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HYDROLOGICAL EFFECTS OF A CHANGED CLIMATE IN HUMID AND ARID MOUNTAIN REGIONS

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SUMMARY

The effect of a hypothetical temperature increase of +4°C on snow cover and on year-round runoff is evaluated for the very humid basin Illecillewaet (1155 km^2, 509-3150 m a.s.l., British Columbia, Canada), the semi-humid basin of Kings River (3999 km^2, 171-4341 m a.s.l., California, USA), and the semi-arid basin of Rio Grande at Del Norte (3419 km^2, 2432-4215 m a.s.l., Colorado, USA). In contrast to current methods of evaluating the climate effect, a realistic seasonal snow cover from satellite monitoring is used to represent the present climate. The non-calibrated SRM model is applied to transform this snow cover under conditions of a warmer climate and to compute the climate-affected runoff.

The winter snow accumulation is particularly reduced in the Kings River basin which has the greatest elevation range. In absolute terms, the smallest snowpack reduction occurred in the semi-arid basin of Rio Grande at Del Norte. The decline of snow covered area in the snowmelt season in accelerated by about one month in all basins. The runoff in the winter half year is about doubled at the expense of the summer half year in the basins Illecillewaet and Kings River. This effect is smaller in the basin Rio Grande at Del Norte. Because the climate change was limited to a temperature increase, there is no significant change in the yearly runoff volume in the basins Kings River and Rio Grande. There is a yearly runoff increase in the Illecillewaet basin due to enhanced glacier melt.

INTRODUCTION

The effect of global warming on runoff is particularly significant in mountain basins due to changed conditions of snow accumulation and snowmelt. In glacierized basins, an increased glacier melt component also enters the picture. The runoff regime is affected by increased temperature even if no change in precipitation or other climate variables are assumed. There are of course studies (e.g., Kite, 1993) in which precipitation and even land use has been changed as well. However, it is then difficult to quantify the effects of the respective components of climate change. Coincidentally, the SRM model, which is used in this study, has been already applied with regard to land use change (Mitchell and DeWalle, 1998), and there is no obstacle to including this aspect in future evaluations of the climate effect. Surprising increases of runoff for higher temperatures has been reported from a Himalayan basin (Singh and Kumar, 1997), but due to the lack of snow cover monitoring, it is difficult to determine whether it resulted from an excessive glacier runoff or from inaccuracies in calibrated model parameters.

The objective of this study is to evaluate quantitatively the effect of a hypothetical temperature increase of +4°C on the winter accumulation of snow and on the runoff during a hydrological year. An opinion is gaining weight that calibration models are not suitable for climate effects studies (Becker and Serban, 1990; Klemeš, 1985) because the model parameters cannot be adequately adjusted to the new climate. Consequently, a non-calibration model with a deterministic approach is used in this study. The method used makes it possible to evaluate not only the changed runoff but also, as an intermediate product, the climate-affected conditions of the snowcover and glaciers.

TEST BASINS

In order to compare the effect of global warming in different climatic zones, the test basins listed in Table 1 are situated in very humid, semi-humid, and semi-arid regions. The respective locations are shown in Figure 1.

Table 1 Test basins for climate-affected snow cover and runoff

Basin	Geographic coordinates	Area (km^2)	Elevation range m a.s.l.	Climate	Average yearly runoff depth cm
Illecillewaet	51°N, 118.1W	1155	509-3150	very humid	145.4
Kings River	37°N, 119.5W	3999	171-4341	semi humid	48.3
Rio Grande	37.4°N, 107.2W	3419	2432-4215	semi arid	22.5

The yearly runoff depths reflect a

wide range of climate conditions. The actual losses are determined from the precipitation/runoff depth ratio. In high mountain basins, it is difficult to evaluate the representative amount of areal precipitation because of the gauge catch deficit for snowfalls and a lack of measurements in the upper parts of the basins.

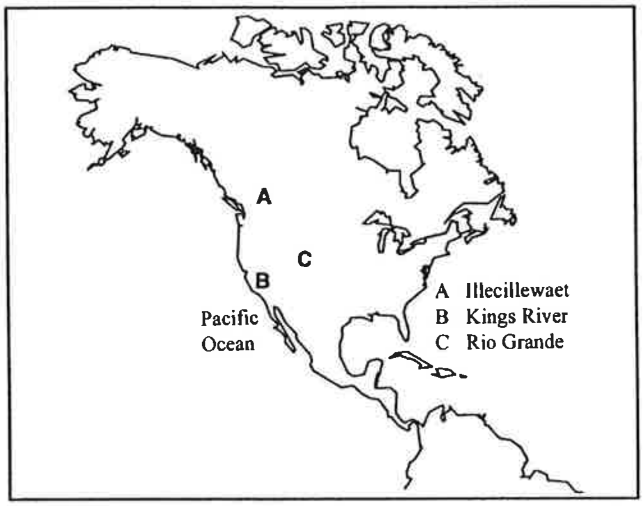

Figure 1 Map location of the test basins: A - Illecillewaet, B - Kings River, C - Rio Grande at Del Norte

In the Illecillewaet basin (British Columbia, Canada), three precipitation gauging stations were available: Revelstoke, 443 m a.s.l.; Glacier Rogers Pass, 1323 m a.s.l.; and Glacier Mount Fidelity, 1875 m a.s.l. Precipitation measurements in the test hydrological year 1984 from these stations were averaged as 155.48 cm for their average elevation of 1214 m a.s.l. From this reference elevation, precipitation amounts in the respective elevation zones of the basin were extrapolated by an altitude gradient of 4% per 100 m, estimated from actual station measurements. The introduction of the altitude gradient for precipitation in this paper serves to refine an earlier evaluation of the effects of climate change on runoff (Rango et al., 1995), although the results are still very similar. In accordance with prevailing opinion,

Table 2 Evaluation of areal precipitation, Illecillewaet River, hydrological year 1984

Elevation zone	Area (km^2)	Mean hypsometric elevation (m a.s.l.)	Adjustment by 4% per 100 m	Extrapolation coefficient	Precipitation	
					Zone cm	Weighted by area cm
A	184.8	980	-9.36%	0.9064	140.93	22.55
B	408.9	1510	+11.84%	1.1184	173.89	61.56
C	468.9	2084	+34.8%	1.348	209.59	85.09
D	92.4	2731	+34.8%	1.348	209.59	16.77
Basin	1155.0					185.97

the increase of precipitation amounts with altitude was stopped for the highest zone D. The results are listed in Table 2.

The average runoff coefficient for the hydrological year 1984 was obtained from this estimate of basin precipitation and the runoff depth measured in the same period:

$$C = \frac{R}{P} = \frac{144.94\,\text{cm}}{185.97\,\text{cm}} = 0.779$$

In the Kings River basin (California), the average precipitation from the available stations in the hydrological year 1973 was 122.35 cm with an average elevation of 2134 m. From this reference elevation, precipitation amounts in the respective elevation zones of the basin were again extrapolated by an altitude gradient of 4% per 100 m. The precipitation increase was stopped in the two highest zones. Results are listed in Table 3.

Table 3 Evaluation of areal precipitation, Kings River, hydrological year 1973

Elevation zone	Area (km^2)	Mean hypsometric elevation (m a.s.l)	Adjustment by 4% per 100 m	Extrapolation coefficient	Precipitation	
					Zone cm	Weighted by area cm
A	595.7	650	-59.34%	0.407	49.80	7.42
B	399.4	1385	-29.94%	0.701	85.77	8.57
C	706.0	2028	-4.22%	0.958	117.21	20.71
D	780.4	2535	+16.06%	1.161	142.05	27.74
E	752.4	2975	+33.66%	1.337	163.58	30.80
F	446.0	3347	+33.66%	1.337	163.58	18.26
G	316.0	3725	+33.66%	1.337	163.58	12.94
Basin	3995.9					126.44

The average runoff coefficient for the hydrological year 1973 can thus be estimated as:

$$C = \frac{R}{P} = \frac{64.57\,\text{cm}}{126.44\,\text{cm}} = 0.511$$

In the basin Rio Grande at Del Norte (Colorado), precipitation was averaged for the stations Del Norte (2402 m a.s.l.) and Wolf Creek Pass (3243 m a.s.l.), amounting to 115.9 cm in 1979. This value was extrapolated from the reference level 2823 m a.s.l. to the mean hypsometric elevations of the respective zones as outlined in Table 4. In this case, the precipitation increase was maintained in the zone C because this zone is not much higher than the Wolf Creek Pass station.

The average runoff coefficient for the hydrological year 1979 can be estimated as:

$$C = \frac{R}{P} = \frac{35.36\,\text{cm}}{134.24\,\text{cm}} = 0.263$$

Summing up, the runoff in the very humid basin Illecillewaet amounts to 78% of precipitation, in the Kings River basin to 51%, and in the semi-arid basin Rio Grande at Del Norte only 26% for the respective years chosen.

Table 4 Evaluation of areal precipitation, Rio Grande at Del Norte, hydrological year 1979

Elevation zone	Area (km^2)	Mean hypsometric elevation (m a.s.l)	Adjustment by 4% per 100 m	Extrapolation coefficient	Precipitation	
					Zone cm	Weighted by area cm
A	780	2719	-4.16%	0.9584	111.08	25.34
B	1584	3155	+13.28%	1.1328	131.29	49.31
C	1355	3566	+29.72%	1.297	150.35	59.59
Basin	3419					134.24

EFFECT OF A WARMER CLIMATE ON SNOW ACCUMULATION

The SRM snowmelt runoff model (Martinec et al., 1998) was used in this study. Figure 2 shows a runoff simulation for the Illecillewaet basin.

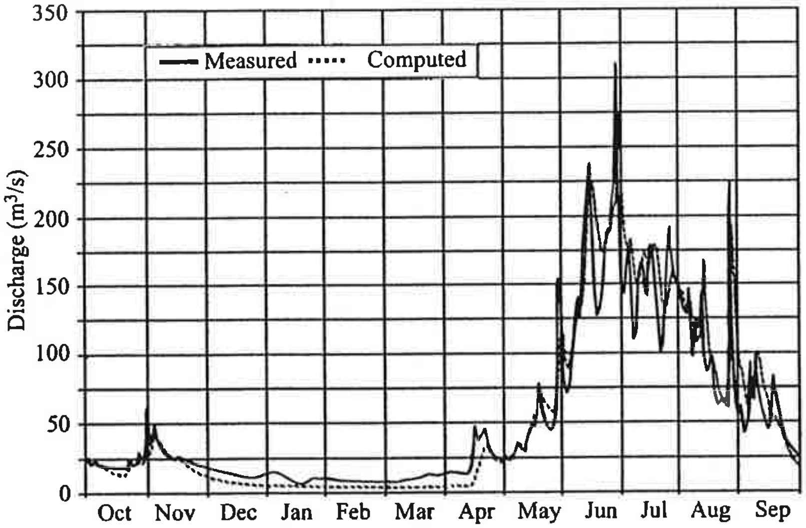

Figure 2 Runoff simulation in the Illecillewaet basin in hydrological year 1984

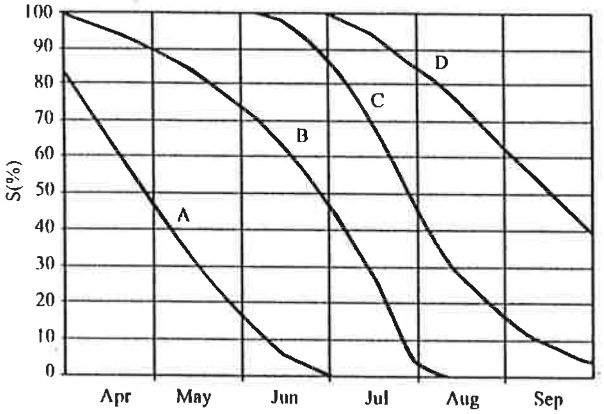

Figure 3 Conventional snow cover depletion curves in elevation zones A, B, C, and D of the Illecillewaet basin for the 1984 snowmelt season

One of the input variables for this computation is the snow coverage during the snowmelt season. The depletion curves of snow covered area derived for the respective elevation zones from a periodical satellite snow cover mapping are shown in Figure 3. As has been explained elsewhere (Hall and Martinec, 1985), the so called modified depletion curves (MDC) can be derived from the conventional ones which indicate the average areal water equivalent at the starting date, in this case, on 1 April 1984. The occasional summer snowfalls are integrated into the seasonal snow cover which is observed by satellites. Consequently, modified depletion curves including new snow (MDC_{INCL}) are first derived. In order to evaluate the initial snow water equivalent, the computed melt depth of new snow must be eliminated from snowmelt totals resulting in modified curves excluding new snow (MDC_{EXCL}), as illustrated in Figure 4. Based on snow conditions in the given year thus evaluated, the effect of a warmer climate can be computed by the SRM program as follows:

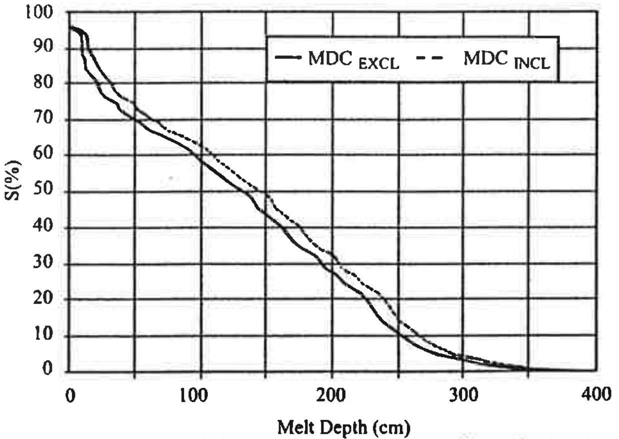

Figure 4 Modified depletion curves MDC_{INCL} (including new snow) and MDC_{EXCL} (excluding new snow) for zone B of the Illecillewaet basin for the 1984 snowmelt season

$$\Delta HW = \sum_{N=1}^{183} [a_n \cdot T_n \cdot S_n + a_n \cdot T_n (1-S_n) + P_{Rn}] - \sum_{N=1}^{183} [a_n \cdot T_n' \cdot S_n' + a_n \cdot T_n' (1-S_n') + P_{Rn}'] \quad (1)$$

where

ΔHW = 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, represented by the year 1984, in degree-days [°C · d]
T' = temperature hypothetically changed by + 4°C [°C · d]
S = ratio of snow covered area to total area, 1984
S' = ratio of snow covered area to total area, T + 4°C
P_R = rain according to a critical temperature, 1984
P_R' = rain according to a critical temperature, T + 4°C
183 = the number of days for the October through March accumulation period (182 days in a non-leap year)

If the losses by evaporation from the snow surface in the winter half year can be neglected, the difference of the winter input to runoff from Equation 1 equals the difference in the snow accumulation on 1 April, ΔHW.

Figure 5 shows the winter-adjusted modified depletion curve $MDC_{EXCL\ WA}$, for the zone A of the Illecillewaet basin. It is derived from MDC_{EXCL} by cutting off the area corresponding to ΔHW = 41 cm, computed by Equation 1. As will be explained in the next section, $MDC_{EXCL\ WA}$ can be used to derive the climate-affected depletion curve of the snow coverage which is one of the input variables for modeling the runoff in a changed climate.

As an intermediate result, $MDC_{EXCL\ WA}$ indicates snow reserves for a changed climate in terms of areal water equivalents in the respective elevation zones. The SRM program computes these values by accumulating the zonal melt from daily melt depths multiplied by the corresponding snow coverage. In this way, snow reserves have been evaluated for the remaining zones of the

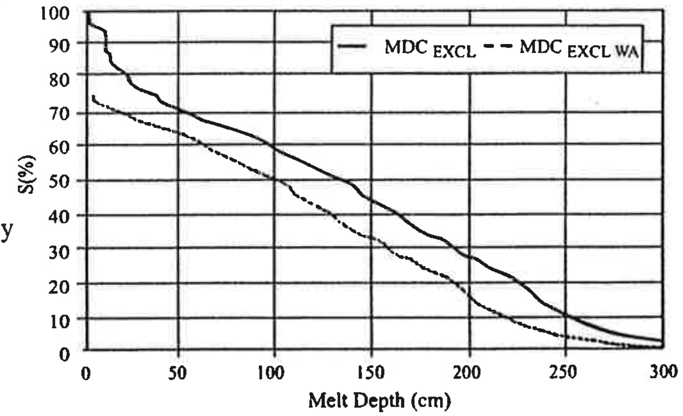

Figure 5 Winter adjusted modified depletion curve MDC_{WA} for zone B of the Illecillewaet basin for 1984

Illecillewaet basin as well as for the other basins under study. Results are listed in Table 5. The values of ΔHW from the SRM program are slightly higher than the values computed by Equation 1 because MDC_{EXCL} is cut off where the accumulated zonal melt depth (obtained by adding daily values) equals or exceeds ΔHW from Equation 1.

Table 5 Effect of temperature increase on the water equivalent of snow cover on 1 April (HW)

BASIN, ZONES		HW (T) cm	ΔHW cm Equation 1	ΔHW cm Program	HW (T + 4°C) cm
Illecillewaet 1984					
A	509-1200 m	58.0	-41.0	-41.9	16.1
B	1200-1800 m	127.1	-27.8	-28.8	98.3
C	1800-2400 m	160.3	-14.1	-14.3	146.0
D	2400-3150 m	NA	0	0	NA
Kings River 1973					
A	171-1100 m	0	0	0	0
B	1100-1700 m	6.6	-6.6	-6.6	0
C	1700-2300 m	78.9	-80.7	-78.9	0
D	2300-2750 m	88.1	-33.5	-33.6	54.4
E	2750-3200 m	89.4	-14.0	-14.4	75.0
F	3200-3500 m	96.7	-4.5	-5.8	90.9
G	3500-4341 m	90.8	-1.1	-1.7	89.1
Rio Grande 1979					
A	2432-2926 m	58.1	-36.9	-37.7	20.4
B	2926-3353 m	88.2	-10.1	-10.7	77.5
C	3353-4215 m	94.1	-2.2	-2.2	91.9

NA: The water equivalent cannot be evaluated because snow was not completely melted by 30 September.

CHANGES OF RUNOFF REGIME IN A WARMER CLIMATE

In order to predict the yearly hydrograph for the hypothetical temperature increase T + 4°C, it is necessary to derive the climate-affected depletion curves of the snow coverage, CDC_{CLIM}, because snow covered areas are, as in Figure 2, one of the input variables for the SRM model. To this effect, the winter adjusted modified depletion curve (excluding new snow), used for evaluation in the previous section, must be converted into the climate-affected modified

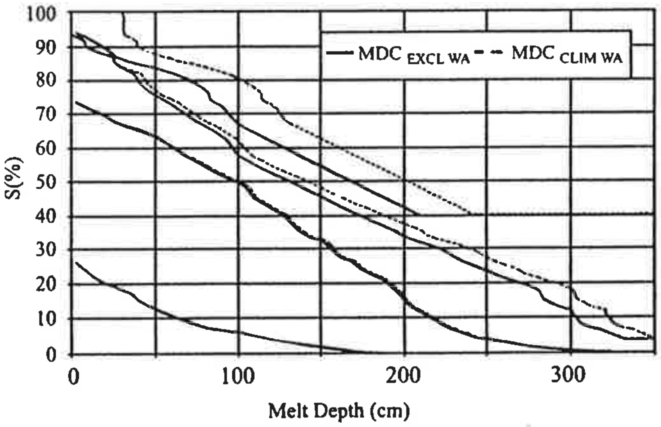

Figure 6 Climate-affected and winter adjusted modified depletion curves, $MDC_{CLIM\ WA}$ for zones A, B, C, and D of the Illecillewaet basin

depletion curve $MDC_{CLIM\ WA}$ by taking into account the "surviving" summer snowfalls.

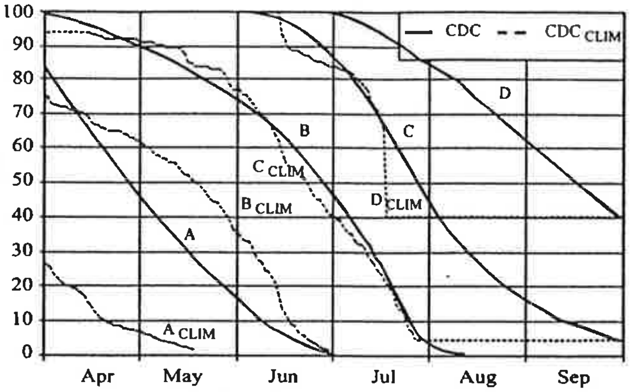

Figure 7 Climate-affected conventional depletion curves of the snow coverage, CDC_{CLIM}, compared with the original depletion curves for elevation zones A, B, C, and D of the Illecillewaet basin

As shown in Figure 6, the computer program produced identical curves for zone A because there were no snowfalls in April-September. There is however a small difference in zone B and a greater difference in zone C as also illustrated in Figure 6. As can be expected, more snowfalls are preserved in the warmer climate with increasing altitude.

Finally, the climate affected depletion curves of the snow coverage ($CDC_{CLIM\ WA}$) are derived from these climate affected and winter-adjusted modified curves. Figure 7 shows the curves for all zones. The decline of

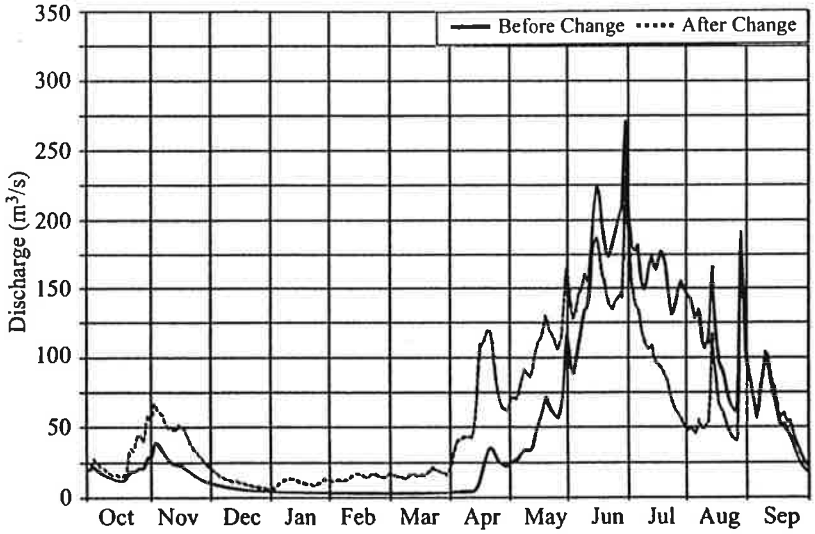

Figure 8 Computed runoff in the Illecillewaet basin for T (temperatures in hydrological year 1984) and T + 4°C

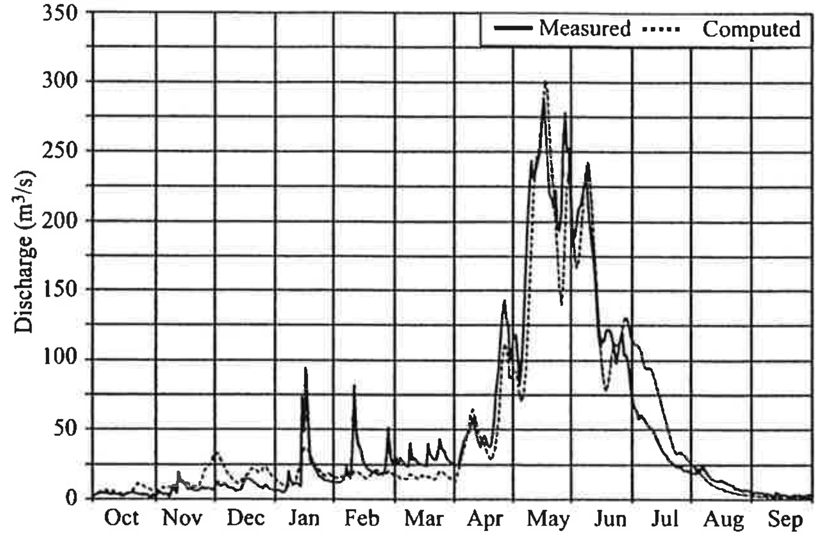

Figure 9 Runoff simulation for the Kings River in hydrological year 1973

the snow coverage stops in C zone at S = 0.04 and in D zone at S = 0.4 due to the presence of glaciers.

Figure 8 shows the original runoff simulation for the hydrological year 1984 and the model run for T + 4°C with climate-affected depletion curves of snow coverage. The difference between these hydrographs may be considered as the effect of the temperature increase. The shift of the CDC's (Figure 7) shows that the snowmelt season takes place by about one month earlier due to the temperature increase. Accordingly, the seasonally changing values of the degree-day factor and of the runoff coefficient for snow have been shifted to

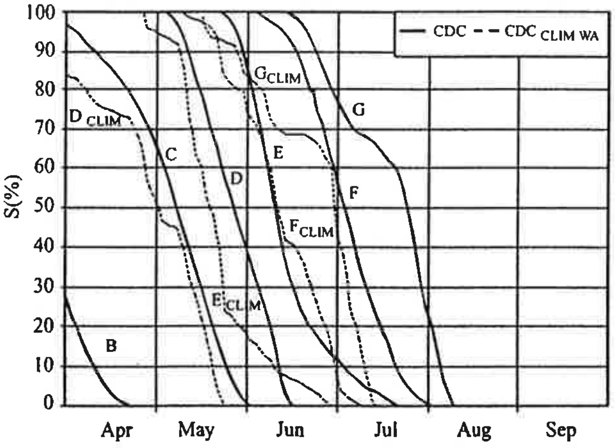

Figure 10 Climate-affected conventional depletion curves of the snow coverage, CDC_{CLIM}, compared with the original depletion curves for elevation zones B, C, D, E, F, and G of the Kings River basin

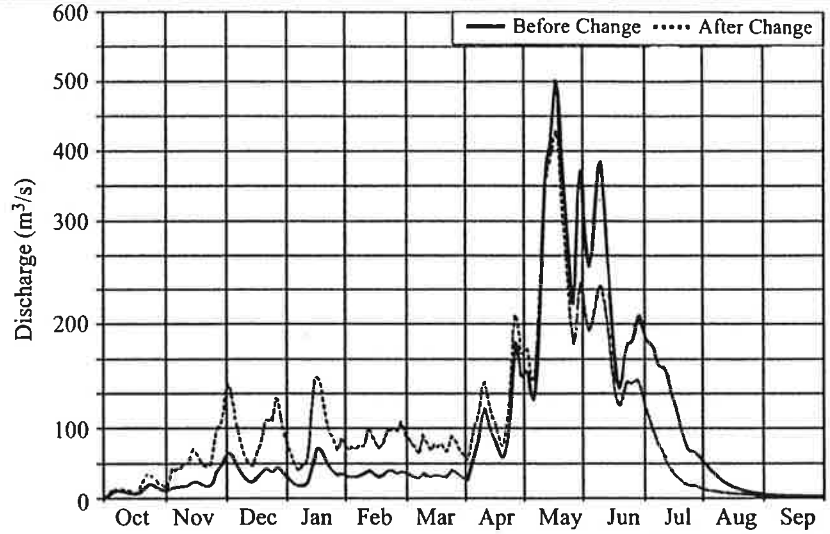

Figure 11 Computed runoff in the Kings River basin for T (temperatures in the hydrological year 1973) and T + 4°C

earlier months in the climate model run. The present climate scenarios supplied by General Circulation Models are not yet specific enough to make other changes of model parameters.

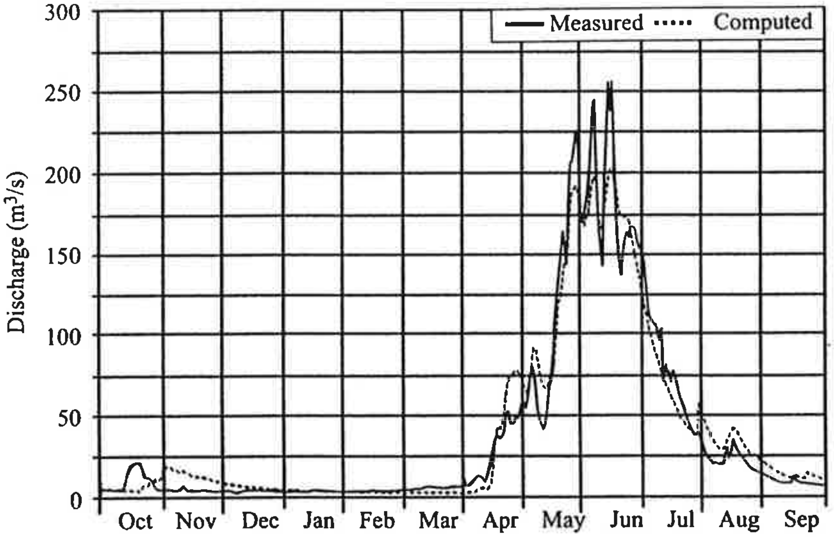

Figure 12 Runoff simulation for the Rio Grande at Del Norte in hydrological year 1979

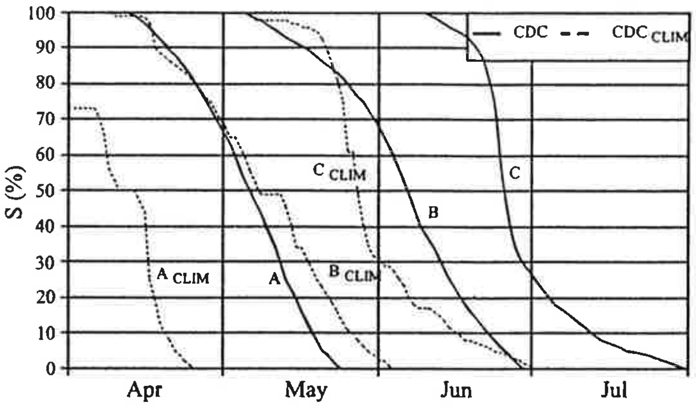

Figure 13 Climate-affected conventional depletion curves of the snow coverage, CDC_{CLIM}, compared with the original depletion curves for elevation zones A, B, and C of the Rio Grande at Del Norte basin

Results in the other basins have been obtained by the same procedure as demonstrated for the basin Illecillewaet. Figure 9 shows the year 1973 for the Kings River. The original and climate-affected depletion curves are shown in Figure 10. A comparison of runoff simulated for the present climate, represented by the year 1973, and for a temperature increase T + 4°C, is shown in Figure 11. For the basin Rio Grande at Del Norte, analogical results are shown in Figures 12, 13, and 14, with the year 1979 representing the present climate. In this basin, the measured runoff

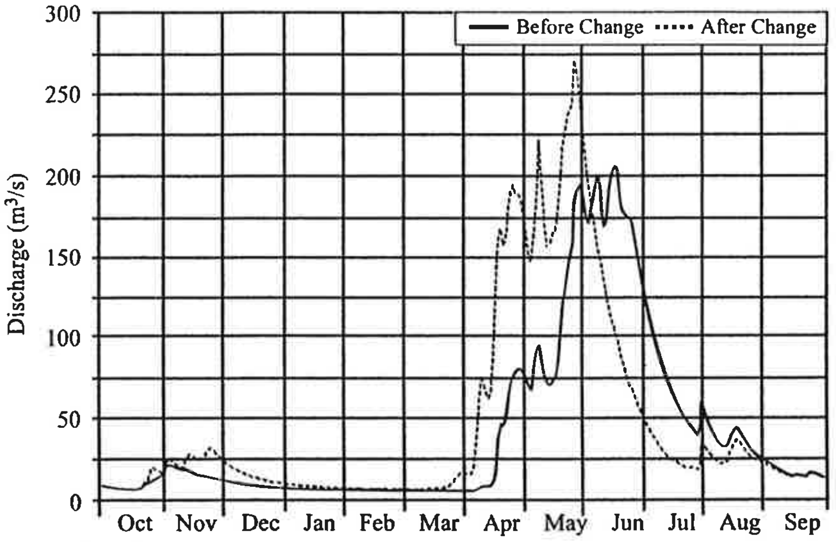

Figure 14 Computed runoff in the Rio Grande basin for T (temperatures in the hydrological year 1979) and T + 4°C

data were corrected for reservoir operation in order to obtain natural runoff. Data listed in Table 6 indicate the redistribution of runoff in a warmer climate between the winter and summer as well as during the summer half year.

Table 6 Redistribution of runoff under present and warmer climate conditions

BASIN		Oct.-March.		April-Sept.		Entire year		Percent of Apr.-Sept. runoff	
		$10^6 m^3$	%	$10^6 m^3$	%	$10^6 m^3$	%		
Illecillewaet 1984								Apr.-June	July-Aug.
Present	T°C	169.3	10.2	1495.6	89.8	1664.9	100	41.4	49.1
Future	T + 4°C	341.6	18.9	1465.3	81.1	1806.95	100	58.3	30.9
Kings River 1973								Apr.-May	June-July
Present	T°C	428.8	17.1	2080.5	82.9	2509.3	100	49.8	47.5
Future	T + 4°C	973.7	37.2	1642.6	62.8	2616.3	100	63.1	35.5
Rio Grande 1979								Apr.-May	June-July
Present	T°C	91.9	7.6	1120.1	92.4	1212.0	100	31.8	63.2
Future	T + 4°C	146.7	12.3	1046.2	87.7	1192.9	100	57.2	27.8

ASSESSMENT OF RESULTS

Snow conditions

If there is an increase of temperature and no change of precipitation, the snow reserves on 1 April naturally decrease in all three basins. As listed in Table 5, this effect in terms of the average areal water equivalent is largest in the lowest zones of the basin Illecillewaet and Rio Grande and decreases with the altitude. In the highest zone of the Illecillewaet basin, there is no decrease of the snow cover because the winter temperatures, even after a hypothetical increase of +4°C, never exceeded 0°C. Consequently, no snowfalls were converted to rainfalls, and no snow was melted in the winter. In the Kings River basin, there is again practically no effect in the highest zone due to low temperatures but also no effect in the lowest zones because there was no snow to start with. The greatest decrease of the snow water equivalent occurs when winter temperatures are around or slightly below 0°C. This appears to be the case around 2000-2700 m a.s.l. in the Kings River and Rio Grande basins. In the Illecillewaet basin, which is located about 1500 km to the north, the maximum effect occurs at a lower altitude of about 1000 m a.s.l.. The decrease of the snow water equivalent stops or becomes insignificant in the Kings River and Rio Grande basins at about 3800 m a.s.l.. In the Illecillewaet basin, this occurs already at about 2500 m a.s.l., again due to the comparatively low temperatures in this northern basin.

According to Table 5, the greatest snow accumulation in the present and future climate occurs in the humid climate of the Illecillewaet basin. However, an adequate comparison between basins would only be possible if average years would have been available for this study. Instead, the annual runoff of 1984 in the Illecillewact basin was 99% of the average, the annual runoff of 1973 in the Kings River basin was 130% of the average, and the annual runoff of 1979 in the Rio Grande basin was 157% of the average.

Even so, the weighted average snow water equivalent in Table 5 shows that the water volume stored in the seasonal snow cover on 1 April was reduced by the warmer climate to about 64% in the Kings River basin and to about 83% in the other two basins. It appears that the great elevation range of the Kings River basin enables the temperature increase to take the full effect.

Additional information about the future snow conditions concerns the snow covered areas. As illustrated by Figures 7, 10, and 13, the depletion curves of the snow coverage will be shifted in the warmer climate by about one month. Particularly in the Rio Grande basin (Figure 13), the snow coverage in zone C in the warmer climate becomes approximately the snow coverage of zone B in the present climate, and the curve for zone B approaches the original curve for zone A. This means that for a temperature increase of +4°C, the snow line is modeled to be about 400 m higher (or almost one full elevation zone) on the same corresponding dates.

Runoff conditions

In the present climate, the major part of the runoff occurs in the summer half year, as in characteristic for mountain basins. As indicated in Table 5 for the years studied, it amounts to 92.4% in the Rio Grande basin, to 89.8% in the Illecillewaet basin, and to 82.9% in the Kings River basin. It can be noted that the yearly runoff volume in the semi-arid Rio Grande basin is smaller (in spite of the wet year) than in the humid Illecillewaet basin, although the catchment area is three times larger. The overwhelming proportion of the summer runoff in the Rio Grande basin can be attributed to its altitude, a cold 1978-1979 winter, a high accumulation of snow, and possibly to high losses in the semi-arid climate which affect rainfall runoff more than snowmelt runoff.

In order to evaluate quantitatively the effect of a warmer climate, the hypothetical climate change was limited to a temperature increase of +4°C. Consequently, the yearly runoff volumes computed for T + 4°C remained approximately unchanged with the exception of the Illecillewaet basin in which an increase in glacier melt resulted in an excess. The winter runoff was doubled, but the summer runoff remained nearly the same thanks to this glacier contribution. The computation of the glacier melt will have to be improved when more basins with large glacier areas are studied. SRM will be modified in the near future to account for a decrease in glacier area as the warmer temperatures of the changed climate persist.

In the other two basins, the winter runoff was increased in the warmer climate, in this case at the expense of the summer runoff. In the semi-arid basin of Rio Grande, this effect was smaller in relative terms as well as in absolute terms than in the Kings River basin.

Apart from this seasonal redistribution of runoff, it can be noted in Figures 8, 11, and 14 that most of the summer runoff was shifted from July-August to April-June in the Illecillewaet basin and from June-July to April-May in the other two basins, as also documented in Table 6. No increase of flood peaks occurred in the examined years but it cannot be excluded in other cases.

An increase of temperature affects the snow accumulation, the snow coverage, and the runoff regime in present climates ranging from semi-arid to very humid conditions. The effect is particularly significant in the Kings River basin with a great elevation range. It decreases with altitude and also for colder temperatures in the more northern Illecillewaet basin. In absolute magnitudes, the smallest effect naturally occurs in the semi-arid Rio Grande at Del Norte basin.

Data from single years were used which deviate from long term average conditions. In order to improve such evaluation, it is envisioned to derive normalized data sets which would better represent today's average climate.

CONCLUSIONS AND OUTLOOK

The SRM computer program can handle climate scenarios with temperature and precipitation changed independently in the winter and summer half year. For example, as mentioned elsewhere (Ehrler, 1998), T + 1.8°, P + 5% in the winter and T + 1.9°, P - 10% in the summer, is one of the scenarios developed for the European Alps for the year 2030. Also, the values of the seasonally changing model parameters such as the degree-day factor and the runoff coefficient can be shifted by a selected number of days according to the new climate conditions.

Currently, new versions of the computer program are being developed enabling temperature and precipitation to be changed not only on a half-yearly basis, but also monthly and daily. It is envisioned to take into account changes of cloudiness and solar radiation (Kustas et al., 1994) as soon as such scenarios become available. Evaluations of the hydrological effects of climate change are important for the planning of water power generation, allocation of water supply, and with the outlined method, also for winter tourism. A North American meeting (Gleick et al., 1993) provided an impulse to stimulate these efforts, but further coordination and comparison of results would now be useful.

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