Water storage in mountain basins from satellite snow cover monitoring

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Abstract The average areal water equivalent of the seasonal snow cover on 1 April in the basin of the Rio Grande at Del Norte, Colorado (3419 km^2, 2432-4215 m a.s.l.) is evaluated from periodical snow cover mapping by Landsat. A dry, near-average and wet hydrological year are examined. Snow reserves in terms of water storage volumes are computed in three elevation zones for actual temperatures and for a projected climate change of +4°C. The decrease of snow accumulation in a warmer climate results in a significant increase of the winter runoff and a corresponding decrease of the summer runoff. The computed winter/summer proportions change from 24/76% to 29/71% in the dry year 1977, from 13/87% to 28/72% in the average year 1976, and from 7.5/92.5% to 12/88% the wet year 1979. An assessment of the seasonal recession from winter to summer reveals that the actual climate effect is even greater.

INTRODUCTION

Remote sensing provides new possibilities for evaluating water storage in the seasonal snow cover. Efforts in this field are stimulated by the need of the hydropower industry to use runoff forecasts for the efficient operation of reservoirs. With regard to long term planning of water management and electricity production, it is important to predict how the snow cover and the runoff regime will be affected by a changed climate. In this paper, snow reserves are evaluated from snow cover monitoring by use of satellite sensors in the visible wavelengths. With this approach, the present and future snow conditions can be modelled as realistically as possible, providing a basis for runoff computations.

SNOW COVER MONITORING AND SNOW RESERVES

The basin of the Rio Grande at Del Norte, Colorado was selected for this study. The periodic snow cover mapping from Landsat data was carried out separately for three elevation zones indicated in Table 1.

Table 1 Elevation zones of the basin Rio Grande at Del Norte, Colorado.

Zone	Elevation range (m a.s.l.)	Area (km^2)	% of the basin area
A	2432-2926	780	22.8
B	2926-3353	1284	37.6
C	3353-4215	1355	39.6
Total	2932-4215	3419	100.0

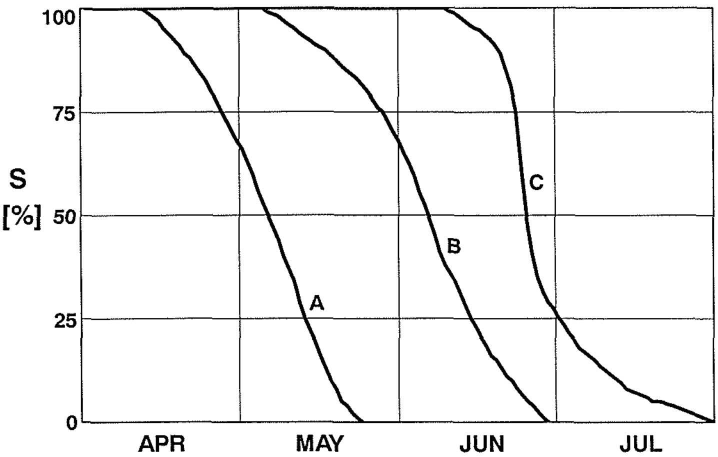

Fig. 1 Depletion curves of the snow coverage in the elevation zones A, B, C of the basin Rio Grande at Del Norte, Colorado, 1979.

Depletion curves of snow covered areas were derived in an extremely wet year 1979, in a dry year 1977, and in a near-average year 1976. Figure 1 shows depletion curves for the respective zones in the snowmelt season 1979 derived from Landsat data. Naturally, the snow coverage declines faster in a lower zone than in a higher zone because the initial snow accumulation is smaller and the temperature for melting is higher. Nevertheless, as has been explained elsewhere (Hall & Martinec, 1985), the snow cover depletion measured in different years cannot reliably indicate the snow water equivalent, although it has been used for this purpose (Ødegaard & Østrem, 1977). The course of a conventional depletion curve (CDC) depends not only on the initial snow water equivalent, but also on the climatic conditions during the snowmelt season in question, notably on temperatures and summer snowfalls. Consequently, the curves in Fig. 2 do not quantitatively indicate the snow reserves in

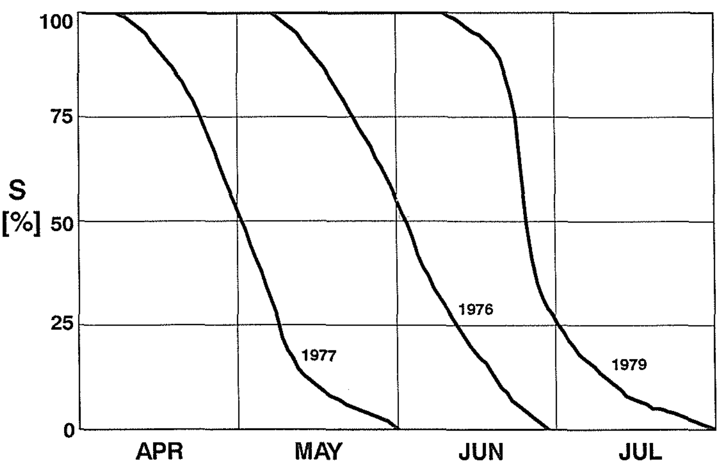

Fig. 2 Conventional depletion curves of the snow coverage for the zone C of the Rio Grande basin in the years 1976, 1977, and 1979.

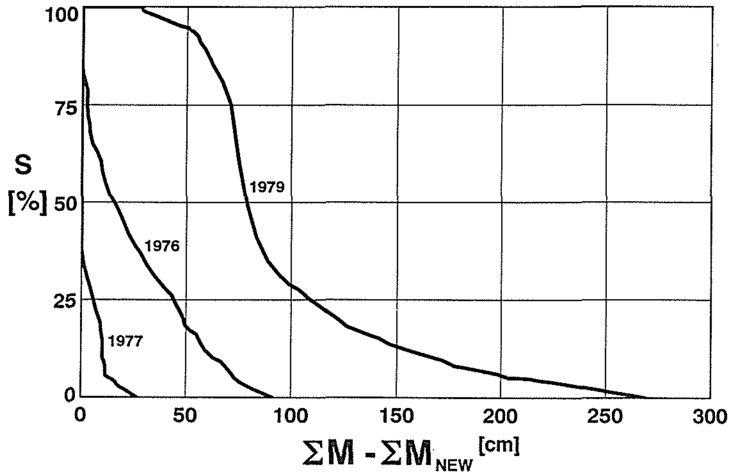

Fig. 3 Modified depletion curves (new snow excluded) for zone C of the Rio Grande basin in the years 1976, 1977, and 1979, with the cumulative snowmelt starting on 1 April.

the respective years. To overcome this difficulty, modified depletion curves (MDC) can be derived from the conventional ones (Martinec, 1985). In Fig. 3, the areas below the MDCs indicate the initial snow reserves in terms of water equivalent. Melt depths needed to eliminate new snow falling in the summer are excluded from the cumulative melt depths which are computed using degree-day factors between 0.4 and 0.5 cm °C^{-1} day^{-1}. When similar MDCs are derived in the other elevation zones as well, the snow reserves in the whole basin can be evaluated. Snow covered areas are used as input variables for the Snowmelt Runoff Model (SRM). In the winter, snow covered areas had to be estimated taking into account precipitation, temperatures and the snow coverage evaluated on 1 April.

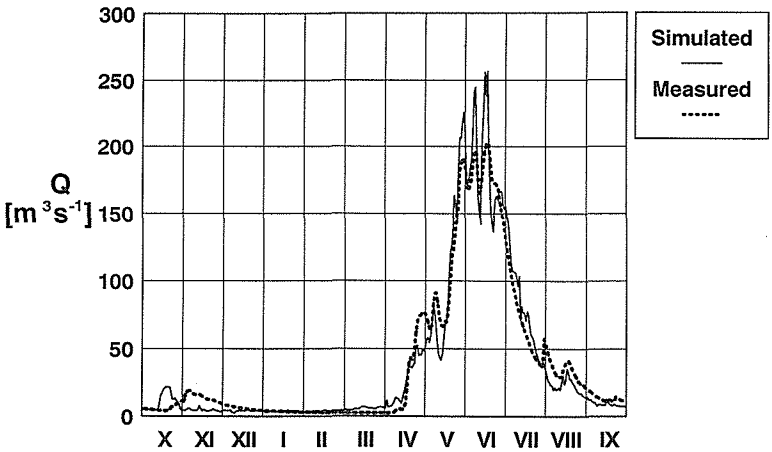

Fig. 4 Runoff simulation in the Rio Grande basin at Del Norte in the hydrological year 1979.

The good agreement between the measured and computed runoff volume in the hydrological year 1979 shown in Fig. 4 can be considered as an indirect confirmation that the snow covered areas and the snow water equivalents evaluated from MDCs are realistic. Such a conclusion is possible because the SRM parameters are predetermined and not calibrated (Martinec & Rango, 1986). It should be also noted that the measured runoff in Fig. 4 has been corrected with regard to reservoir operation so that it represents the natural runoff.

REDUCTION OF SNOW RESERVES IN A WARMER CLIMATE

The concept of modified depletion curves is suitable for evaluating the effect of a changed climate on snow cover and runoff. These curves indicate, for a given snow cover, what snowmelt depth is necessary to reduce the snow coverage to a certain proportion of a total area. In a warmer climate, this total snowmelt, as well as the corresponding snow coverage, is attained at an earlier date. Consequently, the depletion curves of the snow coverage are shifted as explained in detail elsewhere (Rango & Martinec, 1994). In addition, the initial snow cover (usually as of 1 April) is diminished due to increased winter melt and by a partial conversion of snowfalls to rainfalls in the winter. The modified depletion curves derived for the present climate therefore, must be deprived of this amount of water equivalent which would be missing from the snowpack in a warmer climate (Martinec *et al.*, 1994). The conventional depletion curves, which can again be derived, will thus be shifted still further towards earlier dates. These curves are used as input to compute the climate-affected runoff. Coming back to the evaluation of snow reserves, Fig. 5 shows an example of MDCs derived in 1979 for the zone A (MDC_{EXCL}) and adjusted for a temperature increase of +4°C, in other words, deprived of a certain volume of water

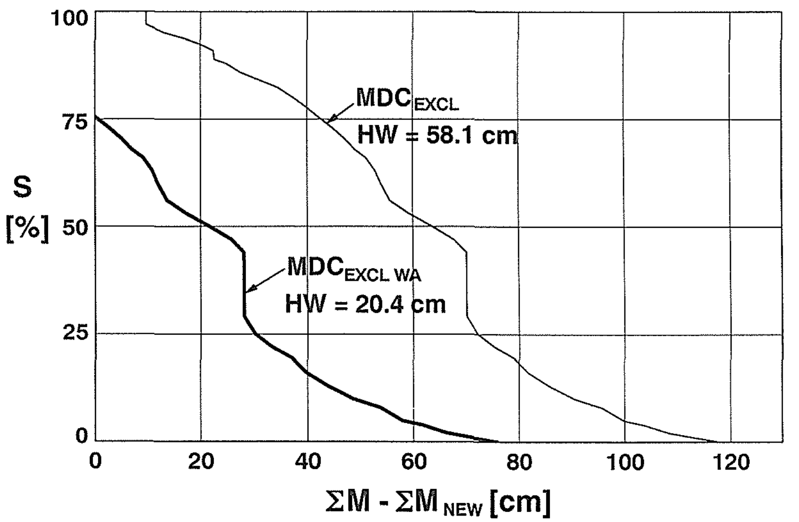

Fig. 5 Modified depletion curves for zone A of the Rio Grande basin in 1979 with new snow excluded: The area below MDC_{EXCL} indicates the snow water equivalent on 1 April 1979, the area below $MDC_{EXCL\ WA}$ indicates the snow water equivalent for a temperature increase of + 4°C.

Table 2 Snow reserves on 1 April in the basins of Rio Grande at Del Norte.

Zone	1977				1976				1979			
	Present		$T + 4°C$		Present		$T + 4°C$		Present		$T + 4°C$	
	(cm)	($m^3 \cdot 10^6$)	(cm)	($m^3 \cdot 10^6$)	(cm)	($m^3 \cdot 10^6$)	(cm)	($m^3 \cdot 10^6$)	(cm)	($m^3 \cdot 10^6$)	(cm)	($m^3 \cdot 10^6$)
A	0.10	0.78	0	0	15.94	124.33	6.82	53.20	58.10	453.2	20.41	159.2
B	3.03	38.90	0	0	18.46	237.03	0	0	88.23	1132.9	77.48	994.8
C	2.96	40.11	1.52	19.51	23.61	319.92	17.17	232.60	94.11	1275.2	91.87	1244.8
Basin	2.33	79.79	0.60	20.60	19.93	681.28	8.36	285.85	83.69	2861.3	70.16	2398.8

by additional snowmelt in the winter ($MDC_{EXCL\ WA}$). The degree-days needed to melt new snow during the snowmelt period are excluded from the cumulative snowmelt computation so that the curves (MDC_{EXCL}, $MDC_{EXCL\ WA}$) indicate the water equivalent of the snow cover on 1 April, in the respective elevation zones. A preselected critical temperature determines whether precipitation is considered to be rain or new snow. By applying the same procedure in 1976 and 1977, a broad range of snow reserves in the present climate and in a climate experiencing a temperature increase of +4°C can be evaluated for the respective elevation zones and for the whole basin of Rio Grande at Del Norte. Results are listed in Table 2 and illustrated by Fig. 6.

In 1976, snow disappeared in Zone B due to increased temperatures in the winter while a residual snow cover remained in the Zone A. This discrepancy might be explained by a possible redeposition of snow due to wind. Without a transfer of 7 cm snow water equivalent from Zone B to Zone A, for example, the temperature increase would have left no snow in Zone A and still some snow in Zone B. The snow reserves on 1 April could also be evaluated from total winter precipitation by deducting the winter snowmelt and rain. In view of insufficient precipitation data which are characteristic of mountain basins, especially in the winter, the presented method appears to be more reliable.

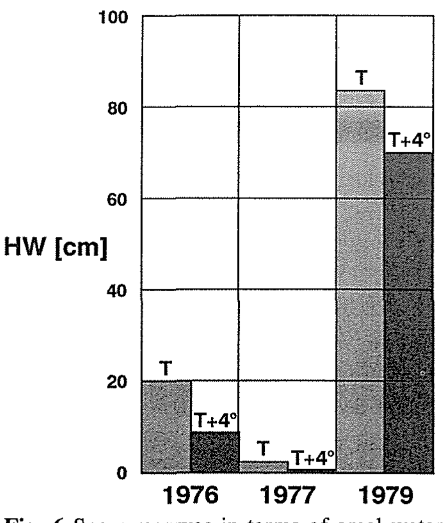

Fig. 6 Snow reserves in terms of areal water equivalent in the Rio Grande basin at Del Norte on 1 April in the present and future climate.

Actual temperatures in 1976, 1977 and 1979 are assumed to represent the present climate. This is not quite accurate because deviations may occur from whatever would be considered as the present "standard". However, as shown in Fig. 7, deviations from the long-term average 1957-1994 are not great. The annual average temperature in 1976, +3.34°C, corresponds to the long-term average of +3.38°C, while in 1977 and 1979 it is only by 0.45°C lower. These are small values in comparison with the hypothetical temperature increase of +4°C. On the other hand, precipitation differs significantly from the long term average in the individual years and there is no consensus yet how precipitation should be adjusted under conditions of climate change. Therefore, contrary to other studies (Kite, 1995; McCabe & Hay, 1995), this aspect is left aside in this paper in order to isolate the effect of an increased temperature. Precipitation changes can, of course, be also handled by the SRM climate program if required.

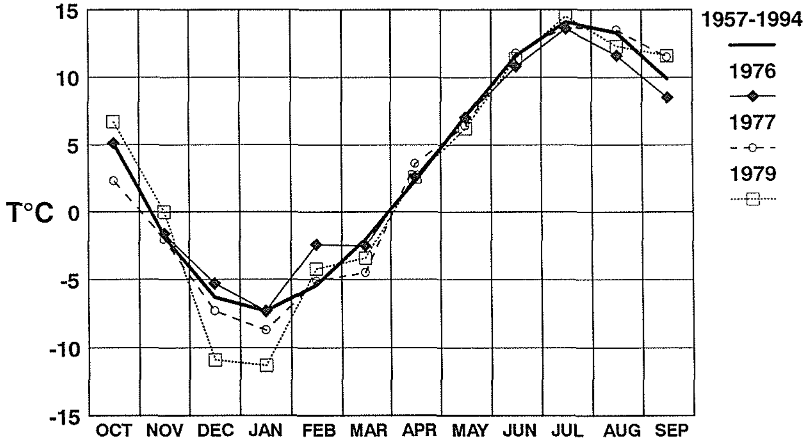

Fig. 7 Average monthly temperatures in the basin Rio Grande at Del Norte in 1976, 1977 and 1979 compared with the long term averages 1957-1994.

RUNOFF COMPUTATION FOR PRESENT AND FUTURE CLIMATE

The climate effect on runoff can be demonstrated by taking the wet hydrological year 1979 as an example. Recalling Fig. 7, temperatures can be considered as approximately representative for the present climate. As described in a previous paper (Martinec *et al.*, 1994), the climate affected depletion curves of the snow coverage can be derived from the modified depletion curves (MDC) taking into account the "surviving" snowfalls in the warmer climate and, if the temperature increase occurs in the whole year, also the decrease of the snow cover on 1 April due to a warmer winter. Modified depletion curves excluding new snow and adjusted for increased winter snowmelt (see Fig. 5) are thus used to derive the climate-affected conventional depletion curves which are shown in Fig. 8 together with the original curves. In all elevation zones, the decline of the snow coverage appears to be accelerated by about one month. Accordingly, it was decided to shift the seasonally

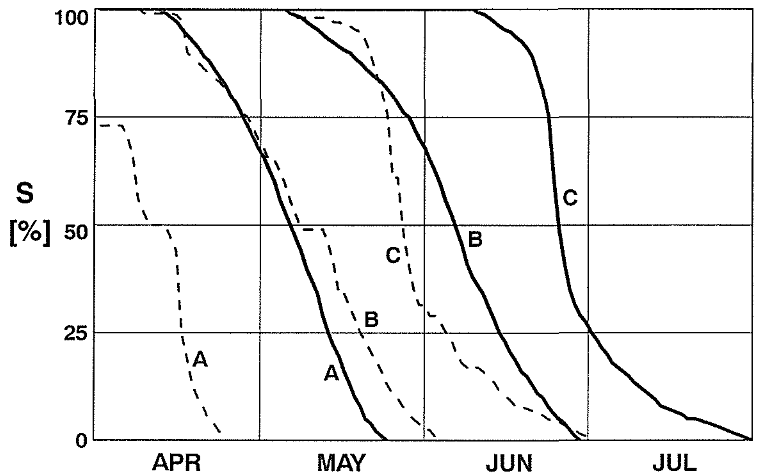

Fig. 8 Conventional depletion curves in the zones A, B, C of the Rio Grande basin in 1979 and climate-shifted depletion curves.

changing values of the degree-day factor and of the runoff coefficient for snowmelt one month ahead, (uniformly 31 days ahead by the automatic program). Figure 9 shows the runoff simulation in 1979 (see also Fig. 4) and the runoff computed with temperatures increased by +4°C as well as with climate-affected snow covered areas shown in Fig. 8. The winter half year had to be computed with snow covered areas estimated from temperatures and precipitation. In view of uncertainties concerning the climate effect on evapotranspiration (Carlson & Bruce, 1991; Gifford, 1988), the runoff coefficient for snow (apart from time shifting) and for rain were left unchanged in the climate run. Because no change of precipitation was assumed, either, there is no significant change of the annual runoff volume. There is, however, a major increase of runoff in the winter half year at the expense of the summer half year, as indicated in Table 3.

It remains to be explained why the winter runoff is increased in a warmer climate by $54.9 \cdot 10^6 m^3$ while $462.5 \cdot 10^6 m^3$ of water is missing in the snow cover on 1 April (see Table 2). When the runoff coefficients in winter, which are mostly around 0.3, are taken into account, it appears that the missing snow contributed by about $140 \cdot 10^6 m^3$ to runoff.

Also, the runoff increase in the winter was only the first part of this contribution. The second part followed as recession flow after 31 March where the spring snowmelt runoff was superimposed on the winter carry-over runoff. This carry-over can be estimated as the difference between the summer runoff volume computed for $T + 4°C$ and starting with the climate-affected increased discharge on 31 March (23.27 $m^3 s^{-1}$) and the summer runoff volume computed for T + 4°C but starting with the original low discharge on 31 March (2.53 $m^3 s^{-1}$). With the predetermined recession formula, it amounts to $87.9 \cdot 10^6 m^3$. The total runoff increase due to the temperature increase in winter is $54.9 \cdot 10^6 m^3 + 87.9 \cdot 10^6 m^3 = 142.8 \cdot 10^6 m^3$ which agrees well with the volume computed above for the missing snow on 1 April. The carry-over from winter to summer could be also estimated from a hypothetical

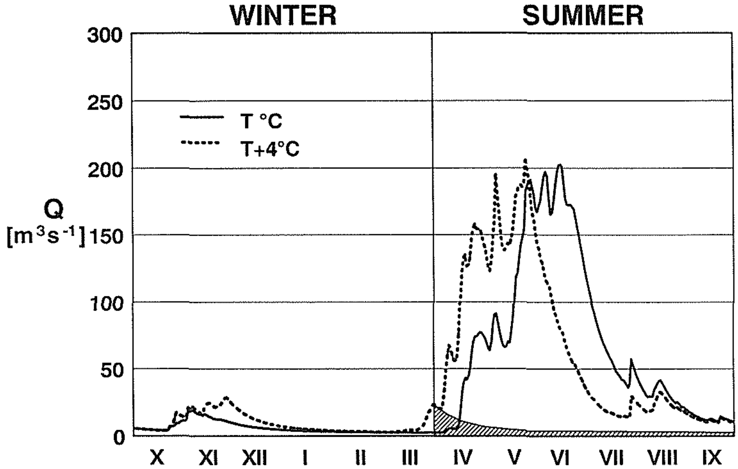

Fig. 9 Simulated runoff in the Rio Grande basin for the hydrological year 1979 (see also Fig. 4) and for a temperature increase of +4°C. The shaded area indicates the hypothetical recession flow due to the carry-over from the winter.

recession flow after 31 March indicated by the dotted line in Fig. 9. In this case, it appears to be smaller (less than $75 \cdot 10^6 m^3$) and corresponds better to the decrease of the summer runoff: In the warmer climate, the snow cover on 1 April is deprived of about $140 \cdot 10^6$ m^3 water, the summer runoff decreases by $73 \cdot 10^6$ m^3, which leaves $67 \cdot 10^6$ m^3 for the runoff carry-over. The runoff increase in the winter does not exactly correspond to the runoff decrease in the summer because the yearly runoff volumes computed for T and for T + 4°C, respectively, are not quite identical.

The effect of a warmer climate on runoff was evaluated in the same way in the years 1976 and 1977. Computed runoff volumes in the winter and summer are listed in Table 4.

Table 3 Seasonal runoff volumes in 1979 and in a warmer climate.

Hydrological year 1979	Winter: October-March ($m^3 \cdot 10^6$)	(%)	Summer: April-September ($m^3 \cdot 10^6$)	(%)	Year: October-September ($m^3 \cdot 10^6$)	(%)
Measured	86.5	7.2	1122.5	92.8	1209.0	100
Simul. T°C	91.9	7.6	1120.1	92.4	1212.0	100
Simul. T + 4°C	146.8	12.3	1046.1	87.7	1192.9	100

Table 4 Redistribution of runoff in a warmer climate in the years 1976, 1977, 1979.

Hydrological year	Winter October-March ($m^3 \cdot 10^6$)	(%)	Summer April-September ($m^3 \cdot 10^6$)	(%)	Year October-September ($m^3 \cdot 10^6$)	(%)
1977 T°C	63.5	24.3	198.2	75.7	261.7	100
T + 4°C	77.3	29.2	187.4	70.8	264.7	100
1976 T°C	93.2	13.1	616.5	86.9	709.7	100
T + 4°C	192.9	28.1	494.8	71.9	687.7	100
1979 T°C	91.9	7.6	1120.1	92.4	1212.0	100
T + 4°C	146.8	12.3	1046.1	87.4	1192.9	100

The extremely low snow reserves on 1 April in 1977 (see Table 2 and Fig. 6) are reflected in the summer runoff. However, the summer precipitation in 1977 was twice as high as the winter precipitation so that the river flow was to a certain extent restored.

In 1976, less runoff was computed for $T + 4°C$ than for T. The deficit may be at least partially attributed to the runoff increase in the last days of September and to a higher carry-over to October which does not appear in the runoff volume for 1976.

CONCLUSIONS

The SRM model has been designed with the snow covered area as an essential input variable in mind. Consequently, it was ready to use remote sensing data from Landsat, NOAA and SPOT satellites as soon as they became available. In addition to the runoff computation, the evaluation of snow reserves in terms of the areal water equivalent was included in the computer program.

Concerning the climate change, it has been pointed out (Nash & Gleick, 1991), that calibration models are not suitable for these studies because only physically based parameters can be meaningfully changed if so required by climate scenarios.

Again, the SRM model has taken up this new task without problems because the parameters are not calibrated but predetermined according to hydrological and physical conditions. In this study, only a temperature increase was considered but changed precipitation and other aspects can be also taken into account.

The increase of winter runoff in a warmer climate generally means a potential increase of hydropower production in the winter at the expense of the summer. A quantitative evaluation for three hydrologically different years shows that this effect in terms of the runoff volume may significantly vary from year to year.

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