	21.7	19.8
1974	117.7	87.3	104.8	113.5	73.9	88.0
1975	185.5	210.4	230.5	174.0	165.7	184.4
1976	157.3	277.3	304.4	160.5	203.2	187.5
1977	19.4	60.3	54.7	16.4	22.5	19.0
1978	97.0	94.5	110.9	83.6	72.4	85.4
1979	73.1	88.1	105.0	65.1	66.3	77.7
1980	128.1	223.3	235.2	118.8	187.2	198.6
1981	96.1	128.2	134.4	86.5	81.5	84.6
1982	146.7	269.3	299.4	130.9*	219.5*	219.8*
1983	97.8	124.3	134.0	66.9	69.7	77.2
1984	137.2	127.2	145.5	115.9	89.3	97.4
Total						
73-84	1285.2	1722.2	1890.4	1157.8	1272.9	1339.4
Avg.	107.1	143.5	157.5	96.5	106.1	111.6
Avg. (Sim-Obs)		36.4	50.4		9.6	15.1

* for 3-month period (May-Jul)

Table 3. Values of HYDRO-17 parameters used in the initial and secondary calibrations, using both snow water equivalent (SWE) and streamflow (Q) as objective functions.

	Initial Calibration				Secondary Calibration			
	Black Pine SWE	Upper Zone Q	Combination SWE	Lower Zone Q	Black Pine SWE	Upper Zone Q	Combination SWE	Lower Zone Q
SCF	1.95	2.70	1.50	1.00	1.74	2.10	1.21	1.25
PXADJ	1.0	1.0	1.0	1.0	1.70	1.70	1.50	1.50
MFMAX	0.85	1.80	1.45	1.80	1.15	1.27	1.20	1.37
MFMIN	0.18	0.30	0.25	0.50	0.30	0.40	0.30	0.50
SI	700	500	500	500	1.00	900	1.00	400
MBASE	2.15	0.60	1.90	0.50	3.00	0.00	2.60	0.00
PXTEMP	1.30	0.40	1.60	0.00	-0.10	0.00	0.00	0.00
UADJ	0.03	0.12	0.05	0.15	0.11	0.10	0.15	0.01
NMF	0.10	0.40	0.10	0.30	0.19	0.18	0.11	0.18
TIPM	0.10	0.10	0.40	0.25	0.11	0.25	0.21	0.21
PLWHC	0.30	0.03	0.25	0.02	0.05	0.05	0.06	0.06
DAYGM	0.05	0.10	0.05	0.02	0.10	0.10	0.10	0.10

SCF - Snow correction factor
 PXADJ - Precipitation adjustment factor
 MFMAX (mm/°C) - Maximum melt factor
 MFMIN (mm/°C) - Minimum melt factor
 SI - Mean areal water equivalent above which there is always 100% snow cover
 MBASE (°C) - Base temperature for snowmelt computations during non-rain periods
 PXTEMP (°C) - Temperature which separates precipitation into either rain or snow
 UADJ (mm/mb) - Average wind function during rain on snow periods
 NMF (mm/°C) - Maximum negative melt factor
 TIPM - Antecedent temperature index
 PLWHC - Percent liquid water holding capacity
 DAYGM (mm) - Daily ground melt

Although none of the parameters were the same for all combinations, the output was rather insensitive to small changes in several of the parameters under the conditions encountered in this study. For example, the range of values shown for UADJ, NMF, TIPM, PLWHC, DAYGM, and even MFMIN (Table 3) is relatively small, and if a mean value for each of these parameters had been used, the results would not have been altered significantly in this case. Even considering the complication created by the variability of parameter values, it is apparent that the value of SCF required when calibrating on SWE differed from that needed when calibrating on streamflow (Q). This suggests that the SWE at the snow pillow site (point) is not the same as an average SWE for the zone (area). In this case the Combination site seems to represent the lower zone (area below 1860 m elevation) better than the Black Pine site represents the upper zone (above 1860 m elevation). For both calibration procedures, Black Pine SWE was less than that required on the upper zone to produce the proper volume of streamflow. Combination SWE was greater than required for the first calibration and about equal to that required for the second calibration. The first relationship is probably more accurate, since the Combination site is near the upper boundary of the lower zone and receives more snow than the majority of the zone. The value of SI was set at 1.0 during the secondary calibration to assure that the areal depletion curve was not used, thereby more realistically simulating a point or snow pillow site.

Statistical measures of the results of the two calibrations indicated that timing of peaks and correlation coefficients were better when only SCF was used to adjust volume; while volume comparisons were better when both SCF and PXADJ were used to adjust the volume. Overall, results of this study indicated that a calibration procedure different from that suggested in NWSRFS documentation may be required if real-time data is to be used. A suggested method would be to calibrate the HYDRO-17 parameters using snow pillow data, then calibrate the other NWSRFS model parameters on streamflow. In this way the model is calibrated to the snow pillow sites which are then an index to the SWE for the zone selected. The study also points out the need for carefully selecting zones where the snow pillow data is representative of the area involved. Watersheds with a wide range of

conditions (i.e., deep snow, drifts, shallow snow, and bare areas) will present problems with respect to selection of zones since most snow pillow sites will generally represent only the deeper more uniform snow conditions.

Since snow water equivalent and precipitation data are now available from most SNOTEL sites, a more likely approach to future use of this real-time data will be to eliminate HYDRO-17 entirely. The rain plus melt file created within HYDRO-17 and used as input to the Sacramento Soil Moisture Accounting algorithm (SAC-SMA) can be obtained directly from the snow pillow and precipitation data. However, a method of keeping track of the portion of the basin covered by snow, such as the areal depletion relationship used within HYDRO-17, would be needed to make proper accounting of rainfall inputs to the file. The need for careful selection of SNOTEL sites and/or representative zones for determining streamflow would still be essential.

SUMMARY AND CONCLUSIONS

The NWSRFS model and the snow accumulation and melt submodel HYDRO-17 were evaluated using streamflow and snow water equivalent data from the Lower Willow Creek watershed near Hall, Montana. HYDRO-17 simulations of SWE were similar to observed SWE at two snow pillow sites under most conditions. However, there are times when air temperature alone fails as an index of the accumulation and melt process, and this limitation is recognized.

In general, simulated values of streamflow displayed the same patterns and volumes as observed values, although the model overpredicted volume considerably some years, and produced runoff peaks occasionally when none were observed. In all evaluations the need for accurate on-site temperature and precipitation data was evident, if model simulations are to be improved.

Using real-time SNOTEL data in the model may improve results, but will probably require modification of the calibration procedures and careful selection of zones represented by the snow pillow data.

ACKNOWLEDGMENTS

I wish to express my appreciation to Dave Robertson for performing the many computer runs required and for the constructive suggestions provided. I also appreciate the willing contribution of data and watershed information provided by Phil Farnes, SCS snow supervisor in Montana. Thanks also to Bernie Shafer, Leon Huber, Gerald Day, Larry Brazil, and Shari Hennefer for their assistance.

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