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# Areal Extent of Seasonal Snow Cover in a Changed Climate

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In mountain snow basins, a change in climate will likely cause a change in the basin snow cover extent. A procedure for evaluating whether a given climate change scenario will speed up or slow down the seasonal decrease of snow covered area is outlined with hypothetical examples for a simple basin. This procedure has two main purposes. First, it can be used to generate snow covered area data in a new climate for input to runoff models such as the Snowmelt-Runoff Model (SRM). Second, it could potentially be used to provide input to climate models that require knowledge of the land area covered by snow at a given time. A computer program is now operational for use on real basins and is demonstrated on the Rio Grande basin in Colorado and the Illecillewaet River basin in British Columbia.

## Introduction

The second World Climate Conference (SWCC) in Geneva 1990 brought the problem of a changing climate to the attention of the general public. The SWCC concluded that the most important impacts of climate change will be its effects on the hydrological cycle and water management systems along with attendant increases in extreme hydrological events (Askew 1991). There appears now to be a consensus that the air temperature will gradually increase in the next decades (Schneider 1989). The future precipitation change is less predictable, with increases and decreases envisaged over different parts of the globe. An important factor of the future climate is the areal extent of seasonal snow cover. There is such a vast difference in physical properties of snow and other natural surfaces that the occurrence of snow on a drainage basin can cause significant changes in the energy exchange. Because of its high albedo, snow reflects a much higher percentage of incoming solar shortwave radiation than snow free surfaces (something like 40%-90% *vs* 15%). This causes a large difference in energy absorption and subsequent thermal heating. In the longwave portion of the spectrum, snow absorbs and emits radiation very efficiently in contrast to other natural surfaces. Additionally, the low thermal conductivity of snow sharply reduces heat exchange between the ground and the atmosphere so that snow serves as an insulating blanket.

In the spring the snowpack undergoes rapid transformation which involves bringing the snowpack temperature to an isothermal situation at 0°C and satisfying the snowpack liquid water holding capacity. When both of these conditions have been met, the snowpack is in a ripe condition and absorption of additional energy will produce snowmelt. This process takes place at varying rates depending on aspect, slope, elevation, vegetation cover, and atmospheric conditions. Once snowmelt is occurring, runoff increases rapidly and snow disappears from the basin in a relatively short time period of several weeks to several months.

This paper presents a method based on the degree-day approach to calculating snowmelt to predict the time shifting of the depletion curves of the snow coverage for different climate scenarios. The general degree-day method, which has been described by many investigators (*e.g.* Collins 1934; Linsley 1943; Westerstrom 1982), takes the form: $M = a\,(T_a\text{-}T_b)$ where $a$ is the degree day factor (cm °C$^{-1}$d$^{-1}$), $T_a$ is the average daily temperature (°C), $T_b$ is the base temperature (°C), and $M$ is the snowmelt rate (cm d$^{-1}$). The Snowmelt Runoff Model (SRM) is a simple model using the degree-day method as described by Martinec *et al.* (1983). If the basin is not subdivided into zones, the equation for SRM is

$$Q_{n+1} = (c_{Sn}\, a\, T_n\, S_n + c_{Rn}\, P_n)\frac{A\,0.01}{86400}\,(1 - k_{n+1}) + Q_n\, k_{n+1} \qquad (1)$$

where: $Q$ – average daily discharge (m$^3$s$^{-1}$); $c_S$ – runoff coefficient for snowmelt expressing the losses as a ratio (runoff/precipitation); $c_R$ – runoff coefficient for rainfall; $a$ – degree-day factor (cm °C$^{-1}$ d$^{-1}$); $T$ – number of degree days above the base of 0°C (°C d); $S$ – ratio of the snow covered area to the total area; $P$ – precipitation (cm); $A$ – area of the basin or zone (m$^2$); 0.01/86400 – conversion from cm m$^2$ d$^{-1}$ to m$^3$s$^{-1}$; $k$ – recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall: $k = Q_{m+1}/Q_m$ ($m$, $m$+1 – the sequence of days during a true recession flow period); and $n$ – sequence of days during the discharge computation period. The SRM equation is written for a time lag, $L$, between the daily temperature cycle and resulting discharge cycle of 18 h although other time lags can be used (see Martinec and Rango 1986). This lag time must be incorporated in SRM because it is physically impossible for snow melting somewhere in the basin to appear instantaneously at the outlet as streamflow (unless the melting snow is right at the gauge site). In the case of $L$ = 18 h, the number of degree days measured on the $n$th day corresponds to the discharge on the $n+1$ day.

The procedure described in this paper for estimating the time shift of snow cover depletion curves in response to a changed climate is applicable in mountain areas where the snow cover is built up in the winter and gradually disappears during the spring and early summer. The method is presented in its most simple form in order to adequately explain the procedure used to approximate the complex interaction between snow cover, temperature, and precipitation on a mountain basin. Naturally, in mountain basins with subbasin areas such as elevation zones, a computer program will be needed to facilitate application of a variety of climate change scenarios. This program has been completed and is available in the latest version of SRM operating on a microcomputer. The microcomputer version of SRM is described in Rango and Roberts (1987). SRM is extremely easy to apply by users, and the results of applications on over 50 basins worldwide are documented by Rango (1992). In addition, SRM has been used several times and on several basins to produce snowmelt runoff hydrographs under conditions of climate change (Rango 1992; Rango and van Katwijk 1990).

Temperature and precipitation are not the only climate variables that will change as the greenhouse effect is enchanced by increasing $CO_2$ emissions. In addition, both cloudiness and solar radiation will be affected. So far, climate change scenarios produced by climate modellers have only dealt with temperature and precipitation. When the climate models become sophisticated enough to produce an expected change in cloudiness and thus a change in radiation, the degree-day method for computing the snowmelt will be refined by taking the radiation component into account. This approach has been tried on a snow lysimeter (Martinec 1989). With regard to drainage basins, the radiation component for SRM is in the research stage (Kustas *et al.* 1994).

## Depletion Curves of Snow Covered Areas

A typical depletion curve of snow covered area during a snowmelt season is shown in Fig. 1. In this hypothetical example, the time scale is reduced to 10 days although the decline of the snow cover in mountain basins can take several months. This example curve allows demonstration of the method in a simple way.

Depletion curves indicate the snow coverage on each day of the melt season which is an important input variable for numerical models such as the Snowmelt Runoff Model (SRM) (Martinec *et al.* 1983). They have been also used as indicators of snow reserves or water equivalent (Meier 1973, Odegaard and Ostrem 1977, Rango *et al.* 1977). Because the decline of snow cover extent depends not only on the initial snow reserves, but also on the climatic conditions of the year in question, the so called modified depletion curves have been proposed to normalize

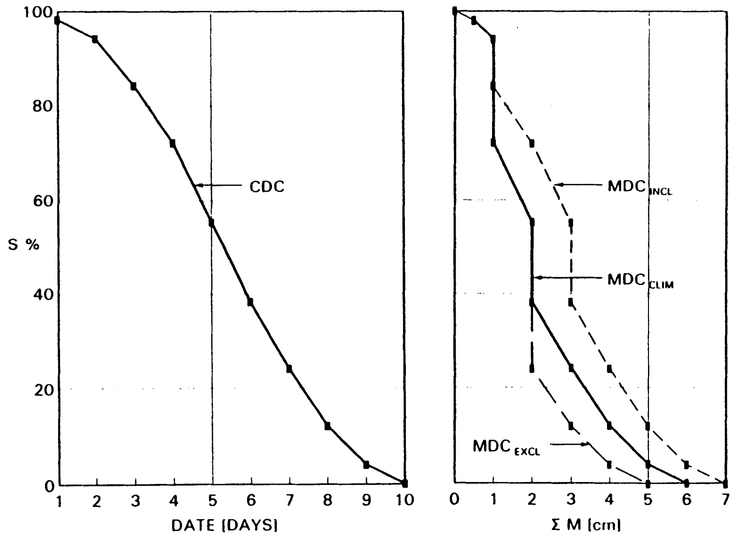


Fig. 1. Example of a conventional depletion curve of snow covered areas, CDC, and auxiliary curves for evaluating the effect of a changed climate: Modified depletion curves including and excluding the effect of new snow, $MDC_{INCL}$ and $MDC_{EXCL}$, and the modified depletion curve for a changed climate ($T$ + 1°C), $MDC_{CLIM}$.

such differences between years (Martinec 1985). These modified depletion curves relate the snow covered area to the cumulative snowmelt depth computed each day rather than to time. A modified depletion curve can be used to reveal the initial accumulation of snow if the effect of snowfalls during the snowmelt season is eliminated, as illustrated by the numerical example in Table 1. The energy input (as indexed in terms of degree-days) on days 4 and 7 is needed to melt the new snow so that the cumulative snowmelt depth referring to old snow remains the same on these days. Thus the following curves can be distinguished (see Fig. 1):

Conventional depletion curves, CDC
Modified depletion curves including new snow, $MDC_{INCL}$
Modified depletion curves excluding new snow, $MDC_{EXCL}$

To recapitulate, CDC indicates snow covered areas in the course of time. If the snow free areas are briefly covered by new snow, such situations are disregarded (Hall and Martinec 1985).

$MDC_{INCL}$ indicates how much snow, including new snow falling during the snowmelt period, must be melted (in terms of calculated cumulative snowmelt depth) in order to decrease the snow covered area to a certain proportion of the total area and ultimately to zero. Thus the shape of this curve changes in a given basin from year to year according to the initial accumulation of snow and to the amount of snow falling during the snowmelt period.

Table 1 – Computation of x-coordinates for $CDC_{CLIM}$ for a climate change: $T$ + 1°C (y-coordinates are the corresponding snow coverage values S(%)). Assumed parameters: Degree-day factor $a$=0.5 cm $°C^{-1}d^{-1}$; Critical temperature $T_{CRIT}$ =0.5°C.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 98 | 1 | 0.5 | 0.5 | | | 0 | 0.5 | 2 | | | 0 | 0.5 | 1 | 1 | 1 |
| 2 | 94 | 1 | 0.5 | 1 | | | 0 | 1 | 2 | | | 0 | 1 | 1 | 2 | 1 |
| 3 | 84 | 0 | 0 | 1 | 1 | | 0 | 1 | 1 | 1 | | 0 | 1 | 0.5 | 2.5 | 1 |
| 4 | 72 | 2 | 1 | 2 | | 1 | 1 | 1 | 3 | | | 0 | 1 | 1.5 | 4 | 1 |
| 5 | 55 | 2 | 1 | 3 | | | 1 | 2 | 3 | | | 0 | 2 | 1.5 | 5.5 | 2 |
| 6 | 38 | -1 | 0 | 3 | 1 | | 1 | 2 | 0 | 1 | | 0 | 2 | 0 | 5.5 | 2 |
| 7 | 24 | 2 | 1 | 4 | | 1 | 2 | 2 | 3 | | 1 | 1 | 3 | 1.5 | 7 | 4 |
| 8 | 12 | 2 | 1 | 5 | | | 2 | 3 | 3 | | | 1 | 4 | 1.5 | 8.5 | 4 |
| 9 | 4 | 2 | 1 | 6 | | | 2 | 4 | 3 | | | 1 | 5 | 1.5 | 10 | 5 |
| 10 | 0 | 2 | 1 | 7 | | | 2 | 5 | 3 | | | 1 | 6 | 1.5 | 11.5 | 7 |

1 Date, x-coordinates for CDC
2 Snow covered area (S in %), y-coord. for CDC,$MDC_{INCL}$,$MDC_{EXCL}$,$MDC_{CLIM}$,$CDC_{CLIM}$
3 Temperature (T in °C), present climate
4 Snowmelt depth (M in cm), T•a
5 Cum. snowmelt depth (ΣM in cm), x-coord. for $MDC_{INCL}$
6 Precipitation (P in cm), present climate
7 Melt depth of new snow ($M_{NEW}$ in cm)
8 Cum. new snowmelt depth ($\Sigma M_{NEW}$ in cm)
9 Col.5-Col.8 ($\Sigma M_{EXCL}$ in cm), x-coord. for $MDC_{EXCL}$
10 Temperature in the new climate ($T_{CLIM}$ in °C)
11 Precipitation in the new climate ($P_{CLIM}$ in cm)
12 Melt depth of new snow in the new climate ($M_{NEW CLIM}$ in cm)
13 Cum. melt depth of new snow in the new climate ($\Sigma M_{NEW CLIM}$ in cm)
14 Col.9+Col.13 ($\Sigma M_{EXCL}+\Sigma M_{NEW CLIM}$ in cm), x-coord. for $MDC_{CLIM}$
15 Snowmelt depth in the new climate ($M_{CLIM}$ in cm), $T_{CLIM}$•a
16 Cum. snowmelt depth in the new climate ($\Sigma M_{CLIM}$ in cm)
17 Shifted dates for the new climate, x-coord. for $CDC_{CLIM}$. To determine these dates always take a value in Col.14 and look in Col.16 for a value that equals or exceeds the Col.14 value; then look in Col.1 for a date corresponding to the Col.16 value.

CDC - Conventional Depletion Curve
$MDC_{INCL}$ - Modified Depletion Curve including new snow
$MDC_{EXCL}$ - Modified Depletion Curve excluding new snow
$MDC_{CLIM}$ - Modified Depletion Curve for the new climate
$CDC_{CLIM}$ - Conventional Depletion Curve for the new climate
$T_{CRIT}$ - temp. used to divide precip. events into rainfall or snowfall

$MDC_{EXCL}$ indicates how much of the initial seasonal snow cover must be melted (in terms of calculated cumulative snowmelt depth) in order to decrease the snow covered area (new snow excluded) to a certain proportion of the total area and ultimately to zero. The shape of this curve changes from year to year but only according to the initial accumulation of snow at the start of the snowmelt period, independent of subsequent snowfalls.

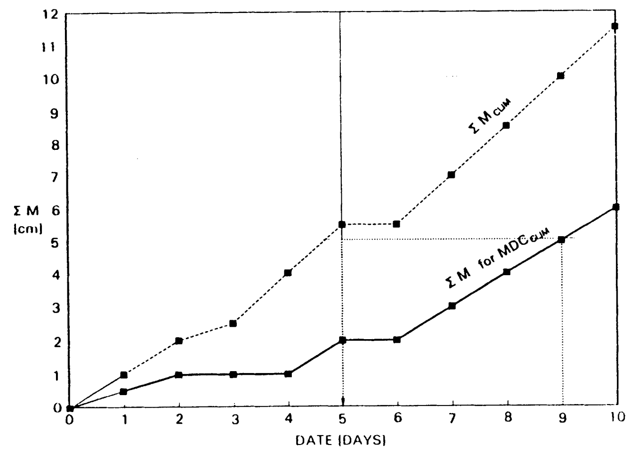


Fig. 2. Graphical determination of time shifting of snow covered area by a changed climate ($T$ + 1°C): In the present climate, a cumulative snowmelt depth of 5 cm is reached on day 9 (with new snow falls adjusted to $T$ +1°C), in the changed climate 5 cm is reached already on day 5.

## Change of the Snow Coverage by Higher Temperature

$MDC_{INCL}$ has been used to derive CDC in a warmer climate (Martinec 1980), but Table 1 illustrates a refinement taking into account the transformation of some of the snowfalls to rainfalls due to higher temperatures. First, melt depths referring to all snow falling during the snowmelt season are eliminated ($MDC_{EXCL}$ results); then the "surviving" snowfalls (precipitation events that remain as snow even in the higher temperature regime) in the warmer climate are added back. Thus the modified depletion curve for the new climate is obtained ($MDC_{CLIM}$) (Fig. 1) which serves for deriving the conventional depletion curve as changed by the new climate ($CDC_{CLIM}$). This is done by looking for a date (Table 1) on which the cumulative snowmelt depth in the new climate attains or exceeds the cumulative snowmelt depths referring to $MDC_{CLIM}$. For example, as shown in Fig. 2, $MDC_{CLIM}$ indicates a cumulative snowmelt depth of 5 cm on day 9, but in the new, warmer climate, this snowmelt depth is reached (even exceeded) already on day 5. Recalling Fig. 1, if the snowmelt depth of 5 cm reduces the snow coverage to 4%, as indicated by $MDC_{CLIM}$, this snow covered area which occurred according to CDC on day 9 will occur in the new climate already on day 5. By shifting all other points of CDC in this way, the new conventional depletion curve, $CDC_{CLIM}$, is obtained as shown in Fig. 3. This curve can be used to input daily snow covered area values to SRM in order to predict runoff patterns in a changed climate. Additionally, these estimates of future changes in snow covered areas could be useful for climate modellers as a feedback mechanism and as a way to distribute various energy exchange processes across a drainage basin.

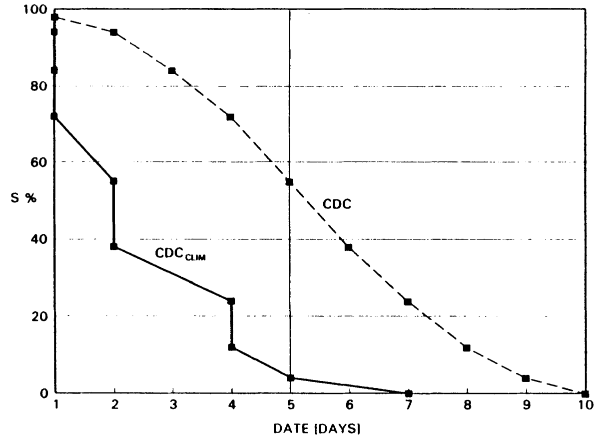


Fig. 3. Depletion curves of the snow coverage in the present climate (CDC) and in a changed climate ($T$ + 1°), $CDC_{CLIM}$.

## Change of the Snow Coverage by Increased Precipitation

While higher temperatures accelerate the decline of the snow cover, increased snowfalls during the snowmelt period slow down this process. The increased new snow that falls must be melted before the seasonal snow cover depletion can proceed. At the same time, more rainfalls accelerate the snowmelt but this effect is neglected in the present context because the additional heat supplied by the liquid precipitation is considered to be small (Wilson 1941). Thus, it is only the snow-part of precipitation which changes the snow covered areas. In order to demonstrate distinctly this effect, the daily precipitation occurring during the snowmelt period used in Table 1 is doubled, but no increase in temperature is applied. Because no air temperature change is assumed, the amount of snowfall is also doubled. As expected, this causes a shift of $MDC_{CLIM}$ to the right of $MDC_{INCL}$ (Fig. 4). $MDC_{CLIM}$ is used to shift the CDC in the same way as described in the previous section for the effect of a higher temperature. As shown in Fig. 4, this precipitation effect takes an opposite direction to the temperature effect (see Fig. 1).

## Change of the Snow Coverage by Increases in Temperature and Precipitation

In many areas, variations in temperature as well as in precipitation may be expected from a climate change. Therefore, the third example takes both effects simultaneously into account. Table 2 includes computations referring to higher temperatures as well as to an increased precipitation. It would be equally possible to consider a decreased precipitation (as well as a decreased temperature, although

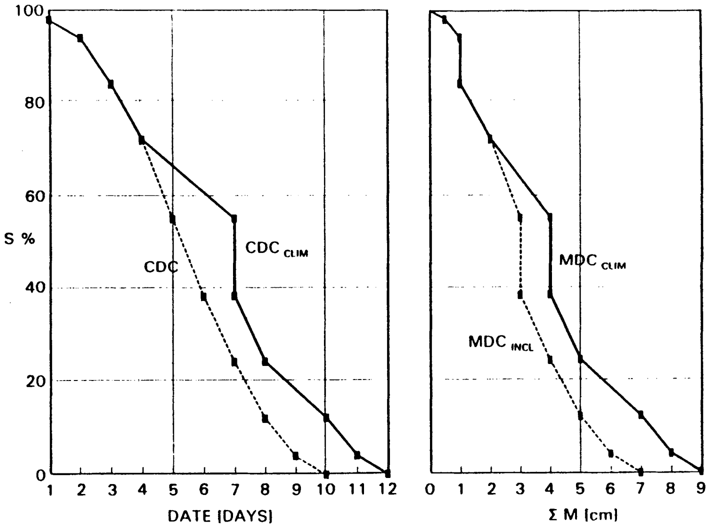


Fig. 4. Depletion curves of the snow coverage in the present climate (CDC) and in a changed climate (precipitation amounts doubled), $CDC_{CLIM}$, as derived from $MDC_{CLIM}$.

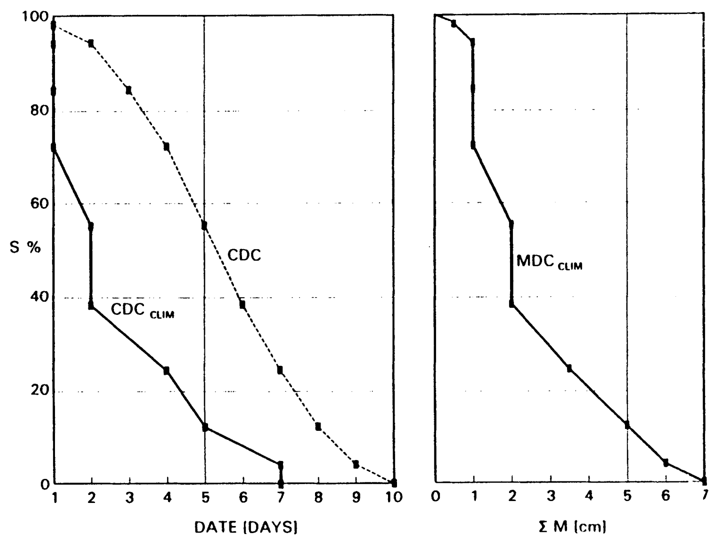


Fig. 5. Depletion curves of the snow coverage in the present climate (CDC) and in a changed climate ($T$ + 1°C, $P \times 2$), $CDC_{CLIM}$, as derived from $MDC_{CLIM}$.

this does not seem likely at the moment). As shown in Fig. 5, the effect of temperature prevails over the effect of precipitation so that the original conventional depletion curve is shifted towards earlier dates. If only a 10-20% increase in precipitation were to occur instead of a doubling, the effect on the snow cover would be relatively insignificant compared to the temperature-related effect.

Table 2 – Computation of x-coordinates for $CDC_{CLIM}$ for a climate change: $T$ + 1°C, $P \times 2$ (y-coordinates are the corresponding snow coverage values S(%)). Assumed parameters: Degree-day factor $a$=0.5 cm °C$^{-1}$d$^{-1}$; Critical temperature $T_{CRIT}$ =0.5°C.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 98 | 1 | 0.5 | 0.5 | | | 0 | 0.5 | 2 | | | 0 | 0.5 | 1 | 1 | 1 |
| 2 | 94 | 1 | 0.5 | 1 | | | 0 | 1 | 2 | | | 0 | 1 | 1 | 2 | 1 |
| 3 | 84 | 0 | 0 | 1 | 1 | | 0 | 1 | 1 | 2 | | 0 | 1 | 0.5 | 2.5 | 1 |
| 4 | 72 | 2 | 1 | 2 | | 1 | 1 | 1 | 3 | | | 0 | 1 | 1.5 | 4 | 1 |
| 5 | 55 | 2 | 1 | 3 | | | 1 | 2 | 3 | | | 0 | 2 | 1.5 | 5.5 | 2 |
| 6 | 38 | -1 | 0 | 3 | 1 | | 1 | 2 | 0 | 2 | | 0 | 2 | 0 | 5.5 | 2 |
| 7 | 24 | 2 | 1 | 4 | | 1 | 2 | 2 | 3 | | 1.5 | 1.5 | 3.5 | 1.5 | 7 | 4 |
| 8 | 12 | 2 | 1 | 5 | | | 2 | 3 | 3 | | 0.5 | 2 | 5 | 1.5 | 8.5 | 5 |
| 9 | 4 | 2 | 1 | 6 | | | 2 | 4 | 3 | | | 2 | 6 | 1.5 | 10 | 7 |
| 10 | 0 | 2 | 1 | 7 | | | 2 | 5 | 3 | | | 2 | 7 | 1.5 | 11.5 | 7 |

1 Date, x-coordinates for CDC
2 Snow covered area (S in %), y-coord. for CDC,$MDC_{INCL}$,$MDC_{EXCL}$,$MDC_{CLIM}$,$CDC_{CLIM}$
3 Temperature (T in °C), present climate
4 Snowmelt depth (M in cm), T•a
5 Cum. snowmelt depth (ΣM in cm), x-coord. for $MDC_{INCL}$
6 Precipitation (P in cm), present climate
7 Melt depth of new snow ($M_{NEW}$ in cm)
8 Cum. new snowmelt depth ($\Sigma M_{NEW}$ in cm)
9 Col.5-Col.8 ($\Sigma M_{EXCL}$ in cm), x-coord. for $MDC_{EXCL}$
10 Temperature in the new climate ($T_{CLIM}$ in °C)
11 Precipitation in the new climate ($P_{CLIM}$ in cm)
12 Melt depth of new snow in the new climate ($M_{NEW\,CLIM}$ in cm)
13 Cum. melt depth of new snow in the new climate ($\Sigma M_{NEW\,CLIM}$ in cm)
14 Col.9+Col.13 ($\Sigma M_{EXCL}+\Sigma M_{NEW\,CLIM}$ in cm), x-coord. for $MDC_{CLIM}$
15 Snowmelt depth in the new climate ($M_{CLIM}$ in cm), $T_{CLIM}$•a
16 Cum. snowmelt depth in the new climate ($\Sigma M_{CLIM}$ in cm)
17 Shifted dates for the new climate, x-coord. for $CDC_{CLIM}$. To determine these dates always take a value in Col.14 and look in Col.16 for a value that equals or exceeds the Col.14 value; then look in Col.1 for a date corresponding to the Col.16 value.

## Assessment of Results

Fig. 6 summarizes the various climate change scenarios outlined. As expected, a seasonal snow cover of today will disappear faster in a warmer climate assuming no changes in precipitation. With less precipitation in a given area, the snow cover will disappear even faster, whereas more precipitation will slow down the snow cover depletion. If precipitation during the snowmelt period in the present climate does not include snowfalls, changes in the precipitation amounts do not affect the snow cover. In the given examples, the effect of a future climate change is evaluated only for the duration of the snowmelt season. This means that, thus far, the existing

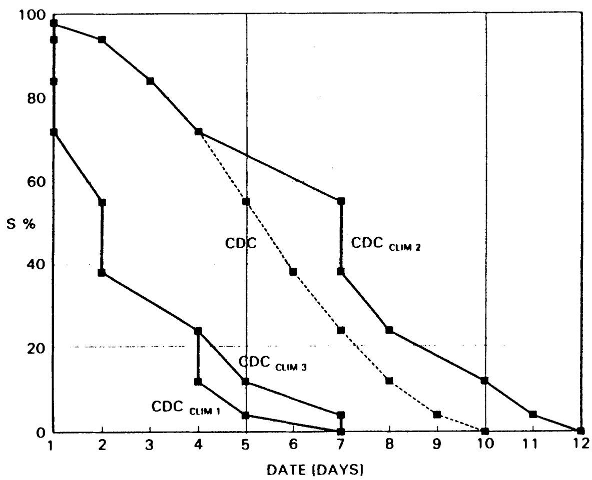


Fig. 6. Comparison of the depletion curve of the snow coverage in the present climate (CDC) with curves for three examples of a changed climate: $CDC_{CLIM1}$ ($T$ + 1°), $CDC_{CLIM2}$ ($P \times 2$) and $CDC_{CLIM3}$ ($T$ + 1°, $P \times 2$).

snow accumulation at the beginning of the snowmelt season has been assumed to be unchanged. However, if the warmer climate would be extended to the winter months, some of today's snowfalls would become rainfalls, and precipitation amounts may also change in the accumulation period. This would result in a changed snow cover accumulation at the beginning of the snowmelt period. Consequently, there will be not only a new climate influencing the seasonal snow cover, but this snow cover to start with will be different as well. The results of a changed April 1 snow accumulation on the snowmelt runoff as part of several different climate change scenarios has been reported by Rango and van Katwijk (1990). In one case on the Rio Grande basin in Colorado, a 25% reduction in the snow accumulation on April 1 resulted in a 22% decrease in total seasonal flow (Rango and van Katwijk 1990).

The climate-adjusted conventional depletion curves ($CDC_{CLIM}$), as shown in Fig. 6, are not smooth like the original CDC. This results from the irregular shape of the modified depletion curves. Some of the deformations are caused by the adopted simplified procedure. There is not much sense in trying to obtain a high accuracy and exact timing of the time shift of the climate adjusted curves ($CDC_{CLIM}$) for the following reasons:

1) The continuous smooth decline of the orginal CDC's result from an interpolation between the measured points. This smooth curve should be corrected in the first place because CDC's should stop decreasing whenever there is new snow and on days with no snowmelt. However, remote observations of the snowpack are not available every day, and a smooth CDC results. Because of this, the MDC's are distorted whereas they, in fact, should be smooth curves. For example, they occa-

sionally indicate a drop in the snow covered area while the cumulative snowmelt depth remains the same.

2) The effect of changed precipitation in the new climate cannot be accurately simulated because it is not known, for example, whether an increase means higher daily amounts or a higher frequency of precipitation events. In the given example, an exaggerated increase of precipitation serves the purpose to demonstrate its effects. Fortunately the expected change of precipitation is in the range of only ± 20% so that no major problems arise if it cannot be taken into account quite accurately. In addition, as already mentioned, only the snow-part of precipitation affects the snow cover.

A computer program has been added to the present SRM program in order to facilitate simulations of these scenarios. If the depletion curve derived for a changed climate has more than one value of snow coverage on a single day, as for example in Fig. 3, the first of these values (for example 55% on day 2) is automatically used as the SRM input. If there is no new value on a certain day, the previous day's value is automatically used for that day (for example 38% on day 3). Fig. 7 shows the resulting conventional depletion curves as produced by SRM for elevation zone B (2,926-3,353 m a.s.l.) of the Rio Grande basin in Colorado for 1979. The daily snowmelt rates have been calculated by degree-day ratios ranging from 0.4 to 0.55 $cm°C^{-1}d^{-1}$. The temperature data have been extrapolated to the hypsometric mean elevation of this zone by lapse rates ranging from 0.65 to 0.95 °C/100 m. Critical temperatures to distinguish between rain and snow were in the range of 0.75-2.5 °C. Original runoff simulations by SRM using the same parameters agreed well with the measured runoff for this basin. This is considered as a verification of the above mentioned values. In this example, the temperature is increased by 2°C ($CDC_{CLIM1}$), 4°C ($CDC_{CLIM2}$), precipitation is doubled ($CDC_{CLIM3}$), and a 4°C increase and a precipitation doubling are combined ($CDC_{CLIM4}$). The 4°C higher temperature accelerates the depletion of snow covered areas by about 20 days. The doubled precipitation with no increase of temperature slows down this process by about five days.

In a similar example in Fig. 8 for the Illecillewaet River basin of British Columbia, the 4°C higher temperature accelerates the depletion of snow covered areas by about 30 days in a year like 1981. The doubled precipitation with no increase of temperature slows down this process also by about five days.

## Conclusions and Outlook

The aim of the procedure described in this paper is to evaluate whether a given climate scenario will speed up or slow down the seasonal decrease of snow covered areas and what the time shift will be. This information can serve two main purposes:

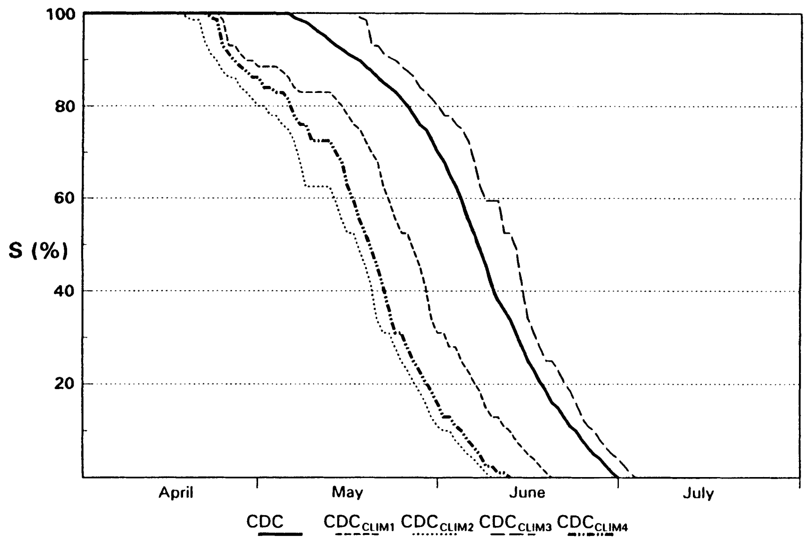


Fig. 7. Comparison of the conventional depletion curve (CDC) for 1979 in elevation zone B (2,926-3,353 m a.s.l.) of the Rio Grande basin, Colorado with curves for four examples of changed climate as generated by the Snowmelt-Runoff Model computer program: $CDC_{CLIM1}$ ($T$ + 2°C), $CDC_{CLIM2}$ ($T$ + 4°C), $CDC_{CLIM3}$ ($P \times 2$), and $CDC_{CLIM4}$ ($T$ + 4°C, $P \times 2$).

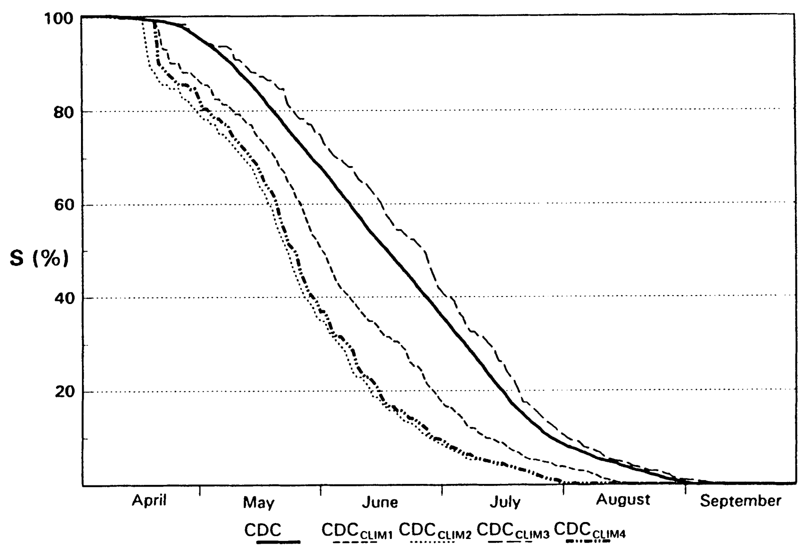


Fig. 8. Comparison of the conventional depletion curve (CDC) for 1981 in elevation zone B (1,200-1,800 m a.s.l.) of the Illecillewaet River basin, British Columbia with curves for four examples of changed climate as generated by the Snowmelt-Runoff Model computer program: $CDC_{CLIM1}$ ($T$ + 2°C), $CDC_{CLIM2}$ ($T$ + 4°C), $CDC_{CLIM3}$ ($P \times 2$), and $CDC_{CLIM4}$ ($T$ + 4°C, $P \times 2$).

1) Input to snowmelt runoff models, in particular to SRM, for computing the new runoff pattern in a changed climate in terms of daily flows.

2) Input to climate models because the changed snow covered areas will influence the albedo of the earth's surface by a feedback effect.

In addition, other purposes could be served by this procedure, for example, estimates of ecosystem responses to a changing snow cover would be possible using this procedure to generate input data.

Although several simple test cases are used for illustration, a computer program has been added to SRM that automatically makes the changes in snow cover as dictated by the climate change scenarios being used and the simple degree day index. In the climate change test cases reported, changed temperatures of +2°C and +4°C both had a much more important effect on the snow cover than a doubling of precipitation. The resulting changed snow cover values are directly input to SRM to produce hydrographs indicative of the climate change scenarios. If the snow cover values are needed for applications other than snowmelt runoff, the program can produce an output file for these purposes. Both the simple test case data and actual watershed data have shown that basin snow cover is very sensitive to changes in climate. Wherever snow reserves are an important part of the hydrological cycle, the response of the snow cover extent to the climate change must be considered.

## Acknowledgements

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