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CLIMATE EFFECTS ON FUTURE RUNOFF REGIMES OF PACIFIC MOUNTAIN TRIBUTARIES

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ABSTRACT: Because most Pacific mountain tributaries are situated in the Northern hemisphere, the runoff regime is characterized by high river flows in April-September and low river flows in October-March. With regard to global warming, a partial shift of inflows into the Pacific Ocean from the summer to the winter has to be expected. For quantitative evaluations, the SRM snowmelt runoff model is applied in several basins in the Pacific rim, ranging from 57° North (west coast of Canada) to 45° South (east coast of New Zealand). In the Kings River basin of California (4000 km^2, 171-4341 m a.s.l.) with the envisaged rise of temperature, runoff in October-March is significantly increased at the expense of snow accumulation in winter and summer runoff. Also, summer runoff peaks are shifted to earlier dates. Similar redistribution of runoff is evaluated for the Illecillewaet River basin of British Columbia (1155 km^2, 509-3150 m a.s.l.), a tributary to the Columbia River. However, an additional effect is observed: Because nearly 10% of the surface is covered with permanent snowfields and glaciers, runoff would be temporarily increased from these frozen reserves. A quantitative analysis reveals that in the Illecillewaet basin, even a moderate increase of precipitation would not offset a gradual disappearance of glaciers due to increased melting.

KEY TERMS: Global warming; snowmelt runoff; models; runoff redistribution; snow accumulation; glaciers.

INTRODUCTION

As the attention of the world community is increasingly focused on global warming, hydrologists must provide answers to questions about the climate effect on runoff regimes. In mountain basins dominated by snowmelt, it can be expected that runoff will be partially shifted from the summer to the winter. Most of the Pacific mountain tributaries are situated in the Northern hemisphere, so that the inflow from these basins into the Pacific Ocean may increase in October through March at the expense of the period April through September. The total yearly runoff may also change, in particular if precipitation changes would also take place.

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This paper concentrates on the quantitative evaluation of the effect of temperature increased by 4°C in a whole hydrological year, in line with predictions for the western United States (Gutowski et al., 1988). The presented method can equally take into account varied changes of temperature as well as specified changes of precipitation.

RUNOFF MODELLING FOR PACIFIC MOUNTAIN RIVERS

The SRM snowmelt runoff model (Martinec et al., 1994) is used to simulate the year-round runoff in the present climate and to predict the future runoff resulting from a temperature increase. The model has been applied or is under application in over 60 basins around the world. Figure 1 shows locations of basins which are pertinent to the Pacific rim:

Iskut, Canada, 9350 km^2, 200-2556 m a.s.l., 57°N, 131.3°W
Illecillewaet, Canada, 1155 km^2, 509-3150 m a.s.l., 51°N, 118.1°W
Kings River, USA, 4000 km^2, 171-4341 m a.s.l, 37°N, 119.5°W
Yellow River, China, 121972 km^2, 2500-5224 m a.s.l., 34.5°N, 99.5°E
Gongmisi, China, 2000 km^2, 1776-3200 m a.s.l., 43°N, 88°E
Okutadami, Japan, 422 km^2, 782-2346 m a.s.l., 37°N, 113°E
Pukaki basin, New Zealand, 1405 km^2, 524-3760 m a.s.l., 44°S, 169°E
Grande (Terra del Fuego), Argentina/Chile, 9050 km^2, 54°S, 68°W

Figure 1. Location of basin runoff simulations on the Pacific rim using SRM

The Kings River and Illecillewaet River basins have been selected in this paper to demonstrate the climate effect on future runoff regimes. The SRM model computes melt from the snow covered area which gradually decreases during the snowmelt season as monitored by earth observing satellites. If temperature is increased, the depletion curves of the snow coverage are shifted towards earlier dates, as has been shown in prior papers, for e.g., Martinec and Rango, (1989). This shift is further increased if the climate effect on the winter accumulation of snow is also taken into account (Martinec et al., 1994).

This effect is automatically determined by SRM as the difference between the winter input to runoff in the present and future climate, respectively:

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

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 [°C] at mean hypsometric elevation
T' = temperature in the changed climate [°C]
S = ratio of snow covered area to total area
P_R = rain according to a critical temperature

182 is the number of days from October to March (183 in a leap year).

The input to runoff thus consists of snowmelt from the stable snow cover (S), melting of snow which temporarily covers the snow free area (1-S) (this snow is kept on storage by the SRM precipitation algorithm until melting days occur), and rain.

CLIMATE EFFECT ON RUNOFF IN THE ILLECILLEWAET BASIN

The Illecillewaet River is a tributary to the upper Columbia River. For model computations, the basin is divided into four elevation zones which are listed in Table 1.

The hydrological year 1984 (October 1983 - September 1984) has been selected to represent the present climate and runoff regime. The measured and SRM simulated runoff is shown in Figure 2. In the absence of satellite snow cover monitoring in the winter, the snow cover in the respective elevation zones and months has been assumed either as temporary (snow coverage = 0) or stable (snow coverage = 1). The model parameters have been predetermined in a usual range for this size of a mountain basin with the exception of the temperature lapse rate, which was lowered in winter to 0.5°C/100m. Even lower values might be

TABLE 1. Elevation Zones of the Illecillewaet Basin, British Columbia

Zone	Area km^2	Percent	Elevation range m a.s.l.	Mean hyposometric elevation m a.s.l.
A	184.8	16.0	509-1200	980
B	408.9	35.4	1200-1800	1510
C	468.9	40.6	1800-2400	2084
D	92.4	8.0	2400-3150	2731
TOTAL	1155.0	100	509-3150	

applicable according to actual temperature data from different altitudes and according to the local climate as described for a World Meteorological Organization project (WMO, 1986). As expected for a mountain basin, runoff in the winter half year constitutes only a minor part of the yearly total. An assumed temperature increase of +4°C results in a significant increase of the winter proportion as shown by the runoff simulation in Figure 3. The following increase of the winter input to runoff shown in Table 2 is evaluated by Eq. (1).

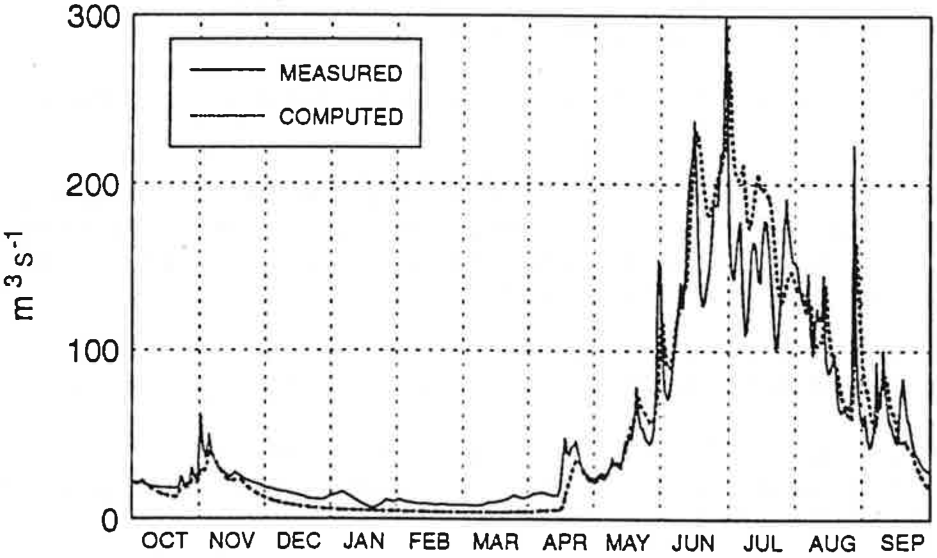

Figure 2. Measured and simulated runoff in the Illecillewaet basin (British Columbia) for the hydrological year 1984.

In the snowmelt period, runoff in the present climate is computed from the gradually diminishing snow covered area indicated by conventional depletion curves, CDC (See Figure 4). These curves are derived from periodical snow cover mapping by satellites. In order to compute runoff for a temperature increase of +4°C, the climate-affected depletion curves are derived by a computer program which takes into account the decrease of snow accumulation from winter as well as

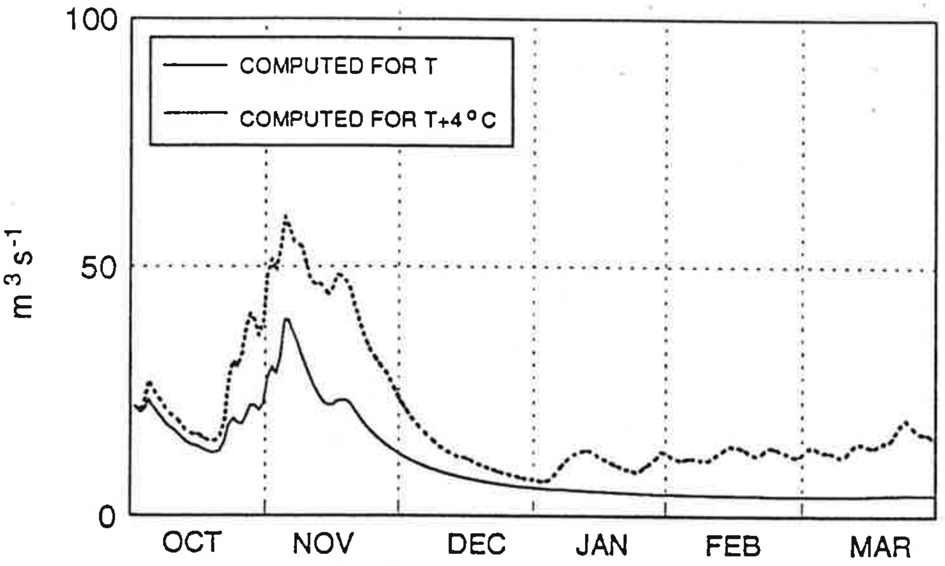

Figure 3. Winter runoff in the Illecillewaet basin computed for present temperatures (represented by the winter 1983-1984) and for an increase of +4°C.

TABLE 2. Increase of Winter Input to Runoff and Decrease of Snow Accumulation in the Illecillewaet River Basin.

Zone	Input present Climate, T, cm	Input future Climate, T+4°C, cm	Decrease ΔHW, cm
A	37.23	69.33	32.10
B	15.91	40.75	24.84
C	0	11.13	11.13
D	0	0	0

increased temperatures continuing in the snowmelt period. This procedure is described by Rango and Martinec (in press).

The climate-affected and winter-adjusted depletion curves, $CDC_{CLIM\,WA}$, are plotted in Figure 4 for comparison with the original curves. Figure 5 shows runoff in a hydrological year computed for the present climate and for temperatures increased by 4°C. Runoff volumes are summarized in Table 3.

As a result of higher temperatures, the winter runoff is almost doubled but there is no corresponding decrease in the summer runoff so that the yearly runoff increases by $194.4 \times 10^6 m^3$. Recalling Figure 4, this additional runoff appears to be at least partially produced at the expense of permanent snowfields and glaciers in the zones C,D: Without

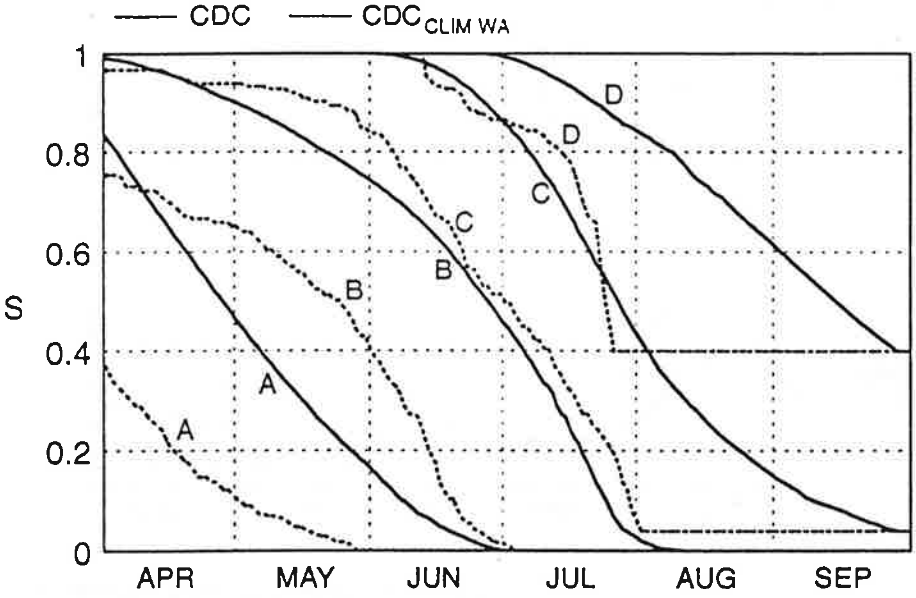

Figure 4. Depletion curves of snow coverage for the elevation zones of the Illecillewaet basin from satellite monitoring in 1984 and derived for a temperature increase of 4°C throughout the hydrological year.

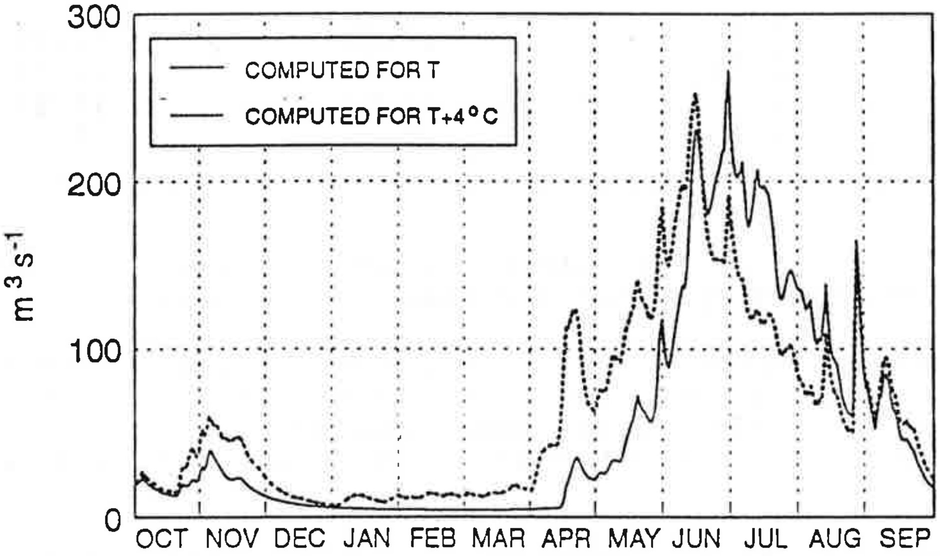

Figure 5. Runoff in the Illecillewaet basin in a hydrological year computed for the present climate (represented by the year 1984) and for a temperature increase of 4°C.

TABLE 3. Winter and Summer Runoff Volumes in the Illecillewaet Basin

	October - March $\times 10^6$ m^3	 %	April - September $\times 10^6$ m^3	 %	Hydrological Year $\times 10^6$m^3	 %
Computed with T°C	167.7	10.0	1508.4	90.0	1676.1	100
Computed with T+4°C	311.6	16.7	1558.9	83.3	1870.5	100

glaciers, the snow covered area would decline to zero in early August, but the glacier area does not diminish and continues to be available for melting until the end of September. Also, the temperature increase converts most snowfalls in September in the C and D zones to rainfalls immediately contributing to runoff whereas most snowfalls occuring in the present climate in September are not melted by the end of the month and are carried over to the next hydrological year. Another reason for the runoff excess is the shift of snowmelt to months with higher runoff coefficients (smaller losses), in particular to the winter months when a certain snowmelt or rainfall input is assumed to produce more runoff than in a month with evapotranspiration from vegetation. With regard to the snowmelt period, it has been suggested (van Katwijk et al., 1993) that the seasonally changing model parameters be shifted according to the new climate. Should higher temperatures generally increase losses, the runoff excess would be reduced. However, opinions vary with regard to the opposite effects of increased temperature (increased evapotranspiration) and increased CO_2 (decreased evapotranspiration) on the net evapotranspiration (Carlson and Bunce, 1991, Gifford, 1988).

CLIMATE EFFECT ON RUNOFF IN THE KINGS RIVER BASIN

In view of its elevation range, the Kings River basin is divided for model computations into seven elevation zones which are listed in Table 4.

The hydrological year 1973 (October 1972 - September 1973) has been selected to represent the present climate and runoff regime. The measured and simulated runoff is shown in Figure 6. As in the Illecillewaet basin, snow covered areas in the winter had to be estimated by assuming stable or temporary snow cover conditions in the different elevation zones in the respective months. The summer runoff is again prevailing, but there are more noticeable runoff peaks in winter than in the Illecillewaet basin (see Figure 2). This is due to the low elevation of zone A as well as to the more southerly location of the Kings River basin. With a temperature increase of +4°C, the winter runoff is doubled as shown in Figure 7. The increase of the winter input to runoff evaluated by Eq. (1) is given in Table 5. The unchanged input in the Zone A indicates that there was no snow present before or after the temperature increase. Present temperatures in Zone G are so low that the effect of an increase by +4°C is very small.

TABLE 4. Elevation Zones of the Kings River Basin, California

Zone	Area km$_2$	Percent	Elevation Range m a.s.l.	Mean Hypsometric Elevation m a.s.l
A	597	14.9	171-1100	650
B	404	10.0	1100-1700	1385
C	706	17.7	1700-2300	2028
D	778	19.5	2300-2750	2535
E	751	18.8	2750-3200	2975
F	447	11.2	3200-3500	3348
G	316	7.9	3500-4341	3725
TOTAL	3999	100.0	171-4341	

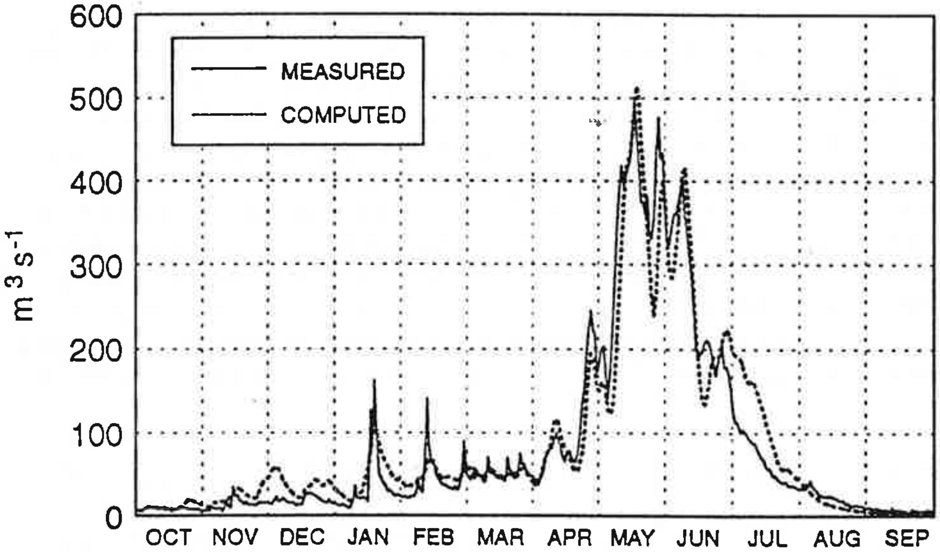

Figure 6. Measured and simulated runoff in the Kings River basin (California) for the hydrological year 1973.

In the snowmelt period, runoff in the present climate is computed from the gradually decreasing snow covered area indicated by conventional depletion curves, CDC, which are shown in Figure 8. As indicated by the small value of ΔHW for zone B in Table 5, there was little snow at this elevation. Taking into account ΔHW, the climate affected, winter adjusted depletion curves of snow coverage, $CDC_{CLIM\ WA}$, are derived (Rango and Martinec, in press) and plotted in Figure 8. In the new climate, there no longer is snow in Zone B and all other depletion curves are shifted towards earlier months. Only curves for the zones C, E, and G are shown in Figure 8 in order to obtain a clearer picture of the time shift. In contrast to the Illecillewaet basin, there is no residual glacier area in the Kings River basin so that no

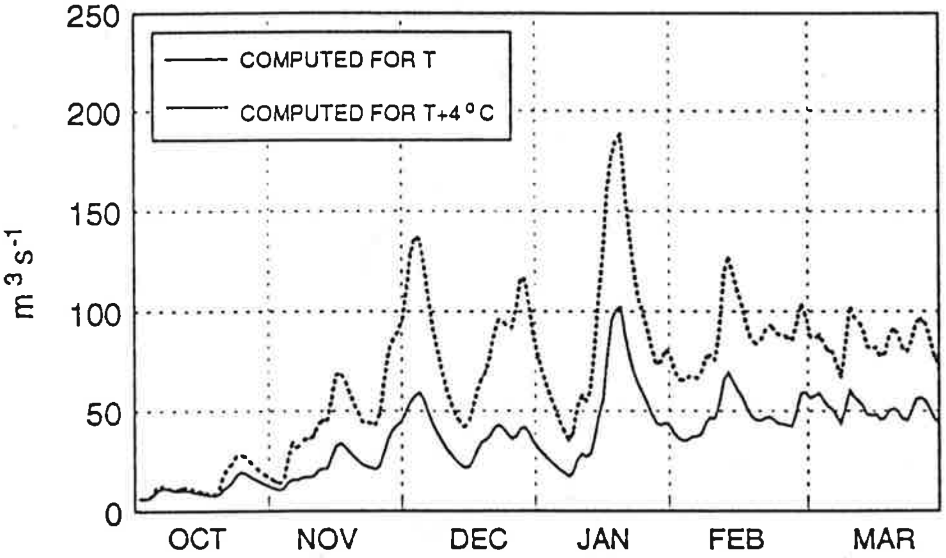

Figure 7. Winter runoff in the Kings River basin computed for the present temperatures (represented by the winter 1972-1973) and for an increase of 4°C.

TABLE 5. Increase of Winter Input to Runoff and Decrease of Snow Accumulation in the Kings River Basin.

Zone	Input Present Climate, T, cm	Input Future Climate, T+4°C, cm	Decrease Δ HW, cm
A	116.2	116.2	0
B	113.1	116.2	3.1
C	35.4	113.8	78.4
D	11.2	44.2	33.0
E	1.8	14.8	13.0
F	0.7	5.2	4.5
G	0	0.83	0.83

additional input to runoff results from the increase of temperature. Figure 9 shows runoff in a hydrological year computed for the present climate with CDC and for temperatures increased by +4°C (with $CDC_{CLIM\ WA}$). Runoff volumes are listed in Table 6.

In a way similar to the Illecillewaet basin (see Table 3), the winter runoff in the Kings basin is almost doubled in the warmer climate. However, there is no glacier to compensate for this shift to winter and so the summer runoff is decreased. The small excess in the annual runoff with T+4°C is due to shifting snowmelt to months with smaller losses as computed by runoff coefficients.

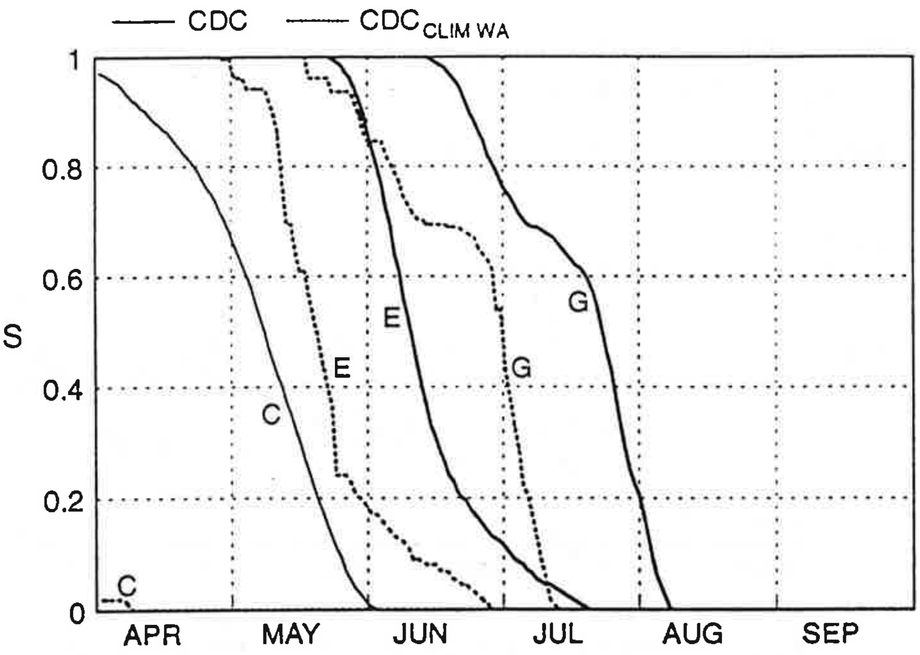

Figure 8. Depletion curves of snow coverage for the elevation zones C, F, G of the Kings River basin from satellite monitoring in 1973 and derived for a 4°C temperature increase throughout the hydrological year.

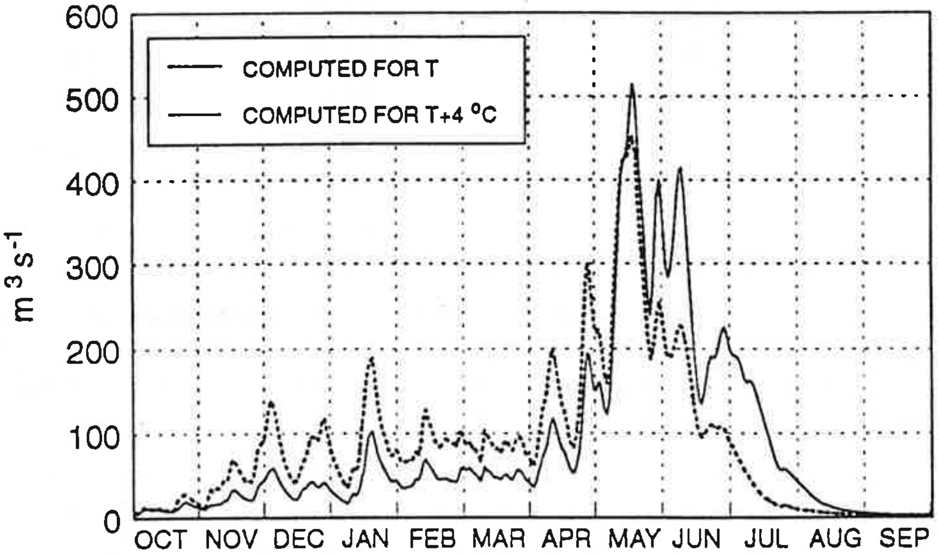

Figure 9. Runoff in the Kings River basin in a hydrological year computed for the present climate (represented by the year 1973) and for a temperature increase of 4°C.

TABLE 6. Winter and Summer Runoff Volumes in the Kings River Basin.

	October - March $\times 10^6$ m^3	%	April - September $\times 10^6$ m^3	%	Hydrological Year $\times 10^6$ m^3	%
Computed with T°C	574.3	21.5	2093.7	78.5	2668	100
Computed with T+4°C	1084.2	39.3	1673.6	60.7	2757.8	100

CONCLUSIONS

A projected temperature rise of 4°C throughout the hydrological year results in substantial changes in the runoff regime of mountain basins on the Pacific rim. For the winter half year period, the presently insignificant snowmelt is increased and some of today's snowfalls are converted to rainfalls. As computed by the SRM model, a corresponding reduction of snow reserves at the start of the snowmelt season results. Consequently, the winter runoff is about doubled at the expense of the summer runoff as illustrated on the Kings River basin. However, in glacierized basins like the Illecillewaet River basin, this decrease of the summer runoff is compensated mainly by additional melting of permanent snowfields and glaciers so that the annual runoff is increased. Assuming no change of precipitation and of runoff coefficients, this effect may last for several years until the glaciers finally melt away. The redistribution of runoff (and its temporal increase in glacierized basins) from summer to winter must be taken into account in planning hydropower, irrigation and water supply in snowmelt runoff basins of the Pacific rim. How it will affect the Pacific Ocean and the future climate itself through feedback mechanisms remains to be studied.

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