GLOBAL WARMING EFFECTS ON SNOWFIELDS AND WATER SUPPLY EVALUATED USING SNOWMELT MODELING AND NORMALIZED ANNUAL DATA

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ABSTRACT

The effect of global warming on the snow cover and runoff in mountain basins can be evaluated by comparing present and future conditions modeled for a climate scenario. Rather than use a single historical year to represent today's climate, an improved method is presented which consists of deriving a so-called normalized year. In the Rio Grande basin near Del Norte, CO (3414 km^2, 2432-4215 m a.s.l.) the effect of a hypothetical temperature increase of +4^o C on the snow cover and runoff as experienced in hydrological year 1979 was evaluated. Because 1979 had relatively frequent temperatures below -4^o C, snowmelt as well as conversion of snowfall to rainfall was limited during winter. Consequently, the redistribution of runoff from summer to winter was not as significant as evaluated in other basins. The data set of 1979 was modified by applying the so-called normalized temperatures for the period 1957-1994. The predicted future snow conditions in the normalized year show a complete disappearance of snow in the lowest elevation zone (2432 – 2926 m a.s.l.) on April 1, due to an increased snowmelt in the winter. The resulting winter runoff which increased from 7.6% to 12.8% of the annual total, in 1979, now increases from 11.7% to 24.2% of the normalized annual total. In evaluations of the impact of climate change in mountain basins, more realistic results can be expected if today's climate is represented by normalized data of several decades instead of one single year.

INTRODUCTION

The impact of global warming on snow cover and runoff in mountain basins can be evaluated by comparing present conditions with future conditions modeled for a climate scenario. In basins where the seasonal snow cover is accumulated and melted away each year, the future conditions can be computed in one step. For example, if a temperature increase of +4^o C is expected in 2100 (with precipitation unchanged), the Snowmelt Runoff Model (SRM) can compute the snow cover and runoff of that year by running a present data set with a climate change algorithm. So far, a simple historical year was used to represent today's climate (Rango and Martinec, 2000). As will be shown, this approach may be inadequate if temperatures of the selected year happen to deviate from normal conditions. In a warmer climate, the winter runoff is increased at the expense of the summer runoff. A frequency analysis of winter temperatures reveals whether a single year is acceptable for a quantitative evaluation of this effect or whether it should be replaced by a normalized data set.

REDISTRIBUTION OF RUNOFF BETWEEN WINTER AND SUMMER

Due to increased temperatures, more snow will be melted in the accumulation period and some of the winter snowfall will be converted to rainfall, both leading to an increase of the winter runoff. The snow accumulation and snow-covered areas will be reduced accordingly, resulting in a smaller runoff in the snowmelt period. All this can be imagined without snowmelt runoff modeling, however, hydroelectric companies (NWR, 1990) and long-term decisions concerning water allocations need more realistic predictions of the hydrological effects of climate change. Such results can be obtained employing SRM (Martinec et al., 1998; 2007), as will be illustrated by the examples in the next sections.

EVALUATION OF THE CLIMATE EFFECT USING A SINGLE YEAR

By way of example, Figure 1 shows the effect of a hypothetical temperature increase of +4^{o}C on the snow accumulation and snowmelt in the Rio Grande basin near Del Norte, CO (3414 km^2, 2432 – 4215 in a.s.l.) in the hydrological year 1979 (Seidel and Martinec, 2004). The water equivalent of the seasonal snow cover on April 1 in the evaluation of Zones A, B, and C is determined from the winter water balance as well as retrospectively from the computed accumulated zonal melt (AZM) by SRM. Both methods were explained elsewhere (Martinec et al., 1998;

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2007). With regard to insufficient precipitation data, the agreement of results obtained either way is acceptable. The decrease of snow accumulation due to warmer temperatures is evident, particularly in the lowest Zone A (2432-2926 m a.s.l.) This shifting of the depletion curves of the snow coverage shown in Figure 2 results from the double effect of the reduced snow accumulation and increased temperatures in the snowmelt season. Using these curves as input variables, the original and climate-affected runoff was computed as shown in Figure 3. Because this climate scenario consists only of a temperature increase for simplicity, the yearly runoff volume remains the same. As expected, the winter runoff is increased from 7.6% to 12.3% and the summer runoff is decreased from 92.4% to 87.7%. This effect is, however, rather small, in particular when compared with a similar evaluation for the year 1976 and with evaluations for other basins [Illecillewaet, British Columbia, Canada, 1155 km^2, 509-3150 m a.s.l. and Kings River, California, 4000 km^2, 179-4341 m a.s.l. (Rango and Martinec, 2000)], as listed in Table 1. The effect is also abnormal in Rio Grande for 1977 which is due to the lack of snow. The snow cover was very abundant in 1979 and so there must be another reason for the small effect of warmer climate.

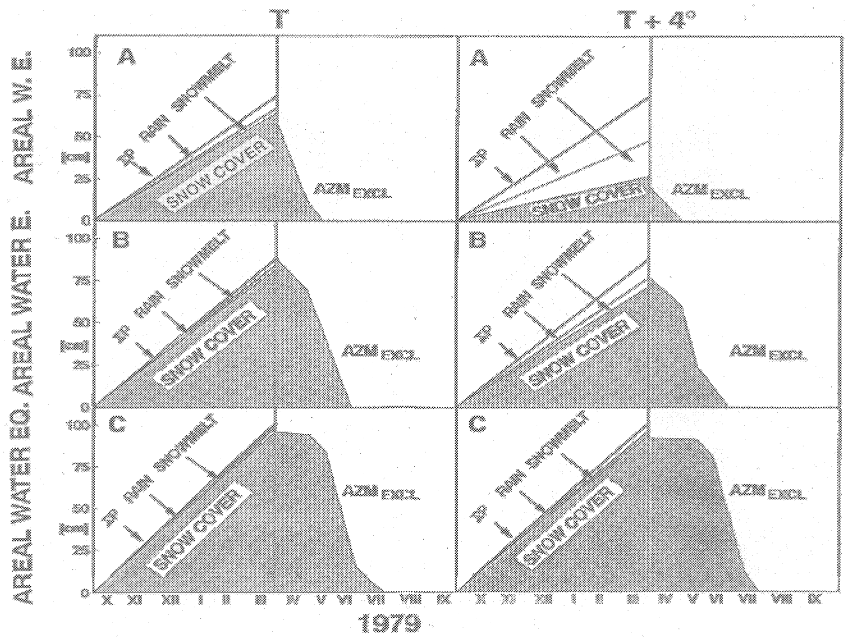

Figure 1. Snow accumulation in the winter and snowmelt in the summer in the Rio Grande basin near Del Norte, CO in 1979 showing the effect of a temperature increase of +4°C in elevation

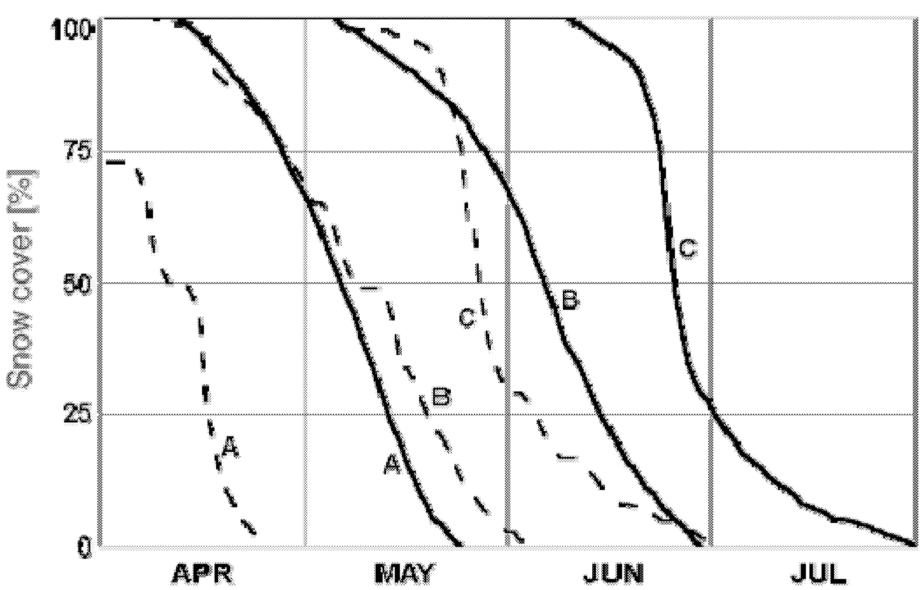

Figure 2. Effect of a changed climate (T+4°C) on snow covered areas in the elevation Zones A, B, and C in 1979 on the Rio Grande near Del Norte, CO. The climate-affected curves (dashed lines) are shifted due to 1) a reduced snow cover on April 1 and 2) increased temperatures in the snowmelt season.

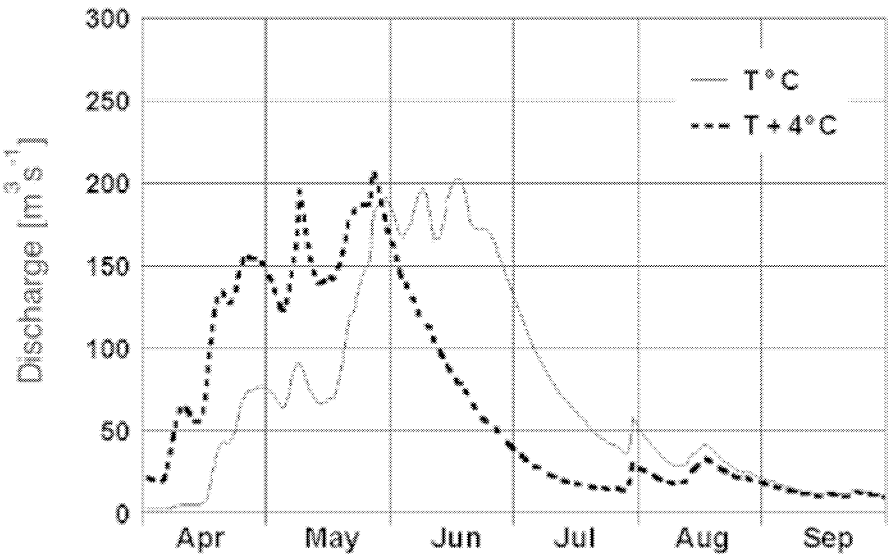

Figure 3. Climate-affected runoff (T+4°C) in the Rio Grande near Del Norte, CO compared with the runoff simulated by data of April – September 1979

Table 1. Redistribution of Runoff in a Warmer Climate

Basin	October - March		April - September		Hydrological year	
	10^6m^3	[%]	10^6m^3	[%]	10^6m^3	[%]
Rio Grande 1979						
measured	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
Rio Grande 1976						
measured	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
Rio Grande 1977						
measured	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
Illecillewaet 1984						
measured	250.69	15.0	1423.40	85.0	1674.09	100
computed *T*	169.29	10.2	1495.56	89.8	1664.85	100
computed *T*+4°	341.63	18.9	1465.32	81.1	1806.95	100
Kings River 1973						
measured	445.97	17.3	2134.00	82.7	2579.97	100
computed *T*	428.78	17.1	2080.53	82.9	2509.31	100
computed *T*+4°	973.66	37.2	1642.67	62.8	2616.33	100

FREQUENCY DISTRIBUTION OF WINTER TEMPERATURES

Under global warming conditions, as mentioned, a higher winter runoff volume in anticipated from an increased snowmelt and from the conversion of snowfall to rainfall. In the first case, there is no additional snowmelt on any day with a temperature below -4° C, for a temperature increase of +4° C. For the second case, snowfalls are not converted to rainfalls in days with a temperature lower by -4° C than the critical temperature. In our case, the critical temperature determining whether precipitation was snow or rain in SRM was +1° C. Therefore, the conversion snow/ rain is ineffective on days with an original temperature below -3° C. Due to the cold winter in 1979, the number of ineffective snowmelt days was higher than normal as can be determined by frequency analysis. To evaluate the deviation from a normal winter by comparison with long-term average temperatures for each day would be misleading. These averages result in a smooth sine curve as opposed to day-to-day irregular fluctuations which are typical for temperatures in a real year. Therefore, daily temperatures in 1979 were adjusted by long-term monthly averages. In this way, the cold temperatures of 1979 were normalized while preserving their inherent daily fluctuations. As illustrated in Figure 4, the number of ineffective days in 1979 is higher than in a normalized year. The difference for the period December – March is illustrated by Figure 4. The number of snowmelt or snow to rain days in the elevation Zone A (2432-2926 m a.s.l.) is 82 + 92 = 174 in 1979 and 68 + 76 = 144 in the normalized year 9979, in the Zone B (2926-3353 in a.s.l.) it is 115 + 117 = 232 in 1979, 103 + 111 = 214 in 9979. The numbers of effective days for additional snowmelt and conversion of snow to rain are correspondingly higher in 9979 than in 1979. In the highest Zone C (3353–4125m a.s.l.), there are no effective days in both cases because temperatures are too low.

These data explain the relatively small effect of climate change on the redistribution of runoff if the year 1979 is used for evaluation. A more realistic result may be expected for a normalized year, as will be demonstrated in the next section.

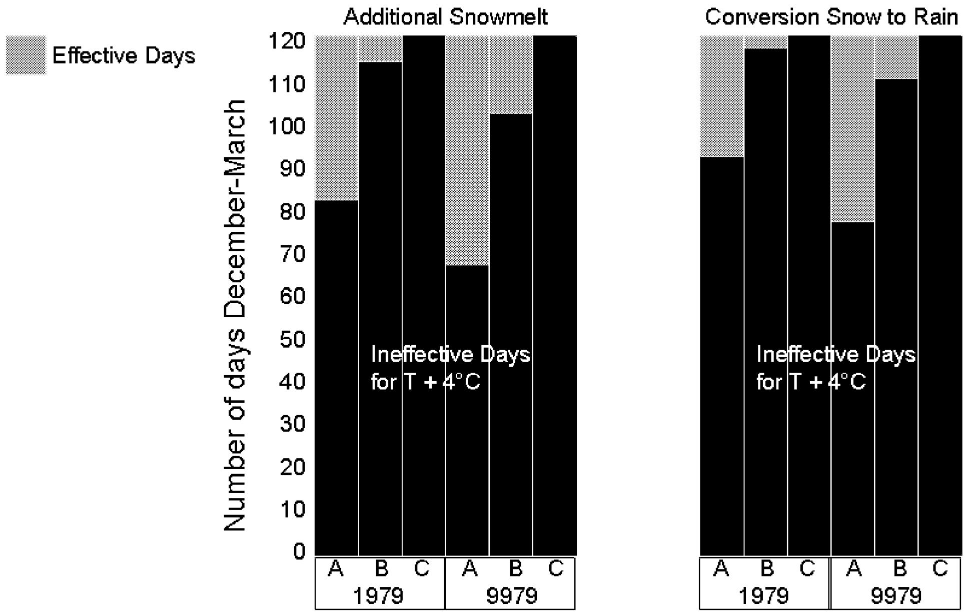

Figure 4. Numbers of ineffective (and effective) days for additional snowmelt (T< -4°C) and for conversion of snow to rain (T< -3°C) in the Rio Grande near Del Norte, CO in elevation Zones A, B, and C in December 1978 to March 1979 resulting from a climate change of T+4°C in 1979 versus the normalized year (9979)

EVAULATION OF THE CLIMATE EFFECT USING ANORMALIZED YEAR

In order to use a normalized year instead of a single year, it is necessary to normalize the three input variables which are required to run the SRM model: Temperature (T) as already mentioned in the previous section, Precipitation (P), and the Depletion Curves of the Snow Coverage (CDCs). As opposed to averaging, the aim is to adjust temperature and precipitation values representing a period of several decades while preserving fluctuating temperatures and a natural true distribution of precipitation events. The normalized CDC's are modeled by applying the normalized P and T to the CDCs of the original year as a new climate. The derivation of a normalized data set is described in Seidel and Martinec (2004).

Figure 5 shows the normalized CDCs compared with the CDCs of 1979 as obtained from the periodical satellite snow cover mapping. These curves and the normalized P and T represent a period 1957–1994, which characterizes the present climate better than any single year. Remembering that 1979 had an exceptionally large accumulation of snow, the normalized CDCs suitably indicate a smaller snow cover. In Figure 6, the normalized computed runoff is compared with the computed runoff in 1979. Again, it is lower than the exceptionally high runoff in 1979.

The normalized year 9979 can now be used to evaluate the effect of a changed climate on the present climate, characterized by the period of 1957–1994. The SRM climate program is run for the hypothetical climate scenario T +4° C, with precipitation unchanged. Figure 7 shows the climate affected snow cover depletion curve, $CDC_{9979\ CLIM}$, compared with CDC_{9979}. Similarly as in Figure 2, CDCs are shifted towards earlier dates due to warmer temperatures. However, the effect is even more distinct. The snow cover in the Zone A disappears completely, while it still exists in Figure 2, thanks to an exceptionally large accumulation of snow in 1979. The prediction of snow conditions in the year when the scenario T+4° C materializes appears to be more realistic according to Figure 7 than according to Figure 2.

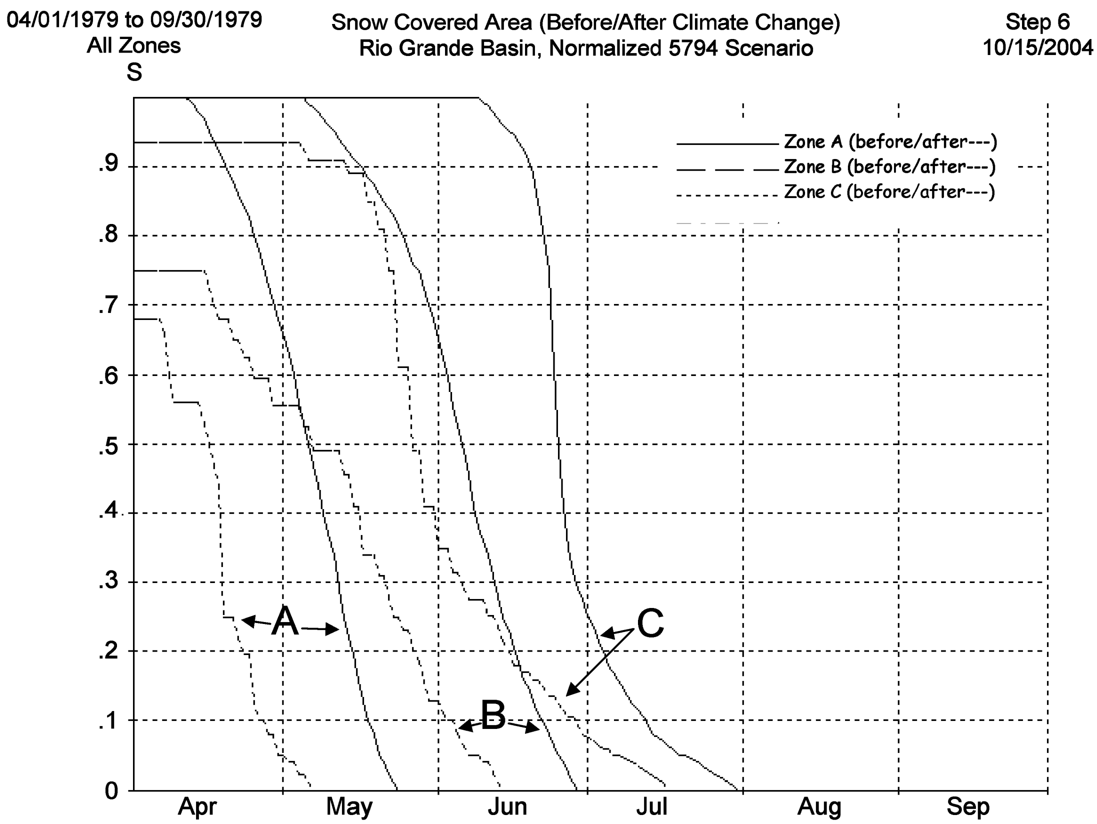

Figure 5. Normalized depletion curves (dashed) in the elevation Zones A, B, and C compared with conventional depletion curves (CDCs) of 1979 for the Rio Grande near Del Norte, CO

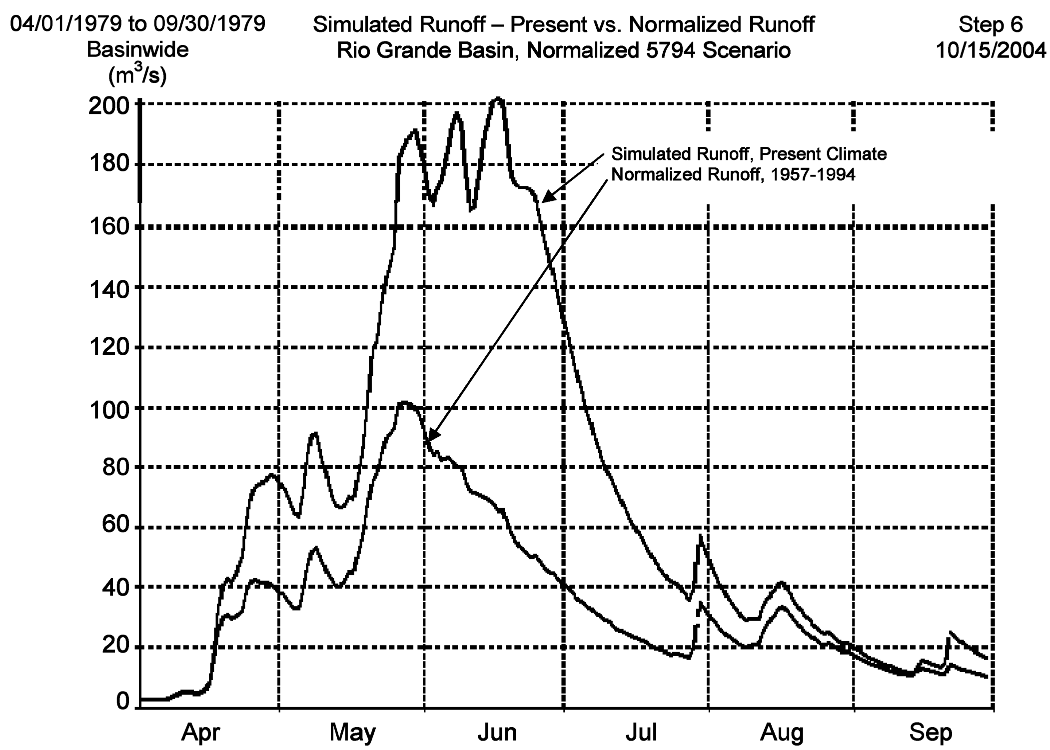

Figure 6. Normalized hydrograph of the Rio Grande near Del Norte, CO for the period 1957-1994 derived from the data set of 1979 (snowmelt period) compared with the 1979 computed hydrograph. The runoff in 1979 was extremely high due to abundant snow cover.

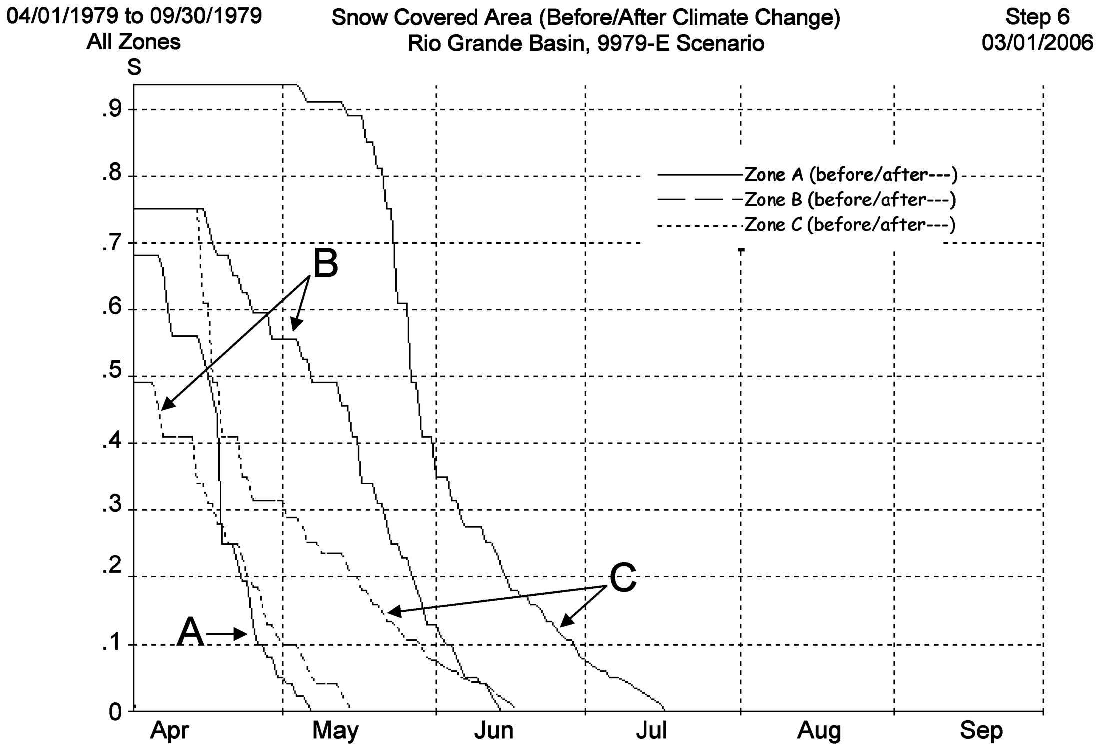

Figure 7. Effect of a +4° C temperature increase on the snow covered areas in a normalized year in elevation Zones A, B, and C in the Rio Grande basin near Del Norte, CO. The climate-affected CDCs are the dashed lines. In contrast to Figure 2 there is no snow left in Zone A due to the temperature increase.

The effect of climate change (T+4° C) on the normalized runoff representing the period 1957–1994 is illustrated in Figure 8. Recalling Figure 3, the discharge peak also occurs earlier, but evidently much more runoff was shifted to winter so that the peak is smaller.

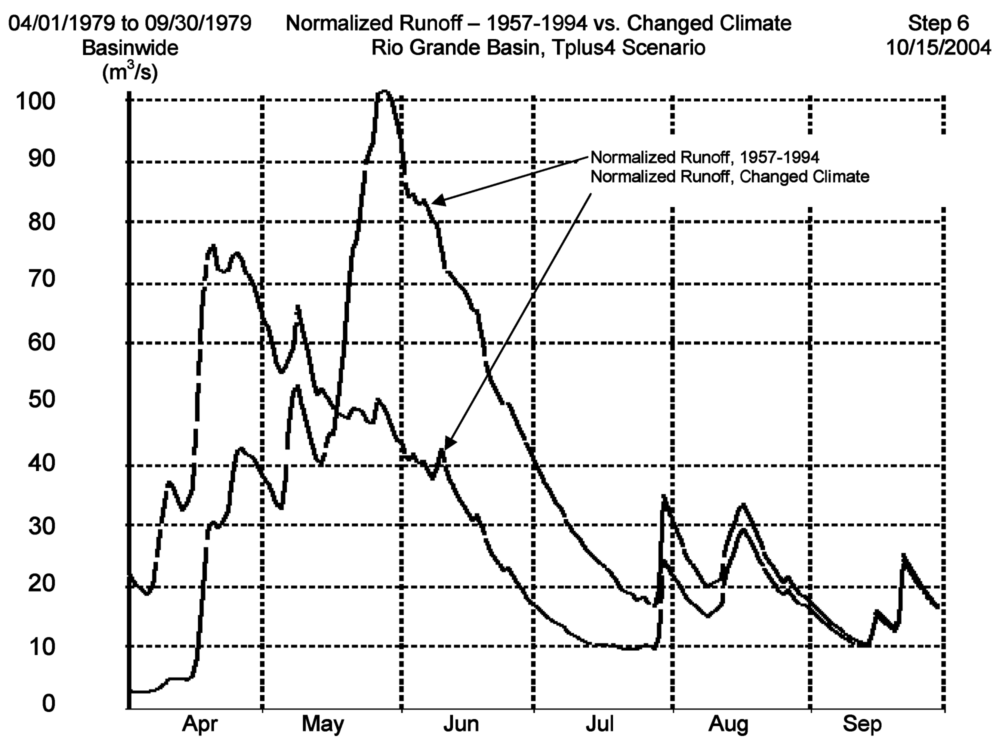

Figure 8. Normalized runoff in the Rio Grande basin near Del Norte compared with the runoff resulting from a +4° C increase

This visual impression is confirmed by Figure 9 (Rango, 2005). If the single year 1979 is used for the evaluation of the climate effect, the redistribution of runoff results in the relatively small increase of the winter runoff from 7.6% to 12.8% of the yearly runoff. If a normalized year is used, a greater increase of the winter runoff from 11.7% to 24.2% results. In absolute terms, the winter runoff evaluated from T+4° C increases from $91.87{\cdot}10^6 m^3$ to $146.76{\cdot}10^6 m^3$ when 1979 is used, and from $74.66{\cdot}10^6 m^3$ to $153.06{\cdot}10^6 m^3$ when the normalized year is used. The figures for the summer decrease accordingly, because there is no gain or loss of runoff with this hypothetical climate scenario.

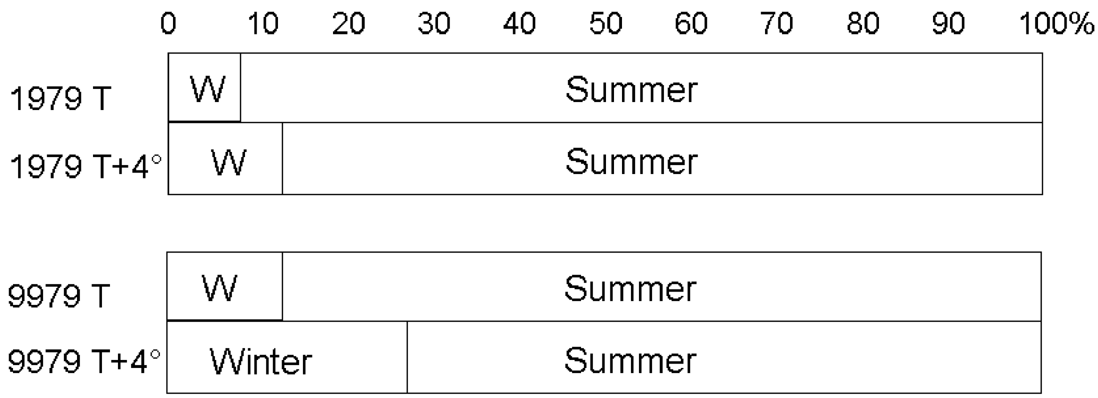

Figure 9. Redistribution of runoff between winter and summer due to a temperature increase of +4° C in the Rio Grande basin, using a single year (1979) and a normalized year (1957-1994) derived from 1979 (9979).

CONCLUSION

The impact of global warming on snow cover and runoff in mountain basins can be evaluated as a difference between the present and climate-affected conditions which can be modeled for a given climate scenario. The frequency distribution of winter temperatures reveals whether a single year selected for this comparison represents well today's climate. The effect of global warming on the redistribution of runoff in the basin Rio Grande near Del Norte, CO was underestimated when the hydrological year 1979 was selected for the evaluation. The frequency distribution of winter temperatures revealed that in 1979, the number of cold days with temperatures preventing any effect of the temperature increase was higher than normal. This reduced the seasonal redistribution of runoff. For absolute terms, the climate-affected annual runoff was too high, reflecting conditions in 1979. Also, the exceptionally high snow accumulation in 1979 influenced the evaluation of snow conditions expected in the future. For example, snow completely disappears in Zone A if a normalized year is used for the evaluation, while some snow survived the warming if the single year 1979 is used. In 1977, in turn, the meager snow cover jeopardized the evaluations. This illustrates the inadequate ability of a single year to characterize the present climate. It is recommended to use instead a normalized year which can be derived with the use of the long term observation series of temperature and precipitation, especially if the frequency analysis of winter temperatures in the candidate year indicates some anomalies. Thanks to this refinement, which is facilitated by the new SRM windows program (Martinec et al., 2007), the evaluation of the effect of climate change on the seasonal snow cover and runoff in mountain basins becomes more realistic.

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