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MODELING SNOW COVER AND RUNOFF RESPONSE TO GLOBAL WARMING FOR VARYING HYDROLOGICAL YEARS

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SUMMARY

The effect of future global warming on the seasonal snow cover and runoff is evaluated in the Rio Grande basin at Del Norte, Colorado for average (1976), low (1977), and high (1979) runoff years. Precipitation data are extrapolated to the respective elevations of the basin by taking into account the snow accumulation obtained from snow cover mapping by satellites. Snow covered areas are used as one of the input variables for the Snowmelt Runoff Model. In order to derive the climate-affected snow covered areas of the future, the decrease of the areal snow water equivalent on 1 April is computed and used to derive new snow cover depletion curves indicative of the accelerated snowmelt in the warmer climate. Day-by-day runoff computations using present temperatures and temperatures increased by +4°C reveal a short-term and seasonal redistribution of runoff which differs according to the character of the selected hydrological years. Winter runoff approximately doubles in 1976 (+ 107%), considerably increases in 1979 (+ 60%), and slightly rises in 1977 (+ 22%). The summer runoff consequently declines in all years, but the seasonal runoff peaks are shifted to earlier in the spring as a result of an earlier beginning of the snowmelt season in the warmer climate.

INTRODUCTION

The objective of this paper is to evaluate the effect of global warming on snow accumulation and snowmelt runoff in a mountain basin for dry, near normal, and wet years. The method is extended from just the snowmelt season to the entire hydrological year so that changes of snow water equivalent at the start of the snowmelt season are properly taken into account.

In order to quantitatively assess the effect of global warming on runoff in mountain basins, snow conditions in the present and future climate should be evaluated as realistically as possible. To do this, the method presented here uses actual satellite monitoring of snow covered areas during a given snowmelt season to arrive at the snow water equivalent at the beginning of the melt season. This differs from evaluations published elsewhere (Gleick, 1987; Lettenmaier and Gan, 1990; and Kite, 1993) which use a simulated snow cover.

A formalized procedure is used to determine the time shift of the snow cover depletion curves for a given temperature increase of the future. These future snow cover depletion curves are input to the Snowmelt Runoff Model (SRM), which is used for runoff computations in this paper. It is important to have a formalized procedure that will work in the same way for SRM users worldwide so that climate change responses can be compared. In the case of a long-term warming, the current date for the beginning of the snowmelt season (1 April in many locations) would be shifted well into March. This study concentrates on a temperature increase because it is the change most commonly agreed upon, but other aspects, such as precipitation, can also be taken into account.

It has been pointed out by Klemes (1985) and Becker and Serban (1990) that calibration models are not suitable for climate change studies because parameters calibrated under present runoff conditions cannot be meaningfully adjusted for a changed climate. SRM parameters are predetermined and not calibrated

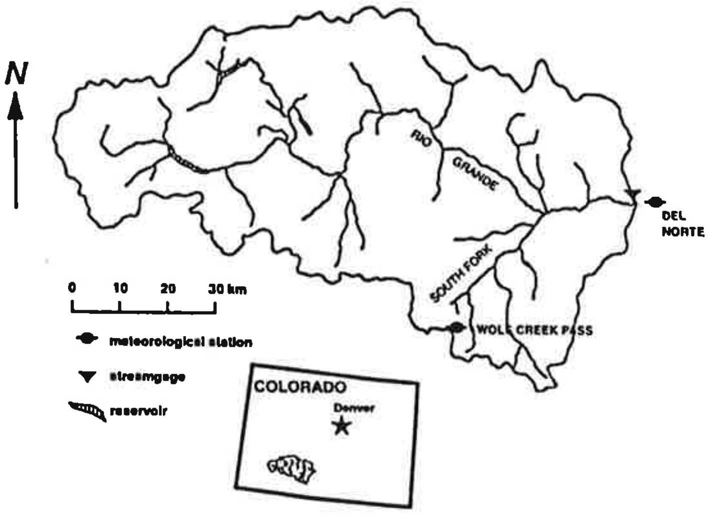

Figure 1 Situation of the Rio Grande basin and location of meteorological and streamgage stations

(Martinec and Rango, 1986; WMO, 1986; and WMO, 1992). When properly applied, the degree-day method for calculating snowmelt (used by many models and also by SRM) has a physical basis (Rango and Martinec, 1995).

In contrast to calibrated models, SRM parameter values must stay within a range limited by physical measurements and hydrological judgement. Consequently, SRM requires accurate data on snow cover which are provided by NOAA, Landsat, and SPOT satellites. The degree-day parameter is evaluated with regard to snow density (if available), stage of the snowmelt season, and presence of glaciers. The runoff coefficient is an expression of hydrological losses and is estimated by comparing the annual precipitation and runoff, by taking into account the progression of vegetation growth and current snow coverage, as well as size of the basin. The critical temperature (the temperature dividing precipitation events into either snowfall or rainfall) is estimated by experience with actual meteorological records and visual observations and stage of the snowmelt season. The temperature lapse rate of 0.65°C/100 m is commonly assumed worldwide but can occasionally be increased (or decreased) according to season and climatic zone. The runoff lag time is determined from hydrographs or estimated from basin size and shape. For more detailed guidance on parameter values, the reader is referred to the SRM User's Manual (Martinec et al., 1994) and Martinec and Rango (1986).

Thanks to the deterministic approach of SRM, parameters can be altered with regard to a changed climate of the future. In this study, the degree-day parameter and the runoff coefficient for snowmelt are shifted to earlier months in accordance with the acceleration of the snowmelt process and with the shift of snow cover depletion curves. At present there is no strong evidence in the climate scenarios to indicate changes in the other parameter values. As the climate change scenarios become more specific, additional parameter changes will be possible.

STUDY BASIN CHARACTERISTICS

In the Rio Grande basin at Del Norte, CO, the seasonal snow cover attains the maximum accumulation around 1 April and is melted in the subsequent months. The locations of meteorological stations and of the hydrometric station are shown in Figure 1 for this mountain basin. The basin of the Rio Grande at Del Norte has an area of 3419 km^2 with an elevation range of 2432-4215 m a.s.l. For application of SRM, the Rio Grande is split into three elevation zones: Zone A - 780 km^2, 2432-2926 m; Zone B - 1284 km^2, 2926 - 3353 m; and Zone C - 1355 km^2, 3353 - 4215 m. Altitude distribution and elevation zones for model computations are illustrated by the area-elevation curve in Figure 2. The discharge, as measured by the streamgaging station, is influenced by the operation of reservoirs, but reconstituted natural runoff (van Katwijk and Rango, 1988) is used for comparison with model computations. The Rio Grande at Del Norte, CO is an important headwater basin which produces spring and summer water supplies for southern Colorado, New Mexico, Texas, and the Republic of Mexico.

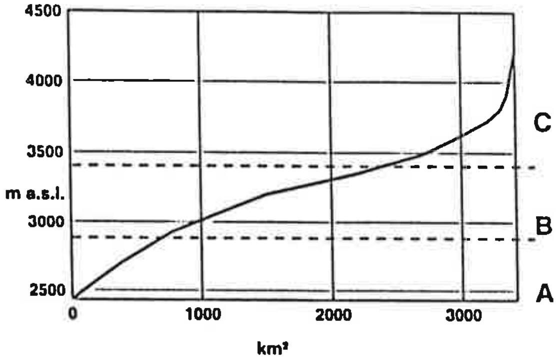

Figure 2 Area-elevation curve of the Rio Grande basin and locations of the elevation zones A, B, and C

HYDROMETEOROLOGICAL DATA ANALYSIS AND INTERPRETATION IN SELECTED YEARS

A wide range of hydrologic conditions were experienced on the Rio Grande at Del Norte in the period of 1976-1979. 1976 experienced flow close to the long-term average, 1977 was the drought year of record, and 1979 had the highest runoff in recent years. Using SRM and these three years we can evaluate hydrological response to climate change under average and extreme hydrological conditions, a situation not normally observed in such a short time period. Data are analyzed and evaluated for all three years (1976, 1977, and 1979), and the results are presented in tabular and graphical form. The high runoff year 1979 is discussed as an example because there has been much interest in hydrological response in extreme years.

Precipitation measurements in mountainous regions are sparse and sometimes completely missing. When precipitation data at high altitudes are available, they are suspect because of raingage catch deficit and wind redistribution of the snow. This usually results in the precipitation data being unreliable and inadequate. Only two meteorological stations are available in or very close to the basin. Totals for the winter and summer half-year precipitation listed in Table 1 indicate unusually high precipitation-elevation gradients between the two meteorological stations compared to previous studies. By extrapolating precipitation to Zone C (Figure 2) using such high gradients, the basin precipitation appears to be excessively high and this would lead, in turn, to unusually high losses if the annual precipitation is compared with the runoff depth. Also, the water equivalent of the snow cover in the respective elevation zones (evaluated in the next section) does not show such a high increase with elevation. In order to render the determination of the basin precipitation more realistic, the average precipitation of both stations was considered to be representative of the average elevation of the two stations, i.e., 2823 m a.s.l. This average value at 2823 m for each daily precipitation event was extrapolated to the hypsometric mean altitudes of the respective elevation zones by a gradient of 4% per 100 m elevation difference. This gradient was derived from snow water equivalent accumulations at different altitudes in the basin and confirmed later by comparing areal snow water equivalents in Figure 8. When data from one of the two meteorological stations were missing, available data were extrapolated from the appropriate station elevation to all zones by the same gradient. Elevation zone precipitation and basin runoff for the three study years are shown in Table 2. With regard to the low runoff coefficient for 1977, it may be noted that this was an exceptionally dry year.

Table 1 Precipitation in the basin Rio Grande at Del Norte during hydrological years 1976, 1977, and 1979

Station:	Del Norte (DN) 2402 m a.s.l.	Wolf Creek Pass (WCP) 3243m a.s.l.	WCP/DN
1976 Oct-March	7.42 cm	55.42 cm	7.5
Apr-Sept	18.19 cm	42.70 cm	2.3
1977 Oct-March	4.04 cm	18.36 cm	4.5
Apr-Sept	14.55 cm	data missing	--
1979 Oct-March	13.79 cm*	134.24 cm	9.7
Apr-Sept	14.48 cm	60.83 cm**	4.2

* February interpolated ** 5 days missing

Table 2 Precipitation and runoff in the basin Rio Grande at Del Norte

Precipitation[cm] evaluated by elevation zone					Runoff depth [cm]	Runoff coefficient
		Winter	Summer	Year	Year	Year
1976	Zone A	30.14	29.18	59.32		
	Zone B	35.63	34.49	70.12		
	Zone C	40.74	39.46	80.20		
	Basin (weighted by areas)			71.64	20.78	0.290
1977	Zone A	10.75	21.20	31.95		
	Zone B	12.71	24.75	37.46		
	Zone C	14.53	28.06	42.59		
	Basin (weighted by areas)			38.24	7.8	0.204
1979	Zone A	74.12	36.60	110.72		
	Zone B	88.03	43.24	131.27		
	Zone C	101.08	49.49	150.57		
	Basin (weighted by areas)			134.23	35.36	0.263

Temperature data were treated similar to precipitation data: The average temperature of both stations was taken and assigned to the reference elevation of 2823 m. The average temperature was extrapolated to all zones by a lapse rate of 0.65°C per 100 m which was seasonally increased to 0.8 and 0.9°C per 100 m during summer months according to experience in similar basins in the Rocky Mountains (Rango and Martinec, 1979; Barry and Chorley, 1970).

EFFECT OF A TEMPERATURE INCREASE ON RUNOFF

Because of atmospheric global CO_2 content increases, air temperature is expected to continue rising throughout the 21st century. Original estimates of the maximum global temperature increase by the year 2100 as a result of a CO_2 content doubling were on the order of 4-6° C, but recent summary studies by IPCC (1996) have reduced that maximum global value to about 3.5° C. In certain regions, however, the maximum increase could be higher than 3.5° C. Giorgi et al. (1994), for example, report a series of runs with global circulation and mesoscale models over the United States, and the average annual increase for the region of the Rio Grande basin in southern Colorado is 4.0° C resulting from a doubled CO_2 content. Whether the doubled CO_2 content is reached by the year 2100 or later is not relevant for this paper. We are interested in the hydrological response of the temperature increase whenever it occurs. To evaluate this response, we have chosen a +4° C temperature increase for analysis.

The widely-used model SRM (Martinec et al., 1994) is used in these evaluations. The SRM parameters can be affected by a climate change scenario. Certain of the parameters can be shifted in time according to the amount of warming as illustrated by van Katwijk et al. (1993). Other parameters can be changed according to the specifications of the climate scenario. The temperature input variable has an immediate effect on the snowmelt produced by SRM. Snow covered area monitored by satellites is another one of the input variables of this model. The meltwater production is computed from temperature and snow covered area. SRM uses an altitude range of approximately 500 m for an elevation zone to facilitate the snow cover mapping (avoiding areas too small for the sensor resolution) while allowing a differentiated snowmelt computation in different areas of

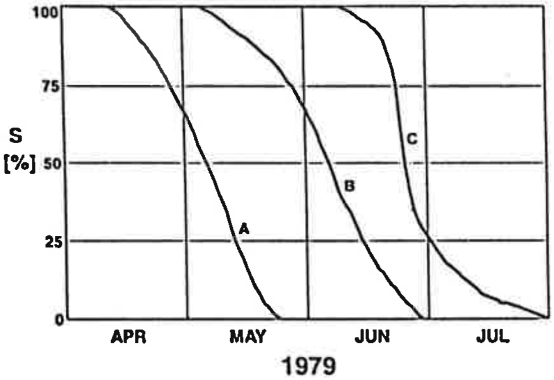

Figure 3 Conventional depletion curves of the snow coverage in elevation zones A, B, C of the Rio Grande at Del Norte, 1979

the basin. As shown in Figure 2, the steep upper part of the area - elevation curve justifies a greater elevation range in zone C.

Figure 3 shows the conventional depletion curves(CDC) of the snow coverage during the 1979 snowmelt season derived from satellite snow cover mapping on the Rio Grande basin. In the winter, when sufficient satellite data is sometimes lacking, a stable complete snow coverage was assumed in February and March in the zones B and C. Otherwise, the snow cover was considered to be temporary, which means that the model derived the runoff from snowmelt by using temperature and precipitation data. Figure 4 shows the year-round runoff simulation with the model parameters in the usual range (Martinec and Rango, 1986) except for the runoff coefficients which are low as a result of high losses in the semi-arid climate of this region, especially in the lowest elevation zone. As has been explained in an earlier paper (Rango and Martinec, 1994), the depletion curves of the snow coverage are shifted in a warmer climate towards earlier dates. This time shift is evaluated by the so-called modified depletion curves (MDC) which relate

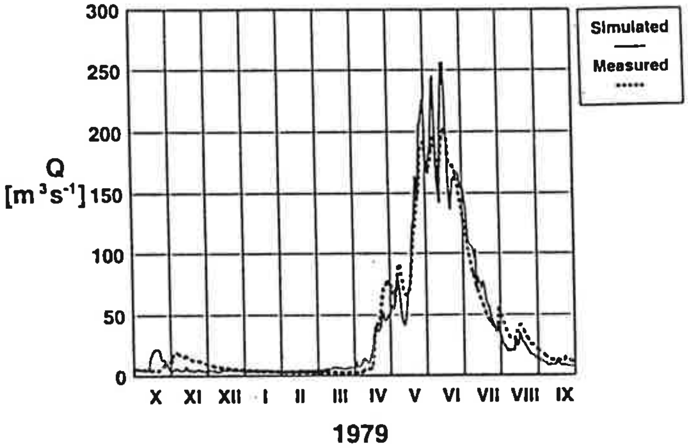

Figure 4 Runoff simulation in the Rio Grande basin at Del Norte in hydrological year 1979

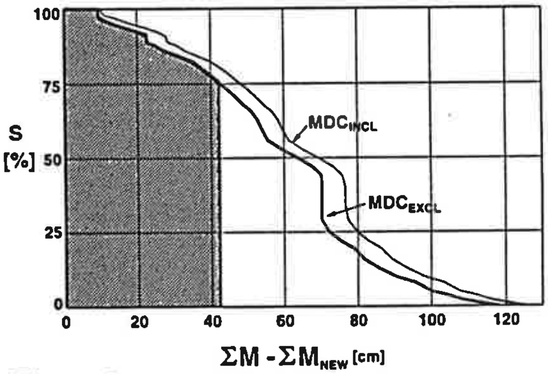

Figure 5 Modified depletion curves MDC$_{INCL}$, MDC$_{EXCL}$ for existing temperatures of 1979, with the adjustment for an increased snowmelt in the winter due to a temperature increase of +4° C (shaded area)

the snow coverage to accumulated snowmelt depths (Σ M [cm]) instead of to time. Figure 5 shows a modified depletion curve, MDC_{INCL} for Zone A which was derived from the depletion curve in Figure 3 and therefore includes snowfalls during the snowmelt period. By eliminating this new snow, MDC_{EXCL} is obtained which indicates the water equivalent of the seasonal snow cover on 1 April 1979 (present climate) for Zone A. The climate change in this example consists of a temperature increase of +4° C throughout a year. As a result of the warmer temperatures after the climate change, more snow will be melted in the winter and some snowfalls will become rain, so that the snow cover on 1 April will be deprived of a certain amount of snow water equivalent, ΔHW, that would exist in the normal 1979 climate. By running SRM from October through March with temperatures of 1979 and then with temperatures of 1979 increased by +4° C, the decrease of the water equivalent on 1 April 1979 in the new climate is obtained as follows:

$$\begin{aligned}\Delta HW = &\sum_{N=1}^{182}[a_n \cdot T_n \cdot S_n + a_n \cdot T_n\,(1-S_n)+P_{Rn}] \\ &- \sum_{N=1}^{182}[a_n \cdot T_n' \cdot S_n' + a_n \cdot T_n'(1-S'_n)+P'_{Rn}]\end{aligned} \tag{1}$$

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 [°C] at the mean hypsometric elevation in degree days [°C d]
T′ = temperature in the changed climate [T + 4°C] in degree days[°C d]
S = ratio of snow covered area to total area, present climate
S′ = ratio of snow covered area to total area, changed climate
P_R = rain according to a critical temperature, present climate
P_R' = rain according to a critical temperature, changed climate
182 = the number of days from October through March

Eq. (1) thus summarizes the SRM input to runoff which is composed of three sources: a) snowmelt from the stable snow cover (S); b) 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 c) rain. When the temporary snow cover has melted away, this b) term ceases to contribute input to runoff. The distinction between a stable and temporary snow cover in the winter is rather arbitrary due to insufficient satellite monitoring, but the total of the retrospective proportions of both snowmelt inputs always equals 1. Consequently, 100% of the occurring snowmelt is computed regardless of whether it is attributed to the stable or temporary snow cover. Coming back to Figure 5, ΔHW is indicated by the

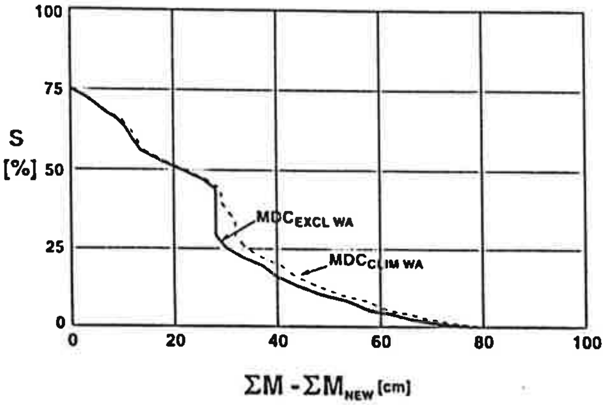

Figure 6 Winter adjusted modified depletion curves MDC$_{EXCL\ WA}$ and MDC$_{CLIM\ WA}$ for a temperature increase of +4°C in 1979, Zone A

shaded area and the winter adjusted modified depletion curve MDC$_{EXCL\ WA}$ is shown in Figure 6, after the shaded area in Figure 5 is subtracted. This curve refers to the snow cover on 1 April in a warmer climate. By adding melt depths of snowfalls that are not converted to rain events, even in the warmer climate, MDC$_{CLIM\ WA}$ is obtained from which the climate-affected conventional depletion curves CDC$_{CLIM}$ can be derived. These curves are shown in Figure 7 in comparison with the original snow cover depletion curves of 1979. The water equivalent of the snow cover on 1 April can be evaluated by adding up total precipitation and subtracting snowmelt and rainfall in the winter half year or by adding up daily snowmelt (new snowfall excluded) in the summer half year. In the first case, the water equivalent is the residual from the winter precipitation minus winter input to runoff as specified in Eq. (1). In the second case, it is the area below the modified depletion curve MDC$_{EXCL}$ or MDC$_{EXCL\ WA}$. In theory, both evaluations would give the same result if precipitation could be accurately measured and correctly evaluated as representative zonal amounts, and if the snow cover monitoring could always be obtained on a frequent and accurate basis.

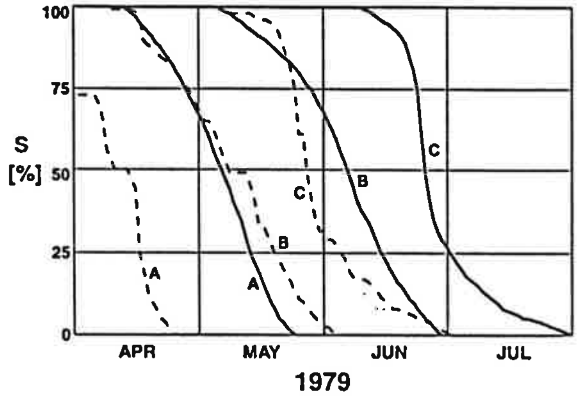

Figure 7 Conventional depletion curves in Zones A, B, and C of the Rio Grande basin 1979 and time shifted depletion curves due to a temperature increase of +4°C

Usually, however, precipitation is underestimated in mountain areas, especially in the winter because of the raingage catch deficit, so that the snow cover approach is considered to be a more

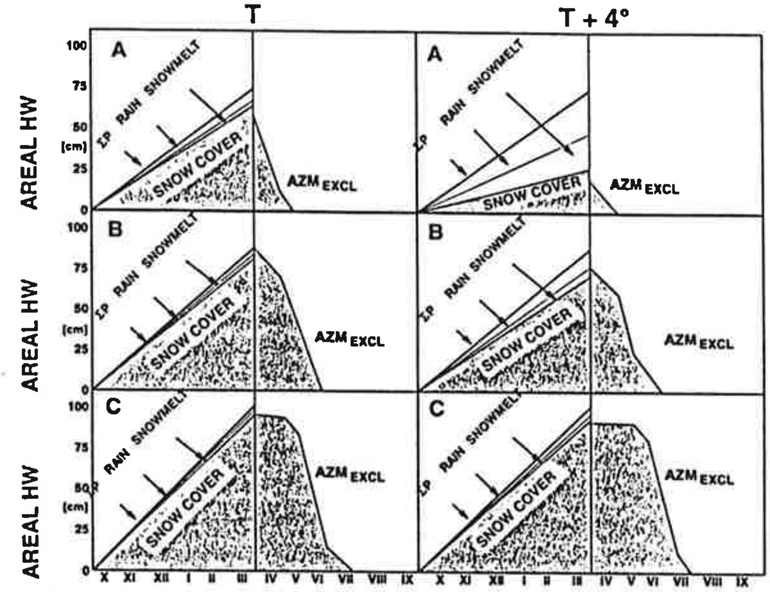

Figure 8 Snow accumulation and ablation in terms of the areal snow water equivalent (HW) in 1979 for zones A, B, and C, under the present temperature regime and for a temperature increase of +4°C

reliable indicator (Martinec, 1985). A surprisingly good agreement results in 1979, with winter precipitation producing similar water equivalents on 1 April as the snow cover monitoring in all elevation zones (see Table 3). However, comparisons for 1976 and 1977 were less satisfactory. This must be expected not only in view of unreliable precipitation data, but also with regard to the use of approximate critical temperatures to decide whether precipitation is either snow or rain. In addition, if snow is redistributed by wind in winter months, the accumulation of snowfalls as they occur in the respective elevation zones may not correspond to snow present there on 1 April. It is, however, this redistributed snow cover which is a source of

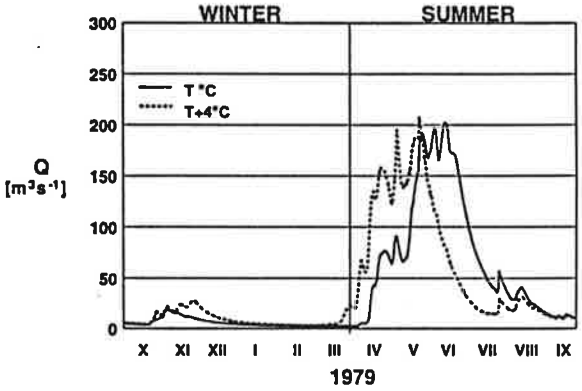

Figure 9 Runoff for the Rio Grande basin in hydrological year 1979 computed for present temperatures and for a temperature increase of +4°C

Table 3 Water equivalent HW of the snow cover on 1 April 1979 from the winter water balance and from snow cover monitoring during the snowmelt season

Water input:	With T cm	With T+4°C cm	ΔHW cm	ΣP Oct-March cm	HW=ΣP - winter input		HW from: MDC_{EXCL}	$MDC_{EXCL WA}$
					T cm	T+4°C cm	T cm	T+4°C cm
A Σ a·T·S	0	0						
Σ a·T(1-S)	2.82	24.177						
ΣP_R	7.52	23.10	36.94					*(21.29)
Total	10.34	47.28		74.12	63.78	26.84	58.10	20.41
B Σ a·T·S	0	3.00						
Σ a·T(1-S)	1.92	3.63						
ΣP_R	4.66	10.08						*(77.90)
Total	6.58	16.71	10.13	88.03	81.45	71.32	88.23	77.48
C Σ a·T·S	0	0						
Σ a·T(1-S)	2.04	1.68						
ΣP_R	3.51	6.04						*(91.94)
Total	5.55	7.72	2.17	101.08	95.53	93.36	94.11	91.87

* Computed by actual ΔHW and not by interpolated ΔHW which was used to cut off the MDC_{EXCL}.

runoff in the summer half year. Evaluations of the water equivalent of the snow cover on 1 April 1979 from winter precipitation and snowmelt on one hand and from the modified depletion curves (MDC) on the other hand are listed in Table 3. Figure 8 illustrates these results for 1979: it shows the winter accumulation of snow on 1 April as a residual from total precipitation with rain and snowmelt deducted (cumulative curves simplified as straight lines) and the retrospective evaluation by MDC, using the accumulated zonal melt with any new snow excluded, AZM_{EXCL}. AZM_{EXCL} integrates the area below MDC_{EXCL} (see Table 3), which is the average water equivalent of the snow cover on 1 April. With temperature increased by +4°C, the winter accumulation, as well as $AZM_{EXEL WA}$ and $MDC_{EXCL WA}$, indicates a smaller water equivalent on 1 April, as is numerically documented in Table 3.

The effect of a temperature increase of +4°C on runoff in the hydrological year 1979 is shown in Figure 9. For October through March,

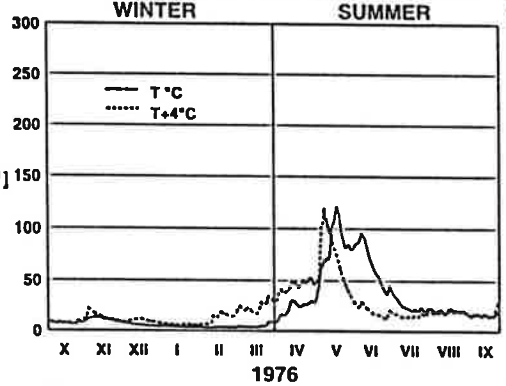

Figure 10 Runoff for the Rio Grande basin in hydrological year 1976 computed for present temperatures and for a temperature increase of +4°C

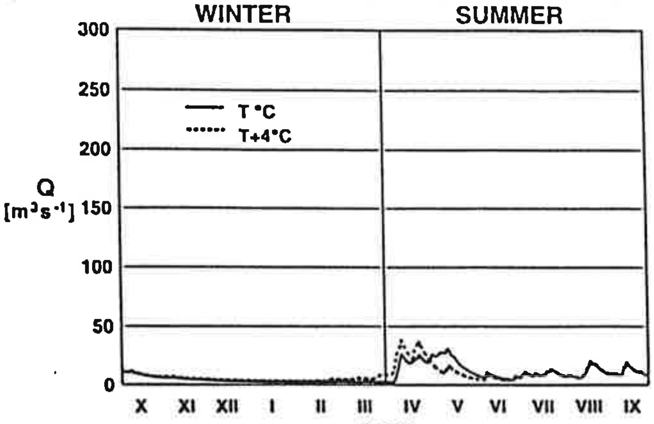

Figure 11 Runoff for the Rio Grande basin in hydrological year 1977 computed for present temperatures and for a temperature increase of +4°C

SRM was run for temperatures of October 1978 - March 1979 and then for temperatures increased by +4°C. For April-September, conventional depletion curves, CDC, and climate-affected depletion curves, CDC_{CLIM}, of the snow coverage (Figure 7) were used as input variables for the model. Along with the time shift of the depletion curves, the SRM parameters *a* (degree-day factor) and c_s (runoff coefficient for snow) were shifted one month ahead. This measure regarding seasonally changing parameters was suggested in an earlier paper (van Katwijk et al., 1993). More experience with climate effect modeling will be necessary in order to decide which other parameters should be shifted and, if higher temperatures increase losses, whether the runoff coefficients should be decreased correspondingly in addition to being shifted in time. At present, opinions vary with regard to an increased evapotranspiration by temperature and a decreased evapotranspiration by the CO_2 increase (Carlson and Bunce, 1991; Gifford, 1988). While various options are kept open, a substantial increase of losses is not considered in this paper. Consequently, the temperature increase results in a higher winter runoff and a lower summer runoff, with the annual runoff remaining approximately the same. Figures 10 and 11 show the

Table 4 Redistribution of runoff by global warming in the basin Rio Grande at Del Norte, CO

Hydrological year		Winter		Summer		Year	
		$10^6 m^3$	%	$10^6 m^3$	%	$10^6 m^3$	%
1979	Natural	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°	146.76	12.3	1046.16	87.7	1192.92	100
1976	Natural	110.26	15.4	603.43	84.6	713.69	100
	Computed T	93.22	13.1	616.52	86.9	709.74	100
	Computed T +4°	192.95	28.1	494.80	71.9	687.75	100
1977	Natural	76.26	28.6	190.37	71.4	266.63	100
	Computed T	63.54	24.3	198.17	75.7	261.71	100
	Computed T +4°	77.34	29.2	187.42	70.8	264.76	100

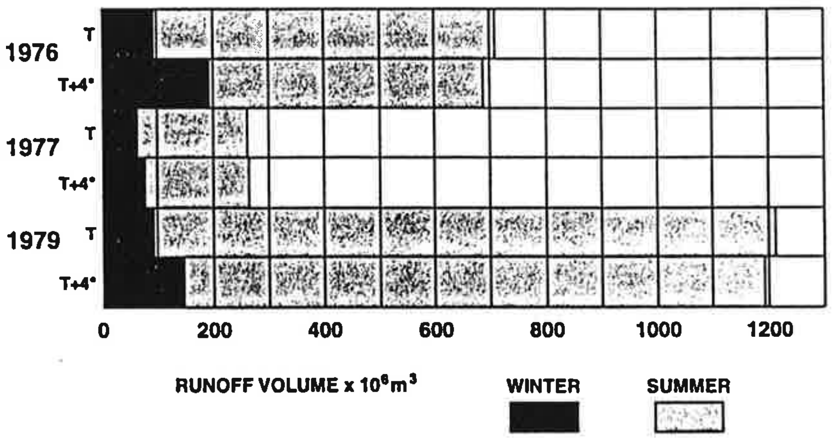

Figure 12 Redistribution of runoff between winter and summer due to a temperature increase of +4°C in 1976, 1977 and 1979

present and climate-affected hydrographs for the years 1976 and 1977 obtained by the same procedure as has been demonstrated for 1979. In 1976, a stable snow cover was assumed in February for zone B and in February and March for zone C. No stable snow cover was assumed in the winter 1977 because of the extreme drought conditions. Runoff data for the selected 3 years are listed in Table 4 and illustrated by Figure 12.

The runoff simulation appears to be less accurate in the winter than in the summer, probably because snow covered areas have to be estimated and because the model has to rely more on precipitation and temperature data. The low runoff volume computed in 1976 for T+4 is at least partially explained by the increased runoff at the end of September (see Figure 10) and a carry-over to October which is missing in the yearly total.

ASSESSMENT OF RESULTS

As a result of the hypothetical, post-climate change increased temperature, a certain part of the pre-climate change summer runoff is shifted backwards to the winter half year when most of the precipitation actually falls. The magnitude of this effect varies at different elevations and from year to year. The greatest increase of the winter input to runoff occurs if the present temperatures are observed to be near 0°C. In this case, higher temperatures cause greater snowmelt as well as conversion of some of the present snowfalls to rainfalls. For a temperature increase of +4°C, there is no effect if the present temperatures are below -4°C. For already warm present temperatures (considerably warmer than 0°C), a further rise causes an increased snowmelt but no change in the snow/rain ratio. Data in Table 4 reflect these varying conditions. In the dry year 1977, the snow accumulation in winter was small. Consequently, the proportion of the winter runoff was higher than in the other years, but the increase in winter runoff in a warmer climate was small, particularly in terms of the actual runoff. There is a significant redistribution of runoff in 1976 because the winter precipitation was sufficient (although not exceptionally high) and temperatures were in a favorable range to convert snowfall to rainfall. The climate effect is also appreciable, but smaller in 1979, partly because of the runoff carry-over from winter to summer due to the runoff increase at the end of March in the warmer climate. In such cases the winter runoff does not entirely reflect the increase of the winter input to runoff.

Aside from the partial shift of runoff volume from the summer to the winter half year, the runoff pattern is shifted in the snowmelt period approximately one month ahead as shown in Figures 9, 10, and 11. Complete hydrographs are presented to enable the reader to make any additional interpretations. Evaluation of the entire hydrological year is essential because the climate effect in the summer can be correctly evaluated only if the climate effect on the winter snow accumulation is taken into account.

CONCLUSIONS

Climate change should have significant hydrological effects in mountain snowmelt basins. In order to evaluate the effect of climate change, it is most expedient to use an established snowmelt runoff model. Furthermore, it is advantageous to use a non calibrated snowmelt model as recommended by the World Meteorological Organization (Becker and Serban, 1990). As a result, SRM was chosen to evaluate the potential hydrological effects of a +4° C increase in temperature in the Rio Grande basin at Del Norte, Colorado in the southern Rocky Mountains. Because the input of the snow cover extent variable to SRM is essential, a formalized method to calculate the change in snow cover in the future under conditions of climate change had to be developed. First, input to runoff from the basin in winter (October-March) is calculated with actual temperatures and then with temperatures increased by +4° C. The difference in winter input to runoff between +4° C and actual temperatures is used to reduce the snowpack water equivalent on 1 April. This change in snow water equivalent is used to produce new modified depletion curves in the new climate and, in turn, new climate change-influenced conventional snow cover depletion curves. These curves are used to calculate the snowmelt runoff in summer (April-September) for the changed climate.

The hydrological response was evaluated for an average year (1976), a record drought year (1977), and a high runoff year (1979). Winter runoff approximately doubles in 1976 (+ 107%) and considerably increases in 1979 (+ 60%), whereas a smaller increase is realized in the very dry 1977 (+ 22%). Consequently, the summer runoff declines in all years with the biggest percentage drop resulting in 1976. The overall annual runoff volume remains about the same for this simple +4°C climate change. Additionally, the summer runoff peaks are shifted to earlier in the spring and summer months which is evidence of the earlier beginning of the snowmelt season in the new climate. Runoff volumes in hydrological years computed with hypothetically increased temperatures may deviate from the present volumes (even without a change of model parameters) because of seasonal changes in flow, the changing snow/rain ratio, and the runoff carry-over from one runoff season to the next one, not to mention glacier runoff if glaciers are present in a basin.

Before these effects are identified and cleared up, it appears justified to limit the evaluation of the climate effect to temperature, as was the case in this study. If other hydroclimatic factors, such as precipitation, evapotranspiration, temperature lapse rate and recession flow characteristics, are affected by the climate change, the pertinent variables and parameters must be changed accordingly. It is therefore essential to use parameters which are based on hydrological and physical judgement and not automatically calibrated by the model.

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