APPLICATION OF A SIMPLE SNOWMELT-RUNOFF MODEL TO LARGE RIVER BASINS

732-83

by

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INTRODUCTION

The snowmelt-runoff model (SRM; also referred to in the literature as the "Martinec model" or the "Martinec-Rango model") is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. SRM was developed by Martinec (1975) in small European basins. With the advent of satellite snow-cover data in the 1970's, it became possible to test SRM in larger basins. Using Landsat data the model was successfully applied to various basins in the United States (Rango and Martinec, 1979; Rango, 1980; and Jones et al., 1981). Figure 1 illustrates the relative size of some of the basins in which the model has been tested so far. For basins larger than about 100 km^2, the use of satellite data is the only effective means for obtaining the required snow-cover extent information.

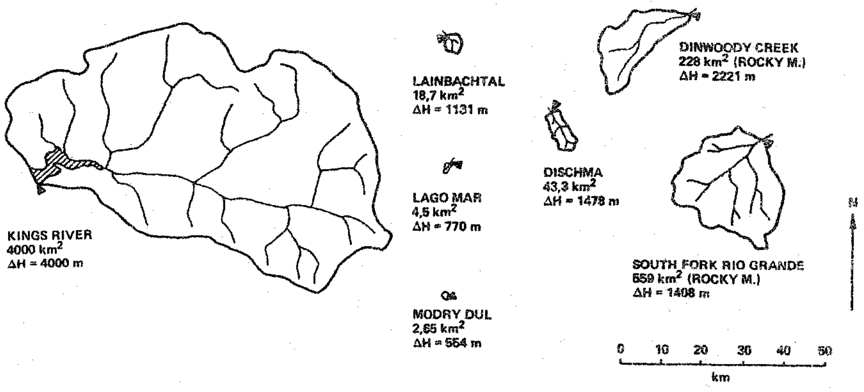

Figure 1. Area and total basin relief (ΔH) of a selection of basins in which SRM has been applied

The use of satellite data has permitted application of SRM to the following large basins in the western United States: Dinwoody Creek, Wyoming (228 km^2); Bull Lake Creek, Wyoming (484 km^2); South Fork, Colorado (559 km^2); Conejos River, Colorado (730 km^2); Rio Grande, Colorado (3419 km^2); and the Kings River, California (4000 km^2). SRM has also been successfully tested on the Okutadami basin (422 km^2) in Japan, the Dunajec River (700 km^2) in Poland, and Durance River (2170 km^2) in the French Alps. In addition to the input of snow-cover data, SRM only requires the input of temperature and precipitation on a daily basis. For model operation, the following parameters must also be determined: runoff coefficient, degree-day factor, temperature lapse rate, recession coefficient, and discharge time lag.

MODEL STRUCTURE AND OPERATION

Equation of Model

Each day during the snowmelt season, the water produced from snowmelt and from rainfall is computed, superimposed on the calculated recession flow, and transformed into the

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daily discharge from the basin by SRM. In a basin with an elevation range of about 1500 m, three elevation zones (A, B, and C) of about 500 m each are recommended and the model equation is:

$$\begin{aligned} Q_{n+1} = \; & c_{An}\,[a_{An}\,(T_n + \Delta T_{An})\,S_{An} + P_{An}]\,\frac{A_A \cdot 0.01}{86400} + \\ & c_{Bn}\,[a_{Bn}\,(T_n + \Delta T_{Bn})\,S_{Bn} + P_{Bn}]\,\frac{A_B \cdot 0.01}{86400} + \\ & c_{Cn}\,[a_{Cn}\,(T_n + \Delta T_{Cn})\,S_{Cn} + P_{Cn}]\,\frac{A_C \cdot 0.01}{86400}\quad (1 - k_{n+1}) + Q_n\,k_{n+1} \end{aligned} \tag{1}$$

where Q = average daily discharge in $m^3\ sec^{-1}$

c = runoff coefficient expressing the losses as a ratio (runoff/precipitation)

a = degree-day factor ($cm \cdot {}^\circ C^{-1} \cdot d^{-1}$) indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days (°C·d)

ΔT = the adjustment (°C) by temperature lapse rate necessary because of the altitude difference between the temperature station and the average elevation of the basin or zone

S = ratio of the snow-covered area to the total area

P = precipitation contributing to runoff (cm). A preselected threshold temperature, T_{CRIT}, determines whether this contribution is rainfall (and immediate) or snowfall (and delayed)

$\frac{0.01}{86400}$ = conversion from $cm \cdot m^2 \cdot d^{-1}$ to $m^3 \cdot\ sec^{-1}$

A = area of the basin or zone (m^2)

k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall ($k = \frac{Q_{m+1}}{Q_m}$ where m and m+1 are the sequence of days during a true recession flow period)

Subscripts:

n = sequence of days during the discharge computation period. Equation (1) is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. As a result, the number of degree-days measured on the nth day corresponds to the discharge on the n+1 day. Different time lags will result in the proportioning of day n snowmelt between discharges occurring on days n, n+1, and possibly n+2.

A, B, C = elevation zone designators ranging from the lowest (A) to the highest (C)

Model Variables and Parameters

Basin Characteristics

After examining the elevation range between the streamgauge and the highest point in the basin (total basin relief) on a topographic map, elevation zones can be delineated in intervals of about 500 m (or 1500 ft). A base map for snow-cover determinations is developed showing the boundaries of the elevation zones and other significant features as shown in Figure 2. An area-elevation curve is used for determining the zonal hypsometric mean elevation ($\bar{h}$) by balancing the areas above and below $\bar{h}$ as shown in Figure 3. The $\bar{h}$ value is used as the elevation to which base station temperatures are extrapolated for the calculation of degree-days.

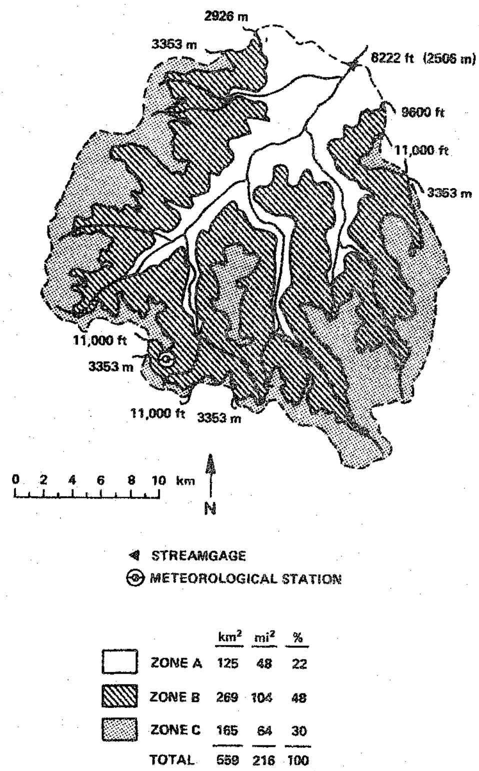

Figure 2. Elevation zones and areas of the South Fork of the Rio Grande basin.

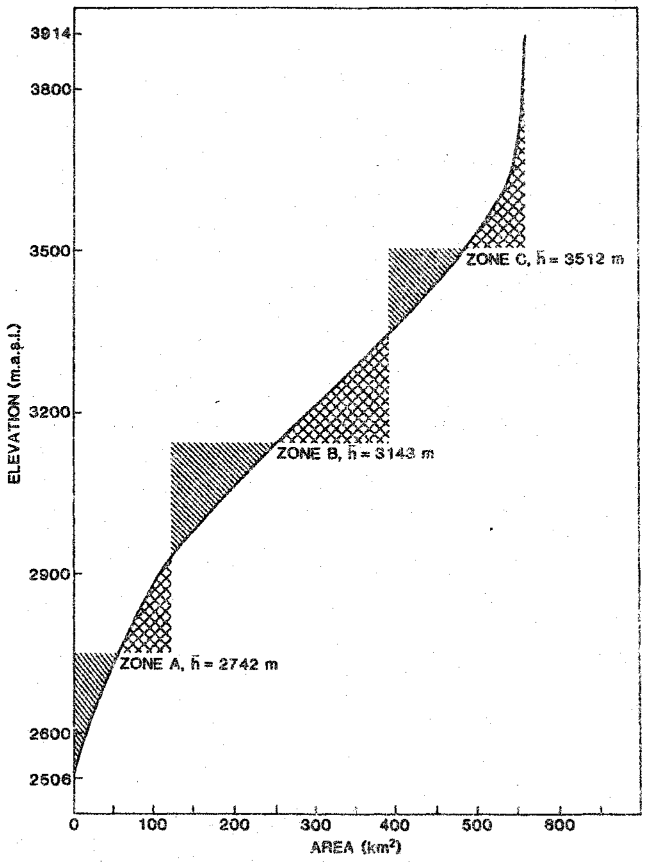

Figure 3. Determination of zonal mean hypsometric elevations ($\bar{h}$) using an area-elevation curve for the South Fork basin.

Temperature and Degree-Days

Air temperature expressed in degree-days is used in SRM as an index of the complex energy balance leading to snowmelt. The model can employ hourly temperature input where those measurements are available. Where only maximum and minimum temperatures (T_{max}, T_{min}) readings are made, the number of degree-days (°C) is determined daily as

$$T = \frac{T_{max} + T_{min}}{2} \qquad (2)$$

The degree-day figures refer to the 24-hour period starting at 0600 hours with the corresponding discharge referring to periods shifted according to the time lag of the basin. As indicated by Linsley et al. (1958) all negative degree-day values produced by Equation (2) are taken as zero. SRM can use either the average daily temperature approach in Equation (2) or the effective minimum temperature approach recommended by Gartska et al. (1958). This second approach, which sets a negative T_{min} equal to zero before entering into Equation (2), allows SRM to generate snowmelt in the early spring when a large nighttime depression of T_{min} would normally cancel out daytime T_{max} values which may reach as high as 10-15°C.

Precipitation

Measurement of representative precipitation amounts in a mountain basin is extremely difficult. Extrapolation of precipitation amounts from one or more base stations to zones in the basin must be based on user knowledge of the study area. Location of a precipitation station at the hypsometric mean elevation of the basin would be optimum.

If precipitation is determined to fall in the basin on a given day, a critical temperature, T_{CRIT}, must be examined to determine whether the precipitation is rain or snow. T_{CRIT} is usually selected to be slightly above the freezing point and may vary from basin to basin. The distinction between rain and snow is important in SRM because the rain contribution to runoff is on the same day that the rain occurs, whereas the snow contribution to runoff is delayed.

When the precipitation is determined to be snow, its delayed effect on runoff is treated differently depending on whether it falls over the snow-covered or snow-free portion of the basin. The new snow that falls over the previously snow-covered area is assumed to become part of the seasonal snowpack and its effect is included in the normal depletion curve of the snow coverage. The new snow falling over the snow-free area is considered as precipitation to be added to snowmelt, with this effect delayed until the next warm day. This precipitation is stored by SRM and then melted as soon as a sufficient number of degree-days has occurred. This may take place on the first day warm enough to produce snowmelt or on a series of days.

When the precipitation is determined to be rain, and it falls on a snow-free area, it becomes available to contribute to runoff immediately. When rain falls on snow, however, its effect on runoff depends upon the condition of the snowpack. Early in the snowmelt season rain falling on the snowpack is assumed to be retained by the snow, which is mostly dry and usually deep. This rainfall is not available for runoff. At some stage during snowmelt the snowpack is assumed to be ripe (the user must decide when this has occurred), and any rain falling on the snow is transferred through the snow layer and becomes available to contribute to runoff the same as over the snow-free area. Both of these options are included in the computer program. In SRM the melting effect of rainfall is neglected.

Snow Coverage

The snow-cover variable, S, of a zone or basin is usually obtained from a depletion curve for input into SRM. A variety of sources of snow-cover data can be used to compile the depletion curves including ground observations (used for Modry Dul), aircraft photography (Dischma), and satellite imagery (all the large basins). If the data are available, it is recommended that satellite imagery be used since it is the easiest to analyze and also quite accurate depending on basin size (area minimums for various satellites: Landsat-10 km^2; NOAA-VHRR-200 km^2; and GOES-1000 km^2). To assist in the use of satellite imagery for snow-cover interpretations, a handbook of analysis techniques is available (Bowley et al., 1981).

When photointerpretation of satellite snow images is used to delineate the snow line on a base map of the study basin (see Figure 2), the area enclosed by the snow line in each elevation zone is planimetered to obtain the snow-covered area. The snow cover by elevation zone is then plotted against elapsed time to construct depletion curves such as those shown in Figure 4 for 1976 in the South Fork basin. For the snowmelt-runoff simulation, daily snow-cover values are taken from the depletion curves and input to SRM.

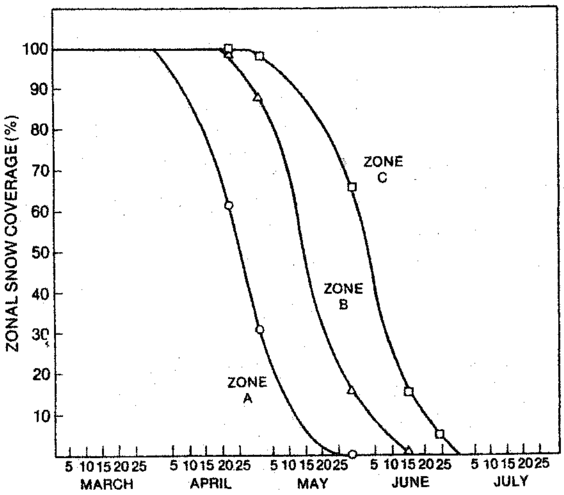

Figure 4. Landsat-derived snow-cover depletion curves for the South Fork basin for elevation zones A, B, and C for 1976 (Landsat snow-cover observations are plotted).

Snowstorms occurring during the snowmelt season can result in a temporary increase of snow cover, but generally with no significant hydrologic effect. The duration of this increase is usually shorter than the interval between snow-cover observations. If the snowstorm occurs shortly before the snow-cover observation, however, it may lead to the interpretation of exaggerated snow-covered areas and a distortion of the true depletion curves of the seasonal snowpack. It is recommended that such anomalous snow-cover values be disregarded and that the depletion curves be drawn only with reference to the snow cover accumulated before the beginning of the snowmelt period (seasonal or "old" snowpack). Precipitation and temperature records should be consulted in order to identify these transitory snow events when drawing the depletion curves. The transitory new snow is accounted for as stored precipitation eventually contributing to runoff as explained in the previous section.

In rare cases massive summer snowstorms can affect the snow coverage for several weeks. If such a situation is revealed by subsequent satellite data, it may be preferable to draw the depletion curves according to this actual snow coverage. Because of this modification to the depletion curves, the model will melt more seasonal snow than before, but the amount of stored or new precipitation will be automatically reduced.

Runoff Coefficient

Because the runoff coefficient, c, is likely to vary throughout the year as a result of changing vegetation and soil moisture conditions, the SRM computer program permits changes in c every 15 days. Usually, c is higher for snowmelt than for rainfall. Therefore, the model can handle different runoff coefficients for snow, c_S, and for rain, c_R, as determined by the user. In basins studied, when snowmelt is concentrated in a short time period, c_S can approach 1.0. With prolonged snowmelt runoff in a semiarid region, c_S may go down to 0.3. In addition c will vary from zone to zone in a basin, and SRM has the capability to handle different c values by zonal input. It is possible that with rain falling in the low elevations of a semiarid basin, c_R may be 0.2, whereas at the same time in the high elevations with snow still melting, c_S can be 0.9. The selection of c requires first hand knowledge of the basin and its hydrologic behavior under different hydrometeorological conditions.

Degree-Day Factor and Lapse Rate

The degree-day factor a is used to convert degree-days to snowmelt expressed in depth of water. In the absence of detailed temperature and snow pillow or lysimeter data, the degree-day factor can be obtained from an empirical equation developed by Martinec (1980):

$$a = 1.1 \frac{\rho_s}{\rho_w} \tag{3}$$

where a = the degree-day factor in cm $\cdot°C^{-1}\cdot d^{-1}$

ρ_s = density of snow

ρ_w = density of water

The general seasonal increase in ρ_s can be used as an index of the seasonal increase of a. Large variations are expected if the melt season is long or there is a large difference in elevation in the basin. During the snowmelt season for undisturbed snow, however, the typical range is about 0.25 – 0.60 cm $\cdot°C^{-1}\cdot d^{-1}$. The fact that increasing a is related to increasing snow density as snowmelt progresses is in response to a number of factors. A greater density is usually associated with older snow with a lower albedo, thus a higher a value. In addition, high densities toward the end of the snowmelt season are also associated with increased liquid water content and low thermal quality of the snow. Because of these expected seasonal changes in a, SRM is structured to allow modifications of a every 15 days, if necessary. Because of different stages of snowpack ripening in different elevation zones, a can also be varied between zones. Sometimes the occurrence of a large, late season snowfall will produce depressed a values for several days due to the new low-density snow. The a values in the model can manually be modified and inserted to reflect these unusual snowmelt conditions.

The calculated degree-day values must be extrapolated from a base station to an elevation zone using a suitable lapse rate using the following equation:

$$\Delta T = \delta \ (h_{ST} - \bar{h}) \tag{4}$$

where ΔT = temperature lapse rate correction factor in °C

δ = temperature lapse rate in °C per 100 m

h_{ST} = altitude of the temperature station in m

$\bar{h}$ = zonal hypsometric mean elevation in m

The temperature lapse rate must be carefully determined, especially if the observation station is situated at a low altitude and the extrapolation of degree-days is made in only one direction (upwards). The lapse rate should be indicative of the mountainous region where the basin is located based on some kind of prior climatic knowledge. As the snowmelt season progresses, lapse rates may change depending on the basin. Such changes can be instituted every 15 days in SRM, if necessary. When applying SRM it is advisable to conduct a regional analysis of monthly lapse rates to determine the seasonal variation. In some cases it may be necessary to modify the mean monthly lapse rates obtained in such an analysis because of basin peculiarities (such as frequent temperature inversions) or an abnormal climatic progression in a particular year. In basins with little seasonal variation, a lapse rate of 0.65°C/100 m has been found to be adequate.

Recession Coefficient

The recession coefficient, k, depends upon the current stream discharge in the following way:

$$k_{n+1} = xQ_n^y \tag{5}$$

where Q is the daily discharge and the constants x and y must be determined for the given basin. For this determination, daily discharge values for the snowmelt season or the whole year are used. The discharge on a given day, Q_n, is always plotted against the value on the following day, Q_{n+1}, whenever the hydrograph is falling. Once these points have been plotted for several years, an envelope line is drawn to enclose most of the points. This lower envelope line represents the extreme discharge decline, i.e., the recession without any partial delay by possible precipitation or snowmelt. This lower envelope has been found to be valid on small basins, however, when the model is applied to larger basins, it is recommended that this curve be replaced with an average curve halfway between the lower envelope line and the 1 to 1 line. The average curve should probably be used on basins greater than about 50 km^2. For year round simulations, it was found useful to derive constants x and y for Equation (5) separately for the summer and winter half year.

If no discharge data are available for a basin, recession coefficients can be estimated using the following formula (Martinec, 1970):

$$k_{B2} = k_{B1}^{\sqrt[4]{A_{B1}/A_{B2}}} \tag{6}$$

where A_{B1} and A_{B2} are the respective areas of the basins B1 and B2, and k_{B1} and k_{B2} are the recession coefficients for the average discharge in both basins. Under this approach, SRM could be used to simulate discharge in an ungauged basin.

Time Lag

Equation (1) is written for a time lag between the rise in temperature and the rise of the hydrograph of 18 hours. If the time lag is not conveniently 18 hours, the computed discharge values must be shifted by a certain number of hours to facilitate comparison with published streamflow data. In large basins with multiple elevation zones, the time lag changes during the snowmelt season as a result of the changing spatial distribution of snow cover with respect to the basin outlet. The model will accept varying time lag correction factors by zone to account for time lags other than 18 hours and to account for the change in time lag from the beginning to the end of the snowmelt season.

SIMULATION RESULTS ON LARGE BASINS

One of the first indicators of how well a model simulates actual flow conditions is a comparison plot of computed and measured hydrographs. Figure 5 illustrates this comparison for the Rio Grande basin (3419 km^2) in Colorado for the 1973 snowmelt season. Results of applying the model on a large European basin are shown in Figure 6 for the Durance River basin (2170 km^2) in the French Alps for the 1975 snowmelt season. Goodness-of-fit measures D_V (percentage volume difference for simulation period) and R^2 (Nash-Sutcliffe value analogous to coefficient of determination and measures the proportion of the variance of the recorded daily flows explained by the model) are plotted on the hydrographs for reference.

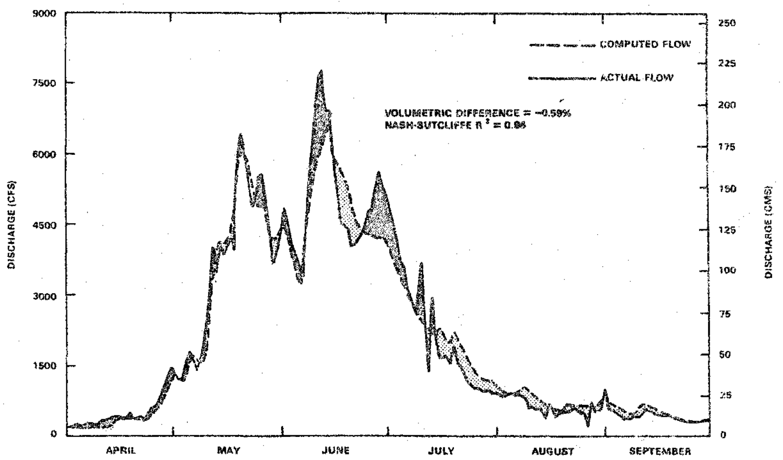

Figure 5. Snowmelt-runoff model simulated versus measured hydrograph for the Rio Grande near Del Norte, Colorado (3419 km^2) in 1973.

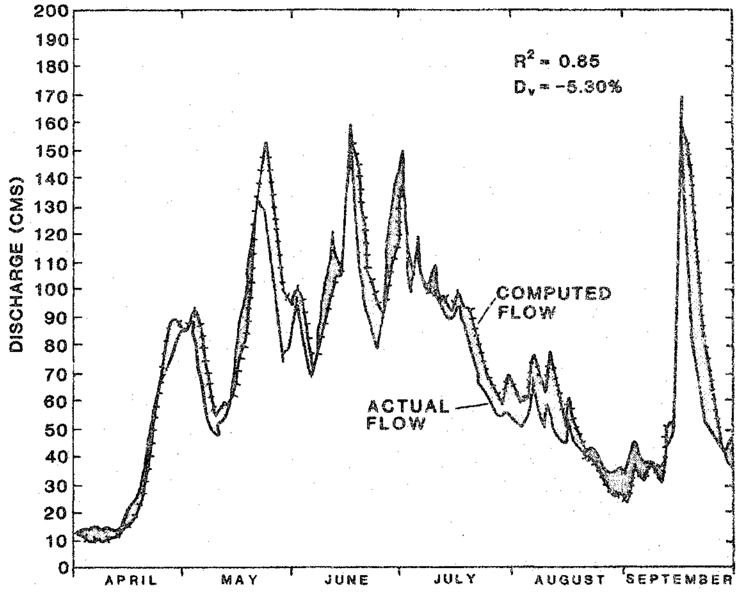

Figure 6. Snowmelt-runoff model simulated versus measured hydrograph for 1975 for the Durance River (2170 km^2) in France.

SRM has thus far been tested on a minumum of 14 international basins, 9 of which are larger than 200 km^2 and required satellite snow-cover input. The characteristics of these basins are listed in Table 1 along with the corresponding goodness-of-fit statistics averaged over the number of years (n) tested. The average absolute error between actual and simulated runoff volume for the snowmelt season on the nine large basins was 3 percent. The average Nash-Sutcliffe R^2 value for the large basins was 0.85. A general trend of decreasing goodness-of-fit values with decreasing quality of input data (usually with increasing basin size) can be perceived, however, many complexities are introduced by amount of snowmelt season precipitation, availability of snow-cover data, incomplete discharge diversion records, and varying quality of climatological data. From these results, it appears that SRM is applicable for runoff simulation on basins as large as 4000 km^2.

Table 1 Basin characteristics and snowmelt-runoff model simulation results

Country	Basin	Size (km^2)	Elevation range (m)	Average goodness-of-fit statistics D_V(%)	NSR^2	n
Czechoslovakia	Modry Dul	2.65	554	+1.7	0.95	2
France	Durance	2170	3319	-2.5	0.89	1
Japan	Okutadami	422	1564	+2.4	0.80	1
Poland	Dunajec	700	1724	-3.8	0.73	1
Spain	Lago Mar	4.5	770	N/A	N/A	N/A
Switzerland	Dischma	43.3	1478	+0.2	0.88	6
United States	W-3	8.42	331	+3.3	0.82	6
	Dinwoody Cr.	228	2221	+3.3	0.85	2
	Bull Lake Cr.	484	2395	+4.8	0.82	1
	South Fork	559	1408	-1.5	0.89	7
	Conejos	730	1496	+0.5	0.87	7
	Rio Grande	3419	1783	+4.4	0.86	7
	Kings River	3999	4170	+6.3	0.78	3
West Germany	Lainbachtal	18.7	1131	N/A	N/A	N/A

D_V = percent volume difference; NSR^2 = Nash-Sutcliffe R^2 value; N/A = not available.

MODIFICATIONS FOR FORECASTING PURPOSES

A few modifications of the model are necessary to operate it in the forecast mode as opposed to operation in the simulation mode. Most important is acquisition of forecasts of the major input variables—temperature, precipitation, and snow cover—during the forecast period. The most difficult of these variables to forecast is precipitation. Generally, average daily values of precipitation or selected historical time series will have to be used. Temperature forecasts can be obtained for several days to one or two weeks. For longer durations, average values should be used and should be as good as forecasted values. The temperature forecasts are doubly important because of the effect of the temperature on the depletion of the snow cover.

The use of snow-cover depletion curves from prior years is not possible because the curves vary from year to year, and the actual curve for a given year is not known at the beginning of the snowmelt season. When using standard depletion curves, which relate the percent of the basin or zone covered by snow to elapsed time during the snowmelt season, it isn't possible to detect extreme high or low accumulations of snow. In addition, a steep decrease of the snow-covered area in the standard depletion curve can reflect either a shallow snowpack or high melt rates. Conversely, a slow decrease results from either a deep snow cover or slow melt rates resulting from low temperatures. In order to forecast the snow-cover depletion, it is first necessary to modify the depletion curves by relating the snow coverage to accumulated degree-days instead of elapsed time as described by Rango and Martinec (1982).

When several years of snow accumulation, snow-cover depletion, and temperature data are available, a nomograph for selection of the appropriate modified depletion curve based on snow water equivalent at the beginning of snowmelt can be derived as shown in Figure 7. Several weeks after the selection of a modified depletion curve from the nomograph the satellite snow-cover measurements can be related to the actual accumulated degree-days to determine whether the decrease of snow-covered area agrees with the initially chosen curve. If the decrease of snow-covered area has not occurred at the rate initially assumed at the beginning of the snowmelt period, e.g., the snow-cover decrease is considerably slower than the assumed modified depletion curve indicating a greater accumulation of snow for the basin, a more appropriate modified depletion curve should be substituted.

Some very preliminary attempts at using this approach have been made with some success. The hydrograph shown in Figure 8 for the South Fork of the Rio Grande basin resulted from using average daily temperatures for the entire snowmelt season and an appropriate modified depletion curve with no updating for the period (Shafer et al., 1982). The results were encouraging and indicate that the method should be developed further.

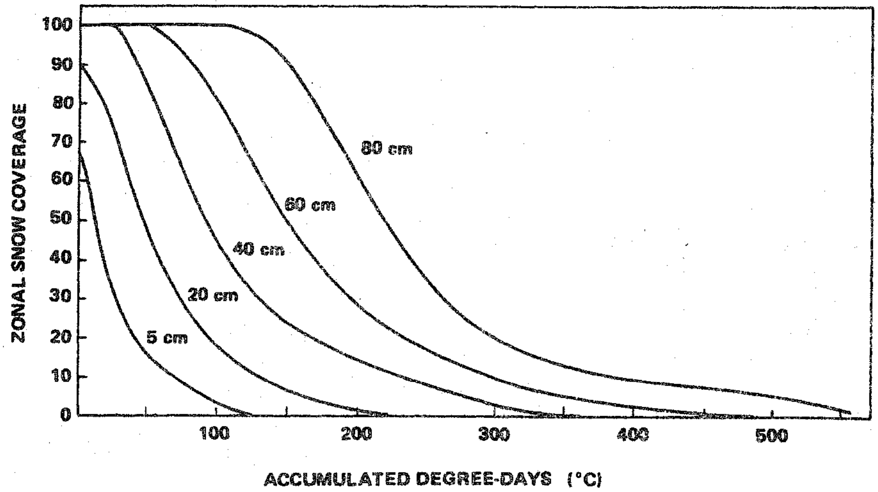

Figure 7. Nomogram for selection of modified depletion curve in zone B of the South Fork basin using estimated snow water equivalent (in cm) as the criterion.

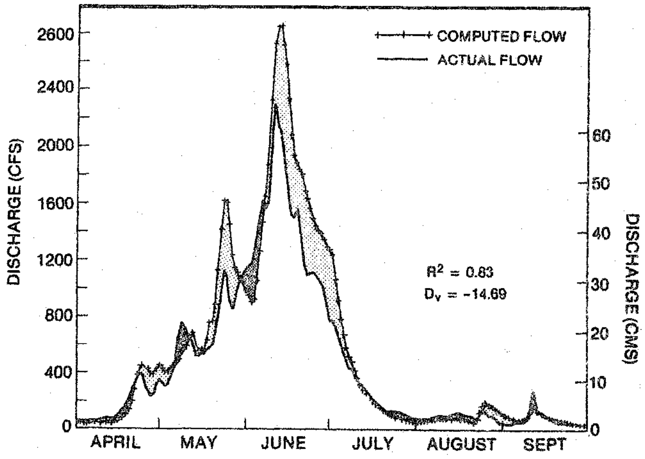

Figure 8. First attempt at using the modified depletion curve nomograph and the snowmelt runoff model for forecasting runoff on the South Fork basin in 1980.

In an operational situation, it is not necessary to continuously run the model with calculated streamflow as input data for the entire runoff period. SRM has the provision which allows updating with actual streamflow information every seven days. Although not employed in any of the results shown in Table 1, tests of this feature show a definite improvement in the goodness-of-fit statistics for simulations and forecasts.

APPLICATION OF THE MODEL

Data Requirements

The optimum conditions for accurate simulation of runoff have been identified as follows (Rango and Martinec, 1981): (1) temperature and precipitation are recorded at the mean elevation of the basin inside the basin boundaries (or at the zonal mean elevation for large basins); (2) snow cover is available reliably once per week to detect short-term variations in zonal areal extent; (3) several climatological stations are available for large basins, especially in areas with frequent summer precipitation events; and (4) several years of daily runoff records have been acquired for the determination of the recession coefficient. Decreases in accuracy will be expected as these optimum conditions are compromised. However, acceptable simulations will result even under the following minimum conditions:

(1) temperature and precipitation data are observed outside the basin at a considerable horizontal and vertical distance; (2) snow-cover observations are only available two to three times during the snowmelt season; (3) climatological observations are not possible at multiple stations; and (4) no runoff records are available so that the recession coefficient must be estimated from the basin size.

Necessary Computing Facilities

For use of SRM in situations where manpower is not limited but computing resources may be, any pocket calculator with the function x^y is sufficient for day-to-day computation of the discharge. In addition, in the initial stages of setting up the computer program to run SRM, the pocket calculator can be indispensible in the checking of computations. The fact that the basic form of SRM (Equation 1) is relatively simple, which permits use of the now widely available pocket calculator, also opens the possibility that the model may be run in the field or at local offices as opposed to only at central computing facilities. Such flexibility increases the chances that SRM can be used in operational situations.

In utilizing the model, it is naturally more convenient to use a computer program. The use of the computer approach provides a great savings in time which is especially important for calculations of extended periods, such as the snowmelt runoff season or even a year. In addition, the computer program can easily handle many complicated calculations which become extremely tedious on a pocket calculator. Examples of this involve the different handling of precipitation depending on the form (rain vs. snow), the introduction of different time lags for different elevation zones, and the use of multiple climatic stations. In order to facilitate computer application of the model, a user manual has recently been completed (Martinec et al. 1982).

Computer Program and User's Manual

The SRM computer program presented in the user manual is designed to operate on an IBM 3081 available at Goddard Space Flight Center (GSFC). However, the SRM program can execute on any 32-bit IBM computer using FORTRAN IV. The program can run on any minicomputer that utilizes FORTRAN IV with the NAMELIST feature, with minimum revisions (such as variable type declarations). Some versions of FORTRAN on some computers do not support the NAMELIST input of data, particularly the DEC PDP FORTRAN or PDP FORTRAN-FOUR-PLUS. Consequently, major revisions would have to be made in subroutine READIN to read input data as formatted input. No changes, however, would have to be made in the program computations.

In order to execute the program on much smaller computers, such as microprocessors where execution time and core storage is limited, some major modifications would have to be made. All formatted output options can be eliminated, except for output statistics. The number of elevation zones can be cut down to reduce the size of the input arrays. The capability to process input temperatures can be eliminated, thus eliminating some input arrays. The user would have to provide input temperatures in degree-days and per zone, or at least provide a pre-determined lapse rate to extrapolate temperatures in degree-days to each elevation zone.

Presently, the SRM program can be run for a snowmelt season of variable length, and it can also be operated in both snowmelt and non-snowmelt situations for up to 366 days. Up to eight basin elevation zones can be accommodated. For a six-month snowmelt season, the computer requirements to execute the program on the GSFC IBM 3081 are as follows: CPU time = 3 sec.; I/O time = 35.4 sec. Total core requirements for compilation, linkage and loading of input data sets, producing printer plots and input temperature processing amount to approximately 170 K bytes of core.

The user's manual provides much more detailed information on the computer program along with an example data set. Reference should also be made to the manual for detailed information on estimation of model variables and parameters. Possible sources of error are discussed and methods of remedying these errors presented.

ACKNOWLEDGEMENTS

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