15 Effects of global warming on runoff in mountain basins representing different climate zones

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INTRODUCTION

The redistribution of runoff in response to global warming may vary in hydrological years of different character as reported by Rango and Martinec (1998). In the present paper, effects of global warming on snow accumulation, snowmelt and runoff are studied in three North American mountain basins with widely varying climate conditions. Although snowmelt is a result of a complex energy balance in mountain basins, the degree-day approach is used as an effective index of this snowmelt so that the Snowmelt Runoff Model (SRM) can be used to assess the effects of global warming. In order to get a clear picture of the effect of increased temperatures, the total precipitation is left unchanged except for conversion from snow to rain when the warmer temperatures dictate.

CHARACTERISTICS OF TEST BASINS

The location of basins selected for this study on the North American continent is shown in Figure 1. The main features of these basins are listed in Table 1. The yearly runoff depth variability reflected a wide range of climate conditions. The ratio precipitation/runoff depth (or losses) would be a still better indicator. However, in order to evaluate the

Table 1 Test basins for evaluation of the climate effect on runoff

Basin	Area *(km²)*	Elevation range *(m a.s.l)*	Climate	Average yearly runoffdepth *(cm)*
Illecillewaet River (British Columbia)	1155	509-3150	very humid	145.5
Kings River (California)	3999	171-4341	semi humid	48.3
Rio Grande at Del Norte (Colorado)	3419	2432-4215	semi arid	22.5

Hydrology in a Changing Environment. Volume I

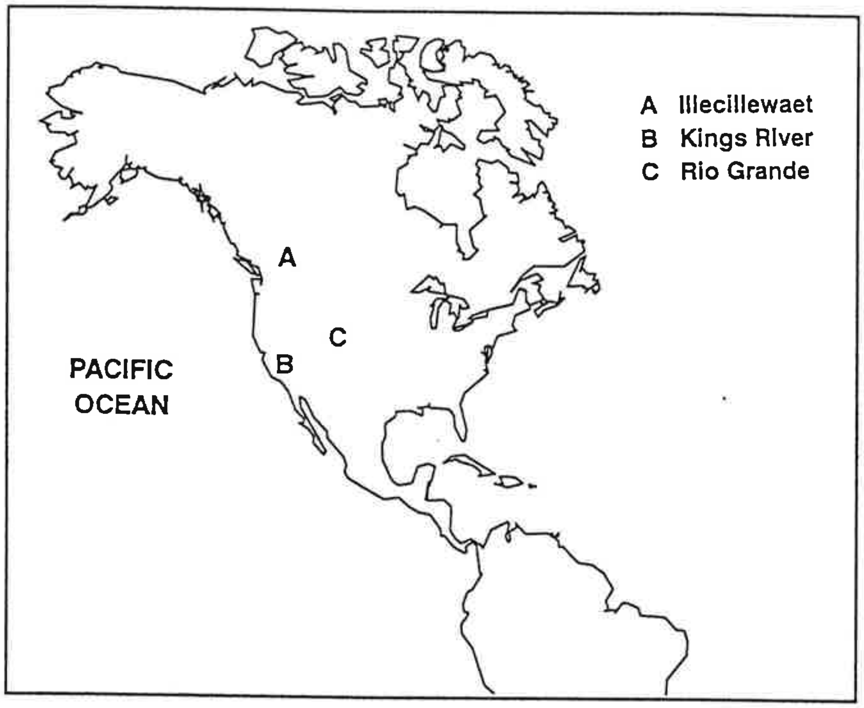

Figure 1 Map location of the test basins: A - Illecillewaet, B-Kings River, C-Rio Grande at Del Norte

representative areal amount of precipitation in high mountain basins, a special study is required for two main reasons: (i) Lack of measurements in the upper parts of the basins where the heaviest precipitation occurs; and (ii) The large catch deficit of precipitation gauges when precipitation falls in the form of snow. It can be estimated approximately that losses in the semi-arid basin of the Rio Grande at Del Norte, Colorado exceed 70% of precipitation while in the humid Illecillewaet River basin (British Columbia), less than 30% of precipitation is lost.

METHOD OF EVALUATING THE CLIMATE CHANGE EFFECT ON RUNOFF

The runoff regime in mountainous basins is dominated by the accumulation and subsequent melting of the seasonal snow cover. The adopted method simulates this process for the present climate as realistically as possible in order to evaluate the changed snow conditions and the resulting runoff for a future climate. Instead of using a snow cover empirically derived from precipitation and temperature data, the existing snow cover is monitored by satellites, snow covered areas are periodically mapped, and the areal water equivalent is derived as explained by Martinec and Rango (1987).

Using the areal extent of the seasonal snow cover as an input variable, SRM simulates the runoff as shown by an example in Figure 2 for the basin Rio Grande at Del Norte. The depletion curves of the snow coverage for the present and future climate are shown in

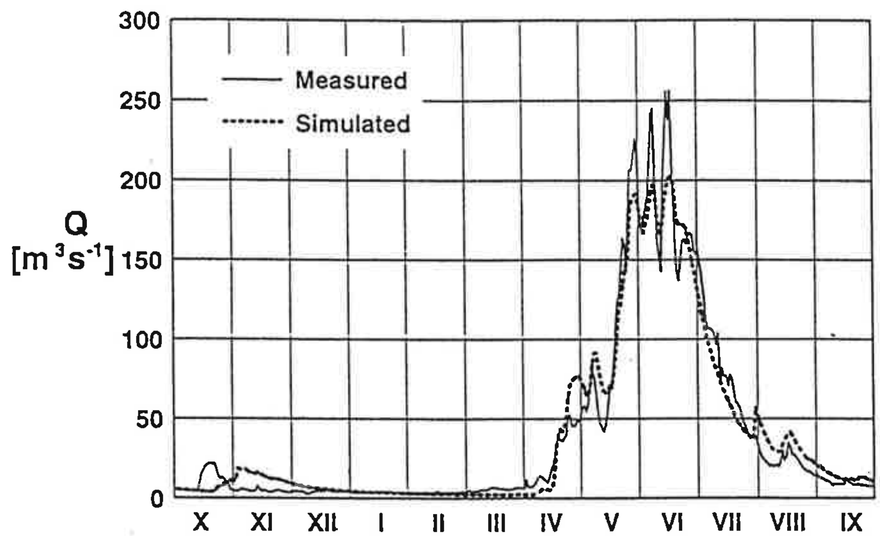

Figure2 Runoff simulation in the Rio Grande basin at Del Norte, Colorado in the hydrological year 1979

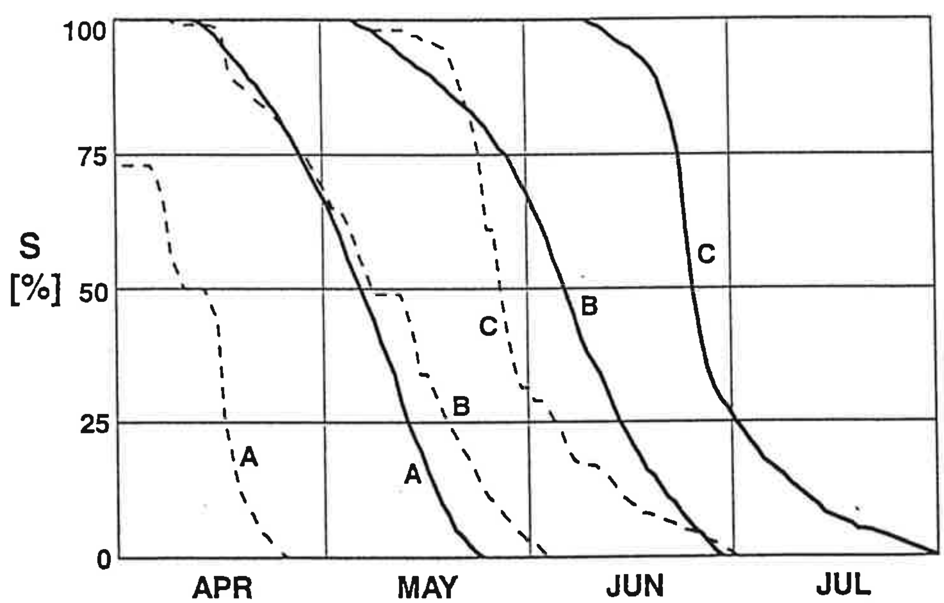

Figure 3 Conventional depletion curves in the zones A,B,C of the Rio Grande basin in 1979 and climate-shifted depletion curves

Figure 3. The climate-affected curves refer to a hypothetical increase of temperature of +4°C. Due to this increase, the decline of the snow coverage takes place earlier, as described by Rango and Martinec (1994). In addition, there is less snow accumulated at the beginning of the snowmelt season due to increased snowmelt in the winter. The SRM computer program takes into account these effects and determines the time shift of the climate-affected depletion curves.

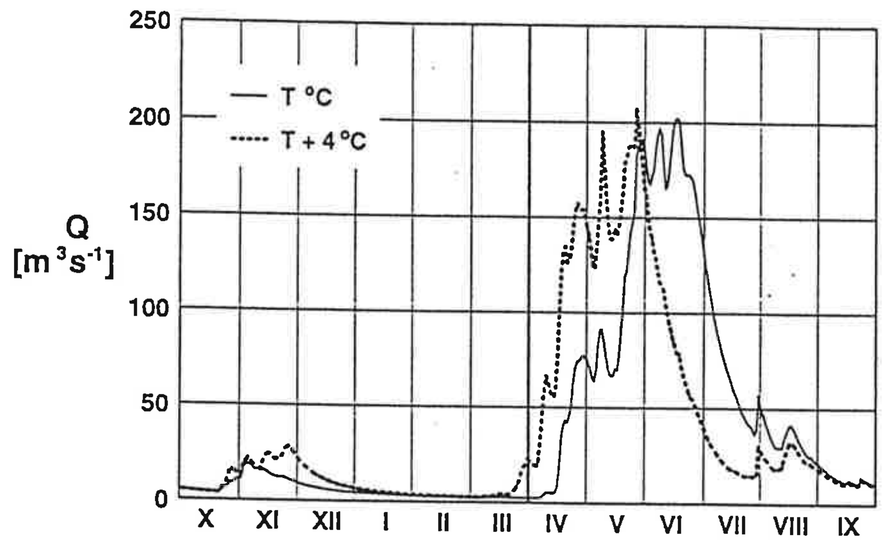

Figure 4 Simulated runoff in the Rio Grande basin for the hydrological year 1979 (see also Figure 2) and for a temperature increase of +4°C.

In order to compute the runoff for the warmer climate in a hydrological year, the winter half year is simulated with the increased temperatures and the summer half year is computed using the climate-affected depletion curves. The conversion of some of the present snowfalls to rainfalls as a result of the warmer temperatures throughout the year must also be taken into account. Figure 4 shows the runoff in the hydrological year 1979 in the Rio Grande basin computed for actual temperatures and for temperatures increased by +4°C, climate-affected hydrographs for the basins Illecillewaet and Kings River (California) were derived in the same way.

As has been pointed out on several occasions (e.g., Nash and Gleick, 1991), calibration models are not suitable for climate change studies because the parameters cannot be adjusted to a future climate scenario in a deterministic way. The SRM parameters are not calibrated but predetermined according to the climatic conditions and other characteristics of the given basin as explained in detail in the User's Manual (Martinec *et al.*, 1994). The degree-day factor increases during the snowmelt season in accordance with the decreasing albedo and increasing density of snow. Losses by evapotranspiration increase in the summer which is reflected in seasonal changes of runoff coefficients.

Recalling Figure 3, the depletion curves of snow coverage are shifted by about one month in a +4°C warmer climate which means that the future snowmelt season will start about one month earlier. Consequently, the values of the degree-day factor and of the runoff coefficient for snow have been also shifted in the runoff computation for T+4°C. It is to be expected that when climate scenarios become more specific, other model parameters will be also affected with regard to time shifting and other adjustments.

CHANGES OF SNOW COVER AND RUNOFF DUE TO INCREASED TEMPERATURES

The presented method evaluates not only the climate-affected runoff but also, as an intermediate result, the climate-affected snow covered areas and the change of the areal water equivalent at the beginning of the snowmelt season. In a warmer climate, more snow is melted during the winter and some of the original snowfall events become rainfalls. The resulting decrease of snow reserves on 1 April as computed by SRM is given in Table 2 for the three respective basins and elevation zones.

Table 2 Decrease of the snow water equivalent on 1 April (Δ HW) due to a temperature increase of +4°C in the winter

Kings River Elevation zones	Δ HW *(cm)*	Illecillewaet Elevation zones	Δ HW *(cm)*	Rio Grande Elevation zones	Δ HW *(cm)*
171-1100m	0				
1100-1700m	0	509-1200m	-41.0		
1700-2300m	-80.7	1200-1800m	-27.8		
2300-2700m	-33.5	1800-2400m	-14.1		
2750-3200m	-14.0	2400-3150m	0	2432-2926	-36.9
3200-3500m	-4.5			2926-3353	-10.1
3500-4341m	-1.1			3353-4215	-2.2

The decrease of snow water equivalent is very small or zero in the highest elevation zone of all basins because the present temperatures are too low to be affected by an increase of +4°C. There is no decrease, either, in the lowest elevation zones of the Kings River basin because the present temperatures are sufficiently high to prevent the existence of a snow cover on 1 April. 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 in the lowest zones of the basins Illecillewaet and Rio Grande at Del Norte and in an intermediate zone of the Kings River basin. Since the Illecillewaet basin is situated at 51°N and the Rio Grande basin at 37°N, temperatures in the lowest zone of Illecillewaet correspond to temperatures at a much higher elevation of the Rio Grande. Concerning the magnitude of this "winter deficit", the data do not indicate a relation to the respective climates although the snow accumulation is of course much higher in the humid Illecillewaet basin than in the semi-arid Rio Grande basin.

Because precipitation amount was left unchanged in this hypothetical climate scenario, the redistribution of runoff between winter and summer due to a temperature increase alone can be evaluated. As listed in Table 3, the winter runoff is nearly doubled in all basins. The proportion of the winter runoff in the Kings River basin is higher than in the other basins because of the relatively warm present-day climate in the low zones. The annual runoff volume in the Illecillewaet basin is about 10.9% greater after the temperature increase because of additional melting of existing glaciers and permanent snowfields. The runoff depth in the semi-arid basin Rio Grande at Del Notre is only 35.4 cm (although 1979 was a high year), while it amounts to 66.7 cm in the semi-humid basin Kings River and to 144.1 cm in the very humid Illecillewaet basin (162.2 cm for T+4°C).

Table 3 Winter and summer runoff volumes under present and warmer climate conditions

	October - March		April - Sept.		Entire year	
	10^6m^3	%	10^6m^3	%	10^6m^3	%
Illecillewaet 1984						
Present T°C	169.3	10.2	1495.6	89.8	1664.9	100
Future T+4°C	341.6	18.9	1465.3	81.1	1806.95	100
Kings River 1973						
Present T°C	428.8	17.1	2080.5	82.9	2509.3	100
Future T+4°C	973.7	37.2	1642.6	62.8	2616.3	100
Rio Grande 1979						
Present T°C	91.9	7.6	1120.1	92.4	1212.0	100
Future T+4°C	146.7	12.3	1046.2	87.7	1192.9	100

The present climate was represented in each basin by a different historical year with regard to the availability and quality of data. In particular, it was necessary to evaluate the snow covered areas from satellite imagery with a sufficient frequency during the snowmelt season. For these reasons, the hydrological year 1979 was used in the basin Rio Grande at Del Norte, although precipitation and snow accumulation were above normal and winter temperatures were below normal. Even so, the difference between model runs with actual temperatures and with temperatures increased by +4°C illustrates the effect of a temperature increase. The year 1984 on the Illecillewaet basin is closest to average runoff conditions of the three years and basins chosen.

CONCLUSIONS

The effect of increased temperatures on the seasonal snow cover provides a good opportunity to evaluate snow conditions and the runoff regime in mountainous basins in a future climate. Effects of a temperature increase on the snow cover and runoff are evaluated in the very humid Illecillewaet basin (British Columbia), in the semi-humid Kings River basin (California), and in the semi-arid Rio Grande basin (Colorado). The decrease of the seasonal snow accumulation varies in the respective basins and elevation zones. Accordingly, the runoff is partially shifted from the snowmelt period to the winter half year, and runoff peaks are shifted to earlier dates in the spring. In addition, the total annual runoff increases in the Illecillewaet basin due to increased glacier melt.

In this paper, the climate scenario was deliberately simplified. In order to introduce refinements to the hydrological response, the climate change response needs to be clarified with regard to how evaporation will be affected, whether precipitation should be changed by multiplying the present daily amounts by a coefficient or otherwise, whether temperatures can be increased simply by adding a certain number of degrees to present values, or whether the diurnal range should be reduced (Karl *et al.*, 1993). These problems have been brought up at a meeting on hydrological effects of climate change (Gleick *et al.*, 1994) and a coordination of efforts in this field was envisaged to be worthwhile. Furthermore, a question arises how to represent the present climate by the best possible data set. In the present paper, actual years are used but another possibility would be to construct a "normalized" representative year for future studies.

REFERENCES

Gleick, P.H., Rango, A. and Cooley, K. 1994. The use of hydrological models for evaluating the impacts of climate change in snowmelt water supply basins. *Eos Transactions, American Geophysical Union*, **75**, 107.

Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayen, V., Gallo, K.P., Lindseay, J., Charlson, R.J. and Peterson, T.C. 1993. A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. *Bulletin of the American Meteorological Society*, 74, 1007-1023.

Martinec, J. and Rango, A. 1987. Interpretation and utilization of areal snow cover data from satellites. *Annals of Glaciology*, 9, 166-169.

Martinec, J., Rango, A. and Roberts, R. 1994. Snowmelt Runoff Model (SRM) User's Manual, University of Bern, Switzerland, *Geographica Bernensia*, 29.

Nash, L.L. and Gleick, P.H. 1991. Sensitivity of streamflow in the Colorado basin to climate changes, *J. Hydrol.*, **125**, 221-241.

Rango, A. and Martinec, J. 1994. Areal extent of seasonal snow cover in a changed climate. *Nordic Hydrology*, 25, 233-246.

Rango, A., Martinec, J. and Roberts, R. 195. Climate effects on future runoff regimes of Pacific mountain tributaries. *Proceedings of the Symposium on Water Resources and Environmental Hazards: Emphasis on Hydrologic and Cultural Insight in the Pacific Rim*, American Water Resources Association, Honolulu, HI, 161-172.

Rango, A. and Martinec, J. 1998. Expected snow cover/runoff response to future global warming in varying hydrological years. *J. American Water Resources Association*.

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