Contents

SNOWMELT RUNOFF MODEL (SRM) USER'S MANUAL

(UPDATED EDITION 1998, VERSION 4.0)

1 PREFACE

This 1998 Edition of the User's Manual features a new method to evaluate the effect of a changed climate on the runoff regime for the entire hydrological year. Guidance is given for computing runoff in the winter half year and for assessing the redistribution of runoff between the winter and summer in response to climate change.

In order to accommodate these new tasks, the PC program has been restructured resulting in more convenience and versatility for the user.

The Version 4.0 is available on Internet by accessing FTP file server "hydrolab.arsusda.gov" and on diskettes which are distributed on request free of charge.

Since the publication of the 1994 Edition (Martinec *et al.*, 1994), SRM has been applied by independent investigators in Chile, Ecuador, China, Austria, Switzerland, Turkey and Spain. So far, three SRM Workshops have been conducted at the University of Berne, Switzerland (http://saturn.unibe.ch/remsen/), involving about 100 participants from 20 countries. In addition, the authors are available to assist users in overcoming special problems which may be encountered.

2 INTRODUCTION

The Snowmelt-Runoff Model (SRM; also referred to in the literature as the "Martinec Model" or "Martinec-Rango Model") is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. Most recently, it has also been applied to evaluate the effect of a changed climate on the seasonal snow cover and runoff. SRM was developed by Martinec (1975) in small European basins. Thanks to the progress of satellite remote sensing of snow cover, SRM has been applied to larger and larger basins. The largest basin where SRM has been applied so far is about 120,000 km^2. Runoff computations by SRM appear to be relatively easily understood. To date, the model has been applied by various agencies, institutes and universities in about 80 basins situated in 25 different countries as listed in Table 1. About 25 % of these applications have been performed by the model developers and 75 % by independent users. Some of the localities are shown in Figure 1. SRM also successfully underwent tests by the World Meteorological Organization with regard to runoff simulations (WMO, 1986) and to partially simulated conditions of real time runoff forecasts (WMO, 1992).

Approximate Coordinates

A Illecillewaet 51° N, 118.1 W
B Boise 43.4° N, 116.1° W
C Henry's Fork 44.5° N, 111.4° W
D Dinwoody 43° N, 109° W
E Kings River 37° N, 119.5° W
F Sevier 38° N, 112.5° W
G Spanish Fork 40.1° N, 111.4° W
H Rio Grande 37.4° N, 107.2° W
I Tupungato, 33° S, 70° W
J Lago Alumin 38.6° S, 71.1° W
K W-3 37° N, 82° W
L Lago Mar, Pyrenees 42.5° N, 2° E
M Feshie, Scotland 57.1° N, 3.7° W
N Durance 44.3° N, 6.2° E
O Felsburg 46.7° N, 9.5° E
P Lainbachtal 47.3° N, 11.05° E
Q Wintertal 51.7° N, 10.51 E
R Viveli 60.2° N, 7.1° E
S M.Dul 50.7° N, 15.3° E
T Dunajec 49.2° N, 19.5° E
U Kabul River 34.1° N, 71.2° E
V Beas 32.1° N, 77.1° E
W Sai River 36.5° N, 138° E
X Hawea 44.5° S, 169° E
Y Tillouguit 32° N, 5.8° W
Z Grande 53.8° S, 68.3° W
a Yellow 34.5° N, 99.5° W
b Gongnisi 43° N, 88° E
c Upper Yakima 47.3° N, 121° W
d Iskut 57° N, 131.3° W
e Geehi River 36.2° S, 148.3° E
f Pyandzh 37° N, 62° E

Fig. 1 Selected locations where SRM has been tested.

3 RANGE OF CONDITIONS FOR MODEL APPLICATION

SRM can be applied in mountain basins of almost any size (so far from 0.76 to 120,000 km^2) and any elevation range (for example 305-7690 m a.s.l.) (Table 1). A model run starts with a known or estimated discharge value and can proceed for an unlimited number of days, as long as the input variables - temperature, precipitation and snow covered area - are provided. As a test, a 10-year period was computed without reference to measured discharges (Martinec & Rango, 1986).

Table 1 SRM applications and results.

Country	Basin	Size (km^2)	Elevation Range (m a.s.l.)	Zones	Years (seasons)	R^{2*}	D_V[%]*
Germany	Lange Bramke (Harz)	0.76	540-700	1	1	N/A	N/A
Germany	Wintertal (Harz)	0.76	560-754	1	1	N/A	N/A
Czech Republic	Modry Dul (Krkonose)	2.65	1000-1554	1	2	0.96	1.7
Ecuador	Antisana (Andes)	3.72	4500-5760	3	1	N/A	N/A
Spain	Lago Mar (Pyrenees)	4.50	2234-3004	1	1	N/A	N/A
Spain	Llauset dam (Pyrenees)	7.80	2100-3000	2	1	0.69	5.5
USA	W-3 (Appalachians)	8.42	346-695	1	10	0.81	8.8
Germany	Lainbachtal (Alps)	18.70	670-1800	1	5	N/A	N/A
Spain	Salenca en Baserca (Pyrenees)	22.20	1460-3200	3	3	0.72	4.3
Spain	Noguera Ribagorzana en Baserca (Pyrenees)	36.80	1480-3000	3	3	0.71	3.7
Switzerland	Rhone-Gletsch (Alps)	38.90	1755-3630	4	1	N/A	N/A
Switzerland	Dischma (Alps)	43.30	1668-3146	3	10	0.86	2.5
Japan	Sai (Japan Alps)	57	300-1600	3	3	0.86	N/A
Austria	Rofenache (Alps)	98	1890-3771	8	1	0.88	2.4
United Kingdom	Feshie (Cairngorms)	106	350-1265	1	2	0.88	N/A
Switzerland	Sedrun (Alps)	108	1840-3210	3	2	0.79	1.9
Australia	Geehi River (Snowy Mtns.)	125	1032-2062	3	6	0.7	6.6
USA	American Fork (Alps)	130	1820-3580	4	1	0.90	1.7
Switzerland	Landwasser (Alps)	183	1500-3146	3	1	N/A	N/A
India	Kulang (Himalayas)	205	2350-5000	N/A	N/A	N/A	N/A
Switzerland	Tavanasa (Alps)	215	1277-3210	4	2	0.82	3.1
USA	Dinwoody (Wind River)	228	1981-4202	4	2	0.85	2.8
USA	Salt Creek (Utah)	248	1564-3620	5	1	N/A	2.6
Italy	Cordevole (Alps)	248	980-3342	3	1	0.89	4.6

Country	Basin	Size (km^2)	Elevation Range (m a.s.l.)	Zones	Years (seasons)	R^{2*}	D_V[%]*
India	Beas-Manali (Himala-yas)	345	1900-6000	N/A	4	0.68	12
Norway	Laerdalselven (Lo Bre)	375	530-1720	5	1	0.86	5.2
Norway	Viveli (Hardangervidda)	386	880-1613	N/A	N/A	N/A	N/A
Japan	Okutadami (Mikuni)	422	782-2346	3	3	0.83	5.4
USA	Bull Lake Creek (Wind River)	484	1790-4185	4	1	0.82	4.8
Switzerland	Tiefencastel (Alps)	529	837-3418	5	2	N/A	N/A
USA	South Fork (Colorado)	559	2506-3914	3	7	0.89	1.8
Argentina	Las Cuevas (Andes)	600	2500-7000	N/A	N/A	N/A	N/A
USA	Independence R. (Adi-rondacks)	618	261-702	1	1	0.81	5.0
Chile	Mapocho (Andes)	630	1024-4450	3	1	0.42	29.9
Poland	Dunajec (High Tatra)	700	577-2301	3	1	0.73	3.8
India	Saing (Himalayas)	705	1400-5500	N/A	N/A	N/A	N/A
USA	Conejos (Colorado)	730	2521-4017	3	7	0.87	1.1
Switzerland	Ilanz (Alps)	776	693-3614	5	2	N/A	N/A
China	Toutunhe	840	1430-4450	6	3	0.81	2.0
Austria	Ötztaler Ache (Alps)	893	670-3774	6	1	0.84	9.18
Argentina	Lago Alumin (Andes)	911	1145-2496	N/A	N/A	N/A	N/A
China	Urumqi (Tien Shan)	924	1920-4000	N/A	N/A	N/A	N/A
Uzbekistan	Angren	970	1400-3800	5	1	0.3	-13.9
India	Parbati (Himalayas)	1154	1500-6400	5	1	0.73	7.5
Canada	Illecillewaet (Rocky Mtns.)	1155	509-3150	4	4	0.86	7.0
Spain	Segre en Seo d′urgel (Pyrenees)	1217	360-2900	5	N/A	N/A	N/A
India	Buntar (Himalayas)	1370	1200-5000	N/A	N/A	N/A	N/A
Chile	Tinguiririca Bajo Brio-nes (Andes)	1460	520-4500	3	1	0.88	-0.3
New Zealand	Hawea (S. Alps)	1500	300-2500	N/A	N/A	N/A	N/A
Switzerland	Ticino-Bellinzona (Alps)	1515	220-3402	5	1	0.86	-0.6
USA	Spanish Fork (Utah)	1655	1484-3277	4	1	0.85	1.0
Argentina	Tupungato (Andes)	1800	2500-6000	8	1	0.63	6.4
Switzerland	Inn-Martina (Alps)	1943	1030-4049	2	1	0.82	4.3
Argentina	Chico (Tierra del Fuego)	2000	N/A	N/A	N/A	N/A	N/A
China	Gongnisi (Tien Shan)	2000	1776-3200	N/A	N/A	N/A	N/A

Country	Basin	Size (km^2)	Elevation Range (m a.s.l.)	Zones	Years (seasons)	R^{2*}	D_V[%]*
USA	Boise (Idaho)	2150	983-3124	3	3	0.84	3.3
France	Durance (Alps)	2170	786-4105	5	5	0.85	2.6
USA	Madison (Montana)	2344	1965-3234	2	2	0.89	1.5
Uzbekistan	Pskem	2412	800-4300	7	1	0.84	0.5
Morocco	Tillouguit (Atlas)	2544	1050-3411	3	1	0.84	0.5
Austria	Salzach-St.Johann (Alps)	2600	570-3666	N/A	N/A	N/A	N/A
USA	Henry's Fork (Idaho)	2694	1553-3125	3	2	0.91	1.5
USA	Cache la Poudre (Colorado)	2732	1596-4133	3	1	N/A	N/A
Chile	Aconcagua (Andes)	2900	900-6100	3	1	0.91	0.9
USA	Sevier R (Kingston, Utah)	2929	1823-3260	4	1	0.75	5.1
Switzerland	Rhine-Felsberg (Alps)	3249	562-3425	5	7	0.70	7.2
Switzerland	Rhone-Sion (Alps)	3371	491-4634	7	1	0.95	0.02
USA	Rio Grande (Colorado)	3419	2432-4215	3	13	0.84	3.8
USA	Kings River (California)	4000	171-4341	7	5	0.82	3.2
Chile	Maipo en el Manzano (Andes)	4960	850-5600	3	2	0.77	0.9
India	Beas-Thalot (Himalayas)	5144	1100-6400	6	2	0.80	1.5
USA	Upper Yakima (Cascades)	5517	366-2121	5	1	0.92	2.8
Uzbekistan	Chatkal	6309	800-4500	7	1	0.7	-7.4
Canada	Sturgeon (Ontario)	7000	N/A	N/A	N/A	N/A	N/A
Argentina	Grande (Tierra del Fuego)	9050	N/A	N/A	N/A	N/A	N/A
Canada	Iskut (Coast)	9350	200-2556	5	N/A	N/A	N/A
USA	Sevier (Juab, Utah)	13380	1506-3719	4	1	0.93	4.0
USA	Snake River (Idaho)	14897	1524-4196	N/A	11	0.90	0.4
Pakistan	Kabul (Himalayas)	63657	305-7690	1	1	0.66	6.0
Tajikistan/Afghanistan	Pyandzh (Pamirs and Hindu Kush)	120534	2141-5564	8	3	0.65	5.6
China	Yellow (Anyemogen Shan)	121972	2500-5224	3	N/A	N/A	N/A

If more than one year were evaluated, averages of R^2 and averages of D_V (single values taken in absolute terms) are listed.

* The following accuracy criteria listed in Table 1 are defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \qquad D_v = \frac{V_R - V_R'}{V_R} \cdot 100$$

where:
R^2 = a measure of model efficiency
Q_i = measured daily discharge
Q_i' = simulated daily discharge
$\overline{Q}$ = average daily discharge for the simulation year or simulation season
n = number of daily discharge values
D_v = percentage difference between the total measured and simulated runoff (%)
V_R = measured runoff volume
V_R' = simulated runoff volume

In addition to the input variables, the area-elevation curve of the basin is required. If other basin characteristics are available (forested area, soil conditions, antecedent precipitation, and runoff data), they are of course useful for facilitating the determination of the model parameters.

SRM can be used for the following purposes:

(1) Simulation of daily flows in a snowmelt season, in a year, or in a sequence of years. The results can be compared with the measured runoff in order to assess the performance of the model and to verify the values of the model parameters. Simulations can also serve to evaluate runoff patterns in ungauged basins using satellite monitoring of snow covered areas and extrapolation of temperatures and precipitation from nearby stations.

(2) Short term and seasonal runoff forecasts. The microcomputer program (Micro-SRM) includes a derivation of modified depletion curves which relate the snow covered areas to the cumulative snowmelt depths as computed by SRM. These curves enable the snow coverage to be extrapolated manually by the user several days ahead by temperature forecasts so that this input variable is available for discharge forecasts. The modified depletion curves can also be used to evaluate the snow reserves for seasonal runoff forecasts. The model performance may deteriorate if the forecasted air temperature and precipitation deviate from the observed values, but the inaccuracies can be reduced by periodic updating.

(3) In recent years, SRM was applied to the new task of evaluating the potential effect of climate change on the seasonal snow cover and runoff, as explained in Chapter 8. The microcomputer program has been complemented accordingly.

4 MODEL STRUCTURE

Each day, the water produced from snowmelt and from rainfall is computed, superimposed on the calculated recession flow and transformed into daily discharge from the basin according to Equation (1):

$$Q_{n+1} = [c_{Sn} \cdot a_n (T_n + \Delta T_n) S_n + c_{Rn} P_n] \frac{A \cdot 10000}{86400} (1-k_{n+1}) + Q_n k_{n+1} \quad (1)$$

where: Q = average daily discharge [m^3s^{-1}]

c = runoff coefficient expressing the losses as a ratio (runoff/precipitation), with c_S referring to snowmelt and c_R to rain

a = degree-day factor [$cm \cdot {}^oC^{-1} \cdot d^{-1}$] indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days [$^oC \cdot d$]

ΔT = the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone [$^oC \cdot d$]

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. If precipitation is determined by T_{CRIT} to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur.

A = area of the basin or zone [km^2]

k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall:

$$k = \frac{Q_{m+1}}{Q_m}$$ (m, m + 1 are the sequence of days during a true recession flow period).

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. In this case, the number of degree-days measured on the nth day corresponds to the discharge on the n + 1 day. Various lag times can be introduced by a subroutine.

$\frac{10000}{86400}$ = conversion from $cm \cdot km^2 \cdot d^{-1}$ to m^3s^{-1}

T, S and P are variables to be measured or determined each day. c_R, c_S, lapse rate to determine ΔT, T_{CRIT}, k and the lag time are parameters which are characteristic for a given basin or, more generally, for a given climate. A guidance for determining these parameters will be given in section 5.3.

If the elevation range of the basin exceeds 500 m, it is recommended that the basin be subdivided into elevation zones of about 500 m each. For an elevation range of 1500 m and three elevation zones A, B and C, the model equation becomes

$$Q_{n+1} = \{[c_{SAn} \cdot a_{An} (T_n + \Delta T_{An}) S_{An} + c_{RAn} \cdot P_{An}] \frac{A_A \cdot 10000}{86400} + [c_{SBn} \cdot a_{Bn} (T_n + \Delta T_{Bn}) S_{Bn} + c_{RBn} \cdot P_{Bn}] \frac{A_B \cdot 10000}{86400} + [c_{SCn} \cdot a_{Cn} (T_n + \Delta T_{Cn}) S_{Cn} + c_{RCn} \cdot P_{Cn}] \frac{A_C \cdot 10000}{86400}\} (1-k_{n+1}) + Q_n \cdot k_{n+1} \quad (2)$$

The indices A, B and C refer to the respective elevation zones and a time lag of 18 hours is assumed. Other time lags can be selected and automatically taken into account as explained in the Section 5.3.7.

In the simulation mode, SRM can function without updating. The discharge data serve only to evaluate the accuracy of simulation. In ungauged basins the simulation is started with a discharge estimated by analogy to a nearby gauged basin. In the forecasting mode, the model provides an option for updating by the actual discharge every 1-9 days.

Equations (1) and (2) are written for the metric system but an option for model operation in English units is also provided in the computer program.

5 NECESSARY DATA FOR RUNNING THE MODEL

5.1 Basin characteristics

5.1.1 Basin and zone areas

The basin boundary is defined by the location of the streamgauge (or some arbitrary point on the stream-course) and the watershed divide is identified on a topographic map. The basin boundary can be drawn at a variety of map scales. For the larger basins, a 1:250,000 scale map is adequate. After examining the elevation range between the streamgauge and the highest point in the basin (total basin relief), elevation zones can be delineated in intervals of about 500 m or 1500 ft. In addition to drawing the basin and zone boundaries, several intermediate topographic contour lines should be highlighted for later use in constructing the area-elevation curve. Once the boundaries and the contours have been determined, the areas formed by these boundaries should be planimetered manually or automatically. Figure 2 shows the elevation zones and areas of the South Fork of the Rio Grande basin in Colorado, USA. The elevation range of 1408 m dictated the division of the basin into three elevation zones. Once the zones are defined, the various model variables and parameters are applied to each zone for the calculation of snowmelt run-off. To facilitate this application, the mean hypsometric elevation of the zone must be determined through use of an area-elevation curve. Many of these steps can be expedited through the use of computer analysis and a Digital Elevation Model (DEM).

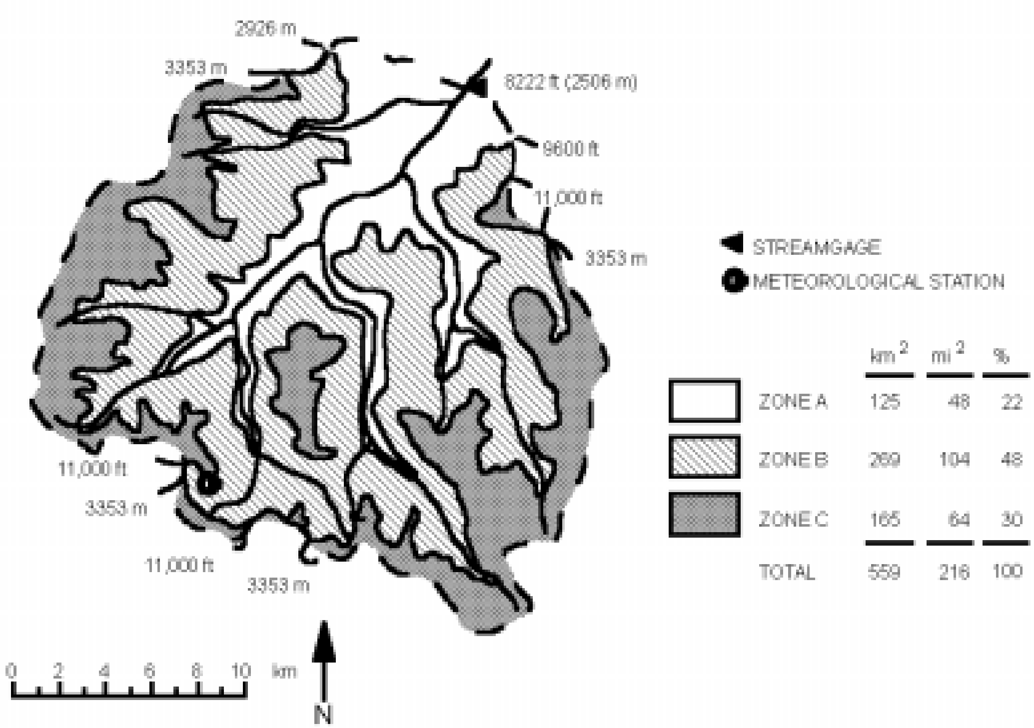

Fig. 2 Elevation zones and areas of the South Fork of the Rio Grande Basin, Colorado, USA.

5.1.2 Area-elevation curve

By using the zone boundaries plus other selected contour lines in the basin, the areas enclosed by various elevation contours can be determined by planimetering. These data can be plotted (area vs elevation) and an area-elevation (hypsometric) curve derived as shown in Figure 3 for the South Fork basin. This area-elevation curve can also be derived automatically if the user has access to digital elevation data and computer algorithms used in an image processing system. The zonal mean hypsometric elevation, $\bar{h}$, can then be determined from this curve by balancing the areas above and below the mean elevation 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 zonal degree-days.

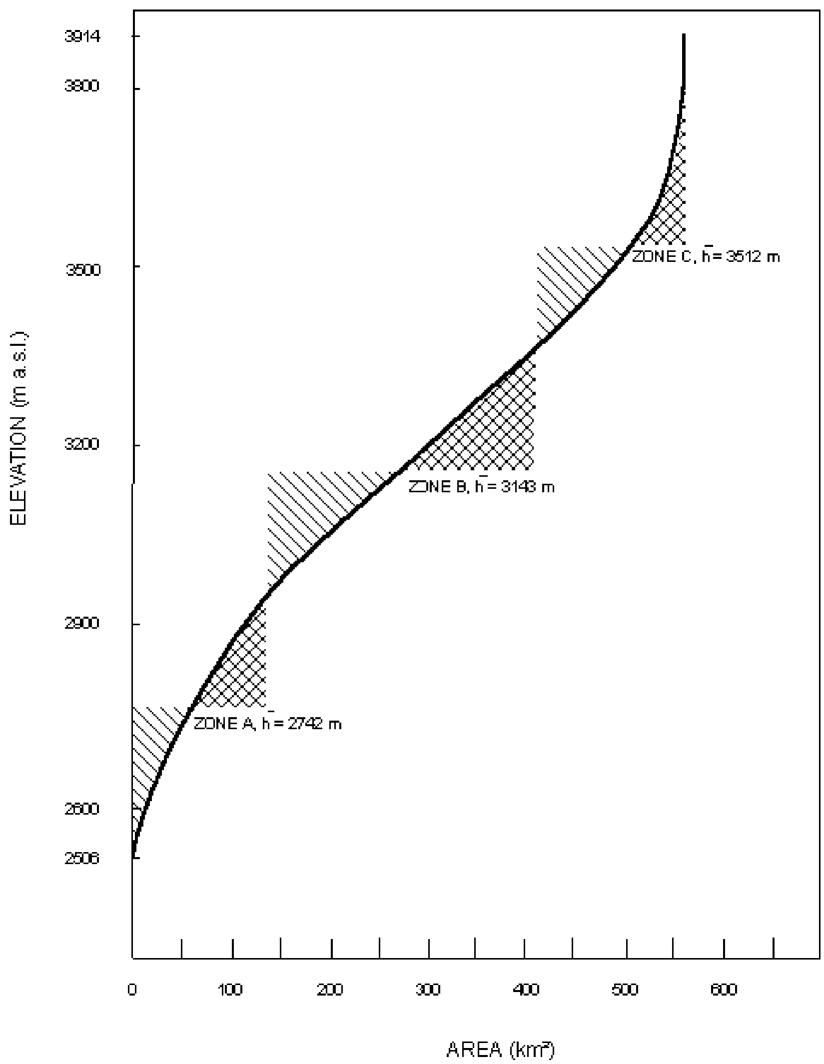

Fig. 3 Determination of zonal mean hypsometric elevations ($\bar{h}$) using an area-elevation curve for the South Fork of the Rio Grande basin.

5.2 Variables

- TEMPERATURE
- PRECIPITATION
- SNOW COVERED AREA

5.2.1 Temperature and degree-days, T

In order to compute the daily snowmelt depths, the number of degree-days must be determined from temperature measurements or, in a forecasting mode, from temperature forecasts.

Program options: Temperature average
0 = daily mean
1 = Min, Max

The program accepts either the daily mean temperature (option 0) or two temperature values on each day: T_{Max}, T_{Min} (option 1). The temperatures are extrapolated by the program from the base station elevation to the hypsometric mean elevations of the respective elevation zones. For option 1, the average temperature is computed in each zone as

$$\bar{T} = \frac{T_{Max} + T_{Min}}{2} \tag{3}$$

When using daily means (option 0) or when using T_{Max}, T_{Min} (option 1), it is recommended that negative temperature values (when they occur) be used in the calculation. In line with this recommendation, the original "effective minimum temperature" alternative (automatic change of negative temperatures to 0°C) was removed from the computer program beginning with Version 3.0. If the user still prefers this alternative, the occasional negative temperatures can be changed manually to 0°C when inputting the data to SRM.

Because the average temperatures refer to a 24 hour period starting always at 0600 hrs, they become degree-days T [°C·d]. The altitude adjustment ΔT in Equation (1) is computed as follows:

$$\Delta T = \gamma \cdot (h_{st} - \bar{h}) \cdot \frac{1}{100} \tag{4}$$

where γ = temperature lapse rate [°C per 100 m]
h_{st} = altitude of the temperature station [m]
$\bar{h}$ = hypsometric mean elevation of a zone [m]

Whenever the degree-day numbers ($T + \Delta T$ in Equation (1)) become negative, they are automatically set to zero so that no negative snowmelt is computed. The values of the temperature lapse rate are dealt with in Section 5.3.3.

Program options: Temperature input
0 = basin wide
1 = by zone

The program accepts either temperature data from a single station (option 0, basin wide) or from several stations (option 1, by zone). With option 0, the altitude of the station is entered and temperature data are extrapolated to the hypsometric mean elevations of all zones using the lapse rate. If more stations are available, the user can prepare a single "synthetic station" and still use option 0 or, alternatively, use option 1. With option 1, the user may use separate stations for each elevation zone, however, the temperatures entered for each zone must have already been lapsed to the mean hypsometric elevation of the zone. Although SRM will take separate stations for each zone in this way, it is only optional. The measurement of correct air temperatures is difficult, and therefore one good temperature station (even if located outside the basin) may be preferable to several less reliable stations.

In the forecast mode of the model, it is necessary to obtain representative temperature forecasts for the given region and altitude in order to extrapolate the expected numbers of degree-days for each elevation zone.

5.2.2 Precipitation, P

The evaluation of representative areal precipitation is particularly difficult in mountain basins. Also, quantitative precipitation forecasts are seldom available for the forecast mode, although current efforts in this field are improving this situation. Fortunately, snowmelt generally prevails over the rainfall component in the mountain basins. However, sharp runoff peaks from occasional heavy rainfalls must be given particular attention and the program includes a special treatment of such events (see Section 5.3.6).

Program options: Rainfall input
- 0 = basin wide
- 1 = by zone

The program accepts either a single, basin-wide precipitation input (from one station or from a "synthetic station" combined from several stations) (option 0) or different precipitation inputs zone by zone (option 1). If the program is switched to option 1 and only one station happens to be available, for example in the zone A, precipitation data entered for zone A must be copied to all other zones. Otherwise no precipitation from these zones is taken into account by the program. Further program options refer to the rainfall contributing area as explained in Section 5.3.5. In basins with a great elevation range, the precipitation input may be underestimated if only low altitude precipitation stations are available. It is recommended to extrapolate precipitation data to the mean hypsometric altitudes of the respective zones by an altitude gradient, for example 3 % or 4 % per 100 m. If two stations at different altitudes are available, it is possible to assign the averaged data to the average elevation of both stations and to extrapolate by an altitude gradient from this reference level to the elevation zones. It should be noted that the increase of precipitation amounts with altitude does not continue indefinitely but stops at a certain altitude, especially in very high elevation mountain ranges.

A critical temperature (see Section 5.3.4) is used to decide whether a precipitation event will be treated as rain ($T \geq T_{CRIT}$) or as new snow ($T < T_{CRIT}$). When the precipitation event 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 day warm enough to produce melting. This precipitation is stored by SRM and then melted as soon as a sufficient number of degree-days has occurred. The following example in Table 2 illustrates a case where 2.20 cm water equivalent of snow fell on day n and then was melted on the three successive days. This procedure is slightly changed in the winter as explained in Section 8.1.

In this example, S is decreasing on consecutive days because it is interpolated previously from the snow-cover depletion curve. In reality it should remain constant as long as the seasonal snowpack is covered with new snow, however, the model currently uses the incremental decrease of S shown in Table 2.

Table 2 Calculation of the melt of new snow deposited on a snow-free area (P_n = 2.20 cm; T_{CRIT} = + 1.0°C).

Day	a [cm·°C^{-1}·d^{-1}]	T [°C·d]	S	P [cm]	Melted Depth a·T [cm]	P Stored [cm]	P contributing to Runoff a·T·(1-S) [cm]
n	0.45	0	0.72	2.20	0	2.20	0
n+1	0.45	0.11	0.70	0	0.05	2.15	0.02
n+2	0.45	2.70	0.68	0	1.22	0.93	0.39
n+3	0.45	3.70	0.66	0	0.93	0	0.32

Sharp peaks of discharge are typical for rainfall runoff as opposed to the relatively regular daily fluctuations of the snowmelt runoff. SRM has been adapted to better simulate these rainfall peaks whenever the average daily rainfall calculated over the whole basin equals or exceeds 6 cm. This threshold can be changed by the user according to the characteristics of the selected basin. The procedure is described in the Section 5.3.6.1 in connection with the recession coefficient. In spite of these precautions, rainfall runoff peaks may cause problems because local rainstorms may be missed if the network of precipitation stations is not dense enough. Also, the timing of rainfalls within the 24 hour period is frequently unknown. Actually, this period (for P_n) usually lasts from 0800 hrs on the day n to 0800 hrs on the day n+1 and is published as precipitation on the day n. In some cases, however, the same precipitation amount is ascribed to the day n+1 on which the measurement period ended. In such case precipitation data must be shifted backwards by one day before input to SRM.

5.2.3 Snow covered area, S

It is a typical feature of mountain basins that the areal extent of the seasonal snow cover gradually decreases during the snowmelt season. Depletion curves of the snow coverage can be interpolated from periodical snow cover mapping so that the daily values can be read off as an important input variable to SRM. The snow cover can be mapped by terrestrial observations (in very small basins), by aircraft photography (especially in a flood emergency) and, most efficiently, by satellites. The minimum area which can be mapped with an adequate accuracy depends on the spatial resolution of the remote sensor. Examples are listed in Table 3.

Figure 4 shows the snow cover in the alpine basin Felsberg mapped from Landsat 5-MSS data (Baumgartner, 1987). When the time interval between the subsequent satellite images becomes too long, e.g. due to visibility obscured by clouds, the depletion curves derived from the measured points may be distorted by occasional summer snowfalls. Figure 5 shows a temporary increase in the snow coverage from 50 % to 100 % by a snowfall in early June. If the preceding Landsat overflight did not deliver data, the points from overflights 2, 4 and 5 might have been connected by a false depletion curve. As a result, excessive meltwater production would have been calculated. To avoid such errors, satellite images showing the short-lived snow cover from the summer snowfalls must be disregarded when deriving the depletion curves. In order to identify the new snow events, coincident precipitation and temperature data should be consulted. The transitory new snow is accounted for as stored precipitation eventually contributing to runoff as explained in the Section 5.2.2.

As an example, Figure 6 shows depletion curves of the snow coverage derived for five elevation zones of the alpine basin Felsberg from the Landsat imagery (Baumgartner, 1987, Baumgartner & Rango, 1995). Together with temperature and precipitation data, such depletion curves enable SRM to simulate runoff in a past year. In September, the depletion curve in zone E refers to the glacier which prevents it from decreasing any further.

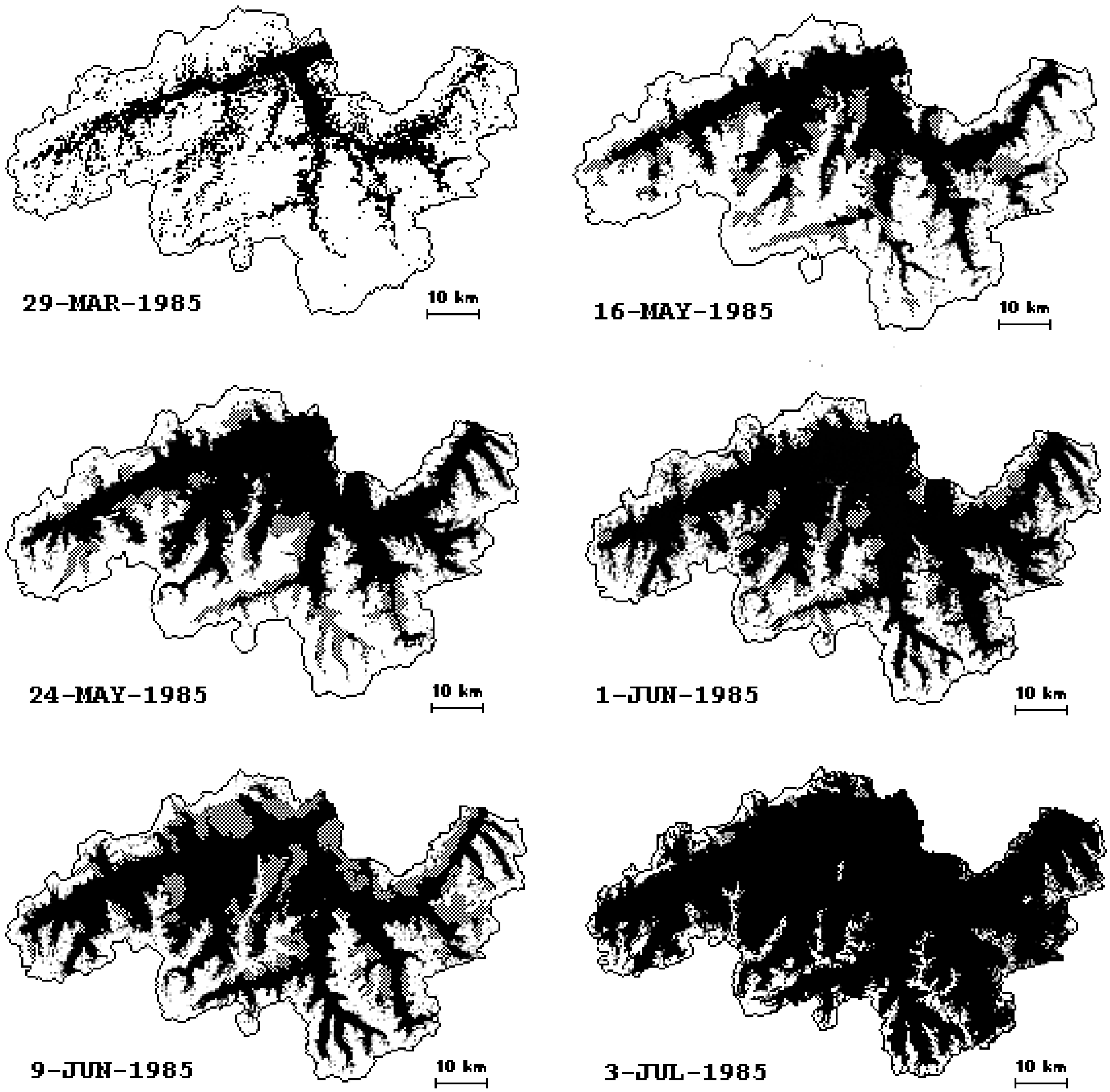

Fig. 4 Sequence of snow cover maps from Landsat 5-MSS, Upper Rhine River at Felsberg, 3250 km^2 , 560-3614 m a.s.l. (Baumgartner, 1987).

For real-time runoff forecasts, however, it is necessary to know the snow covered area within days after a satellite overflight and also to extrapolate the depletion curves of the snow coverage to the future weeks. This procedure is explained in the Section 7.

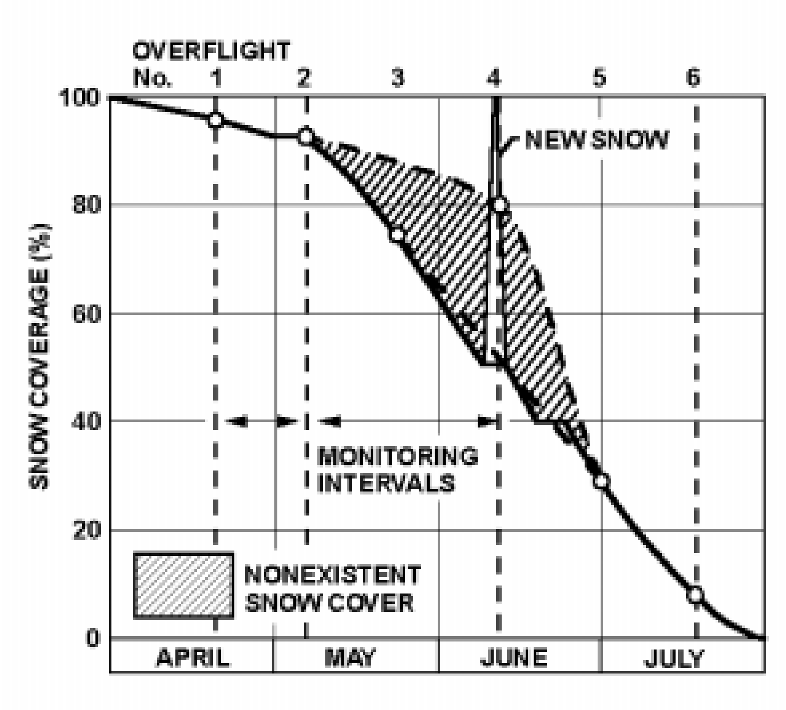

Fig. 5 Example of a possible distortion of a depletion curve due to a temporary increase in the snow coverage by a summer snowfall and to missing Landsat data from the preceding overflight (Hall & Martinec, 1985).

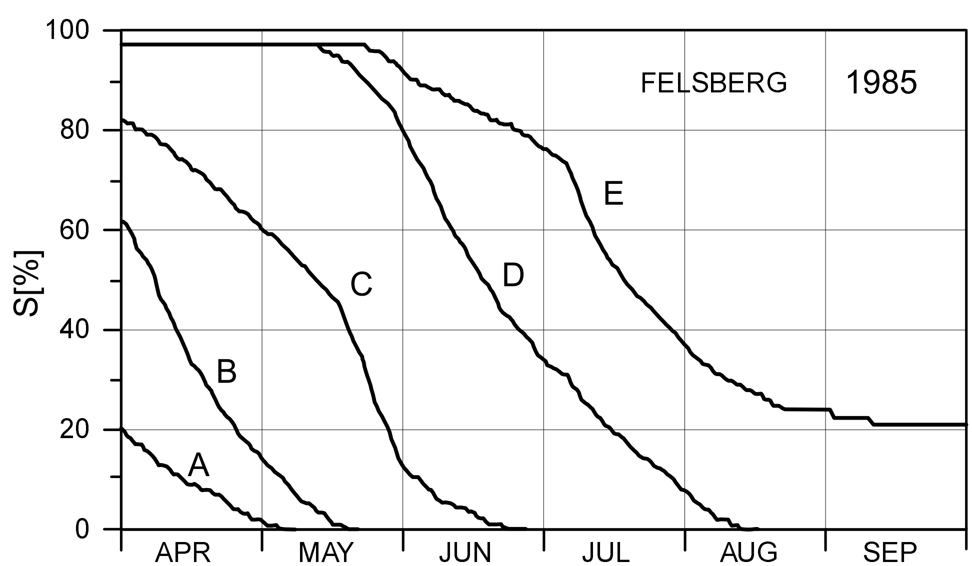

Fig. 6 Depletion curves of the snow coverage for 5 elevation zones of the basin Felsberg, derived from the Landsat imagery shown in Figure 4. A: 560 - 1100 m a.s.l., B: 1100 - 1600 m a.s.l., C: 1600 - 2100 m a.s.l., D: 2100 - 2600 m a.s.l., E: 2600-3600 m a.s.l. (Baumgartner, 1987).

Table 3 Possibilities of remote sensing for snow cover mapping.

Platform Sensor	Spatial resolution	Minimum area size	Repeat period
Aircraft Orthophoto	3 m	1 km^2	flexible
Landsat			16-18 days
MSS	80 m	10-20 km^2	
TM	30 m	2.5 - 5 km^2	
NOAA AVHRR	1.1 km	100-500 km^2	12 hr
Meteosat Visible	2.5 km	500-1000 km^2	30 min
SPOT	10-20 m	2-3 km^2	26 days
MOS	50 m	5-10 km^2	17 days

MSS = Multi Spectral Scanner
TM = Thematic Mapper
NOAA = National Oceanic and Atmospheric Administration
AVHRR = Advanced Very High Resolution Radiometer
SPOT = Système Pour l'Observation de la Terre (France)
MOS = Marine Observation Satellite (Japan)

5.3 Parameters

- RUNOFF COEFF. SNOW
- RUNOFF COEFF. RAIN
- DEGREE DAY FACTOR
- TEMPERATURE LAPSE RATE
- CRITICAL TEMPERATURE
- RAINFALL CONTRIBUTING AREA
- RECESSION COEFF.
- TIME LAG

The SRM parameters are not calibrated or optimized by historical data. They can be either derived from measurement or estimated by hydrological judgment taking into account the basin characteristics, physical laws and theoretical relations or empirical regression relations. Occasional subsequent adjustments should never exceed the range of physically and hydrologically acceptable values.

5.3.1 Runoff coefficient, c

This coefficient takes care of the losses, that is to say of the difference between the available water volume (snowmelt + rainfall) and the outflow from the basin. On a long term basis, it should correspond to the ratio of the measured precipitation to the measured runoff. In fact, comparison of historical precipitation and runoff ratios provide a starting point for the runoff coefficient values. However, these ratios are not always easily obtained in view of the precipitation catch deficit which particularly affects snowfall and of inadequate precipitation data from mountain regions. At the start of the snowmelt season, losses are usually very small because they are limited to evaporation from the snow surface, especially at high elevations. In the next stage, when some soil becomes exposed and vegetation grows, more losses must be expected due to evapotranspiration and interception. Towards the end of the snowmelt season, direct channel flow from the remaining snowfields and glaciers may prevail in some basins which leads to a decrease of losses and to an increase of the runoff coefficient. In addition, c is usually different for snowmelt and for rainfall. The computer program accepts separate values for snow, c_S, and rain, c_R, and allows for half-monthly (and, if required, daily) changes of values in each elevation zone. Examples of seasonal trends of runoff coefficients are given in Figures 7 and 8, with the half-monthly values connected by straight lines. The runoff coefficients can even reach lower values in certain semiarid basins, particularly in the lowest elevation zone of such basins.

Of the SRM parameters, the runoff coefficient appears to be the primary candidate for adjustment if a runoff simulation is not at once successful.

5.3.2 Degree-day factor, *a*

The degree-day factor *a* [cm·°C^{-1}·d^{-1}] converts the number of degree-days T [°C·d] into the daily snowmelt depth M [cm]:

$$M = a \cdot T \qquad (5)$$

Degree-day ratios can be evaluated by comparing degree-day values with the daily decrease of the snow water equivalent which is measured by radioactive snow gauge, snow pillow or a snow lysimeter. Such measurements (Martinec, 1960) have shown a considerable variability of degree-day ratios from day to day. This is understandable because the degree-day method does not take specifically into account other components of the energy balance, notably the solar radiation, wind speed and the latent heat of condensation. If averaged for 3-5 days, however, the degree-day factor is more consistent and can represent the melting conditions. The effect of daily fluctuations of the degree day values on the runoff from a basin as computed by SRM is greatly reduced because the daily meltwater input is superimposed on the more constant recession flow (Equation (1)).

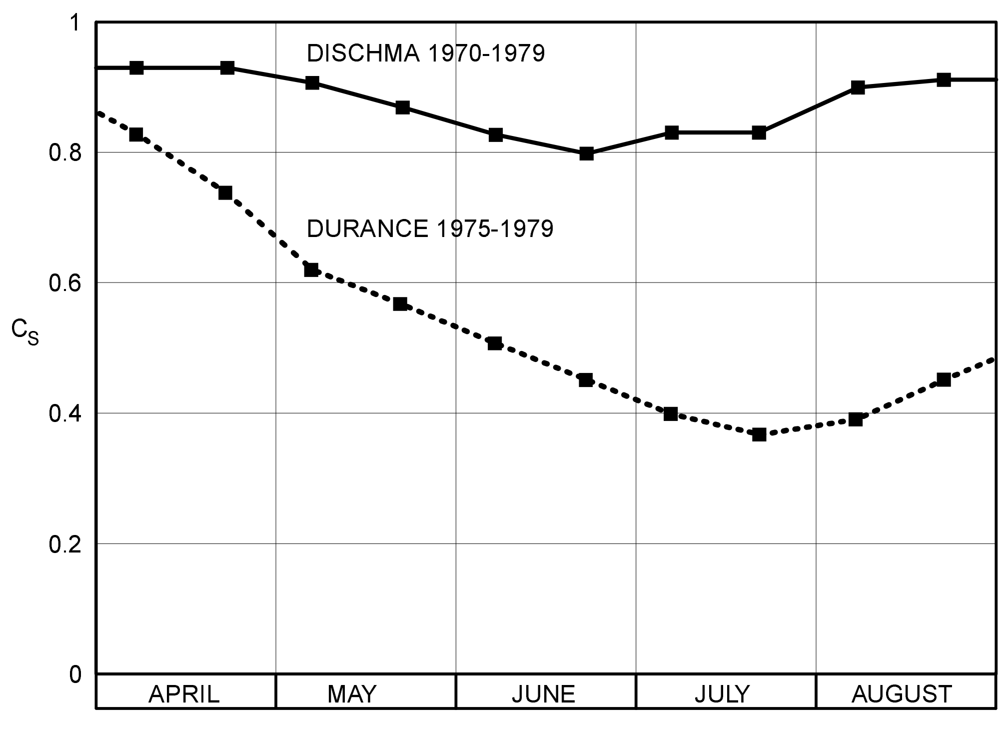

Fig. 7 Average runoff coefficient for snow (c_s) for the alpine basins Dischma (43.3 km^2, 1668-3146 m a.s.l.) and Durance (2170 km^2, 786-4105 m a.s.l.) (Martinec & Rango, 1986).

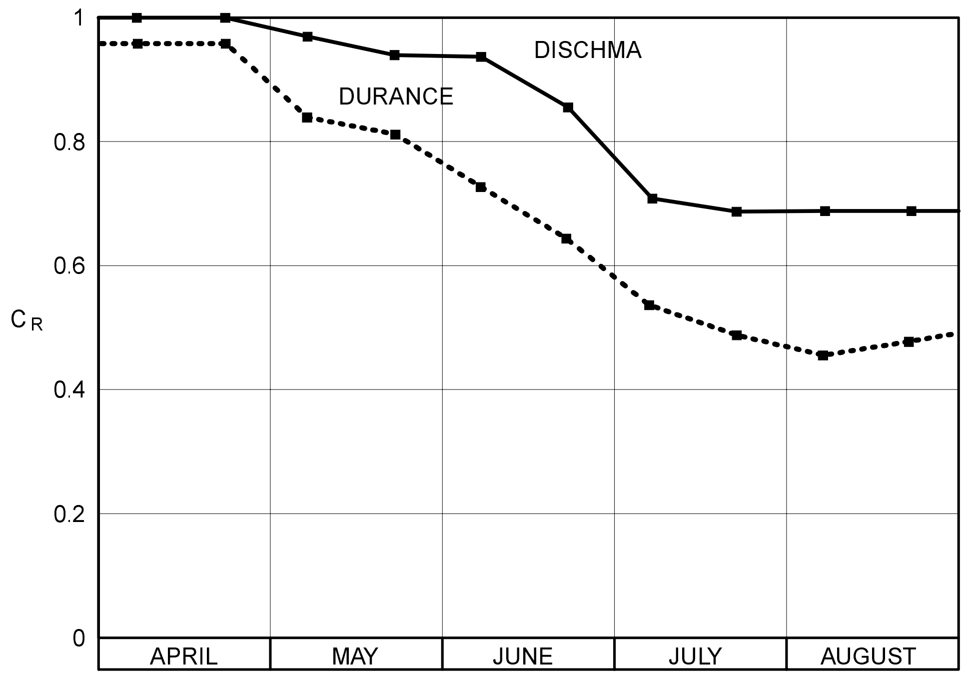

Fig. 8 Average runoff coefficient for rainfall (c_R) for the basins Dischma and Durance (Martinec & Rango, 1986).

The degree-day method requires several precautions:

(1) The degree-day factor is not a constant. It changes according to the changing snow properties during the snowmelt season.

(2) If point values are applied to areal computations, the degree-day values must be determined for the hypsometric mean elevation of the snow cover in question and not, for example, for the altitude of the snow line.

(3) If the snow cover is scattered, a correctly evaluated degree-day factor will produce less meltwater than if a 100 percent snow cover were assumed. A meltwater difference that arises from erroneous snow cover information should not be compensated for by "optimizing" the degree-day factor. Instead, the correct areal extent of the snow cover should be determined and used.

(4) In large area extrapolations, point measurements should be weighted depending on how well a specific station represents the hydrological characteristics of a given zone (Shafer *et al.*, 1981).

In the absence of detailed data, the degree-day factor can be obtained from an empirical relation (Martinec, 1960):

$$a = 1.1 \cdot \frac{\rho_s}{\rho_w} \qquad (6)$$

where a = the degree-day factor [cm °C^{-1}d^{-1}]
ρ_s = density of snow
ρ_w = density of water

When the snow density increases, the albedo decreases and the liquid water content in snow increases. Thus the snow density is an index of the changing properties which favor the snowmelt.

Figure 9 illustrates the seasonal trend of the degree-day factor in the Alps and in the Rocky Mountains. Because the geographic latitude of a basin influences the solar radiation, it may be advisable to adjust the degree-day factors accordingly. In glacierized basins, the degree-day factor usually exceeds 0.6 cm $°C^{-1} \cdot d^{-1}$ towards the end of the summer when ice becomes exposed (Kotlyakov & Krenke, 1982). The computer program accepts different degree-day factors for up to 8 elevation zones which are usually changed twice a month (although daily changes are possible).

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 be manually modified and inserted to reflect these unusual snowmelt conditions.

As is evident from Equation (1), the degree-day method could be readily replaced by a more refined computation of snowmelt without changing the structure of SRM. Such refinement appeared to be imperative in a study of outflow from a snow lysimeter (Martinec, 1989) but is not considered to be expedient for hydrological basins until the necessary additional variables and their forecasts become available. The degree-day method is explained in more detail in a separate publication (Rango & Martinec, 1995).

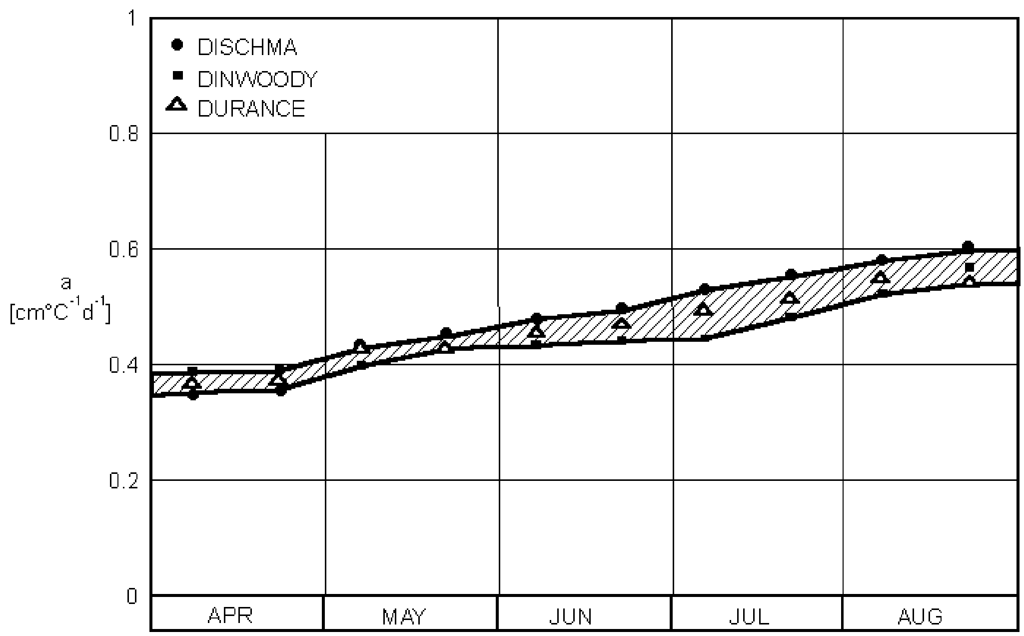

Fig. 9 Average degree-day ratio (*a*) used in runoff simulations by the SRM model in the basins Dischma (10 years), Durance (5 years) and Dinwoody (228 km^2; 1981-4202 m a.s.l., Wyoming, 2 years) (Martinec & Rango, 1986).

5.3.3 Temperature lapse rate, γ

If temperature stations at different altitudes are available, the lapse rate can be predetermined from historical data. Otherwise it must be evaluated by analogy from other basins or with regard to climatic conditions. In SRM simulations, a lapse rate of 0.65°C per 100 m was usually employed. Slightly higher, seasonally changing values appeared to be adequate in the Rocky Mountains.

Program options: Temperature lapse rate
0 = basin wide
1 = by zone

The computer program accepts either a single or a basin wide lapse rate (option 0) or different rates for each zone (option 1). Seasonal variations can also be accommodated by inputting predetermined lapse rates every 15 days, and the lapse rate can be changed manually on selected days if a special meteorological situation (for example, a temperature inversion) requires a different value.

If the temperature station is situated near the mean elevation of the basin, possible errors in the lapse rate are to some extent canceled out because the extrapolation of temperature takes place upwards as well as downwards. If, on the other hand, the temperature station is at a low altitude, SRM becomes sensitive to the lapse rate. For some basins in Wyoming, for example, the closest temperature station was more than 100 km away and 2000 m lower than the highest snow-covered parts of the basins. In such a case, an error in the lapse rate of only 0.05°C per 100 m causes a deviation of 1 degree-day from the correct degree-day value which corresponds to an error of about 0.5 cm of the computed daily meltwater depth late in the snowmelt season.

Such situations sometimes necessitate an adjustment of the originally selected lapse rate taking into account the course of the depletion curves of snow coverage. If high temperatures result from extrapolation by a certain lapse rate but no change in the snow areal extent is observed, then probably no appreciable snowmelt is taking place at this altitude. The high temperatures result from a false lapse rate which must be increased or decreased, depending on whether the temperature station is lower or higher than the mean zone elevation.

5.3.4 Critical temperature, T_{CRIT}

The critical temperature determines whether the measured or forecasted precipitation is rain or snow. Models which simulate the build-up of the snow cover first in order to simulate the runoff depend heavily on this parameter not only in the ablation period but particularly in the accumulation period. SRM needs the critical temperature only in the snowmelt season (unless a year round computer run is made) in order to decide whether precipitation immediately contributes to runoff (rain), or, if $T < T_{CRIT}$, whether snowfall took place. In this case, SRM automatically keeps the newly fallen snow in storage until it is melted on subsequent warm days, as explained in the Section 5.2.2.

When SRM was applied in the alpine basin Dischma, T_{CRIT} started at + 3°C in April at the beginning of snowmelt and diminished to + 0.75°C in July. This seasonal trend with a narrower range appears to be applicable in other basins. At certain times, SRM may not take notice of a sharp rainfall runoff peak because the corresponding precipitation is determined to be snow, the extrapolated temperature being just slightly below the critical temperature. In such cases the assignment of critical temperature and the temperature lapse rate values should be reviewed and logical adjustments made in order to change snow to rain. It is of course difficult to distinguish accurately between rain and snow because the temperature used is the daily mean while precipitation may occur at any time, day or night, i.e., in the warmer or colder portion of the daily temperature cycle.

As a possible refinement, formulas have been proposed (Higuchi *et al.*, 1982) to determine the proportion of rain and snow in mixed precipitation conditions.

5.3.5 Rainfall contributing area, RCA

When precipitation is determined to be rain, it can be treated in two ways. In the initial situation (option 0), it is assumed that rain falling on the snowpack early in the snowmelt season is retained by the snow which is usually dry and deep. Rainfall runoff is added to snowmelt runoff only from the snow-free area, that is to say the rainfall depth is reduced by the ratio snow-free area/zone area. At some later stage, the snow cover becomes ripe (the user must decide on which date) and the computer program should be switched to option 1. Now, if rain falls on this snow cover, it is assumed that the same amount of water is released from the snowpack so that rain from the entire zone area is added to snowmelt. The melting effect of rain is neglected because the additional heat supplied by the liquid precipitation is considered to be small (Wilson, 1941).

5.3.6 Recession coefficient, k

As is evident from Equation (1), the recession coefficient is an important feature of SRM since (1-k) is the proportion of the daily meltwater production which immediately appears in the runoff. Analysis of historical discharge data is usually a good way to determine k. Figure 10 shows such an evaluation for the alpine basin Dischma (43.3 km^2, 1668-3146 m a.s.l.). Values of Q_n and Q_{n+1} are plotted against each other and the lower envelope line of all points is considered to indicate the k-values. Based on the relation $k = Q_{n+1}/ Q_n$, it can be derived that for example $k_1 = 0.677$ for $Q_n = 14\ m^3s^{-1}$ and $k_2 = 0.85$ for $Q_n = 1\ m^3s^{-1}$. This means that k is not constant, but increases with the decreasing Q according to the equation

$$k_{n+1} = x \cdot Q_n^{-y} \tag{7}$$

where the constants x and y must be determined for a given basin by solving the equations:

$$k_1 = x \cdot Q_1^{-y}$$

$$k_2 = x \cdot Q_2^{-y}$$

$$\log k_1 = \log x - y \log Q_1 \tag{8}$$

$$\log k_2 = \log x - y \log Q_2 \tag{9}$$

In the given example,

$$\log 0.677 = \log x - y \log 14$$
$$\log 0.85 = \log x - y \log 1$$
$$x = 0.85$$
$$y = 0.086$$

As a formal change from the SRM User's Manual of 1983 (Martinec *et al.*, 1983), a negative sign appears in the exponent of Equation (7) so that the numerical values of x and y are positive.

The variability of k according to Equation (7) was also confirmed in other basins. This means that the recession does not exactly follow the usual equation

$$Q_n = Q_0 \cdot k^n \tag{10}$$

where Q_0 = the initial discharge

Q_n = the discharge after n days

but the following equation (Jaccard, 1982)

$$Q_n = x^{\frac{1}{y}} \left(\frac{Q_0}{x^{\frac{1}{y}}} \right)^{(1-y)^n} \tag{11}$$

where x and y are the constants of Equation (7).

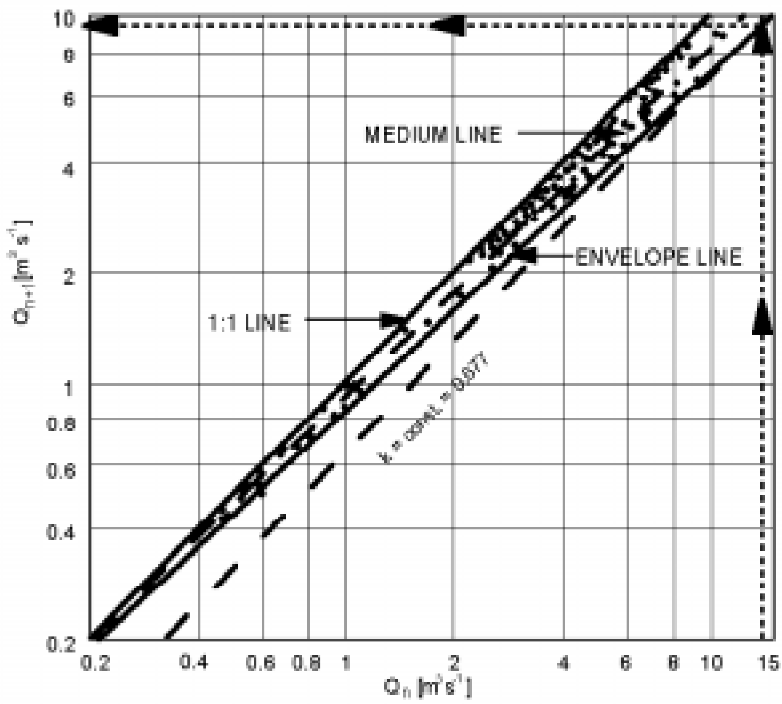

Fig. 10 Recession flow plot Q_n vs Q_{n+1} for the Dischma basin in Switzerland. Either the solid envelope line or the dashed medium line is used to determine k-values for computing the constants x and y in Equation (7) (Martinec & Rango, 1986).

The envelope line in Figure 10 and the resulting values of x and y must be determined for each basin. For ungauged basins and when historical discharge data are insufficient, x and y can be derived indirectly from the size of the basin as follows:

$$k_{Nn} = \left[x_M \left(\frac{\overline{Q}_M}{\overline{Q}_N} \cdot Q_{Nn-1} \right)^{-y_M} \right]^{\sqrt[4]{A_M/A_N}} \qquad (12)$$

where: x_M, y_M are the known constants for the basin M; $\overline{Q}_M, \overline{Q}_N$ are average discharge values from the basin M and the new basin N; and A_M, A_N are the areas of the respective basins.

Equation (12) indicates that recession coefficients are generally higher in large basins than in small basins. If the increase in k with size appears to be too large, the exponent may be replaced by $\sqrt[8]{A_M/A_N}$. Even if the envelope line in Figure 10 can be reliably derived in a basin, it is possible that the resulting k-values may be too low to represent average conditions during the snowmelt season, especially in large basins. In such cases the SRM model will react too quickly to any change of the daily input. The simulated peaks would be too high and the simulated recession too fast. A quick improvement is possible by deriving a new x and y, not from the envelope line, but from an intermediate or medium line between the envelope and the 1:1 line. This modification may especially be needed if the runoff simulation is extended to the whole year. Recession coefficients which may be right for the snowmelt period are usually too low for the winter months so that the simulated flows drop below the measured minimum values.

In very small basins, noticeable differences in the recession flow conditions and the k-values may occur from year to year. Figure 11 illustrates the range of k-values for varying basin size and for the mentioned alternatives of evaluation. For a very small mountain basin, the range includes the variations of k in different years (Martinec, 1970). For a larger alpine basin, the limits refer to the envelope line and to the medium line in Figure 10. For the largest basin, the higher limit (1) of the indicated range was derived by substituting the constants x = 0.085, y = 0.086 derived for the Dischma basin into Equation (12). The lower limit (2) was obtained by replacing $\sqrt[4]{A_M / A_N}$ in Equation (12) with $\sqrt[8]{A_M / A_N}$.

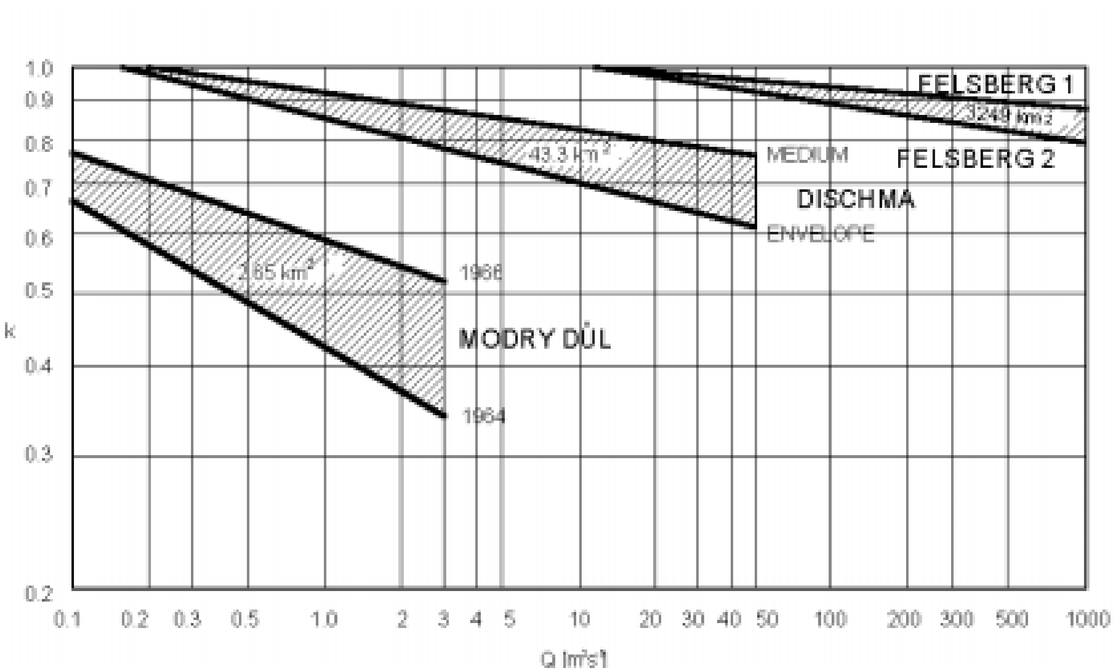

Fig. 11 Range of recession coefficients, k, related to discharge Q resulting from various evaluations: In Dischma, the range results from using either the envelope line or the medium line in Figure 10. In Modry Dul, the relation varies in different years. In Felsberg, the relations (1) and (2) are derived from the size of the basin by two alternative formulas (Martinec & Rango, 1986).

Figure 11 shows that k can theoretically exceed 1 for very small discharges in large basins. This does not really happen because such small discharges do not occur there. Such a situation could be produced, however, by the user inadvertently taking over the x and y values derived in a large basin and using them for a small basin without modification. In this case, if the daily snowmelt input exceeds the previous day's runoff, SRM computes a runoff decrease instead of increase. In order to avoid this error, the computer program prevents k from exceeding 0.99. However, it is advisable to avoid approaching this limiting situation by checking the x and y values with regard to the lowest flow to be expected. Recalling Equation (11), it follows for n = ∞, because y > 0 and (1-y) < 1:

$$Q_\infty = x^{\frac{1}{y}} \left(\frac{Q_0}{x^{\frac{1}{y}}} \right)^{(<1)^\infty} = x^{\frac{1}{y}} \qquad (13)$$

Therefore the values x and y should fulfill the condition

$$Q_{Min} > x^{\frac{1}{y}} \tag{14}$$

where Q_{Min} = the minimum discharge in the given basin.

5.3.6.1 Adjustment of the recession coefficient for heavy rainfalls

The formula (7) for computing the recession coefficient reflects the usual conditions characterizing the snowmelt runoff in the given basin. When a heavy rainfall occurs, the input is concentrated in a short time interval creating an abrupt rise and subsequent decline of the hydrograph. In order to simulate such events, the computer program automatically adjusts the recession coefficient whenever the daily rainfall averaged over the whole basin equals or exceeds 6 cm:

$$\text{If } P\,(\text{rain})_n \geq 6\text{ cm} \longrightarrow \begin{aligned} k_{n+1} &= x\,(4\,Q_n)^{-y} \\ k_{n+2} &= x\,(4\,Q_{n+1})^{-y} \\ k_{n+3} &= x\,(4\,Q_{n+2})^{-y} \\ k_{n+4} &= x\,(4\,Q_{n+3})^{-y} \\ k_{n+5} &= x\,(4\,Q_{n+4})^{-y} \end{aligned} \tag{15}$$

after which it returns to the normal formula (7). In this way, k gets lower so that the basin response to input becomes faster. If the precipitation is recognized by T_{CRIT} as snow and not rain, the mechanism will not be activated. If there is partly rainfall and partly snowfall in the respective elevation zones according to T_{CRIT}, the rainfall value is determined as a total of rainfall volumes from the zones with rainfall, divided by the entire basin area:

$$\overline{P}\,(\text{rain}) = \frac{\sum P\,(\text{rain}) \cdot A\,(\text{rain})}{A} \tag{16}$$

Example (a):

Precipitation input option 0; P = 10 cm
Rainfall contributing area option 1

Zone A: 100 km², P (rain) = 10 cm
Zone B: 100 km², P (snow) = 10 cm
Zone C: 100 km², P (snow) = 10 cm

$$\overline{P}\,(\text{rain}) = \frac{10\text{ cm} \cdot 100\text{ km}^2}{300\text{ km}^2} = 3.3\text{ cm} \rightarrow k = x \cdot Q^{-y}$$

Example (b):

Precipitation input option 0; P = 10 cm
Rainfall contribution area option 1

Zone A: 100 km², P (rain) = 10 cm
Zone B: 100 km², P (rain) = 10 cm
Zone C: 100 km², P (snow) = 10 cm

$$\overline{P}\,(\text{rain}) = \frac{10\text{ cm} \cdot 200\text{ km}^2}{300\text{ km}^2} = 6.7\text{ cm} \rightarrow k = x \cdot (4Q)^{-y} \text{ on 5 consecutive days}$$

Example (c):

Precipitation input option 1; P_A = 7 cm, P_B = 10 cm, P_C = 13 cm
Rainfall contributing area option 1

Zone A: 100 km², P (rain) = 7 cm
Zone B: 100 km², P (rain) = 10 cm
Zone C: 100 km², P (snow) = 13 cm

$$\bar{P}\,(\text{rain}) = \frac{7\ \text{cm} \cdot 100\ \text{km}^2 + 10\ \text{cm} \cdot 100\ \text{km}^2}{300\ \text{km}^2} = 5.7\ \text{cm} \rightarrow k = x \cdot Q^{-y}$$

These examples refer to the rainfall contributing area option 1, that is to say rainfall contributes to runoff from snow-free as well as snow-covered parts of the basin. For rainfall contributing area option 0, with rain retained in the snowpack, the adjustment of the recession coefficient is less likely to be activated:

Example (d):

Precipitation input option 0; P = 10 cm
Rainfall contributing area option 0

Zone A: 100 km², P (rain) = 10 cm, S_A = 0.4
Zone B: 100 km², P (rain) = 10 cm, S_B = 0.6
Zone C: 100 km², P (snow) = 10 cm, S_C = 0.8

$$\bar{P}\,(\text{rain}) = \frac{10\ \text{cm} \cdot (1 - S_A) \cdot 100\ \text{km}^2 + 10\ \text{cm} \cdot (1 - S_B) \cdot 100\ \text{km}^2}{300\ \text{km}^2} = 3.33\ \text{cm} \rightarrow k = x \cdot Q^{-y}$$

but it can still take place if a very heavy rain falls over the whole basin (Example e).

Example (e):

Precipitation input option 1, P_A = 14 cm, P_B = 16 cm, P_C = 18 cm
Rainfall contributing area option 0

Zone A: 100 km², P (rain) = 14 cm, S_A = 0.4
Zone B: 100 km², P (rain) = 16 cm, S_B = 0.6
Zone C: 100 km², P (rain) = 18 cm, S_C = 0.8

$$\bar{P}\,(\text{rain}) = \frac{14\ \text{cm} \cdot (1 - S_A) \cdot 100\ \text{km}^2 + 16\ \text{cm} \cdot (1 - S_B) \cdot 100\ \text{km}^2 + 18\ \text{cm} \cdot (1 - S_C) \cdot 100\ \text{km}}{300\ \text{km}^2}$$

$$= 6.1\ \text{cm} \rightarrow k = x \cdot (4Q)^{-y} \text{ on 5 consecutive days}$$

The threshold value can be changed in order to activate the rainfall peak program for smaller rainfall amounts or to delay activation until higher rainfall amounts are reached. By putting the threshold to 0 cm, the program will be activated on each day with rainfall (in an earlier version of the computer program, the threshold 0 cm resulted in automatic switching to a threshold of 6 cm). With a 0 cm threshold, the recession coefficient will be continuously decreased, and SRM is likely to overestimate the runoff. By putting the threshold higher than the highest daily precipitation, Equation (15) is eliminated, and SRM will probably underestimate the sharp runoff peaks from heavy rainfall.

5.3.7 Time Lag, L

The characteristic daily fluctuations of snowmelt runoff enable the time lag to be determined directly from the hydrographs of the past years. If, for example, the discharge starts rising each day around noon, it lags behind the rise of temperature by about 6 hours. Consequently, temperatures measured on the nth day correspond to discharge between 1200 hrs on the nth day and 1200 hrs on the n+1 day. Discharge data, however, are normally published for midnight-to-midnight intervals and need adjustments in order to be compared with the simulated values. Conversely, the simulated values can be adjusted (Shafer *et al.,* 1981) to refer to the midnight-to-midnight periods. Figure 12 illustrates the procedure for different time lags. For L = 6 hour, 50 % of input computed for temperature and precipitation on the nth day (I_n) plus 50 % of I_{n+1} results in the n+1 day's runoff after being processed by the SRM computer program:

$$L = 6\text{ h} \qquad 0.5 \cdot I_n + 0.5 \cdot I_{n+1} \quad \rightarrow \quad Q_{n+1} \tag{17}$$

similarly:

$$L = 12\text{ h} \qquad 0.75 \cdot I_n + 0.25 \cdot I_{n+1} \quad \rightarrow \quad Q_{n+1} \tag{18}$$

$$L = 18\text{ h} \qquad I_n \quad \rightarrow \quad Q_{n+1} \tag{19}$$

$$L = 24\text{ h} \qquad 0.25 \cdot I_n + 0.75 \cdot I_{n+1} \quad \rightarrow \quad Q_{n+2} \tag{20}$$

This procedure is preferable, at least in mountain basins smaller than 5000 km², to evaluations of L by calculating the velocity of overland flow and channel flow. It has been shown by environmental isotope tracer studies (Martinec, 1985) that overland flow is not a major part of the snowmelt runoff as previously believed. There is increasing evidence that a major part of meltwater infiltrates and quickly stimulates a corresponding outflow from the groundwater reservoir. With this runoff concept in mind, the seemingly oversimplified treatment of the time lag in the SRM model is better understood.

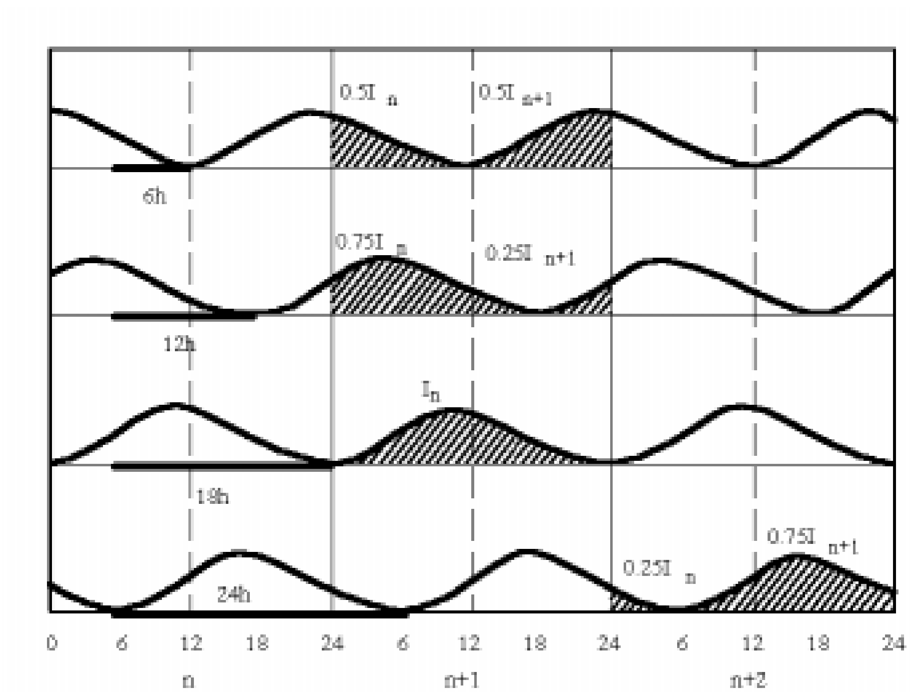

Fig. 12 Snowmelt hydrographs illustrating the conversion of computed runoff amounts for 24 hour periods to calendar day periods. The various time lags (bold lines) are taken into account by proportions of the daily inputs, I (Martinec & Rango, 1986).

If the hydrographs are not available or if their shape is distorted by reservoir operations, the time lag can be estimated according to the basin size and by analogy with other comparable basins. Generally, the time lag in a basin increases as the snow line retreats.

In the WMO intercomparison test (WMO, 1986), most models calibrated the time lag. However, these results appear to be of little help to determine the proper values. Contradictory time lags have been calibrated by different models. However, if the time lags for all models participating in the WMO intercomparison test are averaged for each basin, the resulting values support the expected relation between L and basin size:

Basin W-3 (8.42 km^2)	:	3.0 h
Dischma (43.3 km^2)	:	7.2 h
Dunajec (680 km^2)	:	10.5 h
Durance (2170 km^2)	:	12.4 h

If there is some uncertainty, L (percentages in Equations 17-20) can be adjusted in order to improve the synchronization of the simulated and measured peaks of average daily flows. It should be noted that a similar effect results from an adjustment of the recession coefficient.

6 ASSESSMENT OF THE MODEL ACCURACY

6.1 Accuracy criteria

The SRM computer program includes a graphical display of the computed hydrograph and of the measured runoff. A visual inspection shows at the first glance whether the simulation is successful or not. SRM additionally uses two well established accuracy criteria, namely, the coefficient of determination, R^2, and the volume difference, D_v.

The coefficient of determination is computed as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \tag{21}$$

where: Q_i is the measured daily discharge
Q_i' is the computed daily discharge
$\overline{Q}$ is the average measured discharge of the given year or snowmelt season
n is the number of daily discharge values

Equation (21) also corresponds to the Nash-Sutcliffe coefficient in which case $\overline{Q}$ is a long-term average measured discharge applied to the respective years or seasons.

The deviation of the runoff volumes, D_v, is computed as follows:

$$D_v\,[\%] = \frac{V_R - V_R'}{V_R} \cdot 100 \tag{22}$$

where: V_R is the measured yearly or seasonal runoff volume
V_R' is the computed yearly or seasonal runoff volume

Numerical accuracy criteria are never perfect, as illustrated by Figure 13. From the visual judgment both simulations look good because the fundamental difference between two extreme years is well reproduced. However, R^2 = 0.95 in 1979 while it amounts only to 0.48 in 1977. In spite of this unfavorable value, the simulation (or forecast) in 1977 would certainly be useful for water management because it correctly reveals an extremely low runoff.

With $\overline{Q}$ as a long-term average substituted into Equation (21) (Nash-Sutcliffe) instead of the average for the specific year, a much more favorable but deceptive value for R^2 of 0.97 results for the year 1977. This value is high because the long-term $\overline{Q}$ is much higher than any Q in 1977. Consequently, the daily deviations of the simulated runoff become relatively insignificant although in absolute terms they are not negligible.

In addition to these criteria which are automatically computed and displayed after each model run, the coefficient of gain from daily means, DG, could be computed by the user as follows:

$$DG = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \overline{Q}_i)^2} \qquad (23)$$

where: Q_i is the measured daily discharge
Q_i' is the computed daily discharge
$\overline{Q}_i$ is the average measured discharge from the past years for each day of the period
n is the number of days

Thus, R^2 compares the performance of a model with "no model" (average discharge) and DG with a "seasonal model" (long term average runoff pattern). Negative values signal that the model performed worse than "no model" or worse than the "seasonal model".

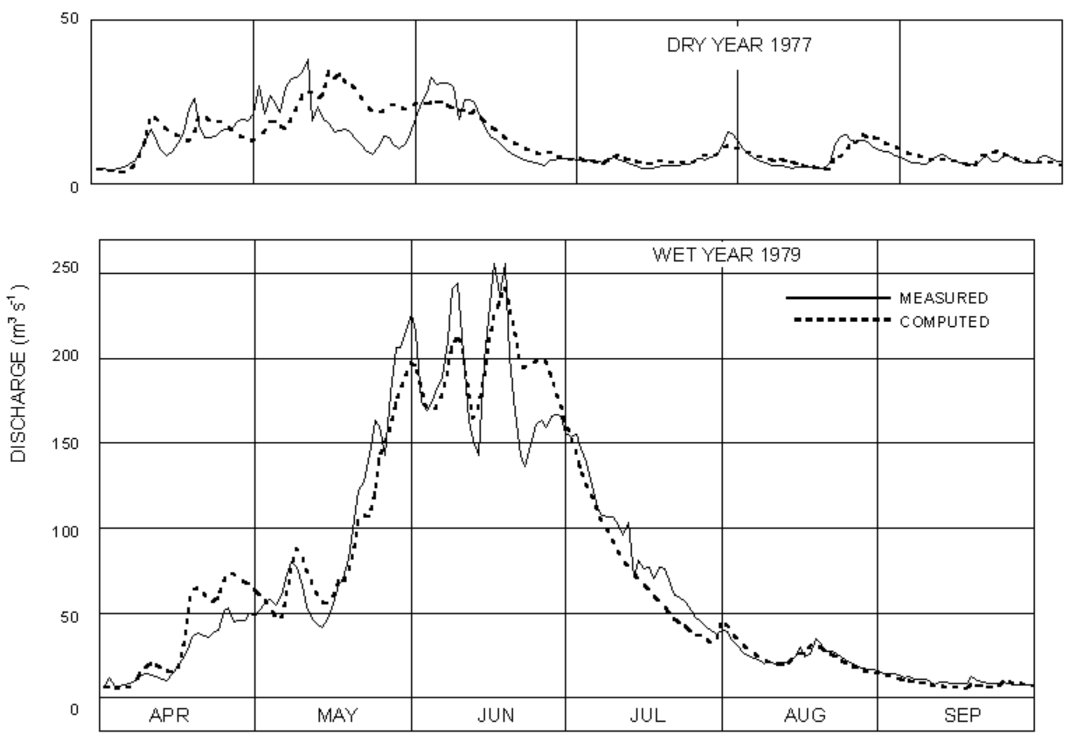

Fig. 13 Runoff simulations in the basin of the Rio Grande at Del Norte, Colorado (3419 km^2, 2432-4215 m a.s.l.) (Martinec & Rango, 1989).

6.1.1 Accuracy criteria in model tests

The World Meteorological Organization (WMO) organized an international comparison of snowmelt runoff models in which hundreds of model runs were performed in six selected test basins. Figure 14 shows a summary of all numerical values of R^2, DG and D_v published by WMO (1986). Each prism refers to a tested model. The length along the x-axis corresponds to the arithmetic mean of all ($1-R^2$) values, length along the y-axis to the arithmetic mean of all (1-DG) values, and length along the z-axis to the

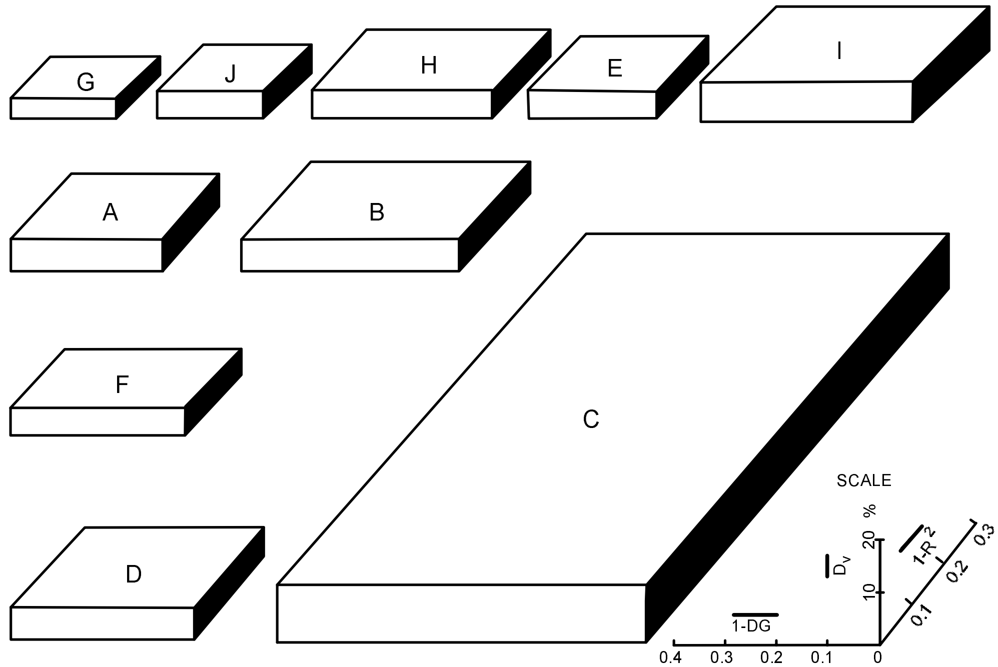

Fig. 14 Combined representation of model performance using three criteria: R^2, DG and D_v. The volumes of the prisms indicate the average inaccuracies of the tested models from all results for snowmelt seasons reported in the WMO project (Rango & Martinec, 1988).

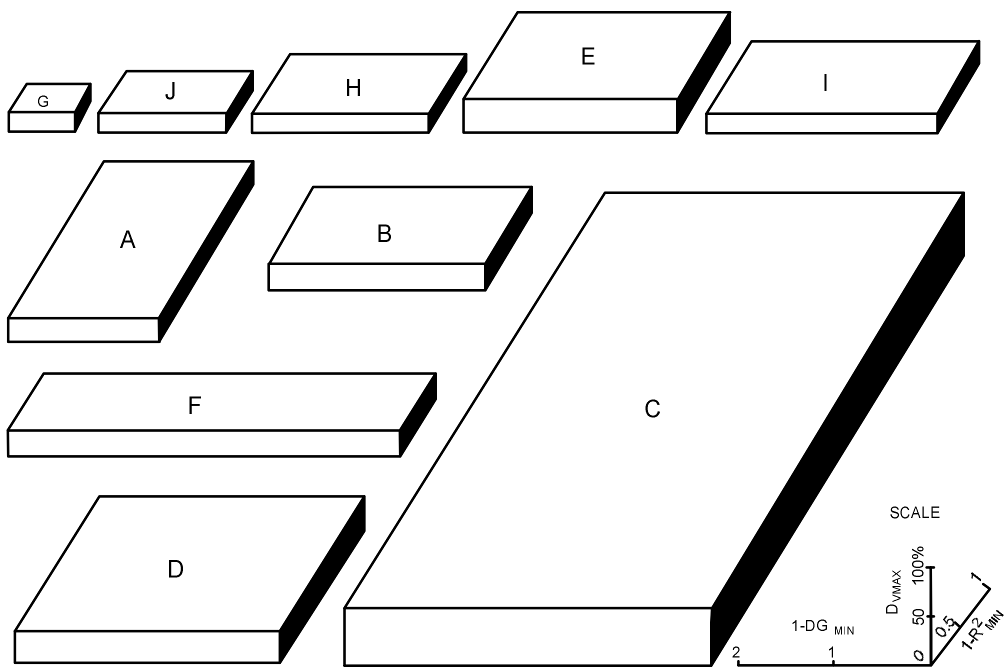

Fig. 15 Combined representation of model performance using three criteria: R^2, DG and D_v. The volumes of the prisms indicate the maximum inaccuracies of the tested models from all results as listed for snowmelt seasons and individual years in the WMO tables (Martinec & Rango, 1989).

arithmetic mean of all D_v values as achieved in the snowmelt seasons of 10 test years. Inaccurate results mean low values of R^2 and DG, thus longer dimensions along the x and y axis. Volume deviations prolong the dimension along the z-axis. Consequently, the volume of a prism is proportional to an overall average inaccuracy of a model.

In Figure 15, the dimensions of the prisms are determined by the worst results of each model for R^2, DG and D_v, i.e., $(1\text{-}R^2)_{MAX}$, $(1\text{-}DG)_{MAX}$, and D_{vMAX}. All available data for the individual years and snowmelt seasons as listed in the WMO tables (WMO, 1986) are thus contained within each prism. The differences between models are larger than in Figure 14 which means that some calibrating models had difficulties in the years with unusual runoff conditions but improved their average results (Figure 14) by the more normal years.

A more detailed assessment of accuracy criteria with regard to the needs of the model user is published elsewhere (Martinec & Rango, 1989). Prisms in Figures 14 and 15 labeled "G" refer to SRM.

6.1.2 Model accuracy outside the snowmelt season

SRM has been designed to compute runoff during the snowmelt season, but it can be run for the whole year if required. According to the mentioned WMO intercomparison test (WMO, 1986), about the same accuracy as for the snowmelt season can be achieved for the entire year in mountain basins with a low winter runoff. An example in Figure 16 shows that SRM can even be run without updating for 10 years.

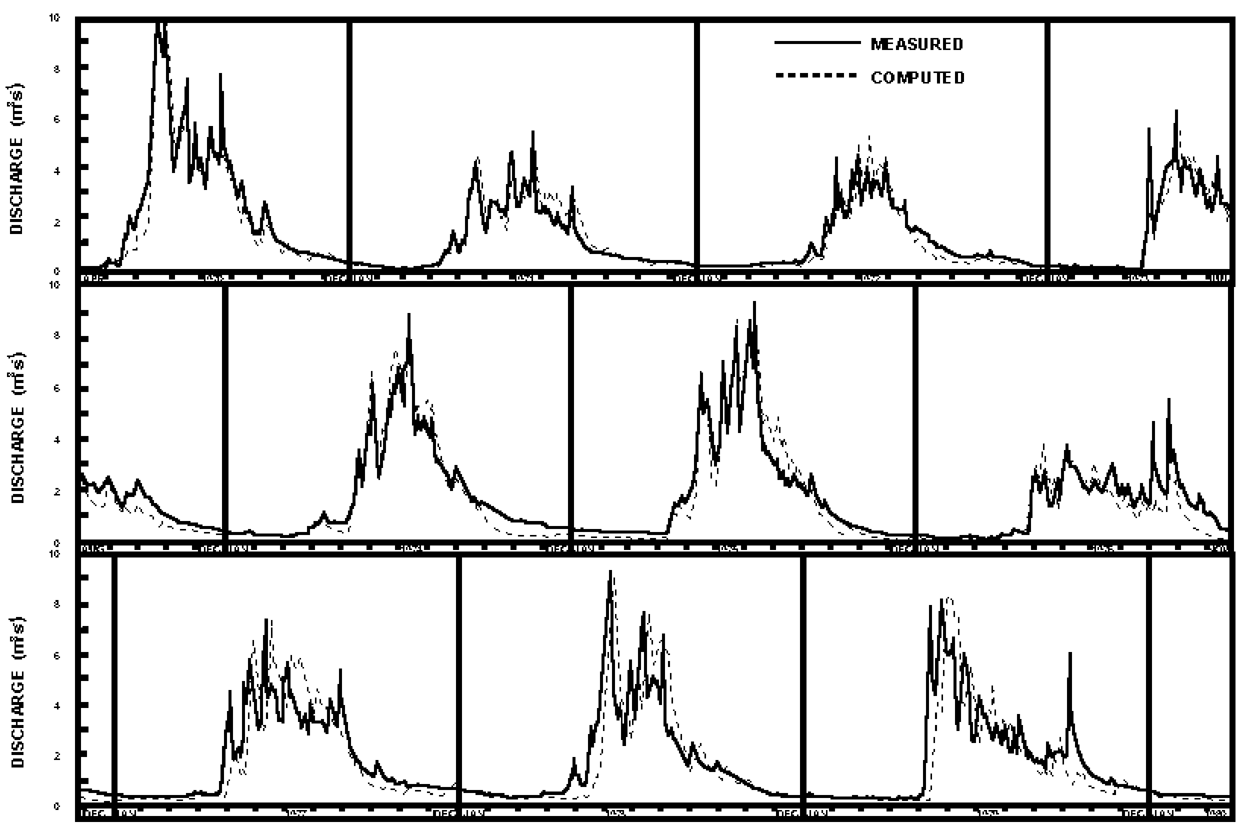

Fig. 16 Runoff simulations in the basin Dischma (43.3 km^2, 1668-3146 m a.s.l.). Computation of daily flows is extended to 10 years without updating (Martinec & Rango, 1986).

6.2 Elimination of possible errors

It is not possible to give threshold values of accuracy criteria which would determine whether a model run is successful or whether something must be changed. With good data, a value like $R^2 = 0.80$ might still be improved. In unfavorable conditions, with incomplete data, a user may be satisfied even with lower R^2 values. Sometimes, however, the graphical display as well as the numerical criteria indicate that something went definitely wrong. Before adjusting one or the other parameter, it is recommended to check several probable sources of error first. Examples in Table 4 are based on the actual experience of various users.

Table 4 Errors experienced by SRM users and their correction.

Error:	Cause:
1 Runoff simulation went too high (Dinwoody, 1976, Dischma, 1977).	Snow cover depletion curves distorted by summer snowfall (see Figure 5): Eliminate satellite observation after a snowfall event and redraw the depletion curves.
2 Runoff simulation suddenly deteriorated (Dischma).	Input of snow coverage data S shifted by 1 month: Correct the S-input.
3 The simulated runoff hydrograph declined uncontrollably in September (Illecillewaet basin).	Input of snow coverage data broken off by the end of August: Complete the S-input.
4 Runoff simulation far below the measured runoff (Illecillewaet).	Decimal point in the measured precipitation and discharge data shifted and thereby increasing the measured runoff 10 x, but the simulated runoff only slightly: Correct the decimal point.
5 After the start of snowmelt, the simulated runoff kept decreasing in spite of snowmelt input (small tributary basins of upper Rhine, 1985).	Values x, y for the recession coefficient formula (Equation (7)) were taken over from a much larger basin so that k exceeded 1.0 for low Q: Correct x, y with regard to the basin size. Possibility of this error was eliminated in the computer program Version 2.01 and later versions (3.0, 3.1, 3.11, and 4.0).
6 Frequent deviations from the measured runoff, periodical lows of the hydrograph not simulated (Felsberg 1982).	SRM simulates natural runoff while the measured runoff was influenced by storage (on weekends) and release from artificial reservoirs for hydropower. These interventions must be corrected in order to compare simulated and measured runoff.
7 Rainfall peaks inadequately simulated (Illecillewaet).	Rainfall input is concentrated to shorter periods than snowmelt input which accelerates the basin response. Program Versions 2.01 and later versions take this feature automatically into account whenever rainfall exceeds a preselected threshold.

8	Rainfall peak inadequately simulated even with the special rainfall peak program (small tributary basins of upper Rhine 25 August 1985).	Temperature extrapolated from station 800 m a.s.l. to zone D 2380 m a.s.l. by 0.65°C/100 m → T = + 0.43°C while T_{CRIT} = + 0.75°C. By decreasing T_{CRIT}, snowfall was converted to rainfall and the runoff peak was better simulated.
9	Rainfall peak inadequately simulated because the daily amount was below the special program automatic threshold. Threshold was lowered but the peak simulation deteriorated further. (small tributary basins of upper Rhine, 1985).	Only 1 precipitation station was available but the "by zone" option was switched on. Consequently precipitation input took place only in 1 zone. With 1 station, select option "basin wide".
10	Runoff simulation went very high in a basin with a large elevation range of 7400 m. (Kabul River, 1976).	Compact snow cover was assumed above the snow line so that the snow covered area was exaggerated. Temperature was extrapolated by too low a lapse rate. Snowmelt was not computed separately for elevation zones but for the entire basin. This usually leads to overestimation of meltwater input. Simulation was improved by reevaluating the snow coverage and selecting a higher temperature lapse rate corresponding to the climate. With regard to the large elevation range, the basin should have been divided in several elevation zones.
11	Distorted runoff simulation (outflow from a snow lysimeter).	Values of recession coefficient false: Negative y values used with the equation $k = x \cdot Q^{-y}$ so that the exponent became positive. Consequently, k increased with the increasing Q while it should have decreased. Use equation $k = x \cdot Q^{-y}$ and positive values of y, so that the exponent is always negative.
12	Difficulties with the timing of rainfall-runoff peaks (WMO test for simulated operational forecasts, Illecillewaet basin).	Precipitation data from one of the stations were ascribed to the date on which it was measured at 0800. Data had to be shifted one day backwards. See also Section 5.2.2.
13	Forecasted runoff for hydroelectric stations Sedrun and Tavanasa too low in April-June 1994. In one run, snow cover was not completely melted by the end of September.	Snowmelt was computed by smooth long term average temperature thus decreasing the number of degree days. Reintroduce the daily fluctuations of temperatures as described in Section 8.3.

14 Discrepancies in runoff simulations for Rio Grande at Del Norte.	Erratic precipitation data. Automatic extrapolation by altitude gradients from two stations resulted in negative precipitation amounts in the highest zone when gradient was negative. Extrapolate averaged precipitation data by a uniform gradient as recommended in Section 5.2. Always visually inspect input precipitation data.
15 Discrepancies in runoff simulations for Rio Grande at Del Norte	Occasionally missing temperature data were interpreted by the computer program as 0 = 0°C. Inspect temperature data and complete missing values by interpolation.
16 Effect of climate change (see Section 8.3, paragraph 11): Decrease of runoff computed by an increased temperature (Rio Grande at Del Norte)	The "winter deficit" was exceeded on a warm day with a high snowmelt depth, so that too much was cut off from MDC_{EXCL}. Consequently CDC_{CLIM} was shifted too much and less runoff resulted. Cut off MDC_{EXCL} by the value of the previous day ("nearly equalled") (see paragraph 9).
17 Overestimation of runoff in the Rhine-Felsberg basin 1-15 May 1993 with usual temperature lapse rate of 0.65°C/100 m.	Frequent föhn-wind in this period, temperature differences between Weissfluhjoch (2693 m a.s.l.) and Davos (1560 m a.s.l.) correspond to a lapse rate as high as 0.95°C/100 m. The value of 0.8°C/100 m was used.

7 OPERATION OF THE MODEL FOR REAL TIME FORECASTS

In order to be applied for real-time discharge forecasts, a model should be able to simulate the runoff not only in selected test basins with good data or in specially equipped experimental basins where a particular calibration model was developed, but also in basins where such forecasts are required by the user. SRM has relatively modest requirements for input variables (temperature, precipitation, and snow covered area) and therefore it was easily possible to shift the runoff simulations to the basins delivering water for hydroelectric schemes, as required by an electric company. Examples of such simulations are shown in Figures 17 and 18.

As mentioned in Section 3, SRM can be used for short term (for example weekly) forecasts of daily flows as well as for longer time period forecasts such as monthly runoff volumes or seasonal runoff volumes. For short term forecasts, temperature, precipitation and snow covered area must be forecasted or predetermined for the coming days and substituted into the model. Temperature and even precipitation forecasts are becoming increasingly available from meteorological services, but the snow covered areas must be extrapolated by the model user.

7.1 Extrapolation of the snow coverage

The future course of the depletion curves of the snow coverage can be evaluated from the so-called modified depletion curves (MDC). These curves are automatically derived by SRM from the conventional curves (CDC) by replacing the time scale with cumulative daily snowmelt depths as computed by the model. Consequently, if SRM is run in a whole hydrological year, the derivation of MDC from CDC starts with the summer half year and not earlier. The decline of the modified depletion curves depends on the initial accumulation of snow and not on the climatic conditions, as is the case with the conventional depletion curve.

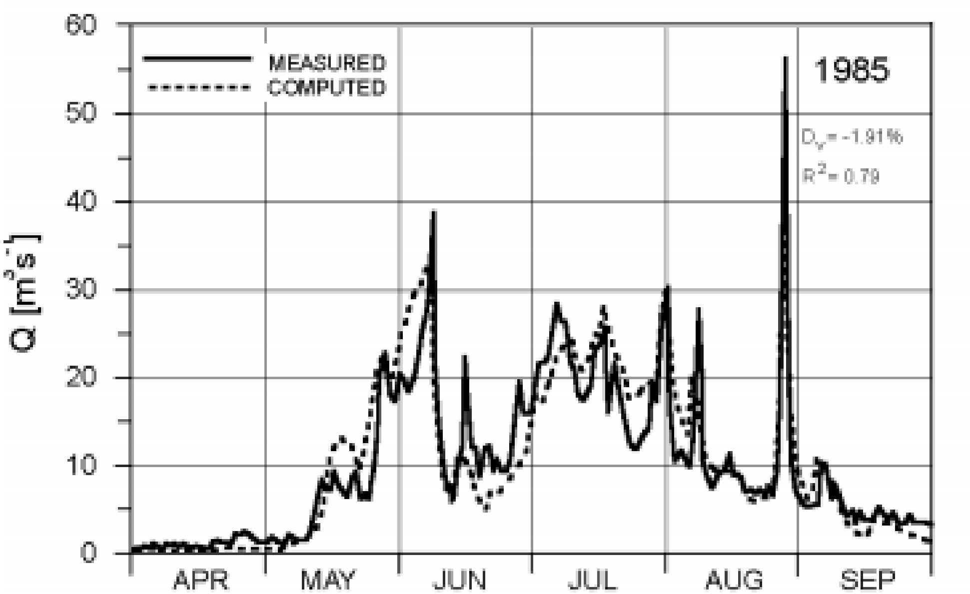

Fig. 17 Runoff simulation in the catchment area of the hydroelectric station Sedrun (Swiss Alps, 108 km^2, 1840-3210 m a.s.l.) (Baumann et al., 1990).

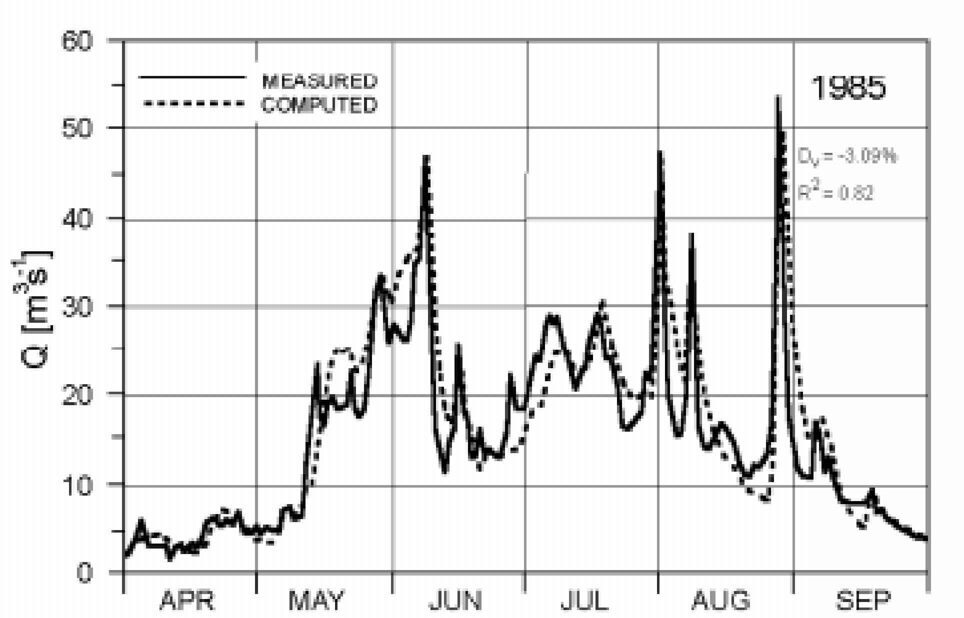

Fig. 18 Runoff simulation in the catchment area of the hydroelectric station Tavanasa (Swiss Alps, 215 km^2, 1277-3210 m a.s.l.) (Baumann et al., 1990).

Procedure for weekly forecasts of daily flows:

Assumption: A family of modified depletion curves has been derived from the past snow cover monitoring and temperature measurements in the given basin. Two of these curves representing the initial water equivalents H_w = 20 cm and H_w = 60 cm are plotted in Figure 19.

Example 1 **-** Snow accumulation in the basin unknown, snow coverage measured by Landsat on 15 May, S = 80 %, cumulative snowmelt depth (from degree-days and degree-day ratios) to date: 30 cm. Temperature forecast: 30 degree days for the next week, converted to meltwater depth M = 15 cm by a degree-day ratio a = 0.5 cm °C^{-1}d^{-1}. S = 80 % and ΣM = 30 cm indicate that the curve for H_w = 60 cm is applicable. The snow coverage will drop to 64 % in 7 days. Extrapolated conventional depletion curve indicates values for day-to-day discharge computations.

Example 2 **-** As above, but the cumulative snowmelt depth to date is only 10 cm. Consequently, the curve for H_W = 20 cm is applicable and the snow coverage will drop to 33 % in 7 days, which leads to a different extrapolation of the conventional depletion curve and to a different weekly total of forecasted daily runoff volumes. If the initial water equivalent is known, for example from SNOTEL (a system of data transmission using meteor paths for reflecting the signals and operated in the USA), the appropriate modified depletion curve can be selected at the start of the snowmelt season. Otherwise, the average curve (dashed line in Figure 19) is used until the correct curve can be identified by satellite data.

Figure 20 illustrates the effect of new snow prior to the date of forecast. In this example, S (1 May) = 74 percent and ΣM = 35 cm seem to indicate that the maximum modified depletion curve (H_w = 60 cm, Figure 19) should be used. The subtraction of the melt depth of the new snow reveals however that the seasonal snow cover is only average, corresponding to the dashed curve in Figure 19. By this curve, if the forecasted snowmelt depth M = 15 cm is added to ΣM = 35 cm, S drops from 60 % to 33 %.

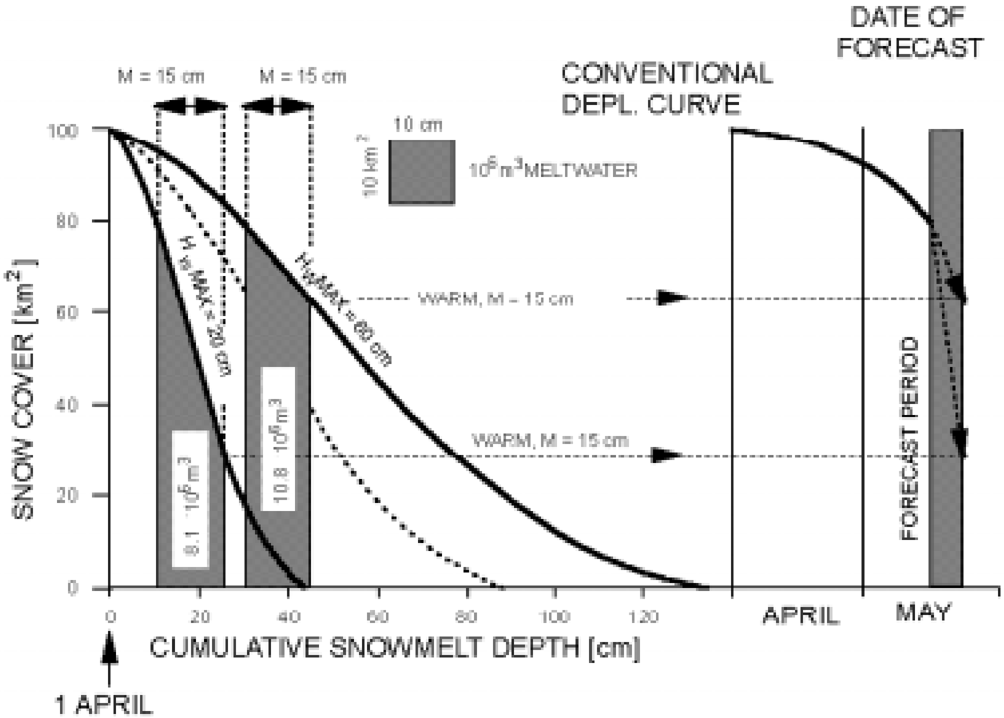

Fig. 19 Extrapolation of snow cover depletion curves in real-time from modified depletion curves with the use of temperature forecasts. $H_{w\,MAX}$ is the water equivalent of the snow cover at the beginning of the snowmelt season (Hall & Martinec, 1985).

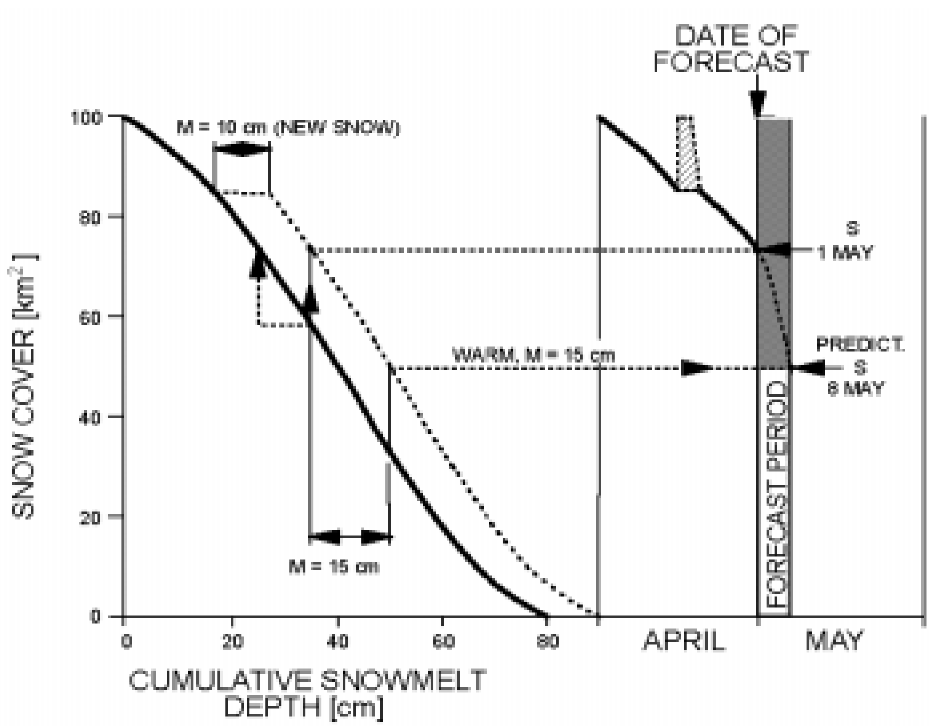

Fig. 20 Elimination of the effect of antecedent snowfall on the extrapolation of depletion curves of snow coverage (Hall & Martinec, 1985).

These auxiliary values are then transferred to the equidistant dashed curve in Figure 20 and the real snow covered areas are obtained: 74 % on the date of forecast and 50 % after one week. These values, together with the interpolated data for the intermediate days, are used for runoff computations. Figure 20 shows just one snowfall but the computer program takes into account each new snowfall during the snowmelt period.

Figure 21 shows that it is possible to derive a nomograph of modified depletion curves (Rango & van Katwijk, 1990) for a given basin from the past years. As noticed in Figure 19, the area below a modified depletion curve indicates the water volume stored in the snow cover if the y-axis scale is in km^2. If the y-axis scale is in percent snow coverage, it indicates the water equivalent of the snow cover as an areal average. Therefore each curve in Figure 21 can be labeled by the water equivalent which it indicates. The rectangular shaded area means 0.1 x 10 cm = 1 cm. Because the area below the highest curve is 83 times larger, this curve indicates that at the beginning of computations of the cumulative snowmelt depth (usually on 1 April), the snow accumulation corresponded to the water equivalent of 83 cm. The values for each curve are automatically determined by the computer program.

The nomograph is used for real time forecasts as follows: In a current year, the snow covered area is monitored from the start of the snowmelt season and simultaneously the cumulative snowmelt depth is computed. The snow covered area must be evaluated as quickly as possible after each satellite overflight. The degree-days necessary for melting the temporary snow cover from intermittent snowfalls are disregarded. If, after some time, for example on 15 May, the snow coverage amounts to 80 % and the cumulative snowmelt depth amounts to 15 cm, the modified depletion curve labeled by 37 cm is identified to be valid for that year. This curve can be used for extrapolating the snow covered area. For example, if another 15 cm will be melted in the next week according to temperature forecasts (total 30 cm), the snow coverage will drop to 55 %. The snow covered areas thus extrapolated are used for real time forecasts of daily flows. The modified curve also indicates the water equivalent of snow (37 cm) at the start of the snowmelt season for seasonal runoff forecasts. If, in another future year, the cumulative computed snowmelt depth coincides for example with the snow coverage of only 36 %, the curve labeled 13 cm is valid. The appropriate curve can thus be identified but with a certain time delay. If the initial water equivalent of the snow cover can be evaluated from point measurements, the proper curve can be selected at the start of the snowmelt season with no time delay.

The computer program also provides an option for plotting a modified depletion curve in which the totalized melt depth includes new snow that falls occasionally during the snowmelt period. It appears in Figure 20 as the dashed line equidistant from the new snow-excluded modified depletion curve. While the new snow-excluded MDC is used to evaluate the water equivalent of the seasonal snow cover at the start of the snowmelt period, the new snow-included MDC can be used to evaluate the shifting of the conventional depletion curves by changed temperatures, as will be explained in the Section 8. The depletion curves of snow covered areas are dealt with in more detail in an earlier publication (Hall & Martinec, 1985).

Figure 22 shows a simulated runoff forecast for the Rio Grande basin in which the forecasted temperatures were replaced by seasonal average temperatures, the precipitation was 110 % of the average precipitation randomly distributed over each month, and the snow covered area was forecasted by using temperatures and the appropriate modified depletion curve. Evidently the seasonal average temperatures do not show the cold spell in the second half of May 1987 and therefore the runoff decline is not simulated.

The difference between the runoff simulation and short-term forecast is illustrated by Figure 23. The temperature T_n, precipitation P_n, and snow covered area S_n are used to compute Q_{n+1} with L = 18 h. At the time of simulation, these values are known. When Q_{n+1} is forecasted in the morning of the day n, T_n and P_n are not yet known and forecasted values must be used. In order to forecast further ahead (Q_{n+2}, Q_{n+3}), the forecasted values T_{n+1} and P_{n+1}, T_{n+2} and P_{n+2} are used. The snow covered areas S_n, S_{n+1}, S_{n+2} are extrapolated by using temperature forecasts and the modified depletion curve MDC.

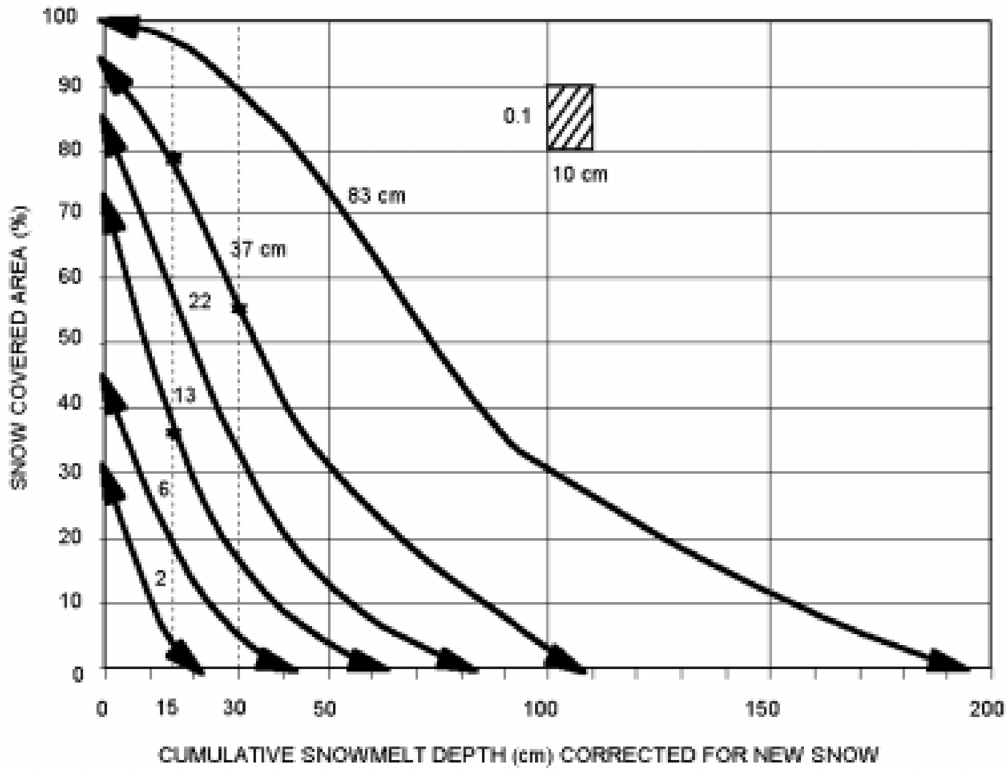

Fig. 21 Nomograph of modified depletion curves for the elevation zone B (1284 km^2, 2926-3353 m a.s.l.) of the Rio Grande basin. The curves are labelled with the areal average water equivalent (1 April) of the snow cover which they represent (Rango & van Katwijk 1990).

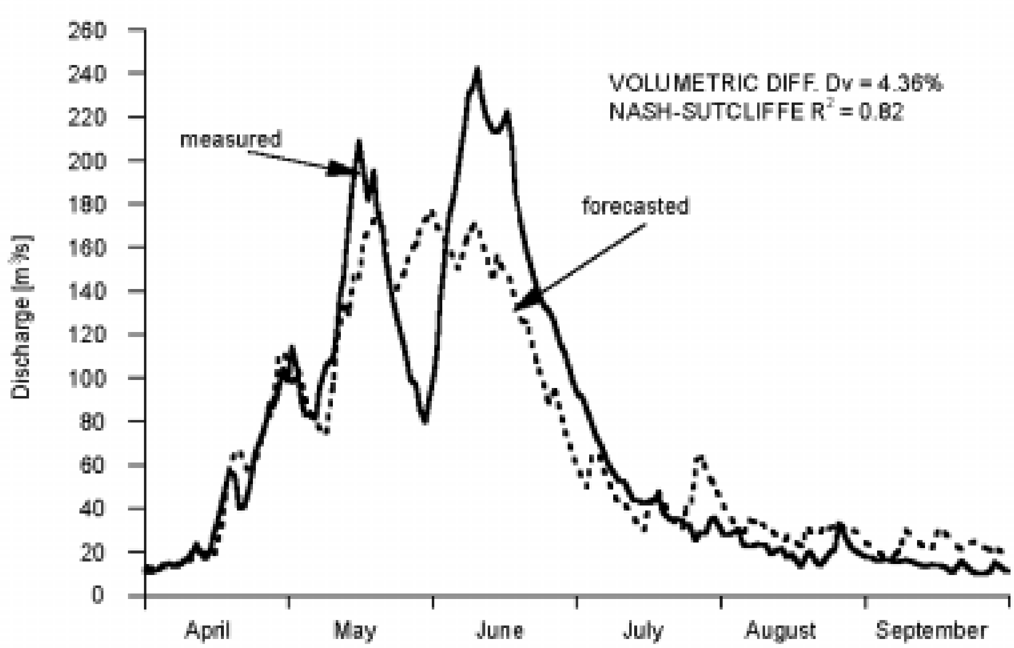

Fig. 22 Simulated real-time runoff forecast for the Rio Grande basin using long-term average temperature instead of actual temperatures for the year 1983 (Rango & van Katwijk, 1990).

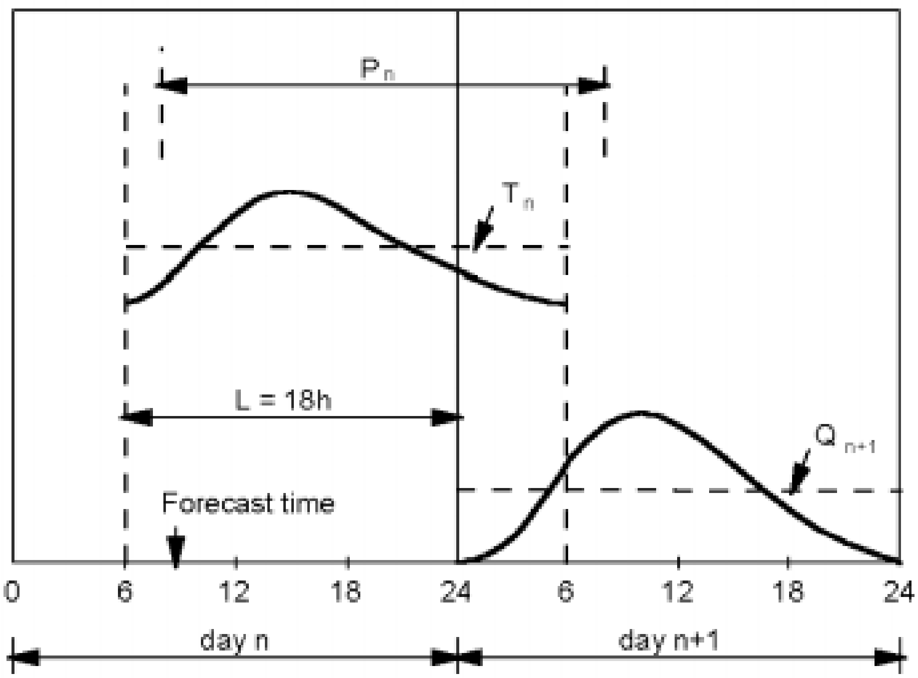

Fig. 23 Real-time availability of temperature and precipitation data for short-term runoff forecasts in contrast to runoff simulation.

For other lag times, SRM automatically combines Q in the appropriate proportions of two subsequent inputs, as explained in Section 5.3.7. For example, if L = 24 h, the input from T_{n-1} and P_{n-1} (which might be already known at the time of the forecast) is represented by 25 % and the input from T_n and P_n (forecasted values) by 75 %.

In the absence of temperature and precipitation forecasts, runoff forecasts can be issued on condition, for example, that long-term average values or extreme values (maxima, minima) will occur. It is also possible to use fictitious values as will be shown in the section dealing with climate change.

The feasibility of real-time forecasts was demonstrated for two hydroelectric stations in the Swiss Alps (Brüsch, 1996). With the use of snow cover monitoring by Landsat as well as of temperature and precipitation forecasts from the Swiss Meteorological Office, the daily runoff was forecasted always for four subsequent days. The runoff volume from April through September was forecasted and updated with the use of modified depletion curves (Martinec & Rango, 1995).

7.2 Updating

The model performance in the forecasting mode is naturally affected by the reduced accuracy and reliability of temperature and precipitation forecasts. The propagation of errors can be avoided by periodical updating. In the more recent versions of the computer program (Versions 3.11 and 3.2), the computed discharge can be replaced every 1-9 days by the measured discharge which becomes known for the corresponding day so that each subsequent forecast period is computed by using a correct discharge value.

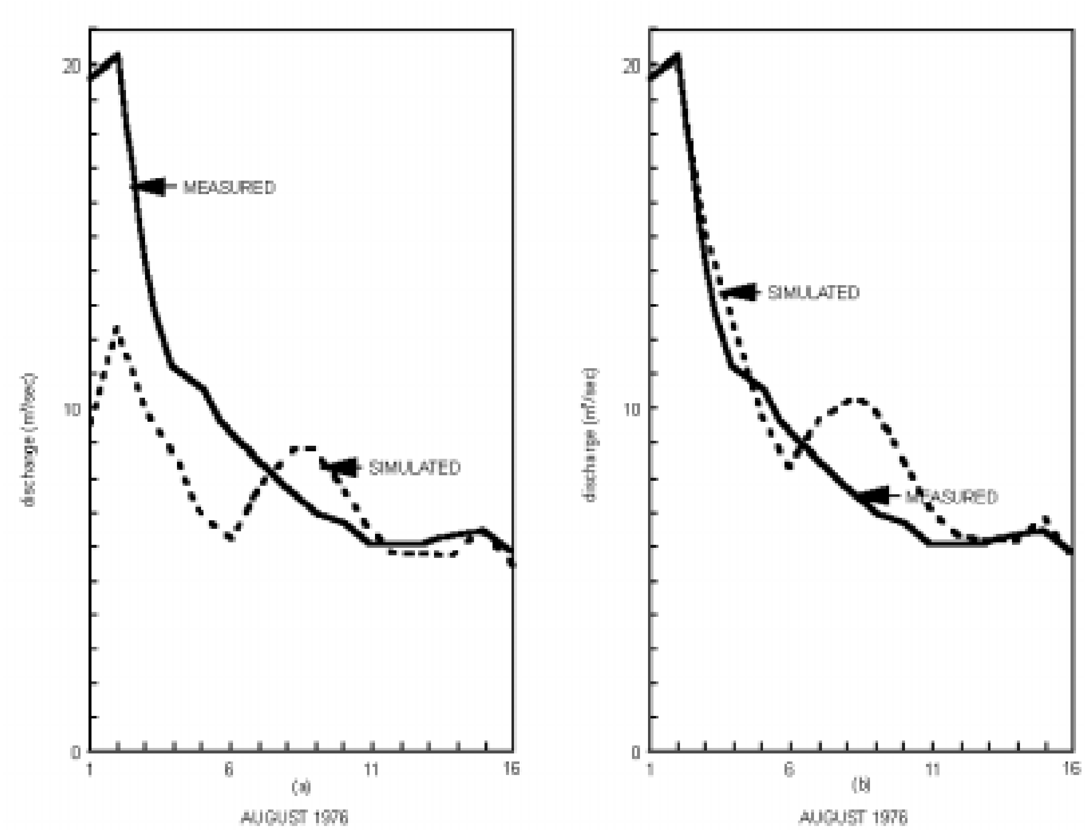

Fig. 24 Discharge simulation in the Dinwoody Creek basin (228 km^2, 1981-4202 m a.s.l.) in Wyoming, (a) without updating, and (b) with updating by actual discharge on 1 August.

Even without this updating, SRM prevents persistent large errors by a built-in self adjusting feature which is efficient if Equation (7) is carefully assessed: Figure 24a shows a model runoff simulation starting with computed discharge of only one half of the correct value. Updating by actual discharge improves the simulation as shown in Figure 24b. Even without updating, however, the initial discrepancy is soon eliminated automatically.

Further possibilities of updating will be made available to users when more experience in real time situations is accumulated. For example, it should be possible to adjust some parameters (e.g., the runoff coefficient) in the progress of the forecast, but only within hydrologically and physically acceptable limits. In any case, false forecasts of temperature and precipitation should be updated whenever a correction by new data is indicated.

What is generally called "updating" can be thus divided into 3 categories:

(1) Updating the computed discharge by the measured discharge when it becomes known, i.e., checking with the measured discharge to avoid carry-over of errors when the next forecast is issued.

(2) Adjustment of model parameters in the process of forecast.

(3) Correction of temperature, precipitation, and snow cover forecasts according to actual observations.

Short-term discharge forecasts can be updated as frequently as each day (Baumann *et al.,* 1990).

8 YEAR-ROUND RUNOFF SIMULATION FOR A CHANGED CLIMATE

SRM uses a real snow cover from satellite monitoring in the present climate in order to produce a snow cover and runoff in a changed climate. This requires a rather sophisticated procedure, but uncertainties arising from a fictitious snow cover simulated from precipitation and arbitrary threshold temperatures are avoided. In any event, the SRM program finishes this task, including printout of figures, tables, numerical results and hydrographs, within minutes. Another advantage is the independence from calibration, enabling the model parameters to be meaningfully shifted in time or adjusted if so indicated by climate scenarios.

If SRM is used only to predict snow covered areas and regional snow accumulation in a changed climate, for example, in mountain areas which are not hydrological basins, the computer program requires the following data:

- Number of elevation zones, their areas, and hypsometric mean elevations
- Current snow covered areas, daily values (S)
- Daily average or Max/Min temperatures (T)
- Precipitation, daily (P)
- Degree-day factor (*a*)
- Temperature lapse rate (γ)
- Critical temperature (T_{CRIT})

For runoff computation, the remaining SRM parameters are required: c_S, c_R, RCA, k, L and the initial Q.

So far, SRM has usually been applied to simulate or forecast runoff during the snowmelt season. It was only run year-round for international tests of model performance (WMO, 1986). However, climate change, as a new field of application, requires SRM to be run during the whole hydrological year. Therefore, the problem of winter runs are dealt with in the next section.

8.1 Snowmelt runoff computation in the winter half year

In the winter half year (usually October-March in the Northern hemisphere), the evaluation of the snow coverage is more difficult than during the snowmelt season. Satellite data, if available, are not frequent enough to distinguish the stable snow cover from frequent transitory snowfalls which are subsequently melted. An assumption of a stable snow cover between two available satellite measurements may lead to an overestimation of the snow coverage.

Option 1: Put S = 0 so that each precipitation event recognized by T_{CRIT} as snow is automatically stored and subsequently melted over the whole area (1 - S = 1). This method is applicable only if precipitation data are good enough to represent the input or if they can be adequately adjusted. This is in many cases not possible due to the well known catch deficit of precipitation gauges and due to the lack of measurements in the high elevations of mountain regions. It is for this reason that SRM uses the snow covered area whenever possible for computing the runoff input.

Option 2: Assume a stable snow cover (S = 1 or a little less in a rugged terrain) in January and February, for example, and S = 0 in October - December. If S = 1 on 1 April from satellite data, assume S = 1 in March as well. If it is less than 1 on 1 April, the snow coverage in March is put to 0 or, which may be more accurate, it is interpolated from 1 on 1 March to the S-value on 1 April. Naturally, S = 1 can be assumed for a longer part of the winter in higher elevation zones while in the lowest zone option 1 may be preferable. The present program keeps the snow coverage estimated for the present climate unchanged for climate runs. It is therefore recommended to assume a complete snow coverage only in months in which it is expected to last in a warmer climate as well.

Whenever S = 1 is introduced, the SRM program cancels any existing storage of preceding temporary snowfalls because such snow becomes a part of the seasonal snow cover. Snow storage is also automatically canceled on 1 April because all existing snow is then accounted for by the depletion curve of the snow coverage.

With the variables thus accounted for, SRM is run as usual. Because the estimated snow coverage is less accurate than CDC in the summer, the water equivalent of new snow is reduced at once by the simultaneous (1 - S) to prevent an inadequate S from influencing the computation on a later melt day. This deviates from the summer procedure explained in Section 5.2.2, Table 2.

The model parameters should be adapted to winter conditions. In particular, the constants x, y for the recession formula (Equation (7)) derived usually for summer conditions sometimes allow the discharge to decrease too low so that a slower recession formula is indicated. By using the Equation (14),

$$Q_{Min} > x^{\frac{1}{y}} \tag{14}$$

x, y can be adjusted in order to prevent the discharge from sinking below a selected level after a long recession period.

In view of frequent snowfalls, values of the degree-day factor lower than those used in the summer are recommended. Values of c_S and c_R higher than in summer can be expected.

The main purpose of the winter runoff simulation is the evaluation of the runoff redistribution in the winter and summer half years. Consequently it is more important to compute the winter runoff volume as accurately as possible than to try to improve the daily accuracy (R^2).

8.2 Change of snow accumulation in the new climate

As the first step, the effect of a climate change on snow covered areas and runoff was evaluated in the summer half year only, assuming an unchanged initial snow cover on 1 April (Martinec *et al.*, 1994). For a year-round temperature increase, the seasonal snow cover on 1 April is deprived of a certain snow water equivalent by additional snowmelt and by a conversion of some precipitation events from snow to rain in October through March.

This decrease of the snow water equivalent is computed by rewriting the input part of the SRM formula as follows:

$$\Delta\, HW = \sum_{n=1}^{182}\left[a_n \cdot T_n \cdot S_n + a_n \cdot T_n \left(1 - S_n\right) + P_{Rn}\right]$$

$$- \sum_{n=1}^{182}\left[a_n \cdot T'_n \cdot S'_n + a_n \cdot T'_n \left(1 - S'_n\right) + P'_{Rn}\right] \tag{24}$$

where Δ HW = difference between the present and future areal water equivalent of the snow cover on 1 April [cm].

a = degree-day factor [cm °C^{-1}·d^{-1}]

T = temperature in the present climate at mean hypsometric elevation, as degree-days [°C·d]

T′ = temperature in a warmer climate as degree-days [°C·d]

S = ratio of snow covered area to total area, present climate

S' = ratio of snow covered area to total area, warmer climate

P_R = rain according to T_{CRIT}, present climate

P'_R = rain according to T_{CRIT}, warmer climate

182 = number of days October trough March

Equation (24) thus summarizes the SRM input to runoff which consists of snowmelt from the stable snow cover (S), melting of snow which temporarily covers the snow free area (1 - S) and rain. The distinction between a stable and temporary snow cover during the snow accumulation in winter is rather arbitrary due to insufficient satellite monitoring, but the total of both snowmelt inputs always equals 100 % of the occurring snowmelt M:

$$M \cdot S + M\,(1 - S) = M\,(S + 1 - S) = M \qquad (25)$$

In March, however, if S is put to 0 while there is a stable snow cover, and there happens to be little snowfall, the snowmelt input may be underestimated.

Figure 25 illustrates the areal water equivalent of the snow cover on 1 April as a difference between the winter precipitation and the winter input to runoff. This water equivalent can be also computed by accumulating the daily zonal melt depths. In this hypothetical example there is an agreement of the water equivalent determined either way. In natural conditions, discrepancies are to be expected mainly due to difficulties in evaluating the areal precipitation value for mountainous regions. In such cases, it is recommended that the value from the accumulated zonal melt be considered as more reliable. The accumulated zonal melt value might even be used to correct the winter precipitation data and to estimate the altitude precipitation gradient. Another advantage of this method is that it takes into account a possible redeposition of snow by wind during the accumulation season.

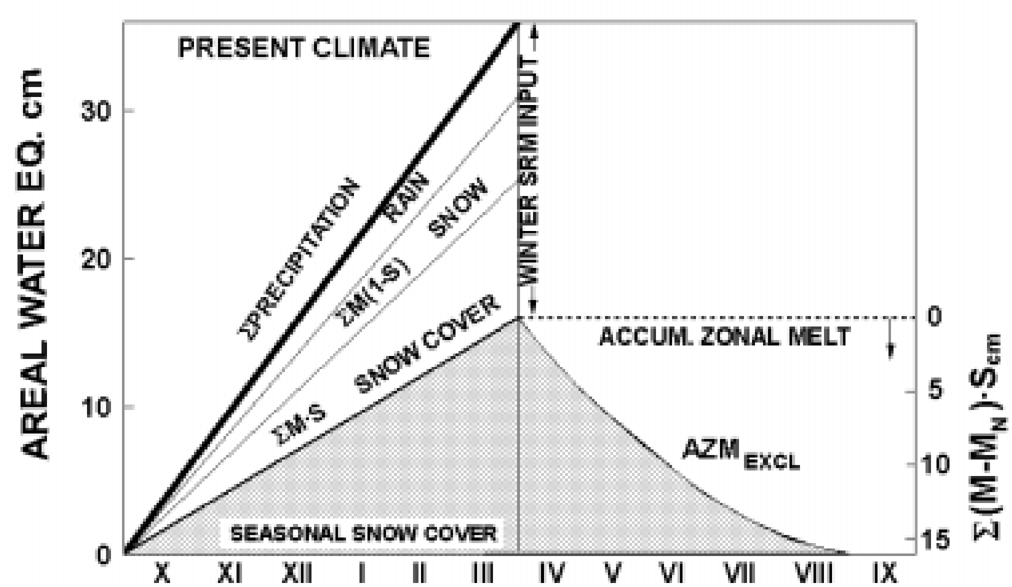

Fig. 25 Illustration of the snow accumulation in the winter and snowmelt in the summer in the present climate (hypothetical example).

On the other hand, no losses are normally considered (losses indicated by the runoff coefficient are assumed to take place after meltwater has left the snow cover). This may lead to underestimation of the retrospectively computed water equivalents if significant evaporation from the snow surface takes place. However, if degree-day ratios are used which have been derived from lysimeter measurements under similar evaporation conditions, this error is eliminated.

In a warmer climate, the winter input to runoff increases, as shown in Figure 26, so that there is less snow on 1 April if winter precipitation remains unchanged. A combined effect of a warmer climate and increased winter precipitation can result in rare cases (low temperatures in high mountains with little or no effect of the temperature increase) in an increased snow accumulation.

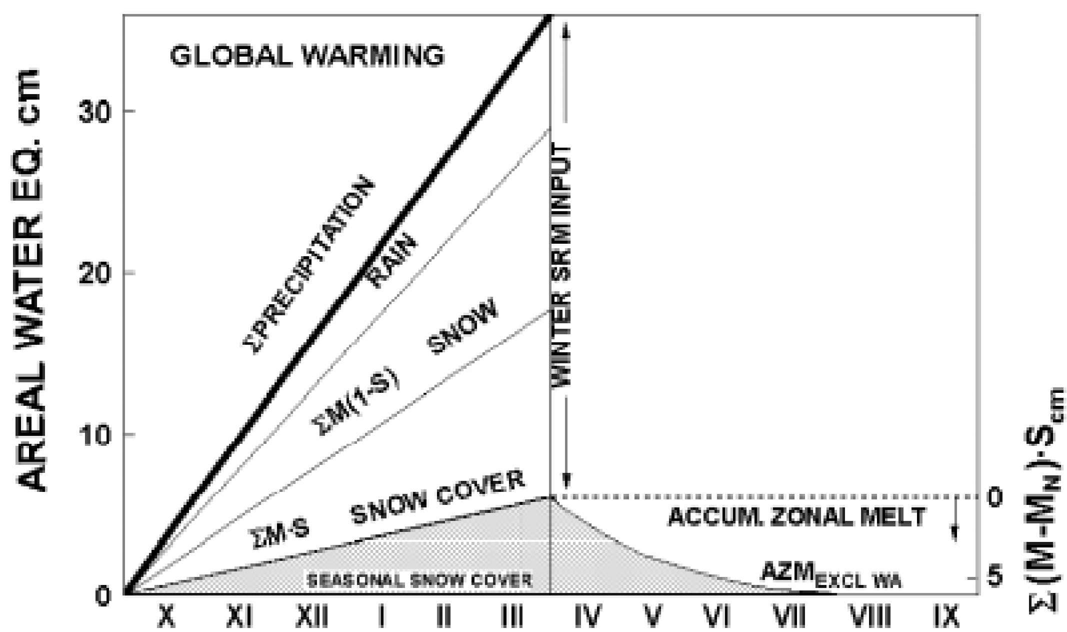

Fig. 26 Illustration of the snow accumulation in the winter and snowmelt in the summer in a warmer climate (hypothetical example).

8.3 Runoff simulation for scenarios of the future climate

In order to evaluate the effect of a warmer climate on runoff in mountain basins, the SRM program uses the real seasonal snow cover of the present as monitored by satellites and models a climate-affected seasonal snow cover.

The future snow conditions in terms of snow covered areas and areal water equivalents in different elevation zones constitute useful information for planning water management and winter tourism. Using snow coverage data as model input, the climate-affected runoff in the whole hydrological year is computed. It allows examination of the changes of daily runoff peaks and the redistribution of runoff volumes in the winter and summer half years.

The procedure is illustrated by evaluating the effect of a temperature increase of + 4°C on runoff in the Rio Grande basin at Del Norte (3419 km^2, 2432 - 4215 m a.s.l., elevation zones A, B and C) in the hydrological year 1979 (Figure 27). The following symbols are used:

CDC = conventional depletion curve of snow covered area interpolated from periodical snow cover mapping.

MDC_{INCL} = modified depletion curve of snow covered area with new snow included. This curve is derived from CDC by relating the snow coverage to the accumulated computed snowmelt depth. It indicates how much snow, including new snow falling during the snowmelt period, must be melted (in terms of computed snowmelt depth) in order to decrease the snow covered area to a certain proportion of the total area and ultimately to zero. The shape of this curve depends on the initial water equivalent of the snow and on the amount of new snow.

MDC_{EXCL} = modified depletion curve of snow covered area with new snow excluded. This curve is derived from MDC_{INCL} by deducting the melt depths of new snow from the accumulated snowmelt depth. The shape of this curve depends on the initial water equivalent of the snow cover and is independent of subsequent snowfalls. The area below this curve indicates the areal water equivalent of the initial snow cover.

AZM_{INCL} = accumulated zonal melt with new snow included. This curve accumulates daily computed snowmelt depths multiplied by the respective snow coverage (as decimal number) and shows the totals on a time scale.

AZM_{EXCL} = accumulated zonal melt with new snow excluded. This curve is derived from AZM_{INCL} by deducting the zonal melt of new snow from the accumulated zonal melt. Again it relates the successive totals to time. The final total is the areal water equivalent of the initial snow cover (as also indicated by MDC_{EXCL}).

MDC_{CLIM} = modified depletion curve of snow covered area for a changed climate. This curve takes into account the amount of snowfalls changed by the new climate. If there is no change, it is identical with MDC_{INCL}.

CDC_{CLIM} = conventional depletion curve of snow covered area in a changed climate.

$CDC_{CLIM\ MA}$ = conventional depletion curve of snow covered area in a changed climate (derived from MDC_{INCL}) adjusted for the input to SRM runoff computation (model adjusted). It appears in publications disregarding the winter effect of a changed climate.

$MDC_{EXCL\ WA}$ = winter adjusted curve. The effect of a warmer winter is taken into account by decreasing the curve according to the "winter deficit". With a simultaneous increase of winter precipitation a positive balance of the winter snow accumulation may result in which case the curve is increased. The area below this curve indicates the areal water equivalent of the initial snow cover in a changed climate.

$AZM_{EXCL\ WA}$ = winter adjusted curve. The effect of a warmer winter and, if necessary, of a changed precipitation is taken into account. The final total is the water equivalent of the initial snow cover in a changed climate.

$MDC_{CLIM\ WA}$ = winter adjusted curve. It is derived from $MDC_{EXCL\ WA}$ by taking into account snowfalls "surviving" in the new climate.

$CDC_{CLIM\ WA}$ = conventional depletion curve of snow covered area in a changed climate. The curve is derived from $MDC_{CLIM\ WA}$.

$CDC_{CLIM\ WA,\ MA}$ = curve adjusted for the model input (model adjusted). If the derivation from $MDC_{CLIM\ WA}$ results in more than one S-value on a date, the first (highest) value is used. If there is no new S-value on a date, the previous day's S-value is repeated until there is a new S-value. With this adjustment $CDC_{CLIM\ WA,\ MA}$ can be used as input to SRM which requires one S-value on each day, like provided by the original CDC. This curve is used to compute the year-round climate-affected runoff.

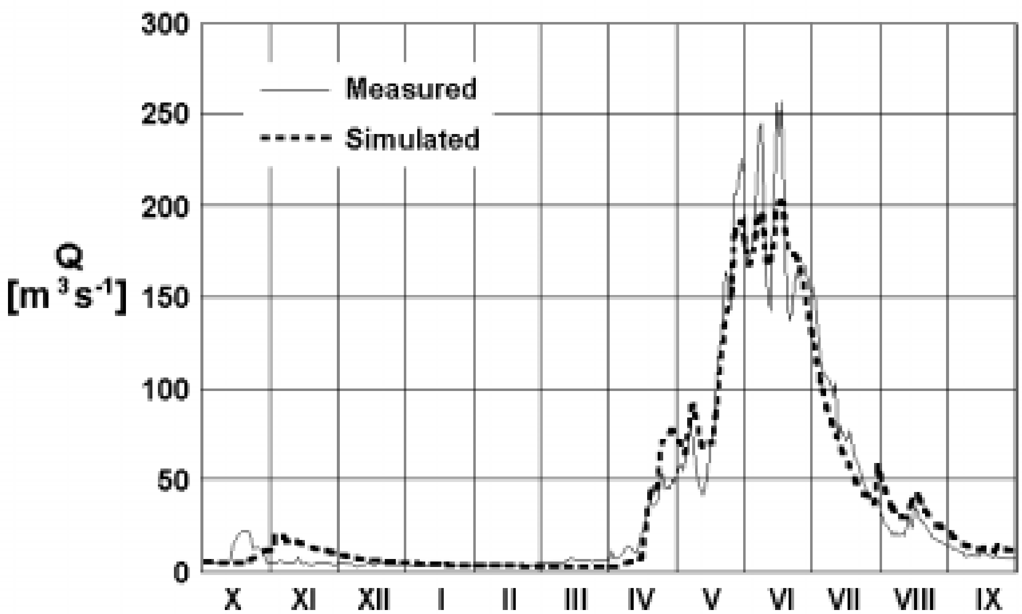

Fig. 27 Measured and simulated runoff in the Rio Grande basin at Del Norte in the hydrological year 1979.

Due to the time shift by the changed climate, the derivation of $S_{CLIM\ WA}$ values from $MDC_{CLIM\ WA}$ may stop before the end of the computation period. If $S_{CLIM\ WA} < S$, the program decreases the depletion curve $CDC_{CLIM\ WA,\ MA}$ to the last S-value of the original CDC, which is typically zero, and repeats it for the missing days. If an elevation zone contains glaciers or permanent snow cover, $CDC_{CLIM\ WA,\ MA}$ drops to the residual snow or ice coverage, again taken over from the original CDC. In less frequent cases (no effect of a temperature increase in a high elevation zone, increased precipitation), $S_{CLIM\ WA} > S$. The program then determines $\Delta S = S_{CLIM\ WA} - S$ and extrapolates $CDC_{CLIM\ WA}$ as CDC + ΔS on the missing days.

In order to evaluate the effect of a temperature increase on the Rio Grande basin, the following steps are to be taken:

(1) Runoff in the whole hydrological year is simulated (Figure 27) in order to verify the preselected parameters and the estimated snow coverage in winter.

(2) Conventional depletion curves of the snow coverage (CDC) used as input variable in the summer are plotted (Figure 28).

(3) Winter runoff is simulated separately for T and T + 4°C in order to obtain the respective runoff volumes (hydrographs are printed).

(4) The decrease of the snow water equivalent on 1 April due to the increased snowmelt in winter ("winter deficit" or "negative winter adjustment") is computed as explained in Section 8.2.

(5) Summer runoff is simulated separately for T in order to obtain the runoff volume (hydrographs are printed).

At this point, the climate-affected conventional depletion curves, CDC_{CLIM}, which are needed as an input variable for computing the summer part (since they do not exist in the accumulation period in the winter) of the climate-affected runoff, are derived as follows:

(6) The modified depletion curve MDC_{INCL} is derived from the CDC. This curve relates the snow coverage with cumulative snowmelt depths including new snow in the summer (Figure 29).

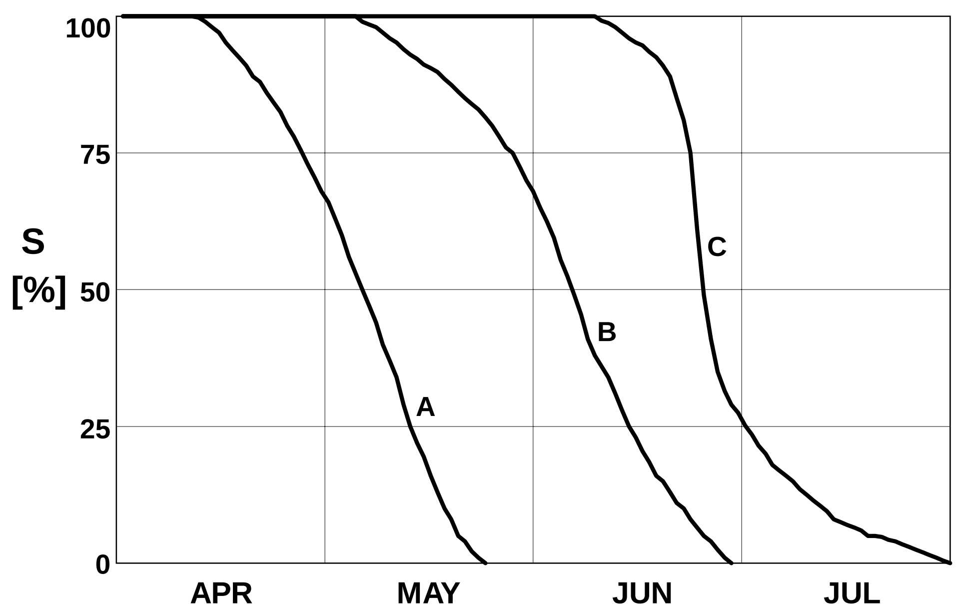

Fig. 28 Conventional depletion curves of the snow coverage from Landsat data in the elevation zones A, B and C of the Rio Grande basin at Del Norte in 1979.

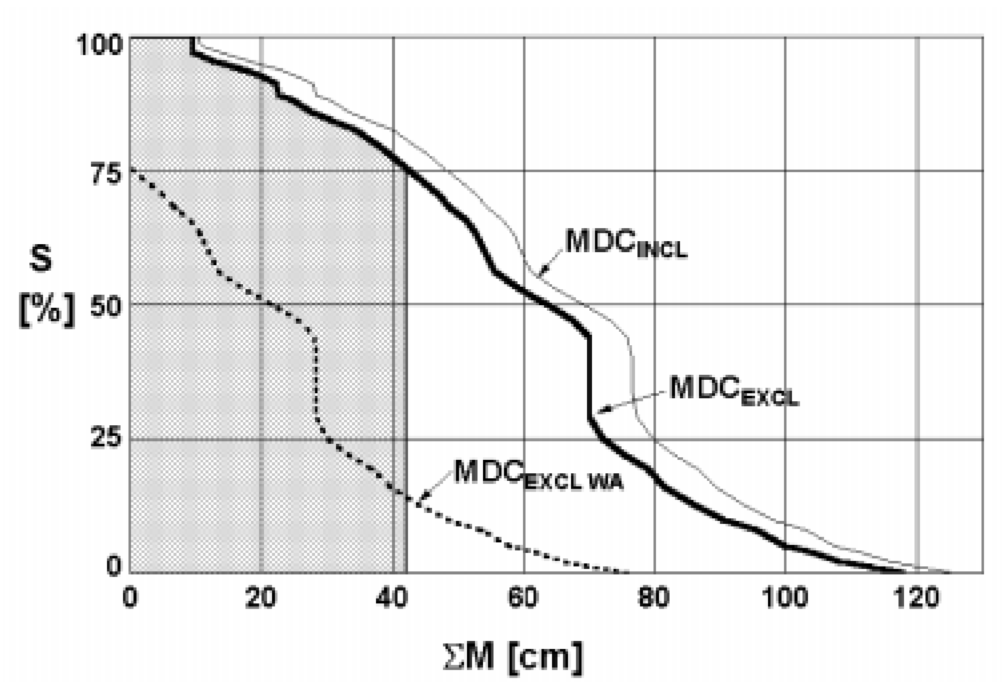

Fig. 29 Modified depletion curves for zone A: MDC_{INCL} derived from CDC, therefore including new snow, MDC_{EXCL} with new snowmelt excluded, $MDC_{EXCL\ WA}$ with "winter deficit" (shaded area) cut off.

(7) MDC_{EXCL} is derived by eliminating melt depths referring to new snow from cumulative snowmelt depth (Figure 29). The area below this curve indicates the initial areal water equivalent of the snow cover, as shown in Section 7.

(8) The climate effect is taken into account by depriving MDC_{EXCL} of the "winter deficit" computed in step (4), and $MDC_{EXCL\ WA}$ (winter adjusted) is derived. The program prints both MDC_{EXCL} and $MDC_{EXCL\ WA}$. In zone A, ΔHW = – 36.94 cm was computed so that MDC_{EXCL} is cut off on the day when this value was equaled or exceeded. This happened on 27 April, when ΣM for MDC_{EXCL} was 42.04 cm (not reduced by S, therefore higher). $MDC_{EXCL\ WA}$ thus derived is shifted to start on 1 April.

(9) The cumulative snowmelt is printed in relation to time as zonal snowmelt, that is to say reduced each day by the respective percentage of the snow coverage. The accumulated zonal melt curve AZM_{EXCL} indicates graphically (Figure 30) that the "winter deficit", in this example ΔHW = – 36.94 cm, was exceeded on 27 April, when the accumulated zonal melt amounted to 37.69 cm. The previous day′s total 35.9 cm is also printed so that the user can cut off the MDC_{EXCL} at the previous day′s value if the next day′s value is much higher than the computed ΔHW.

(10) After melt depths of new snow of the present climate and the winter deficit had been taken out of MDC_{INCL} to derive $MDC_{EXCL\ WA}$, melt depths of new snow "surviving" in the warmer climate are put back to derive $MDC_{CLIM\ WA}$ as illustrated for zone A in Figure 31.

(11) The climate-affected conventional depletion curves adjusted for the "winter deficit", $CDC_{CLIM\ WA}$, are derived as follows: $MDC_{CLIM\ WA}$ indicates, for example, that a snowmelt depth of 22 cm is needed to decrease the snow coverage to 50 % (Figure 31). This occurs in the present climate, according to CDC in Figure 28 on 5 May. In a warmer climate (T + 4°C in this example) a cumulative snowmelt depth of 22 cm and a corresponding decrease of the snow coverage to 50 % are reached already on 9 April, so that the 50 % point is shifted to that date (Figure 32). The program takes the cumulative snowmelt depth computed by present temperatures on each day and searches for the date, on which this snowmelt depth was equalled or exceeded when the higher temperatures are used for computation. If the new climate implies changes of the degree-day factor (see Section 8.4), the cumulative snowmelt depth must be computed not only by higher temperatures, but also by changed (usually higher) a-values. The computer program takes care of this matter. Comparable snowmelt depths are reached about one month earlier so that $CDC_{CLIM\ WA}$ is shifted in time against the original CDC as illustrated in Figure 32 for all elevation zones. The method of CDC shifting in the summer is also explained by a numerical example elsewhere (Rango & Martinec, 1994). In view of the stepwise character of the cumulative snowmelt depths, a slightly higher snow water equivalent than the "winter deficit" may be cut off to derive $MDC_{EXCL\ WA}$ (see Step (9) above) which would ultimately accelerate the decline of $CDC_{CLIM\ WA}$. On the other hand, searching for cumulative snowmelt depths equaled or exceeded in deriving $CDC_{CLIM\ WA}$ may result in a very slight delay of the decline.

(12) $CDC_{CLIM\ WA}$ is used to compute the climate-affected runoff in the summer half year. It should be noted that in contrast to the model runs in the simulation mode, R^2 in the climate change runs does not indicate the model accuracy, but results from the difference between the hydrographs computed for the present and changed climate.

Figure 33 shows the climate-affected runoff computed by original precipitation, temperature T + 4°C and snow covered areas according to $CDC_{CLIM\ WA}$ compared with the original runoff simulation in Figure 27. The run is started by discharge computed on 31 March with T + 4°C (see Step (3)). The year-round climate-affected hydrograph thus consists of a winter simulation with T + 4°C and estimated S and of a summer computation by the climate program with T + 4°C and S from $CDC_{CLIM\ WA}$.

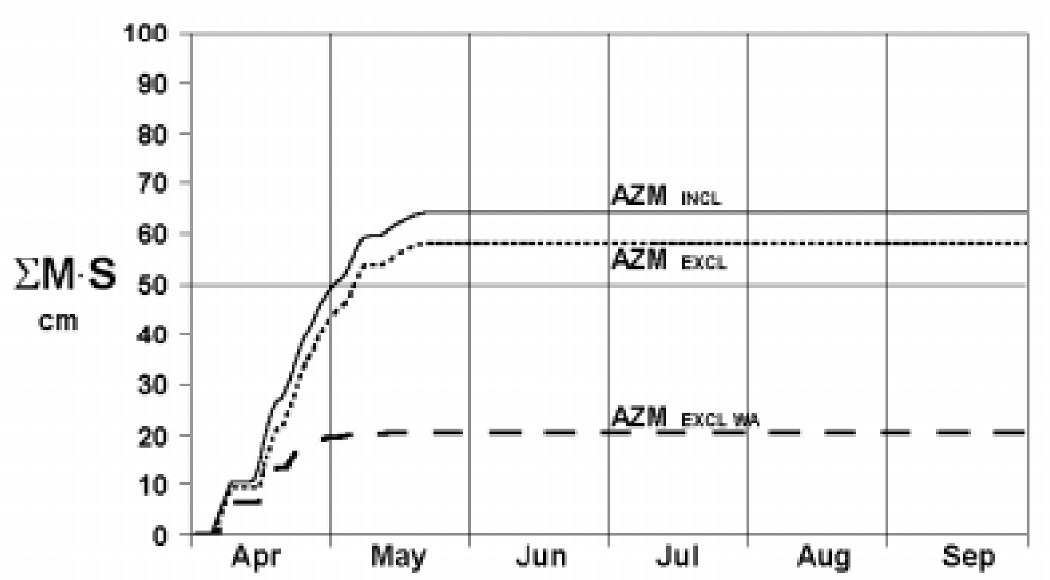

Fig. 30 Accumulated zonal melt curves for zone A: AZM_{INCL}: computed daily melt depth multiplied by S from CDC (= zonal melt). AZM_{EXCL} with new snow zonal melt excluded and $AZM_{EXCL\ WA}$ derived from AZM_{EXCL} by cutting it off on 27 April and transferring it to 1 April.

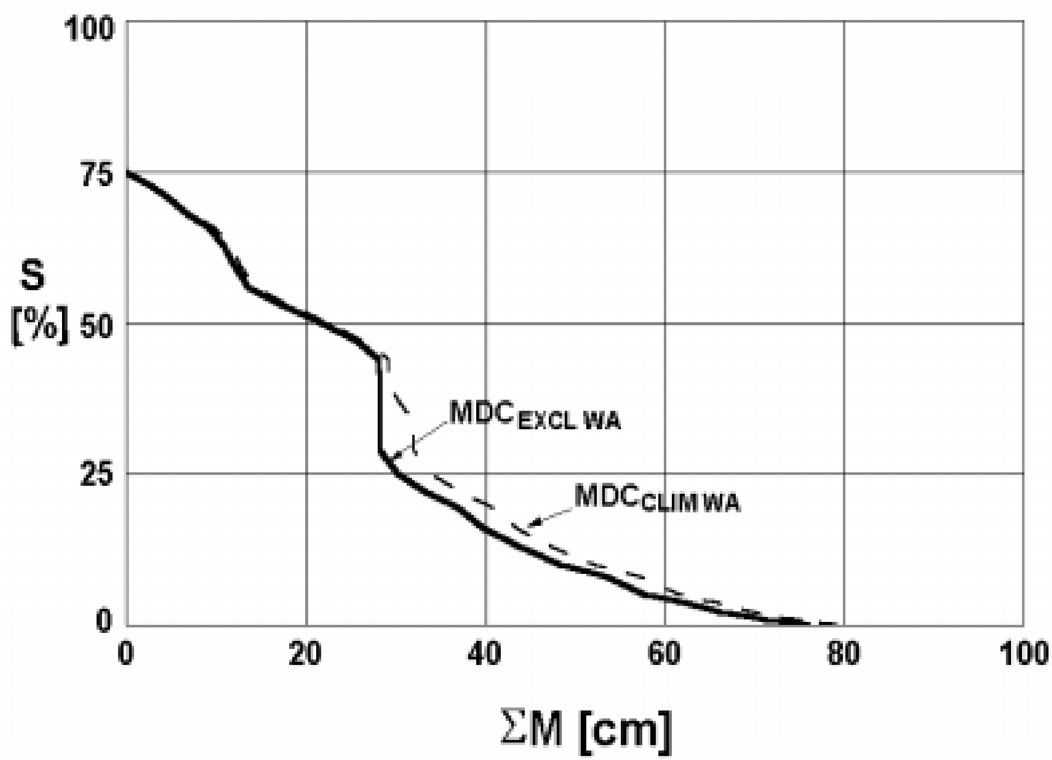

Fig. 31 Modified depletion curve, adjusted for the "winter deficit" and including new snow of the changed climate ($MDC_{CLIM\ WA}$) derived from $MDC_{EXCL\ WA}$ for zone A.

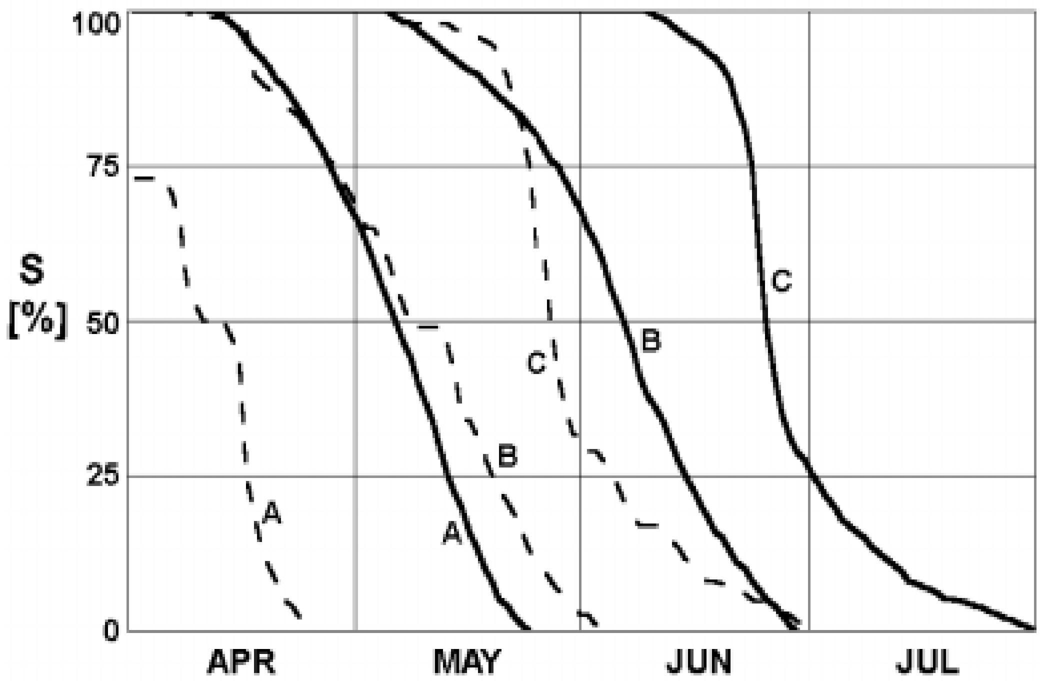

Fig. 32 Effect of a changed climate (T + 4°C) on snow covered areas of 1979 in elevation zones A, B and C of the Rio Grande basin at Del Norte. $CDC_{CLIM\ WA}$ is shifted from the original CDC due to a reduced snow cover on 1 April and due to increased temperatures in the snowmelt season.

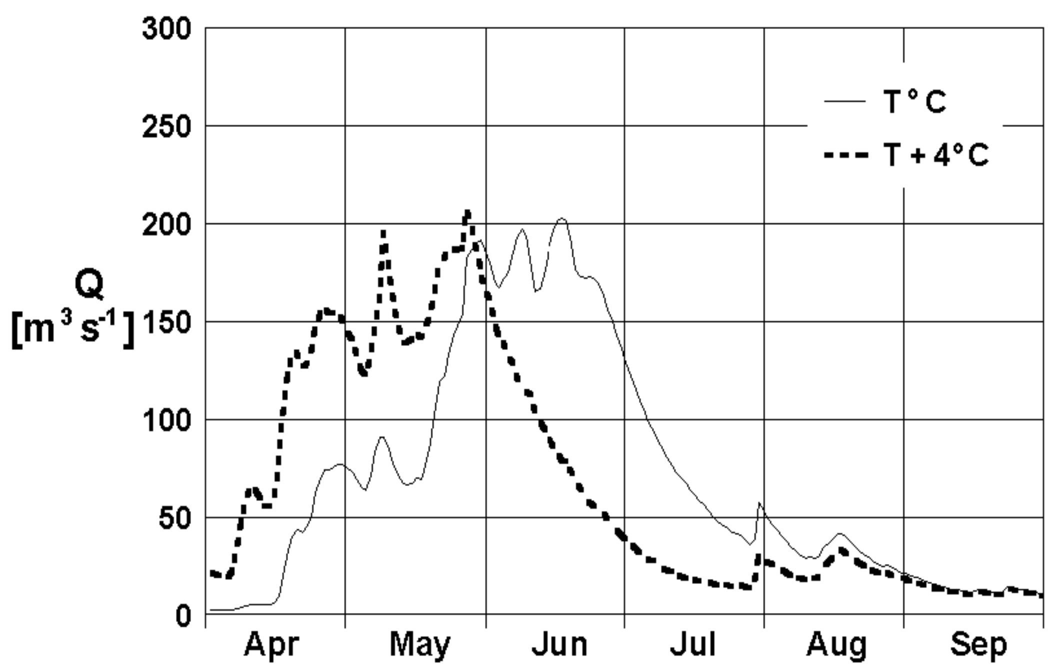

Fig. 33 Climate-affected runoff (T + 4°C) in the Rio Grande basin at Del Norte, compared with the runoff simulated by data of 1979 (as shown in Figure 27) for April-September.

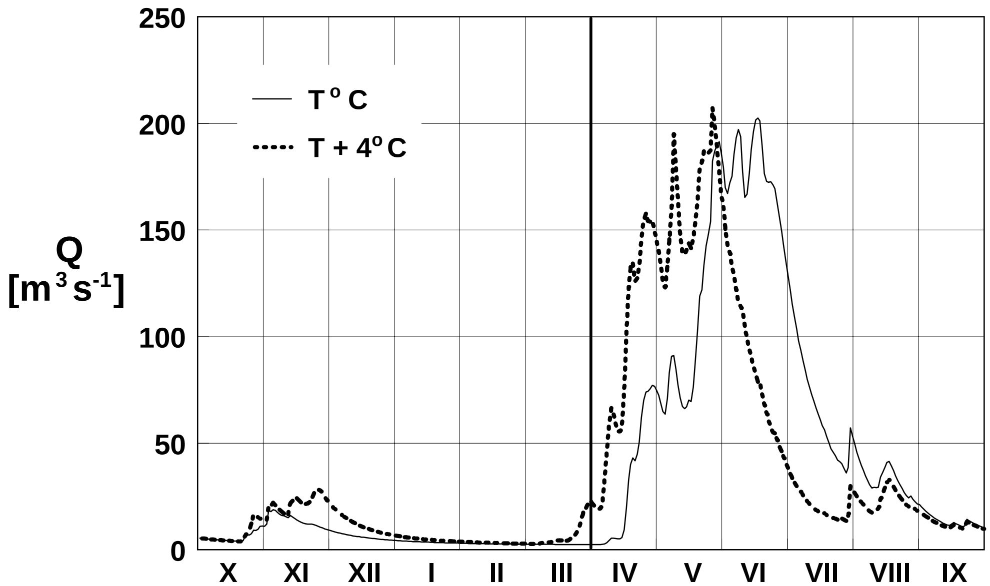

Fig. 34 Simulated runoff in the Rio Grande basin at Del Norte in the hydrological year 1979 and climate-affected runoff computed by increased temperatures (T + 4°C) and correspondingly changed snow conditions.

Figure 34 shows year-round hydrographs computed with temperatures of 1979 and with temperatures increased by + 4°C. As listed in Table 5, the future winter runoff would be increased at the expense of the summer runoff. The actual effect is greater because the increased climate-affected runoff in late March is carried over to April as recession flow as explained elsewhere (Rango & Martinec, 1997). Proportionally the redistribution of runoff is relatively small because the cold winter of 1979 did not allow much snowmelt even with the increased temperatures (see Section 8.5 about normalization).

In the given example, precipitation was not changed in the new climate but the climate program can also handle the combined effect of changed temperatures and changed precipitation. Usually the temperature effect prevails but, as mentioned in Section 8.2, increased precipitation and absence of melting conditions in high altitudes in winter may convert the "winter deficit" to "winter gain" or "positive winter adjustment". In this case, the computer program derives $MDC_{EXCL\ WA}$ by stretching MDC_{EXCL} proportionally to this gain:

$$g = \frac{P' - I'}{P - I} \tag{26}$$

where: P, P′ = precipitation in the present and changed climate.

I, I′ = winter input (see Equation 24) in the present and changed climate.

If there is no winter input in either case due to low temperatures, a precipitation increase by 20 % results in g = 1.2. The x-coordinates of MDC_{EXCL} (cumulative snowmelt depth) are multiplied by g to derive $MDC_{EXCL\ WA}$ which conforms to the increased water equivalent of the snow cover on 1 April. In the summer half year, the position of $CDC_{CLIM\ WA}$ as opposed to CDC results from the balance of the contradictory effects of an increased initial snow cover and of increased melting.

Table 5 Seasonal redistribution of runoff in the Rio Grande basin due to climate change.

1979	Winter		Summer		Hydrological Year	
	10^6 m^3	%	10^6 m^3	%	10^6 m^3	%
Measured	86.53	7.2	1122.43	92.8	1208.96	100
Computed, T	91.87	7.6	1120.15	92.4	1212.02	100
Computed, T + 4°C	146.76	12.3	1046.16	87.7	1192.92	100

8.4 Model parameters in a changed climate

SRM parameters are predetermined which requires more hydrological judgment than mechanical calibration or optimizing. However, as has been pointed out elsewhere (Klemes, 1985, Becker & Serban, 1990, Nash & Gleick, 1991), calibration models are not suitable for climate effect studies because the parameters cannot be meaningfully adapted to the conditions of a changed climate. In the given example from the Rio Grande basin at Del Norte, the seasonal change of the degree-day factor *a* and of the runoff coefficient for snow c_S was taken into account. The degree-day factor gradually increases in line with snow density while c_S reflects the decline of the snow coverage and the stage of vegetation growth. Since the original CDC′s are moved by about one month earlier (see Figure 32), the values of both parameters were shifted accordingly by 31 days in the climate run. For example, $a = 0.45$ cm·°C^{-1}·d^{-1} selected for May in the present climate was used in April in the warmer climate. The climate program provides for automatic shifting by any number of days. When September values are shifted to August, the value of 30 September is repeated in September. The shifting is stopped in January in order to prevent winter conditions being transferred to the autumn. There is no consensus yet whether a warmer climate will increase losses in which case the values of c_S and c_R would be generally decreased, because a decreased evapotranspiration due to the CO_2 increase might offset the temperature effect (Carlson & Bunce, 1991, Gifford, 1988).

Selected parameters can be shifted or changed in accordance with the expected conditions of a future climate. Future versions will also enable the constants x, y for the recession formula to be adjusted if, for example, a steeper recession would be indicated by drier soil conditions.

8.5 Normalization of data to represent the present climate

The climate effect is evaluated by comparing present snow and runoff conditions with conditions modelled for a climate scenario. The current climate can be represented by precipitation, temperatures, snow covered areas and simulated runoff of a single year, especially if this year appears to be "normal". Average data from a number of years would seem to be more representative. However, the use of long term average daily temperatures, with day-to-day fluctuations smoothed out, may considerably underestimate snowmelt depths and the runoff as mentioned in Table 4.

A normalized data set can be prepared by adjusting daily temperatures of a selected year by monthly deviations from long term averages and by multiplying daily precipitation amounts by ratios of long-term and actual monthly totals. The normalized depletion curves of the snow coverage can be derived from the curves of the selected year by considering the normalized temperatures and precipitation as a "new climate" for that year and running the SRM climate program. The normalized temperatures, precipitation, and snow covered areas are then considered as a standard year and the climate program is run again with specifications of a changed climate.

The present climate program Version 4.0, however, allows only uniform changes of temperature and precipitation for the winter and summer half year. The next version will be adjusted in order to carry out the outlined normalization of data as well as to take into account more detailed climate scenarios.

8.6 Outlook

The SRM program Version 4.0 evaluates the snow coverage, the areal water equivalent, and computes runoff for any increase of temperature and any change of precipitation in the winter and summer half year. Options are open concerning model parameters to be shifted in time or adjusted in magnitude in response to a changed climate. Currently, data from actual years are used to represent today′s climate. The next program version will enable temperature and precipitation to be changed monthly. With this refinement, it will be possible to derive daily temperatures, precipitation and snow covered area for a "normalized" year which will represent the current climate better than a selected actual year. A refined computation of snowmelt and glacier melt with a radiation component is under preparation in order to take into account climate scenarios with changed cloud conditions and to predict the behavior of glaciers in the next century.

Information about new developments will be available on Internet and in SRM-Workshops.

9 MICRO-SRM COMPUTER PROGRAM

9.1 Background

The Martinec/Rango Snowmelt Runoff Model (SRM) was originally a FORTRAN model designed to operate on an IBM 370-series mainframe computer. The first computerized version of the model was developed by Martinec *et al.* (1983). In 1986 the model's FORTRAN code was downloaded to an IBM PC and modified to operate in the PC environment. That same year a decision was made to develop a unique PC-oriented version of the model, taking full advantage of the PC's inherent capabilities. The results of that decision was Micro-SRM, Version 1.0.

Additional refinements have been incorporated in several subsequent Micro-SRM Versions up to and including 4.0. However, SRM itself remains unchanged and relatively simple, so that the computations by Equation (1) can still be performed by any pocket calculator which has a function x^y. Of course the PC program automatically handles the multiple input of temperature and precipitation for up to 8 elevations zones of a basin, any desired lag time, and complicated snow/rain situations. A model run for up to 365 days is finished within several seconds, the computed hydrograph is immediately displayed in comparison with the measured discharge and, if desired, quickly printed. Also, the achieved accuracy is automatically computed and displayed. A summary of parameter values can be displayed after each run so that adjustments can be made and their effect assessed.

SRM does not require numerous runs because calibration is not necessary. The ease with which the results are obtained should not lead to a replacement of the deterministic approach of SRM by a "try and see" philosophy. SRM is designed to operate with physically based estimates of parameters which should not require much change after the initial selection. As mentioned earlier, seemingly unsatisfactory results have been frequently improved not by adjusting the parameters but by correcting errors in data sets and in the input of variables.

A prime consideration in the design of Micro-SRM was to develop a snowmelt modeling "environment" such that the model user was provided not just model algorithms, but a complete set of tools for managing the associated model processes: data entry, storage and retrieval, display of data, and results. Traditionally, the most time consuming and error prone activity involved in using any physically based model has been the accumulation of large amounts of input data in the form and format needed to drive the simulation, with actual execution of the model a trivial task by comparison. Recognizing this, we chose to pattern the design of Micro-SRM after that originally developed during the automation of the Soil Conservation Service's (SCS) Technical Release Number 55 (TR-55), Urban Hydrology for Small Watersheds (Soil Conservation Service, 1986). This joint Agricultural Research Service (ARS)/SCS effort provided valuable experience in developing highly interactive "front-ends" for interfacing complex models with model users. The approach used by the ARS/SCS programming team that automated TR-55 was to develop an efficient, easy to use, highly interactive data entry/manipulation environment, and include model algorithms as just one of many functions that support and use that environment (Cronshey *et al.*, 1985). Micro-SRM consists of an integration of the mainframe SRM FORTRAN algorithms converted to Basic and a variation of TR-55's data entry/data management algorithms.

The current version of the model, Micro-SRM, Version 4.0, was developed using Microsoft QuickBASIC 4.5 and contains several subroutines from QuickPak Professional, a BASIC toolbox developed by Crescent Software, Inc.[1]

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[1] Trademarks used in this document (e.g., IBM PC, IBM CORP.; MS-DOS, QuickBASIC, Microsoft Corp.; QuickPak Professional, Crescent Software) are used solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty for the product by the U.S. Department of Agriculture or an endorsement by the Department over other products not mentioned.

9.2 Getting started

9.2.1 System requirements

Micro-SRM requires the following personal computer resources:

- Any 100% IBM PC compatible machine
- 1 floppy disk drive. The model is distributed on a 3½" floppy disk. By special request, 5¼" media are available. The latest version release and documentation are also available via the Internet at:

  http://hydrolab.arsusda.gov/cgi-bin/srmhome

- A minimum of 600K available random access memory (RAM)
- A PC DOS operating system, Version 3.0 or later. SRM will run in a MS-DOS window under Microsoft Windows 3.1/95
- If graphics are desired, a graphics adapter is required. Micro-SRM supports the following graphics modes:

  - CGA - Color Graphics
  - EGA - Enhanced Graphics
  - HGA - Hercules Graphics
  - VGA - Virtual Graphics

- For printed output, a dot-matrix or other printer that supports a 132-character print line, either physically or using "compressed-mode" print characters
- A Microsoft-compatible mouse (optional).

9.2.2 Installing Micro-SRM

Micro-SRM is completely contained on one distribution diskette. It may be executed directly from that diskette. The following steps describe installation on a hard disk, and assume C: and A: are the hard disk and floppy disk drives, respectively:

(1) Put Micro-SRM diskette in your floppy drive.

(2) At the C> prompt, enter the following command lines, ending each line by pressing Enter ↵

C> **cd **	: change to C: 's root directory
C> **md \srm**	: create a model subdirectory
C> **copy a:*.* c:\srm**	: copy all files from floppy A: to new subdirectory C:\SRM

9.2.3 Configuring Micro-SRM

The model uses an external "configuration" file to define the variables that Micro-SRM uses to control the interface between model and user. The configuration file is specified on the command line invoking Micro-SRM (see Section 9.2.4). If no filename is specified, the model uses the configuration file residing on the default directory named "SRM.CFG". The file initializes program variables that define available disk devices, printer control codes, screen display color characteristics, audio tone level, and video graphics mode. Included on the distribution disk are several sample ".CFG" files and a utility program, CONFIG.EXE, that gives a user the ability to customize the model's interface for his/her unique hardware configuration.

9.2.4 Operating instructions

The following command syntax runs Micro-SRM from the default directory. *Filenames* must be complete pathnames if the target file does not reside in the default directory.

SRM4 *configfile* {option(s)} Enter ↵

The following list describes valid Micro-SRM command line options. Values enclosed in brackets [] denote SRM default values.

Argument	Description
ConfigFile	See description above [SRM.CFG].
/TIN = *tracefile*	Control SRM via a trace file, not the keyboard. See Section 9.8 for accomplete description of the trace feature.
/TOUT = *tracefile*	Save keypresses from current run in a tracefile.
/TDELAY = *seconds*	Use with /TIN to vary speed of trace operation [.5]. See Section 9.8 for more on the trace delay.
/P = *printfile*	Redirect LPT1: (printed output) to a disk file.

The following examples demonstrate several common command line option combinations for initiating Micro-SRM:

C > **SRM4**
Run the model from the default (in this case the root) directory, using the default configuration file, C:SRM.CFG, stored in that directory.

C > **A:**

A > **SRM4 EGA.CFG /P=SRMPRINT.PRT**
Switch to the A: drive, then run the model from the A: default directory. Use the A:EGA.CFG configuration file. Reroute any printed output to a disk file, A:SRMPRINT.PRT.

C > **SRM > SRM4 /TOUT=trace.fl**
From the SRM subdirectory, run SRM using the default config file, and capture all keypresses during the run, storing then in a trace file named C:\SRM\TRACE.FL

C > **C:\SRM\SRM4 C:\SRM\SRM.CFG /TIN=C:\SRM\TRACE.FL /TDELAY=2**
Run SRM from the root directory, using full pathnames for all file references. Drive the model with keypresses stored in C:\SRM\TRACE.FL, with a 2 second delay between commands.

C > **MSHERC**
SRM4 HERC.CFG
Load Microsoft's Hercules graphics driver and run SRM in the Hercules graphics mode.

<u>HINT</u>*:* Create a batch file to run Micro-SRM. Store the batch file on the root directory of your hard disk and include the root directory in your PATH statement (refer to your DOS manual for a description of PATH). To create a batch (.BAT) file, type the following commands, each terminated by Enter↵ :

**C> cd **	: Make root dir the current dir
C> copy con SRM.BAT	: Copy from keyboard to SRM.BAT
cd \srm	: Line #1, change to model dir
srm4	: Line #2, run model
**cd **	: Line #3, change to root dir

<F6> : Press Function Key F6, then Enter⮠ to terminate copy con;

To run Micro-SRM using a batch file, simply type the batch file name, followed by Enter ⮠

9.3 Program features

9.3.1 Screen display types

The model user interacts with Micro-SRM through a combination of text, data and menu screens. Each screen display can be broken into several component parts (see Figure 28).

- The screen header, lines 1-3 of the display, identifies the screen and in some cases includes run-specific information.
- The prompt line, line 24, columns 1-71, provides a location where the program can display prompts and warning/error messages as required.
- The keyboard "state" indicators, line 24, columns 74-80, display the current state (on/off) of the CapsLock and NumLock keyboard keys.
- The function key line, line 25, describes important functions available while the screen is displayed.
- Screen "hot" areas, highlighted (**bold)** text or characters, may appear anywhere on the screen. They draw attention to the screen area, as with function keys, and they provide a region that may be "mouse-clicked", to provide a mouse equivalent to a keypress response.
- The remaining screen area, lines 4-23, will have a type-specific definition. Micro-SRM uses three types of screen display to communicate with the model user.

9.3.2 Text screens

The model introduction screen and fifteen "Help" screens provide the user with on-line documentation to assist in resolving questions concerning the use of the computer program and to provide limited information about the model and the variables and parameters required to use it. The introduction screen appears immediately after the program welcome screen. The help screen most appropriate to the user's current location in the data entry process is displayed upon user request (by pressing Function Key #1). Once in "help" mode, the user may "PgUp" to a prior help screen, "PgDn" to the next help screen, or "ESCape" to return to the screen from which help was initiated.

9.3.3 Menu screens

Micro-SRM uses the menu screen to provide a simple method for controlling processes that require a single selection from among an array of possible choices. The menu screen presents the user with a list of possible selections along with their associated letter code. The user indicates a menu selection by entering its appropriate letter code, "clicking" on the selection with left mouse button, or by moving the "light bar", the menu selection displayed in contrasting color or reverse video, up/down the menu list using the arrow up/down (↑↓) keys. The user activates the selection by pressing Enter⮠ .

There are three full screen menus used within SRM. The "Plot" and "Print" Menus control selection of available plot and print products respectively. The "Basin Variable/Parameter" Menu (Figure 29) controls which of the 13 daily basin variable or parameter data input screens is to be displayed for data entry. In addition to these three "full screen" menus, SRM uses several "pop-up" menus. A "pop-up" is a display that is temporarily superimposed over some existing screen. An example is the FileIO function's "pop-up" menu that controls selection of the model's input/output options (Figure 29).

```
<┘ └>          Snowmelt Runoff Model Help Screen        Version 4.0
                    HELP - Program Options

Start/End      - 4 digits to define the processing period.  The period runs
  Date             from day DD of Start MM through day DD of End MM.

Model Mode     - 0=Simulation, n=Updating (where calculated Q is adjusted
                   every nth day using actual flow values).

Temperature    - 0=Daily mean temperature provided
Average (°F/C) - 1=Use daily max,min temperature to calculate daily means

Temperature    - 0=a single set of daily temperatures will be applied to each
  Input            hypsometric mean elevation using temperature lapse rates.
               - 1=Daily mean temperature to entered by user for each zone,
                   SRM will NOT lapse temperature.  Not used for Max,Min temp.

Lapse Rates    - 0=Enter variable/parameter values for zone A only, all
Precipitation      remaining zones will be assumed identical to A.
Runoff Coeffs  - 1=Enter zone specific variable/parameter values.
Critical Temp

Runoff Avail   - required to run SRM in updating mode.

Esc-exit help      PgUp-go to prior help screen     PgDn-go to next help screen
```

Fig. 28 Typical Help Screen.

```
<┘                 Snowmelt Runoff Model (SRM)          Version 4.0
             Basin Variable/Parameter Definition Menu

                      ↓↑ to select, Enter<┘ to edit values

                      A - Actual Stream Runoff (ACTUAL)
                      B - Maximum Daily Temperature (TMAX)
       Basin          C - Minimum Daily Temperature (TMIN)
       Variables      D - Average Daily Temperature (T)
                      E - Precipitation (P)
                      F - Snow-Covered Area in Zone (S)

                      G - Critical Temperature (Tc)
       Basin          H - La┌──────────┐age (L)
       Parameters     I - Te│ Action?  │apse Rate (LR)
                      J - De├──────────┤ctors (AN)
                      K - Sn│ Load     │oefficients (CS)
                      L - Ra│ Save     │oefficients (CR)
                      M - Ra│ Delete   │ributing Area (RCA)
                            │ Import   │
                            └──────────┘
                      Variable  Code = A

F1Help     F2Summary     F3FileIO     F5Plot     F6Print     F7Compute
```

Fig. 29 Full Screen Menu and FileIO "Pop-Up" Menu.

9.3.4 Data entry screens

Micro-SRM's data input screens are simply electronic versions of standard printed forms (income tax forms being a good example), which consist of one or more pages of information requests with associated reply spaces or "fields" provided for entering data values. In Micro-SRM, the basic data entry screen display consists of background text that names and/or briefly describes each field, field "shadows", strings of a special character (·····) that visually define both the physical dimension and screen location of each data field, and a blinking data character or cursor (░) that marks the model user's current position within a data screen (Figure 30). The current value of the model variable represented by each field is superimposed over its corresponding field shadow. Field values are accentuated on the display by varying light intensity or color on monochrome and color monitors, respectively.

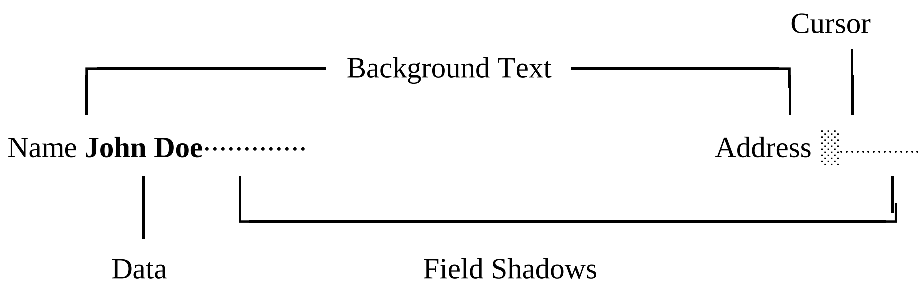

Fig. 30 Data Entry Screen Components.

The model user types text or other data onto the data fields provided on the screen display, at the position marked by blinking cursor. Micro-SRM interactively controls and validates the characters entered using each data field's three associated data validation attributes: maximum length, context, and content range.

Maximum Length **-** each data entry field displayed on the screen has a predefined physical dimension that is displayed via the field's "shadow". Any attempt by the user to exceed a field's "shadow" is ignored and a warning message is displayed.

Field Context **-** each field has a predefined "context" that dictates the type of characters which it may receive. If the context rule for the field is violated, the illegal character is ignored and a warning message is displayed. There are 3 basic contexts:

Alphanumeric: the default context. Any character is valid.

Binary: a value of 0 or 1.

Numeric: valid numeric character (i.e., 0-9, ., -, +).

Field Content **-** Content validation differs from the first two validation forms in that it occurs after all the characters for a given field have been entered. The information may then be validated as a distinct entity. It is at this point that field values are checked for valid range, consistency with previously entered data, etc. Violation of a field's range or consistency checks causes a error message to be generated and locks the cursor on the invalid field until the condition is corrected. These techniques help insure that data entry errors are minimized and are caught "before the fact", that is, before the data are introduced to the actual model algorithms.

There are three data entry screens used within Micro-SRM.

```
<┘  └>                Snowmelt Runoff Model (SRM)            Version 4.0
                            Program Options

Model Run Number 17                                Start Date (MMDD) 0401

Units (0=Metric 1=English) 1                       End Date (MMDD)   0831

Model Mode 0                                       Temperature Average (°F/°C) 0
(0=Simulation 1-9=Updating)                        (0=Daily Mean  1=Max,Min)

Temperature Input 1                                Temperature Lapse Rates 0
(0=basin wide  1=by zone)                          (0=basin wide  1=by zone)

Precipitation Input 1                              Runoff Coefficients 1
(0=basin wide  1=by zone)                          (0=basin wide  1=by zone)

Critical Temperature 1                             Actual Runoff Available 1
(0=basin wide  1=by zone)                          (0=No  1=Yes)

Comments Beginning with Version 3.10, three comment lines are provided .........
that allow a user to describe the current data, making it easier ..............
to keep track of individual data files. .......................................


  EscQuit    F1Help    F2Summary    F3FileIO    F5Plot    F6Print    F7Compute
```

Fig. 31 Program Options Data Entry Screen.

9.3.5 Program options

The "Program Options" data entry screen (Figure 31) displays run-specific data values. These items are initialized by the model on program entry.

9.3.6 Basin definition

The "Basin Definition" data entry screen (Figure 32) is used to enter basin-wide values (e.g., zone area and hypsometric mean elevation) which identify and physically define the subject basin.

9.3.7 Basin variables/parameters

The "Basin Variable/Parameter" data entry screen (Figure 33) manages the process of providing daily values for each required variable and parameter for the entire snowmelt period and for each elevation zone within the basin. Micro-SRM paints a screen display format that represents two calendar months of a given parameter or variable for a given elevation zone. The initial two months of data displayed in the format are for the first two months of the specified snowmelt period and for the lowest (or only) elevation zone, zone A. The model then uses the PgUp/PgDn keys to superimpose the next/prior two months' values onto the screen. If the basin contains multiple zones, Function keys F5/F6 are used to superimpose the prior/next zone's values for the 2-month period shown. Any given display is self-explanatory, showing the variable/parameter name, elevation zone, month names, and "hot" key areas and definitions. See Section 9.4.5 for more information on these "hot" keys.

```
<┘  └>            Snowmelt Runoff Model (SRM)           Version 4.0
                        Basin Definition

Basin Name Durance Basin .....           Number of Zones (1-8) 5

Model Year 1975                          Initial Runoff 12 .......

Parameters for computing recession coefficients:

     X= 1.0849 .....                    X1=........
     Y= 0.0528 .....                    Y1=........
     Effective Date = 0401              Effective Date =...

Reference Elevation 0 .....             Rainfall Threshold 6......

         Zone         Hypsometric               Zone       Hypsometric
Zone     Area       Mean Elevation       Zone   Area     Mean Elevation
===================================      =================================
  A      219 ...         1141...          B     495 ...       1680 ...
  C      783 ...         2154...          D     536 ...       2577 ...
  E      120 ...         3074...          F      ░.....          .....
  G        .....           .....          H       .....          .....


    EscQuit   F1Help   F2Summary   F3FileIO   F5Plot   F6Print   F7Compute
```

Fig. 32 Basin Definition Data Entry Screen.

```
1975                 Snowmelt Runoff Model (SRM)           Version 4.0
Durance Basin              Basin Variables                    Zone A

=====================================  Precipitation (P)  ================
   Function Keys     Apr  Value     Apr  Value  ║  May  Value     May  Value
=================================================================== 
                   ║ 1     ░ ...    16   .01..  ║  1    ....      16   .02..
F5 - Prior zone    ║ 2      ....    17   .....  ║  3    .04.      18   .....
F6 - Next zone     ║ 4     .58 .    19   .....  ║  4    .7..      19   .12..
                   ║ 5     2.74     20   .....  ║  5    .03.      20   .06..
F7 - Duplicate an  ║ 6     .65 .    21   .....  ║  6    .24.      21   .11..
    existing zone  ║ 7     .1 ..    22   .....  ║  7    .15.      22   .53..
                   ║ 8     .37 .    23   .....  ║  8    .31.      23   .....
F8 - Repeat prior  ║ 9     .45 .    24   .....  ║  9    .04.      24   .....
     value 1 time  ║ 10     ....    25   .....  ║  10   1.36      25   1.07.
                   ║ 11     ....    26   .....  ║  11   1.58      26   .13..
F9 - Repeat prior  ║ 12     ....    27   .....  ║  12   ....      27   .....
    value n times  ║ 13     ....    28   .....  ║  13   ....      28   .05..
                   ║ 14    .02 .    29   .....  ║  14   .06.      29   .41..
F10-Adjust day(s)  ║ 15    .58 .    30   .....  ║  15   .07.      30   .....
                   ║                            ║                 31   2.41.

  Esc-Exit process    F1-Help    PgUp-Prior 2 months    PgDn-Next 2 months
```

Fig. 33 Variable "Precipitation" Data Entry Screen.

9.3.8 Climate Change Processing Control Screens

Beginning with Version 4.0, the Snowmelt Runoff Model supports an expanded climate change modeling component that supports year-round climate change modeling (see Section 8, and Section 9.7 for a complete description of SRM's climate change approach). Two additional screens have be added to the computer program to manage the additional complexity required to support this new capability.

9.3.8.1 Climate Change Control Screen

The "Climate Change Control" data entry screen (Figure 34) provides the user with a template for defining the winter and summer periods of a hydrologic year and the seasonal climate change scenario associated with each. During climate change processing steps, SRM modifies the affected variables/parameters as described by the scenarios detailed on this screen.

The two variables and five parameters listed on the screen can be modified for a new climate in two basic ways.

Snowmelt Runoff Model (SRM) **Version 4.0**
Climate Change Control Screen

	Winter		Summer	
	1001	**0331**	**0401**	0930
	Shift	Amount	Shift	Amount
Temperature (T)	N/A	**4**····	N/A	**4**·····
Precipitation (P)	N/A	**120%**·	N/A	**120%**
Degree Day Factors (*a*)	**31**··	······	**31**··	······
Lapse Rates (γ)	····	······	····	······
Snow Runoff Coefficients (C_S)	**31**··		**31**··	······
Rain Runoff Coefficients (C_R)	····	·····	····	······
Critical Temperature (T_{CRIT})	····	······	····	······

EscAbort **F1**Help **F7**Begin

Fig. 34 Climate Change Control Data Entry Screen.

Shifting: The model user may want to shift parameters most affected by climate to an earlier time period in the hydrologic year to reflect the new climate. The shift "field" allows the user to enter the number of days of shift desired. Shifts are currently restricted to model parameters only. When shifting parameters, the model also modifies the shift in two critical ways in order to impose reality on a mechanistic approach (see Section 8.4).

(1) To insure that parameters for a cooler autumn month/s are not shifted into the final month/s of the melt season (for example, October snow runoff coefficients shifting to September on a defined shift of 31 days), SRM shifts parameters only within a hydrologic year, repeating the final daily value for the year the required number of days to complete the shift. With this approach, a shift of 31 days for a summer half year (4/1 to 9/30) would have September values shifted to August and all September days would take on September 30's daily value.

(2) Winter parameter shifts operate only on the last (coldest) half of the winter season. This precludes the possibility of having the desired warmer winter climate negated by moving parameters associated with colder winter months into autumn months.

Amount: Daily temperature and precipitation values are normally changed for climate by some constant amount or percentage. Values entered in the amount field for a variable are applied to each daily observed value in the period during climate change runs. Values in the amount fields are assumed to be numeric constants unless otherwise noted (by including a % character). Parameters may also be modified by amount, though model developers prefer to utilize shifting to adjust parameters for climate change.

9.3.8.2 Climate Change Progress Screen

The "Climate Change Progress" Screen (Figure 35) tracks the multi-step process that SRM follows when performing a climate change simulation (see Section 9.7 for a detailed explanation of the steps involved). At the completion of Steps 1-4, the progress screen displays basic zonal melt totals the model will use in Step 5 to derive climate modified snow depletion curves. After each of these initial steps, the user can initiate step-specific interim plots and reports, using the function keys displayed near the bottom of the screen.

10-10-97 **Snowmelt Runoff Model (SRM)** **Version 4.0**
(IL840606.SRM) **Climate Change Progress Screen**

√ Step 1: Winter simulation, normal climate (determine total zonal melt)
Step 2: Winter simulation, changed climate (determine total zonal melt)
Step 3: Summer simulation, normal climate (save MDC, simulated runoff)
Step 4: Summer simulation, changed climate (save MDC_{CLIM})
Step 5: Create $CDC_{CLIM\ WA}$ using MDC_{CLIM} (adjusted for Winter Change)
Step 6: Summer simulation, changed climate, using $CDC_{CLIM\ WA}$

Step 1

Zone	ΣM·S	+ M(1-S)	+ ΣP_rain	= Zonal Input	Winter Change
1	2.404	7.029	23.267	32.6998	0.000
2	0.000	4.349	13.040	17.3895	0.000
3	0.000	0.000	0.000	0.0000	0.000
4	0.000	0.000	0.000	0.0000	0.000

Simulated Q on 3/31 = ...

EscAbort **F1**Help **F2**Summary **F5**Plot **F6**Print ↲Next Step

Fig. 35 Climate Change Progress Screen

At the beginning of Step 5, SRM computes net zonal Winter Change, and prompts the user to verify the results. At this point computed zonal Winter Change may be overridden with some other value (see Section 8.3 (9) for discussion of a situation where such replacement would be appropriate).

Step 6 models $CDC_{CLIM\ WA,\ MA}$. During this step, several new output products are automatically generated by the model. A printed report, the Climate Change Statistics Report (or optionally a disk file, SRM.LOG, on systems without a printer) displays the computed values used to derive these "climate-modified" CDC's (Figure 36). The following curves are displayed in four new plots, allowing the user to visualize the modeling process (see Section 9.5.4.1 and Section 9.7):

MDC_{EXCL}, $MDC_{EXCL\ WA}$

AZM_{INCL}, AZM_{EXCL}, $AZM_{EXCL\ WA}$

$MDC_{EXCL\ WA}$, $MDC_{CLIM\ WA}$

CDC_{CLIM}, $CDC_{CLIM\ WA}$

Date: 10-10-1997
File: IL840606.SRM

==

Total P, Winter [P] = 82.57877
Total P, Winter(clim) [P′] = 99.09452
Winter - Total Zonal Input [i], Zone 1 = 32.69977
ΣM·S = 2.404175
ΣM(1-S) = 7.028653
ΣP_rain = 23.26694
Winter(clim) - Total Zonal Input [i′], Zone 1 = 80.41334
ΣM·S = 39.92039
ΣM(1-S) = 0
ΣP_rain = 40.49295
Winter Change (ΔHW), Zone 1 = [i - i’ + P’- P] = -31.198

Zone 1
Winter Change (deficit) of -31.19781 was equaled/exceeded by accumulated zonal melt on 5/5, a shift of 35 days AZM_{EXCL} on 5/5 = 31.42749
Prior day's AZM_{EXCL} = 30.5473

==

Total P, Winter [P] = 122.8147
Total P, Winter(clim) [P′] = 147.3776
Winter - Total Zonal Input [i], Zone 3 = 0
ΣM·S = 0
ΣM(1-S) = 0
ΣP_rain = 0
Winter(clim) - Total Zonal Input [i′], Zone 3 = 16.24898
ΣM·S = .8295755
ΣM(1-S) = 2.494999
ΣP_rain = 12.92441
Gain(g) = (P’ - i’) / (P - i)
g = (147.3776 - 16.24898)/(122.8147/0) = 1.067699
Winter Change (ΔHW), Zone 3 = [i - i’ + P’- P] = 8.314

Zone 3
Winter Change (surplus) 8.313959 was accounted for by stretching MDCs by a factor of 1.067695

==

Total P, Winter [P] = 101.8937
Total P, Winter(clim) [P′] = 122.2724
Winter - Total Zonal Input [i], Zone 2 = 17.38953
ΣM·S = 0
ΣM(1-S) = 4.349365
ΣP_rain = 13.04016
Winter(clim) - Total Zonal Input [i′], Zone 2 = 52.66322
ΣM·S = 7.564875
ΣM(1-S) = 6.676103
ΣP_rain = 38.42224
Winter Change (ΔHW), Zone 2 = [i - i’ + P’- P] = -14.895

Zone 2
Winter Change (deficit) of -14.89496 was equaled/exceeded by accumulated zonal melt on 5/17, a shift of 47 days AZM_{EXCL} on 5/17 = 15.63624
Prior day's AZM_{EXCL} = 14.55844

==

Total P, Winter [P] = 122.8147
Total P, Winter(clim) [P′] = 147.3776
Winter - Total Zonal Input [i], Zone4 = 0
ΣM·S = 0
ΣM(1-S) = 0
ΣP_rain = 0
Winter(clim) Total Zonal Input [i′], Zone 4 = 0
ΣM·S = 0
ΣM(1-S) = 0
ΣP_rain = 0
Gain(g) = (P’ - i’) / (P - i)
g = (147.3776 - 0) / (122.8147 / 0) = 1.2
Winter Change (ΔHW), Zone = [i - i’ + P’- P] = 24.563

Zone 4
Winter Change (surplus) 24.56294 was accounted for by stretching MDCs by a factor of 1.2

The climate change scenario described in Figure 34 produced this Climate Change Statistics Report (T + 4°C, P 120 %, 31 day shift of *a* and C_S.

Note! Zones 3-4 exhibit a positive Winter Change due to the increase in P (120%) overwhelming the temperature-induced (+ 4°C) deficit.

Fig. 36 Climate Change Statistics Screen.

9.4 Keyboard definition

User interaction with the model is initiated via the standard PC keyboard or the optional mouse. During data entry, the program recognizes and accepts all the standard ASCII characters present on the keyboard. In addition, Micro-SRM provides both intuitive and non-intuitive functionality to many of the "special" PC keyboard keys. At any given point in the Micro-SRM modeling process one or more of these keys may be "hot", that is, set to initiate a specific program-defined activity when pressed. These "hot" key definitions are task-specific, and will be redefined or undefined as the model user changes tasks. These "special" keys can be grouped into several broad categories.

9.4.1 Global definitions

The following four keyboard keys initiate logical functions which are available for use at any point in the modeling process. Where defined, the corresponding "mouse click" equivalent is presented in parentheses at the end of the definition.

ESCape **-** The use of the ESCape key in Micro-SRM is consistent with most typical PC applications. Basically, the ESCape key suspends the current activity (inspecting help screens, performing variable/parameter data entry, loading a data file, etc.) and returns control to the point in the program where the suspended activity was originally invoked. It backs the user up one logical processing step. From the Program Option, Basin Definition, or Variable/Parameter Menu screens, the ESCape will terminate Micro-SRM and return control to DOS. ("LeftClick" on Esc, or "RightClick" to simulate ESCape).

PgUp, PgDn **-** The PgUp and PgDn keyboard keys control which screen display is presented to the user of Micro-SRM. They are functionally equivalent to turning forward or back one page in a multi-page form. The exception to this usage rule occurs while entering or editing data values on the variable/parameter data entry screen display. During this type of data entry, the PgUp and PgDn keys are used to superimpose the next two or prior two month's data values for the specific variable/ parameter onto the data entry screen, enabling the user to logically step forward or backward in time through the snowmelt period. ("LeftClick" on ⮜┘ └⮞ PgUp PgDn).

Enter⮜┘ - The Enter⮜┘ key is used by Micro-SRM to terminate keyboard responses. Enter⮜┘ implies that information has been provided to the model, and the model should now react to that information. Most commonly, it signals that data entry for the current input data field is complete. When pressed, the model optionally validates the current field's contents for consistency, range validity, etc. (see field content validation above). Micro-SRM "remembers" each input field's most recent value, and so only initiates validation when field contents change. If the field value is unchanged or the changed value validates successfully, the model accepts it into its internal schema and advances the screen cursor to the next logical field on the screen display. If validation fails, an appropriate error message is displayed and the cursor relocates to the first character of the offending field's value. When used with a menu screen display or pop-up window, the Enter⮜┘ key directs the model to use the menu option marked by the light bar as your choice from that menu. Enter⮜┘ is also used during the FileIO process to terminate a request for a filename by the model. ("LeftClick" another input field or Enter⮜┘).

9.4.2 Cursor movement keys

The keys described here are all capable of moving the screen cursor from the current data entry field to some other field in the same screen display. When that occurs, their use initiates a data validation response identical to that of the Enter⮜┘ key. Using these keys, the model user may move freely about the input data screen, entering new and editing existing field values. ("LeftClick" on any field to move the cursor to that field.)

Movement between input fields initiated by cursor movement key-presses is governed by a forward and a backward progression sequence. The forward progression (via the Enter⮜┘ or Tab keys) on a screen beginning at the top leftmost field, is from left to right, top to bottom. Backward progression is the reverse. Movement vertically is generally from the current field up/down to the next closest field. Movement via the Enter⮐ key during daily variable/parameter data entry is from current day to next calendar day.

Tab - The Tab key functions exactly the same as Enter⮐

{Shift}Tab - If the cursor is not on a field's first character, it shifts to the first character. If on the field's first character, the cursor moves to a prior field, as dictated by the backward progression.

Home/End - These keys move the cursor to the first/last data field, respectively, on the screen display.

↑←↓→ - Within a field value the screen cursor may be moved left or right from character to character. If the cursor is at the leftmost character of the field, a "←" moves the cursor to the prior field as defined by the screen's backward progression. If the cursor is at the rightmost character of the field value, a "→" moves the cursor to the next field in the forward progression. An "↑" or "↓" moves the cursor to the next higher/lower field relative to the current field.

9.4.3 Field editing keys

Micro-SRM uses "type-over" as its standard data entry mode. This means that any valid data character typed through the keyboard will replace that marked by the blinking cursor, with the cursor advancing to the next character position in the field. The model supports "word-processor-like" editing via the following keys:

Insert - The Insert key toggles the data entry mode to "insert", with any typed characters being inserted at the point in the field marked by the reverse-video cursor, and all existing characters shifted rightward. Insert mode is canceled by pressing Insert again, or moving the cursor to another data field or screen.

Delete - The Delete key is logically the opposite of Insert. The character marked by the cursor is deleted, and all characters to the right of the cursor are shifted left one position.

Backspace - The Backspace key deletes the character immediately to the left of the cursor, with all characters at and right of the cursor shifted left one position.

CapsLock - When CapsLock is set (indicator on screen line 24 is visible), any alphabetic character entered will appear in upper case. Press CapsLock again to turn off.

NumLock - When NumLock is set (indicator is visible), characters entered through the keyboard's number pad are treated as numbers. WARNING!! If NumLock is on, the cursor movement key equivalents on the number pad are deactivated. Micro-SRM assumes you are entering numeric data, not trying to relocate the cursor or change the display page.

9.4.4 Function keys

Micro-SRM uses the microcomputer's dedicated keyboard function keys (F1-F10) to provide the user with the ability to interrupt the current model activity (typically data entry) with a single keypress/mouse click, and transfer control to a specific predefined function process. On function termination, control returns to the point of interruption. Each Micro-SRM screen display includes information on the function keys that are "hot" (i.e., active at that point in the program).

The functions described below are Micro-SRM "primary" function key definitions. These functions are "hot" while the "Program Options", "Basin Definition", and "Basin Variable/Parameter Menu" screens are displayed:

F1-Help - The Help function is invoked by pressing/clicking function key F1 at any point in the modeling process. When help is requested from a primary screen display (Program Option, Basin Definition, Variable/Parameter Menu, Variable/Parameter Data Entry), Micro-SRM replaces that screen display with the Help Screen most logically related to the user's position within the model. While help is active, the user may PgUp or PgDn to view all of Micro-SRM's available help screens. The function is terminated with an ESCape, and returns the model to the logical state existing prior to the help request. When help is requested from within another function (SUMMARY, FILEIO, PLOT, PRINT), it is presented slightly differently, through the use of a pop-up window, a transient area nondestructively superimposed over the current display image. These function pop-ups are only accessible after invoking the specific function.

F2-Summary - This function is invoked by pressing/clicking function key F2 from the Program Options, Basin Definition, or Variable/Parameter display screens. The Micro-SRM summary screen provides the user with a "snapshot" of basin definition variables and zone-specific parameter values as they are currently defined. Beginning and mid-month value (day 1 and day 16 if different) for each month in the snowmelt period are displayed for seven model parameters. Each zone in the basin is displayed separately, and is accessed via the PgUp and PgDn keys. A printed version of the summary may be selected through the Print Menu (see below). The following keys are "hot" within the summary function:

F1 - Help info on this function

PgUp/PgDn - display the next/prior zone's configuration.

ESCape - Exit function and return to point where invoke

F3-FileIO - The File Input/Output function is invoked by pressing/clicking function key F3 from Program Options, Basin Definition, or Variable/Parameter display screens. In response to the hot-key, a small "pop-up" menu is displayed. The user specifies one of four sub-options by moving the menu bar using the up arrow or down arrow, then pressing Enter↵, pressing the desired sub-option's highlighted letter, or left-clicking on the menu selection. FileIO provides the modeler with tools to load, save and delete model data files and to import digital input data from non-model sources.

Load - The Load option allows the user to identify and input a .SRM data file (see SAVE below) into the model. After a successful load, the model assumes a state identical to that existing when the referenced data file was created.

Save - The Save option allows a user to create and name a file containing the ASCII representation of the data currently resident in the model's data structures. The file qualifier ".SRM" completes each save file's name, making it easy to recognize and manage model data. A data compression algorithm shrinks the 100K+ internal data structures into a more manageable size (a complete five zone basin might require 10K) using shorthand notation identical to the FORTRAN repeat count concept (IBM VS FORTRAN, 1983).

Delete - This option provides the model user with the ability to delete any SRM data file (.SRM-qualified) currently residing on any of the PC's storage devices.

Import - The Import option provides a method for introducing digital input data from a non-SRM source to the model. Using a simple format (press F1 for a popup describing the import format), any of the 13 model variables/ parameters detailed on the Variable/Parameter Input Data Screen may be generated externally and directly loaded into SRM. To be accessible to SRM, all import data files must be qualified ".DAT".

Once a FileIO option is selected, Micro-SRM displays a file selection/definition screen made up of two display panels. The upper panel displays the individual system's available devices, and lists all subdirectories and filenames for the current default device/directory. The lower panel displays the current pathname (i.e., the device, directory, or filename) that will be used to attempt to fulfill the current FileIO operation.

The selection screen uses two simple approaches for identifying target file names. The first approach is "point and shoot". With the upper panel "active", an object from that panel may be selected by moving the light bar to the desired object using the cursor keys, then pressing Enter↵, or by clicking on the desired object with the left-mouse-button. Alternatively, the user can press the TAB → key to switch to the lower panel and use the keyboard to enter the desired filename, then press Enter↵, to select the file.

If the object selected/entered is a valid pathname (i.e., a device {A:, B:}, directory name ending with "\", or <Parent> the default device\ directory will be changed, and all appropriate files on the new path will be displayed.

***F5-Plot* -** The PLOT Function is invoked by pressing/clicking function key F5 from the Program Options, Basin Definition, or Variable/Parameter Menu display screens. Micro-SRM will refuse this function request and generate an appropriate error message if the PC has no graphics adapter present or a simulation/forecast has not been run since last data entry. If the F5 key is "hot", the plot options menu is displayed (see Section 9.5.4). The five Micro-SRM plot products available during normal processing are:

- Measured vs Computed Streamflow
- Snow Depletion vs Time
- Snow Depletion vs Total Snowmelt Depth
- Accumulated Zone Melt Depth vs Time
- Build External Plot File

If Micro-SRM performs a climate-change run, the state of the plot menu changes, presenting the user with the following choices:

- Computed Flow Before/After Climate Change
- CDC/Clim (Model Adjusted) vs Time
- Build External Plot File

The following keys are "hot" while this menu is displayed:

F1	- Help for Plot Menu
Up/Down Arrow	- Move menu bar to next/prior choice
Enter↵	- Invoke selected plot option
ESCape	- Exit function

After a plot has been displayed, the user may request a hard-copy by pressing function key F10. Press Enter↵ to cycle through any additional zone(s) in the basin. Press ESCape to return to the Plot Menu.

The fifth option on the menu, Build Plot File, generates an ASCII file containing all the information necessary to recreate a user-selected combination of the Micro-SRM plot products using non-model hardware/software.

***F6-Print* -** The PRINT menu is displayed by pressing/clicking function key F6 from the Program Options, Basin Definition, or Variable/Parameter display screens. The print products available (see Section 9.5.5) in Micro-SRM are:

- Temperature Values
- Degree Day Factors, Runoff Coefficients
- Lapse Rate, Critical Temperature, Rain Contributing Area, Lag Time
- Zone Degree-Days, Observed Precipitation, Snow-Covered Area (S)
- Melt Depth (M · S), Melt/New Snow (M (1–S)), Contributing Rain (Cpr)
- Measured vs Computed Snowmelt Runoff
- Input Summary Report, Run Statistics
- All the above

The validity of some of these reports is contingent upon successful completion of a simulation/forecast.

***F7-Compute* -** This function is invoked from the Program Options and Basin Definition data entry screens, or the Variable/Parameter display screen by pressing/clicking function key F7. It initiates actual model processing using the current version of input data. Processing may be suspended due to missing or invalid input variables. If processing is successful, a "results panel" will be displayed, showing results of the computations (Figure 37).

SIMULATION

Measured Volume (10^6 m^3)	:	938.75
Average Measured Q (m^3/s)	:	71.01
Computed Volume (10^6 m^3)	:	910.10
Average Computed Q (m^3/s)	:	68.85
R^2 Goodness of Fit	:	0.8959
Volume Difference (%)	:	3.0526

Fig. 37 Screen display after compute.

9.4.5 Alternate function keys

In addition to the functions described above, there are several alternate function key definitions that supersede the primary function key definitions during basin variable/parameter data entry/data display. These alternate functions provide some additional tools useful in manipulating the complex structures required to store multiple day, multiple zone data. These functions are:

***F5-Prior Zone/F6 Next Zone* -** As explained in Section 9.3.7, these keys change the Variable/Parameter data entry screen display to the same two-month period for the next or prior elevation zone. These keys are "hot" only for multi-zone basins and only for zone-specific variables and parameters.

***F7-Duplicate Existing Zone* -** When invoked, this function prompts the user for a source and destination zone, then copies all the daily values from the source zone to corresponding days in the destination zone. This is particularly useful for some of the model's daily parameters, which may change very little from zone to zone.

***F8-Repeat Prior Value* -** Pressing F8 causes the value for the day preceding that marked by the cursor to be copied into the current day position. The cursor then advances to the next day. If the cursor is on the first day of the earlier of the two months displayed, the prior day value used is out-of-sight, that is, the last day of month preceding the month displayed.

***F9-Repeat Prior Value N Times* -** After prompting the user for a repeat count, the model enters the value from the day preceding the cursor into the next N days, moving the cursor as it proceeds. The repeat count can vary from 1 to 365.

***F10-Insert/Delete Day* -** This function lets the user modify an existing array of daily values without re-entering the entire array. When invoked, the user may insert a blank day at the point marked by the cursor, shifting existing day values one day forward in time, or delete the day marked by the cursor, shifting existing daily values one day back in time.

9.5 Micro-SRM output products

Several different forms of output have been included in Micro-SRM, designed to support a user's specific requirements for information provided to, and generated by the model. Model output is user-selectable, and for several of the forms, interactively controlled. The available output products are described in the following paragraphs.

9.5.1 Simulation/forecast statistics

Each time an F7-Compute is successfully executed, the model suspends further processing while it displays several important statistics which quantify the accuracy of the calculations. Any keypress then returns the model to its precompute state. See Figure 37 for an example of this screen display.

9.5.2 Summary display

Function Key F2 invokes the model summary screen. See Section 9.4.4 for a complete description of this function. It is designed to give the user a quick overview of the state of seven critical model parameters. Summary is useful when making iterative runs, each with slightly different parameter configurations. The basin name and model run number are included, identifying the specific iterative version of the data displayed.

9.5.3 .SRM data file

As described in Section 9.4.4, the FileIO menu option "Save" creates a disk file containing all the information necessary to recreate the model run at some future time, via the "Load" function.

9.5.4 Plot displays

Micro-SRM produces several different plots in one of several different screen modes. Once plotted, and assuming a compatible printer, a hardcopy of the plot image can be produced.

***Measured vs Computed Streamflow* -** Runoff is plotted along the Y-axis (instantaneous flow), time along the X-axis. Run statistics are displayed in the upper right corner.

***Snow Depletion vs Time* -** Snow depletion curves for each zone are produced. The initial image displays all the basin's snow depletion curves on a single image. Press a key to produce a separate plot of each specific zone, in ascending order. Press ESCape to terminate the plot.

***Snow Depletion vs Total Snowmelt Depth* -** Daily snow covered area (%) is plotted on the Y-axis, corresponding accumulated snowmelt depth, and accumulated snowmelt reduced by the effect of new snow, are plotted on the X-axis. Each zone is plotted separately. Press Enter↵ to see the next zone, ESCape to terminate and return to the Plot Menu.

***Accumulated Zone Melt Depth vs Time* -** Accumulated zone melt depth (areal coverage) (y) is plotted against time (x). Press Enter↵ to change zones, ESCape to terminate the plot.

***".PLT" Plot File* -** All the input and model-generated values used to create Micro-SRM's plots are saved to a user-named external disk(ette) file (.PLT-qualified). The .PLT file format is described in more detail in the sample .PLT file included on the Micro-SRM distribution diskette.

<u>9.5.4.1 Plot displays (Climate Change)</u>

SRM, Version 4.0 and later will automatically produce several additional plot displays during climate change simulation runs. See Section 9.3.8.2 and Section 9.7, Steps (5g-k).

MDC_{EXCL} vs $MDC_{EXCL\ WA}$ - The first curve depicts the snow water equivalent of the existing snow pack, new snow excluded, under normal climate conditions (the amount of melt needed to decrease the snow covered area to a certain proportion of the total). The second curve is derived from MDC_{EXCL} by introducing the effect of a winter climate change upon areal snow water equivalent (see Section 9.7).

AZM_{INCL}, AZM_{EXCL}, $AZM_{EXCL\ WA}$ - Accumulated zonal melt curves for the melt season, with and without new snow falls, and "winter-adjusted" AZM. The first two curves depict areal water equivalent of the initial snow cover under normal climate conditions, the last, areal water equivalent in a changed climate (see Section 9.7).

$MDC_{EXCL\ WA}$ vs $MDC_{CLIM\ WA}$ - These curves depict areal snow water equivalent of the initial snow cover in a changed climate, with and without new snow added (see Section 9.7).

CDC vs $CDC_{CLIM\ WA}$ - These curves depict snow covered area for the normal and changed climate. The first curve is taken from input data provided by the user. The second curve is derived by the climate change algorithms of SRM (see Section 9.7).

9.5.5 Printed reports

Micro-SRM includes 7 different printed report formats, each display one or more model variable(s). The menu controlling selection of printed reports allows the user to select an individual report, or the entire report set (see Section 9.4.4 for more information on the F6 print function). Printing can be canceled by pressing ESCape at any time during printing (if print buffering is in effect, there will be some delay before ESCape takes effect). Each selected report will print, even if there are no data present (i.e., neither input nor computed). The following reports are available:

Temperature Values ({form})
Prints temperature values entered by the user in the temperature form selected (max/min, mean) for each day in the snowmelt period, as specified on the Program Options Screen (Figure 31).

Degree-Day Factors, Runoff Coefficients
Daily degree-day factors (AN) and snow/rain runoff coefficients are printed for each day of the melt period.

Lapse Rate, Critical Temperature, Rainfall Contributing Area, Lag Time
Parameters displayed control how discrete temperature values are applied basin-wide (lapse rate), when to treat precip as snow (critical temp), how to calculate the effect of precipitation (RCA), and how to distribute resulting runoff over time (lag time).

Zone Degree-Days, Observed Precip, Snow-Covered Area
A zone-specific report that displays DD temperature (either computed from max/min, average daily temperature, or entered directly as DD's), observed precip (these values may be zone specific or apply across the entire basin), and snow-covered area (% of zone covered on a given day).

Melt Depth, ($M \cdot S$), Melt/New Snow (M ($1 – S$)), Precip Contributing to Runoff
Intermediate results of Micro-SRM computations. For each elevation zone, this report details daily total melt depth, zone contribution to runoff ($M \cdot S$), and precip contributing to runoff, either as rain, or as melted new-snow.

Measured vs Computed Snowmelt Runoff
Simulated/forecast and measured streamflow (if provided) are plotted against time. Run statistics (R^2, % Volumetric Difference) are meaningful only if actual runoff values have been provided.

Input Summary Report, Run Statistics
A printout of the model summary display (see Section 9.4.4). Bi-monthly values (1st, 16th) for 7 model parameters are printed for each zone in the basin. Run statistics are for the most current model run.

All the Above
Generates a complete set of printed reports.

9.5.6 Printed reports (Climate Change)

Version 4.0 of SRM includes one additional printed report, the Climate Change Statistics Report that presents the computed values used to derive climate-affected snow cover. See Figure 36 and Section 9.3.8.2 for additional information.

9.6 Using Micro-SRM

Assuming the availability of the data necessary to run the model, there are only two requirements for using Micro-SRM. The target basin must contain 8 or fewer elevation zones and the physical dimensions of required input data variables may not exceed the size of the screen fields defined for their storage. This should only occur during variable/parameter data entry, where daily values may contain no more than 6 digits.

The following sequence of steps describes a typical Micro-SRM session:

(1) User types SRM4, then presses Enter⮠ to invoke Micro-SRM.

(2) After viewing the Introduction screen, the user presses PgDn to view the "Program Options" data screen (Figure 31).

(3) The user makes any required changes to the program control information displayed on this screen, then presses PgDn to view the "Basin Definition" data screen (Figure 32).

(4) After filling the required data fields on this screen, the user begins the variable/parameter data entry process by pressing PgDn to view the Basin Variable/Parameter Definition Menu (Figure 29).

(5) The user selects a variable/parameter from this menu, then presses Enter⮠ to display daily values for the first two months of the snowmelt period for the selected variable (Figure 33).

(6) The user fills the daily value fields with appropriate data, then presses PgUp or PgDn to view a different two-month slice of daily values for the same variable.

(7) After data entry for the selected variable/parameter is complete, the user presses ESCape to return to the Basin Variable/Parameter Definition Menu.

(8) The user repeats steps 5-7 for all required variables and parameters.

At any point during these steps the user may interrupt the data entry activity by pressing an active function key (to request help, save data, display the data summary screen, etc.). After data entry is complete, the simulation or forecast can be computed (press F7) and the results displayed (F5 for plots, F6 for print).

Prior to each ***F7Compute***, SRM performs a simple, "non-elegant", test to determine if all appropriate variables and parameters have been supplied by the user. For each required variable or parameter type (determined by Program Option field values), SRM simply checks for the presence of a non-zero value anywhere in the period. If any required variable or parameter fails this test, a data validation error screen is displayed that identifies the variable(s) and zone(s) that have failed the test. To view this screen, simply run Micro-SRM, enter some values on the Basin Definition Screen, and press F7Compute. Because certain model variables and parameters may legitimately contain all zero values (i.e., precipitation), the model user is given the opportunity to continue the simulation or forecast, or abort processing so the "missing data" condition may be corrected.

9.7 Using Micro-SRM to simulate a year-round climate change

Beginning with Version 3.11, Micro-SRM allowed a user to define a climate change scenario, a seasonal change of temperature and precipitation, and simulate its effect during the melt season. This feature was an important step in implementing the ongoing "climate-change" research that SRM model developers had conducted over the prior several years. However, we have recognized the limitation of the original climate-change algorithm, the fact that the change was isolated only on the melting season. In other words, the snowpack used during any climate change scenario was the observed real seasonal snow cover.

Version 4.0 incorporates much of the model developers′ latest research on the effect of climate change on snowmelt runoff over an entire hydrological year (see Section 8). The original (SRM, 3.11) program′s climate-change algorithms/processing steps have been replaced with new algorithms that model future snow conditions as well as climate-affected runoff. The computer program has been enhanced to manage the steps involved in simulating climate change, by providing a new data entry screen, the Climate Change Control Screen (see Figure 34). This screen allows the user to easily describe climate change conditions that span an entire hydrological year, specifying both a winter and a summer season climate change scenario. By simulating the effect of winter climate change on the existing snowpack, the program can model the summer season′s climate-affected snow conditions and use those curves ($CDC_{CLIM\ WA}$) during the melt season climate change simulation.

In Version 4.0, a "climate-change run" is in reality five complete iteractions through the model, along with a series of additional steps required to model climate-changed snow cover data. The program′s progress through these steps is monitored using another new screen display, the Climate Change Progress Screen (see Figure 35). The steps defined by that screen are:

Step 1: *Winter simulation, normal climate (determine total zonal melt)*

- Run winter simulation with the normal climate. Compute $\Sigma winter\_zonal\_melt_{NORMAL}$, where zonal melt (*i*) is:

$$M \cdot S \text{ (melt from snowpack)} + M \cdot (1-S) \text{ (melt from newsnow)} + \text{contributing P (Cpr)}$$

where: $M = a \cdot T$
Cpr = contributing precipitation, .i.e., that precipitation falling as rain that fell on the snowfree area, a ripe snowpack, or a combination.)

- Determine ΣPrecipitation (P).

Step 2: *Winter simulation, changed climate (determine total zonal melt)*

- Run winter half-year simulation with the changed climate. Compute $\Sigma winter\_zonal\_melt_{CLIM}$ (*i'*).
- Determine $\Sigma Precipitation_{CLIM}$ (P').

Step 3: *Summer simulation, normal climate (save* MDC's*, simulated runoff)*

- Run summer simulation with the normal climate, save data needed to recreate modified depletion curves, MDC_{EXCL}, accumulated zonal melt curves, AZM_{EXCL}, and the simulated runoff hydrograph, Q_{SIM}.

MDC_{EXCL} [snow depletion vs. $\Sigma(a \cdot T - \text{newmelt})$]

AZM_{EXCL} [$\Sigma((a \cdot T - \text{newmelt}) \cdot S)$ vs time]

Step 4: *Summer simulation, changed climate (save* MDC_{CLIM}*)*

- Run summer simulation with the changed climate. Save $\Sigma(a \cdot T)_{CLIM}$, $\Sigma(\text{newmelt})_{CLIM}$.

Step 5: *Derive* $CDC_{CLIM\ WA}$ *using* MDC_{CLIM} *(adjusted for Winter Change)*

(5a) Compute ΔHW (Winter Change), ($\Sigma winter\_zonal\_melt_{NORMAL} - \Sigma winter\_zonal\_melt_{CLIM}$, from Steps 1, 2 above).

Reduce/enhance effect of temperature-induced deficit by adding any net change to seasonal precipitation resulting from the climate change scenario. In the case of Illecillewaet, 1984, zones C and D, the scenario T + 4°C, P·1.2, results in a positive Winter Change (increases in P overwhelm the winter deficit in melt). In that case, MDC_{EXCL} is "stretched" rather than "cut-off", as explained in Step (5c).

The Climate Change Progress Screen (Figure 35) allows a user to over-ride a calculated zonal Winter Change value at this point in the processing sequence. See Section 8.3 (9) for a description of when such intervention might be advisable.

(5b) For each zone, develop zonal melt curve, AZM_{EXCL} ($\Sigma(a \cdot T \cdot S)$ vs Time) for the normal climate. Find the date along AZM_{EXCL} where zonal Winter Change is equaled or exceeded.

At this point, the Climate Change Statistics Report is produced. This printout (disk file if no printer is available) details the calculated values used by SRM to compute zonal Winter Change and the "cutoff" points or "gain factors" used in Step (5c) to derive $MDC_{EXCL\ WA}$.

(5c) Create data for a new curve, $MDC_{EXCL\ WA}$.

To understand the methodology for modelling CDC_{CLIM}, it is important to understand the MDC_{EXCL} curve. Each point along the curve is a daily intersection of snow water equivalent independent of melt season snowfalls (Σ ($a \cdot$T-newmelt), and daily % snow covered area (% S), on the x-axis and y-axis respectively. The data are saved internally by SRM in ascending order, by date. SRM uses two different methodologies for creating $MDC_{EXCL\ WA}$.

- Methodology for winter deficits: Beginning on the date following that identified by Step (5b) above (i.e., the "cutoff" date), all remaining daily values for MDC_{EXCL} {% S and Σ ($a \cdot$T-newmelt)} are shifted backwards in time to the beginning of the melt season. Additionally, as the curve′s x values are shifted, each daily value is reduced by a constant equal to the 1st x value following the "cutoff" date, reestablishing an x origin of 0.0. For example, if a "cutoff" date of 15 April is identified (15 days into the melt season), then all succeeding days for the data constituting the curve are shifted to the corresponding day 15 days earlier, with each daily $\Sigma(a \cdot$T-newmelt) being reduced by $\Sigma(a \cdot \text{T-newmelt})_{day\ 16}$.
- Methodology for winter surpluses (increased P overwhelms temperature increase for the zone, stretch the MDC). Compute the proportional increase in winter-ending snow water equivalent using values obtained in Steps (1-2) above:

$$\frac{\Sigma\ P_{CLIM}\ -\ \Sigma\ Zonal\_Melt_{CLIM}}{\Sigma\ P-\Sigma\ Zonal\_Melt} \qquad (27)$$

Multiply each x value of MDC_{EXCL} by this factor to "stretch" MDC_{EXCL}, creating $MDC_{EXCL\ WA}$.

(5d) Derive a new curve, $MDC_{CLIM\ WA}$, by adding to $MDC_{EXCL\ WA}$ the corresponding daily melt depths of new snow "surviving" in the warmer climate $\Sigma(\text{newmelt})_{CLIM}$ from Step (4).

(5e) For each daily value, n, in $MDC_{EXCL\ WA}$, find the first day on $\Sigma(a \cdot T)_{CLIM}$ from Step (4) when the value is equaled or exceeded. Move the corresponding day's snow cover % to day n of the $CDC_{CLIM\ WA}$ array. On days when multiple % S values for the same day in CDC_{CLIM} result, the first (highest) value is used, the remaining values are ignored.

(5f) After all derived values have been calculated for $CDC_{CLIM\ WA}$, SRM completes the new curve, $CDC_{CLIM\ WA,\ MA}$ by supplying all missing daily snow cover values using the following logic:

- Missing days that lie between two days with derived values will inherit the earlier day′s derived % S value.

- All missing days following the last derived daily value will inherit a ‘residual value’ that is determined in two different ways depending upon the difference between the last derived daily value and the corresponding value in CDC_{NORMAL}. The normal difference will be negative ($CDC_{CLIM} < CDC_{NORMAL}$). In this situation, the residual value is set equal to the last % S value in the CDC_{NORMAL}. This value will typically be zero, except in cases where the zone includes a glacier or permanent snow cover. In the infrequent cases where the difference is positive ($CDC_{CLIM} > CDC_{NORMAL}$) each missing daily value after the last derived day will take on the corresponding day′s % S value from CDC_{NORMAL} plus the difference.

(5g) Plot MDC_{EXCL}, $MDC_{EXCL\ WA}$ (see Section 9.5.4.1).

(5h) Plot AZM_{INCL}, AZM_{EXCL}, $AZM_{EXCL\ WA}$.

(5i) Optionally plot $MDC_{EXCL\ WA}$, $MDC_{CLIM\ WA}$.

(5j) Plot CDC, $CDC_{CLIM\ WA}$.

(5k) Replace CDC with $CDC_{CLIM\ WA,\ MA}$.

Step 6: *Summer simulation, changed climate, using* $CDC_{CLIM\ WA,\ MA}$.

- Make one final summer "climate-change" simulation, using the existing climate-change scenario with the derived $CDC_{CLIM\ WA}$ curves to produce Q_{CLIM}.

After a successful climate change computation, Micro-SRM "changes state", with references to actual and simulated runoff replaced with simulated runoff before/after climate change. The "post change" data is treated as normal Micro-SRM data with the exception that it may not be used as the "base" for another climate change. If "climate-modified" data is SAVEd and reLOADed, it induces the above referenced "state change". LOADing a normal SRM file resets the model to its normal "state".

9.8 Using Micro-SRM trace file options

Several Micro-SRM command line trace options (see Section 9.2.4) allow the advanced model user to create and use files containing the commands provided to the model via the keyboard or mouse during all or part of a program execution. This feature can prove very useful if a user is faced with the task of performing an elaborate sequence of otherwise identical processing steps on multiple years of data. By building a trace file and using a text editor to modify references to any .SRM filenames, the user insures identical processing for each year of data.

In order for trace file processing to proceed in an orderly fashion, Micro-SRM makes the following assumptions when running in "trace mode":

(1) Micro-SRM processing (/TIN) begins from the same DOS path as did execution when (/TOUT) created the trace file.

(2) All pathnames and filenames referenced in a trace file exist on the PC.

During trace file creation (/TOUT={file}), each keystroke and mouse click is saved in {file}. Trace file creation can be terminated at any point in the model session by pressing **ALT_@**.

When the model runs under control of a trace file (/TIN={file}), the program reads and processes one command from the trace file every ½ second unless the /TDELAY option is included to specify the time increment. This control sequence will continue until one of the following three trace ending events occurs:

End of Program - the trace file includes the keystrokes necessary to end execution of Micro-SRM.

***End of Trace File* -** When the last command is removed from the trace file, a message is displayed and program control is returned to the keyboard and mouse.

***Trace Suspended* -** the user may suspend trace file processing by pressing **Esc**. After suspension, the user may optionally continue trace file processing, with the same or a modified trace delay, or terminate trace file processing at the suspension point, with control returning to the keyboard and mouse.

9.9 Micro-SRM availability

The Hydrology Laboratory supports and distributes the Snowmelt Runoff Model free of charge to any interested party. The program and related files are available via the Internet by accessing the SRM home page at "http://hydrolab.arsusda.gov/cgi-bin/srmhome". This site also includes an electronic version of the SRM User's Manual. A distribution diskette, available on either 5¼" or 3½" media, containing the executable code, supporting files, and example data files can be provided upon request.. To obtain the latest version of Micro-SRM, contact:

USDA-ARS, Hydrology Laboratory
Bldg. 007, Room 104, BARC-W
10300 Baltimore Avenue
Beltsville, MD 20705-2350 USA
(301) 504-7490

or via electronic mail to:

rroberts@hydrolab.arsusda.gov
alrango@hydrolab.arsusda.gov

Micro-SRM has been distributed to several hundred individuals and institutions worldwide since 1985. We appreciate the feedback we receive from users of Micro-SRM, both positive and negative, and view it as a valuable resource in the process of debugging and improving the software.

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