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RELATIVE IMPORTANCE OF GLACIER CONTRIBUTIONS TO WATER SUPPLY IN A CHANGING CLIMATE

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SUMMARY

The Snowmelt Runoff Model (SRM) was designed for simulation, forecasting, and future assessments, such as the effects of climate change. The most recent version of SRM uses the Microsoft Windows operating system and operates efficiently in the PC environment. A formalized algorithm for assessing the effects of climate change on runoff is included in the model. SRM parameters are predetermined from actual measurements or from hydrological experience and, therefore, calibration is not necessary. This deterministic approach allows the parameters to be altered with regard to a changed future climate. SRM variables of daily temperature, precipitation, and snow covered area are also easily acquired. SRM allows contributions of snow, rain, and glacier ice to be separately computed for a present year and for a future climate-changed year. In basins with a significant glacier melt component, such as the Illecillewaet Basin in British Columbia, the glacier runoff component increases as the climate warms. Of course, when the glacier volume is depleted to a certain point, the glacier area will start to decline and the valuable glacier melt component will also be diminished.

INTRODUCTION

In earlier studies of hydrological responses to climate change (Rango and Martinec, 1997a; 1997b), the climate change was restricted to a hypothetical increase of temperature in order to quantitatively evaluate its effect on runoff in mountain snowmelt basins. Because none of the losses (e.g. evapotranspiration) were changed, the yearly runoff volume remained approximately the same. In a glacierized study basin, however, an increase in runoff volume was noticed due to additional glacier melt from warmer temperatures. SRM can also handle climate scenarios involving different changes of temperature and precipitation in the winter and summer half years, as demonstrated by Ehrler (1998). Making use of SRM output products, the carryover from one hydrological year to the next of snow and ice reserves as well as runoff contributions to river flow (in transit through the hydrological cycle at year end) is taken into account in this paper. This improved hydrological balance reveals the role of the seasonal snow cover, glacier, and precipitation in the climate change-affected runoff. These items of the hydrological balance are separately evaluated for these hypothetical climate scenarios and compared with the respective changes of the yearly runoff as computed by the model.

SRM PROGRAM BACKGROUND

SRM is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. Most recently, it has also been applied to evaluate the effect of a changed climate on seasonal snow cover and runoff. SRM was developed by Martinec (1975) in small (<1-2 km^2) European basins. Thanks to the progress of satellite remote sensing of snow cover, SRM has been applied to larger and larger basins. Recently, the runoff was modeled in the basin of the Ganges River, which has an area of 917,444 km^2 and an elevation range from 0 to 8, 840 m a.s.l. Contrary to original assumptions, there appear to be no limits for application with regard to basin size and elevation range. Also, a dominant role of snowmelt does not seem to be a necessary condition. It is, however, advisable to carefully evaluate the formula for the recession coefficient which varies by size of the basin. Figure 1 shows the important components of SRM, including variables and parameters.

Runoff computations by SRM appear to be relatively easily understood. To date the model has been applied by various agencies, institutes and universities in over 110 basins, situated in 29 different countries. More than 80% of these applications have been performed by independent users (Martinec et al., 1998). SRM was also successfully tested by the World Meteorological Organization with regard to runoff simulations (WMO, 1986) and to partially simulated conditions of real-time runoff forecasts (WMO, 1992).

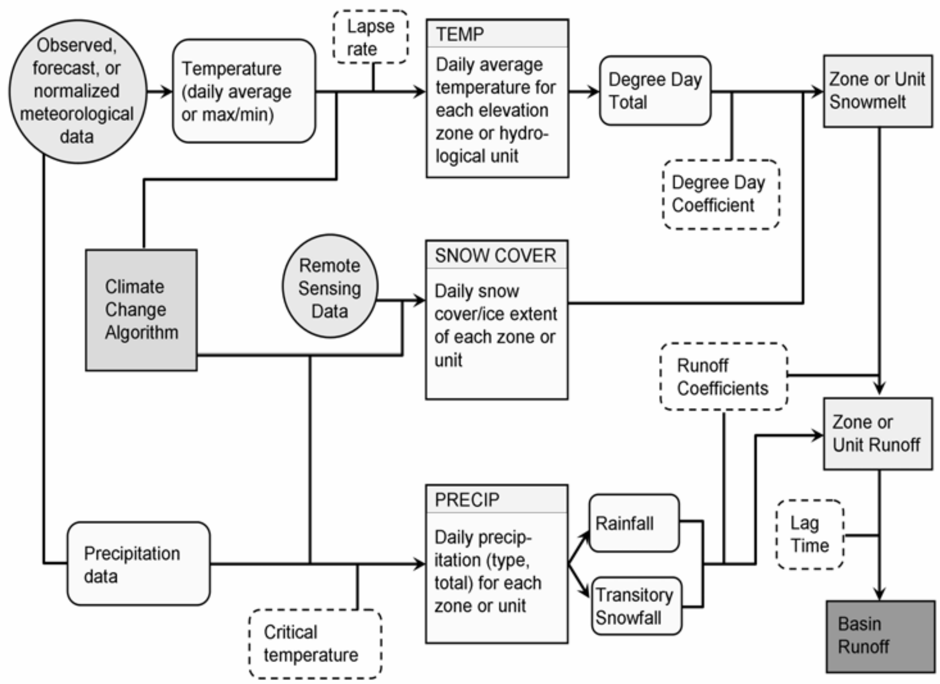

Figure 1 Schematic diagram of the organization of the Snowmelt Runoff Model (SRM)

SRM was originally a FORTRAN model designed to operate on an IBM 370-series mainframe computer. The first computerized version of the model was developed by Martinec et al (Martinec et al., 1983). In 1986 the model's FORTRAN code was downloaded to an IBM PC and modified to operate in the PC environment. That same year a decision was made to develop a unique PC-oriented version of the model, taking full advantage of the PC's inherent capabilities. The developers decided also that the PC platform would be the most likely and accessible computer for water managers. This has been borne out by the number individuals using the model.

Additional refinements were incorporated in several subsequent Micro-SRM versions; but, SRM itself remained unchanged and relatively simple, so that the computations could still be spot-checked using any pocket calculator which has a function of x^y. The DOS PC program automatically handles the multiple input of temperature and precipitation for up to eight elevation zones of a basin, any desired lag time, and complicated snow/rain situations. A model simulation for up to 365 days is finished within several seconds; the computed hydrograph is immediately displayed in comparison with the measured discharge and, if desired, quickly printed. Also, the achieved accuracy is automatically computed and displayed. A summary of parameter values can be displayed after each run so that adjustments can be made and their effect assessed.

SRM does not require numerous runs because calibration is not necessary. The ease with which the results are obtained should not lead to a replacement of the deterministic approach of SRM by a "trial and error" philosophy. SRM is designed to operate with physically-based estimates of parameters that should not require much change after the initial selection. Seemingly unsatisfactory results have been frequently improved not by adjusting the parameters, but by examining input data and correcting errors in data sets and in the input of variables.

In contrast to calibrated models, SRM parameter values must stay within a range limited by physical measurements and hydrological judgment. Consequently, SRM requires accurate data on snow cover which are provided by Landsat, Terra-MODIS, and NOAA-AVHRR satellite sensors. 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 snow or rain) is estimated by experience with actual meteorological records and visual observations and stage of 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 SRM User's Manual (Martinec et al., 1998) and to Martinec and Rango (1986).

A prime consideration in the design of Micro-SRM was to develop a snowmelt modelling "environment" such that the model user was provided not just model algorithms, but a complete set of tools for managing the associated model processes: data entry, storage and retrieval, display of data, and results. Traditionally, the most time consuming and error prone activity involved in using any physically-based model has been the accumulation of large amounts of input data in the form and format needed to drive the simulation, with actual execution of the model a trivial task by comparison. Recognizing this, we chose to pattern the design of Micro-SRM after that originally developed during the automation of the Soil Conservation Service's (SCS) Technical Release Number 55 (TR-55), Urban Hydrology for Small Watersheds (SCS, 1986). This joint Agricultural Research Service (ARS) /SCS effort provided valuable experience in developing highly interactive 'front-ends' for interfacing complex models with model users. The approach used by the ARS/SCS programming team that automated TR-55 was to develop an efficient, easy to use, highly interactive data entry/manipulation environment, and includes model algorithms as just one of many functions that support and use that environment (Cronshey et al., 1985). Micro-SRM consists of an integration of the mainframe SRM FORTRAN algorithms converted to Basic and a variation of TR-55's data entry/data management algorithms.

The Snowmelt-Runoff Model for Windows (WinSRM) is the first version of SRM that has been adapted for use with the Microsoft Windows operation system (Win 95/98/2000/XP) (Martinec et al., 2008). Limitations imposed on existing and future research by the physical constraints of the DOS operating system, as well as its relative obsolescence were the primary reasons for the transition to Windows. This new version of the program is compatible with pre-existing DOS.SRM data files. The basic SRM model algorithm remains unchanged, producing identical simulation results to those obtained by the DOS version of the model. The graphical user interface (GUI) and data storage philosophy have undergone a complete redesign to take advantage of the enhanced capabilities available on the modern "windows" platform. All of the original DOS output products (graphs and reports) remain available, with enhancements provided that improve on-line analysis and usability, and off-line quality.

Basins may now consist of up to 16 elevation zones. Modern database technology is utilized to manage the data storage requirements of the model. Storage is organized using the concept of a basin data base. Within a basin data base resides a single copy of the physical variables for the basin's period of record. All the simulations developed for the basin are likewise located in the same data base along with supporting information used by the modeler, such as climate change scenario definitions. The most significant improvement in the model's capability is in the area of climate change simulation. The limitations imposed on climate change processing by DOS have been removed, allowing a much more detailed and robust definition of change to be studied.

Finally, the path of future research using the model has been laid by moving to an operating system and a model design that minimizes or removes the restraints to development inherent in the earlier design and operating system environment.

SRM AND CLIMATE CHANGE

SRM has been used very successfully for simulating the mountain snowmelt hydrograph. Forecasting of the seasonal streamflow from mountain basins has also been accomplished using SRM (Rango, 2006). Probably the most topical use of SRM recently has been for assessing the hydrological effects of climate change.

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 which use a simulated snow cover based on uncorrected, underestimates of precipitation catch, especially in mountainous areas.

A formalized procedure is used to determine the time shift of the snow cover depletion curves for given temperature increases of the future. These future snow cover depletion curves are input to SRM, which is used for runoff computations. 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, are evaluated also.

It has been pointed out 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 (Klemeš, 1985; Becker and Serban, 1990). SRM parameters are predetermined and not calibrated (WMO, 1986; 1992; Martinec and Rango, 1986). 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).

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.

THE IMPORTANCE OF GLACIERS IN A CHANGED CLIMATE

The study described in this paper uses the formalized climate change approach in SRM, but for a related topic of interest, the effects of climate change on melt from existing glaciers. Glaciers in mountain basins can be an important component of water supply which can be used for irrigation and power generation. Because mountain glaciers do not cover vast land areas, they usually serve as a modulating influence on water supply. Late in the summer melt season they can supply an important quantity of water when the seasonal snowpack has disappeared and snowmelt has concluded. Additionally, in dry, warm years, streamflow is supplemented by glacier melt, and in cold, wet years, the glacier produces little melt water while accumulating additional ice mass. These responses are due to normal seasonal meteorological variability. Glaciers respond differently to climate change consisting of a steady, gradual atmospheric warming from year-to-year superimposed on long-term variability. Such a change results in increasing annual melt with time until the glacier area starts to recede and a reduction in the fresh water resource produced occurs. At this point, the natural modulating effect of the glacier will be diminished. Figure 2 provide a hypothetical graphic of how a snow cover recedes or depletes in a basin subjected to continuous, gradual warming that also has glacial cover. As temperatures increase in the spring, melt begins early and the snow cover depletes fairly quickly. Once the ice cover is exposed, the snow/ice cover remains relatively constant for the remainder of the summer and for a number of years (curve 1) until the glacier starts to recede. Curves 2, 3, and 4 reflect the continuing depletion of the glacier area. At some point, the glacial area may completely disappear if increased warming continues.

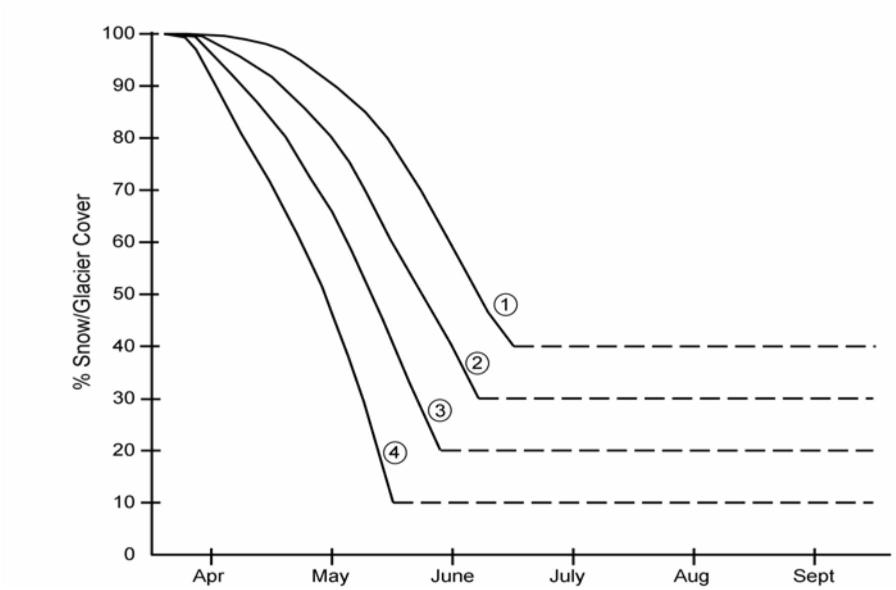

Figure 2 Hypothetical curves of the snow/ice cover area reduction as global warming continues over a period of years.

HYDROLOGICAL BALANCE OF THE TEST BASIN

The Illecillewaet basin in British Columbia, Canada, has been selected for this study. It has an area of 1155 km^2 and an elevation range of 509-3150 m a.s.l. For the purpose of snowmelt runoff modeling, the basin was divided into four elevation zones listed in Table 1.

Table 1 Elevation zones and estimated glacier area percentages in the Illecillewaet basin

Elevation Zone	Area km^2	Elevation Range m a.s.l.	Glacier Area %	Glacier Area km^2
A	184.8	509-1200	-	-
B	408.9	1200-1800	-	-
C	468.9	1800-2400	4	18.8
D	92.4	2400-3150	40	37.0
TOTAL	1155.0	509-3150	5	55.8

The glacier areas were estimated from periodical satellite monitoring at the end of the melt season. When the decline of snow (ice) cover depletion curves levels out late in the snowmelt season, it usually is an indication of the presence of glaciers or possibly of permanent snow fields. Consequently the following runoff component sources have to be considered in a climate change scenario: seasonal snow cover; new snow on snow-free areas; glaciers and permanent snow fields; and rain.

If a climate change consists only of a temperature increase, there is a temporal redistribution of runoff but usually no significant change of the yearly runoff volume, unless evaporative losses are assumed to be increased by the warmer climate. In glacierized basins, however, a runoff increase has to be expected due to additional glacier melt during the summer. This effect was documented in an earlier study (Rango and Martinec, 2000) for a hypothetical temperature increase of +4^{o}C. In this paper, hypothetical changes of temperature as well as of precipitation are taken into account. Consequently, a refined hydrological balance is needed in order to evaluate the increase of the glacier melt in a warmer climate.

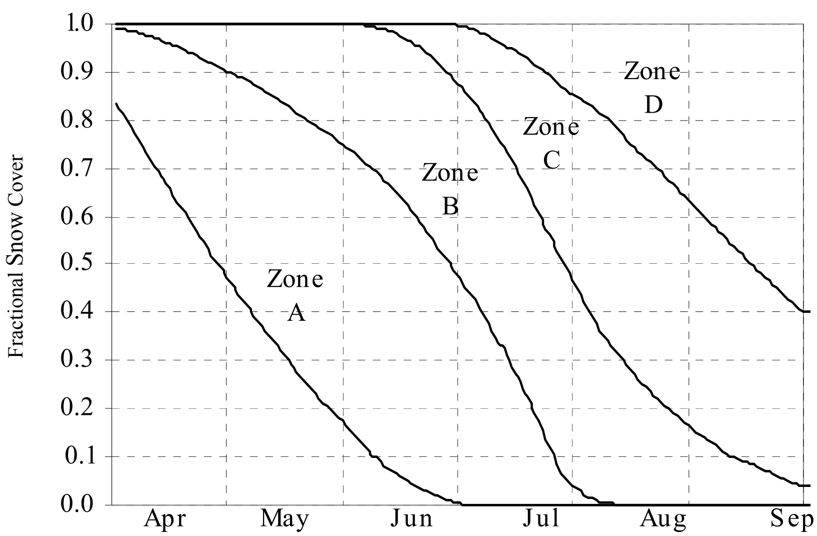

Figure 3 Depletion curves of snow coverage (CDC) from satellite snow cover mapping, elevation zones A, B, C, and D, 1984 in the Illecillewaet basin.

RUNOFF MODELING

The basic input variable for the SRM snowmelt calculation is the area of the seasonal snow cover in the basin, which is now routinely monitored by satellites. This information enables the model to compute runoff and evaluate snow accumulation (see next section) in a deterministic way using physically-based parameters. Figure 3 shows conventional depletion curves (CDC) of the snow coverage interpolated from periodical snow cover mapping from Landsat data in 1984. In the winter half year (October-March), a stable snow cover was assumed in December-February for the elevation Zones A and B and in November-March for zones C and D. In the remaining months, all snowfalls were handled by the SRM precipitation algorithm (Martinec et al., 1998) where a critical temperature determines whether a precipitation event is rain or snow. The runoff simulation in the hydrological year 1984 is shown in Figure 4.

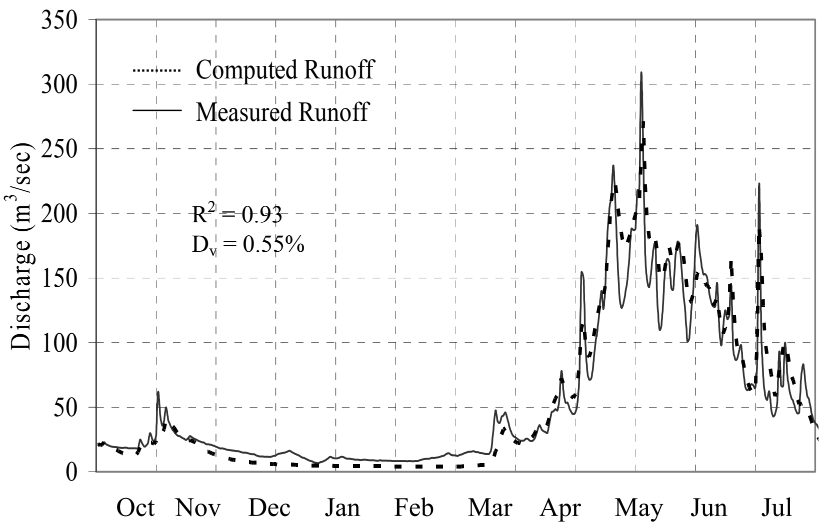

Figure 4 Measured and computed runoff in the Illecillewaet basin in the hydrological year 1984.

The predetermined values of the SRM model parameters were in the following range during the snowmelt season:

degree-day factor, a = 0.3–0.6 cm $^{o}C^{-1}d^{-1}$

runoff coefficient for snow, c_S = 0.6–0.9

runoff coefficient for rain, $c_R = 0.6–0.9$

temperature lapse rate 0.65–0.7 ^oC per 100 m altitude

critical temperature (snow/rain) $T_{CRIT} = 0.75–3\ ^oC$

In winter, the range was more narrow:

$a = 0.2–0.3$ cm $^oC^{-1}d^{-1}$

c_S and $c_R = 0.8–0.9$

temperature lapse rate 0.65 ^oC per 100 m altitude

critical temperature (snow/rain) $T_{CRIT} = 0.75^oC$

Good values of the statistical accuracy criteria (coefficient of determination $R^2 = 0.93$, runoff volume difference 0.55%) in Figure 4 confirm that parameters predetermined for the 1984 runoff simulation are in a realistic range. Consequently, the evaluation of snow conditions and runoff for the present and future climate can be carried out with more confidence than if model-generated accumulated snow cover calculated from observed precipitation and temperature data was used, considering that precipitation data in mountain regions is often severely affected by a large precipitation gauge catch deficit (Hanson et al., 1999; Sevruk, 1982).

SNOW CONDITIONS AND RUNOFF FOR DIFFERENT CLIMATE SCENARIOS

The SRM computer program (Martinec et al., 2007) can evaluate the effect of any changes of temperature and precipitation in a new climate. Three hypothetical examples are given in this paper:

Scenario A: Temperature increase of 4^oC, precipitation unchanged ($T+4^o$, P)

Scenario B: Temperature increase of 4^oC, precipitation increase by 20% ($T+4^o$, $P \cdot 1.2$)

Scenario C: Temperature unchanged, precipitation increase by 20% (T, $P \cdot 1.2$)

The water equivalent of the seasonal snow cover at the end of the winter accumulation period (1 April in this paper) can be evaluated by the so-called modified depletion curves of the snow coverage (MDC). The time scale of CDC is replaced by the cumulative snowmelt depth computed daily so that the area below the curve indicates the initial water equivalent of the snow cover, as explained in more detail in Hall and Martinec (1985). If snowfalls occur during the snowmelt period, this water equivalent is also included (MDC_{INCL}). In order to evaluate the water equivalent of the snow cover on 1 April, the computed melt depth of new snow is excluded from snowmelt totals and a modified depletion curve excluding new snow (MDC_{EXCL}) is derived.

It is thus possible to evaluate the average areal water equivalent of the snow cover on 1 April in each elevation zone of the Illecillewaet basin except in zone D, which requires a modified approach because of the large area of glaciers in this zone (40%). In the winter half year under climate change, there is more snowmelt and some of the winter snowfall is converted to rainfall. Taking this winter deficit into account, the computer program evaluates less accumulated water equivalent on 1 April, as explained by Rango and Martinec (2000). This is the winter-adjusted modified depletion curve, $MDC_{EXCL\ WA.}$

The snow accumulation on 1 April is thus evaluated by MDC's$_{EXCL}$, in which snowfall occurring during the snowmelt season is excluded. For evaluations of the climate change-affected runoff, new snow during the snowmelt season must be taken into account, with amounts adjusted to the new climate, thereby producing the $MDC_{CLIM\ WA}$ curves.

The computation of runoff for different climate scenarios is based on

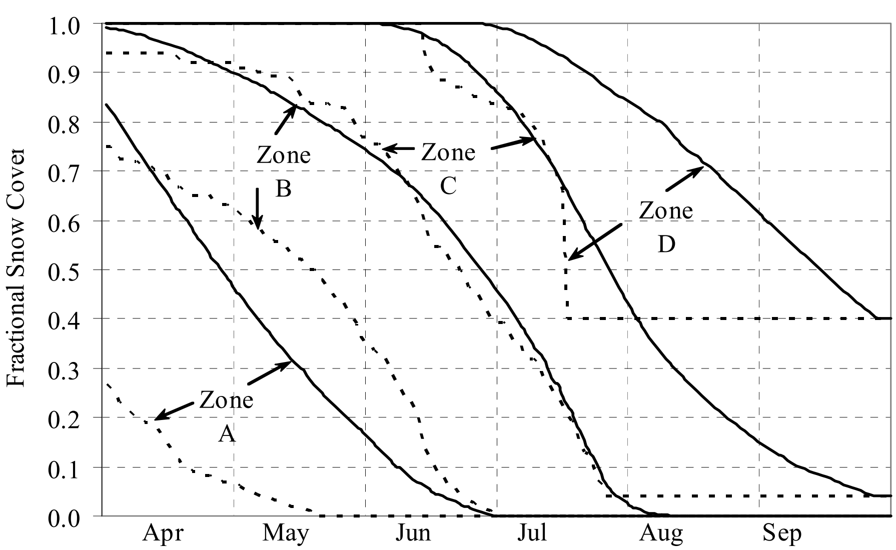

Figure 5 Original depletion curves (solid lines) of the snow coverage (CDC), and climate-adjusted curves (dashed lines), elevation zones A, B, C, and D for Scenario A.

climate change-affected conventional depletion curves of the snow coverage, $CDC_{CLIM\ WA,}$ which are shown in Figure 5 for Scenario A. The summer half year is computed using snow-covered areas from $CDC_{CLIM\ WA}$, T + 4° and unchanged precipitation as input variables. For the winter half year, the snow coverage was estimated as described for the runoff simulation in Figure 6. The computed runoff (original simulation) for the year 1984 (see also Figure 4) and for Scenario A is shown in Figure 6. In the climate run, the seasonally variable degree-day factors and runoff coefficients for snow are shifted to earlier dates by 31 days in accordance with the shift of $CDC_{CLIM\ WA}$ (Figure 5). The redistribution of runoff and changes in the yearly runoff volume are indicated in Table 2 for the scenarios.

The totals for the hydrological year show an increase of the runoff volume for Scenario A due to additional glacier melt. There is a greater increase for Scenario C, indicating that the effect of the precipitation increase is greater than that of the glacier melt. The combination of both effects in Scenario B results in the highest runoff volume amounting to 126% of the original runoff volume. In order to quantitatively evaluate the source components of these effects, it is necessary to analyze the hydrological balance as follows in the next section.

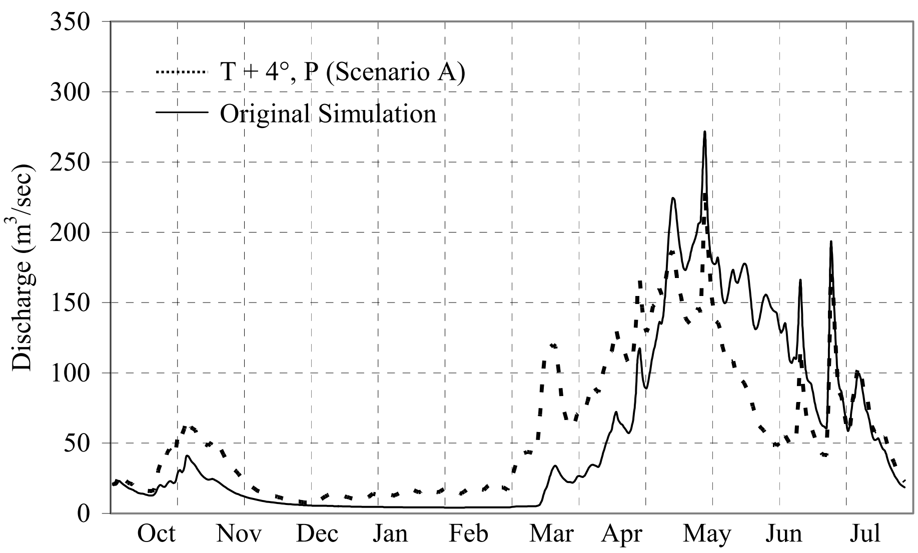

Figure 6. Computed runoff in the Illecillewaet basin for Scenario A (T+4˘) compared with the original runoff simulation for the hydrological year 1984.

Table 2 Winter and summer runoff volumes in the Illecillewaet basin

Climate Scenario	October-March $x\ 10^6 m^3$	%	April-September $x\ 10^6 m^3$	%	HydrologicalYear $x\ 10^6 m^3$	%
T, P (1984)	169.29	10.2	1495.56	89.8	1664.85	100
A: T + 4^o, P	341.63	8.9	1465.32	81.1	1806.95	100
B: T + 4^o, P . 1.2	383.55	8.3	1717.04	81.7	2100.59	100
C: T, P . 1.2	185.91	9.5	1769.01	90.5	1954.92	100

PRESENT AND FUTURE ROLE OF SNOW AND GLACIERS IN RUNOFF

Thanks to the transparent structure of the SRM model, it is possible to retrieve at any time the respective contributions to runoff of the computed snowmelt, glacier melt, new snow, and rainfall. Through use of its recession flow feature, the model also enables the runoff carryovers (for example from one hydrological year to the next one or from the winter to the summer snowmelt season) to be evaluated. The contributions of the respective runoff components become evident if the SRM formula is written as follows:

$$R_n = (M \cdot S \cdot c_S + M_N(1-S)c_S + P_R c_R)(1-k) + R_{n-1} \cdot k \qquad (1)$$

where R = daily runoff depth [cm]

M = snowmelt depth [cm]

S = snow coverage (decimal number)

M_N = melt depth of new snow [cm]

P_R = precipitation as rain [cm]

k = recession coefficient

N = refers to the sequence of days

When snow covering the glacier is melted away and the glacier melt begins, snowmelt becomes glacier melt and S becomes the glacier area. This occurs when the depletion curve of the snow coverage in a particular zone with glaciers present stops declining (see Zones C and D in Figure 5). In contrast to the seasonal snow cover, the glacier area remains approximately unchanged over short time periods in spite of the continued melting because of the large glacier mass. The starting date of glacier melt can be more accurately determined by advanced interpretation of satellite images to distinguish between snow and ice (Schaper et al., 1999).

Changes of the yearly runoff volume caused by glacier melt, changed precipitation, as well as by carryovers of snow and runoff are summarized in Table 3 for Scenarios A, B and C. It can be concluded in Scenario A that the temperature increase by +4°C results in a runoff increase of $142.1 \cdot 10^6$ m^3 per year, to which glacier runoff contributes by about 11.62 cm runoff depth or by $134.2 \cdot 10^6$ m^3 per year. A further small contribution of $13.3 \cdot 10^6$ m^3 is due to a reduced carryover of unmelted new snow and $5.4 \cdot 10^6$ m^3 is lost by an increased carryover by recession flow. In Scenario B, the temperature increase of +4°C and the increase of precipitation by 20% result in a runoff increase of $435.7 \cdot 10^6$ m^3, in which the runoff from the precipitation increase contributes $322.1 \cdot 10^6$ m^3 and the glacier runoff contributes $108.0 \cdot 10^6$ m^3. A small runoff increase of $12.9 \cdot 10^6$ m^3 is due to a reduced carryover of unmelted new snow while $7.3 \cdot 10^6$ m^3 is lost due to an increased carryover by the recession flow. In terms of volume in Scenario C, the precipitation increase by 20% produces $297.6 \cdot 10^6$ m^3 of additional runoff, with $290.1 \cdot 10^6$ m^3 flowing off within the hydrological year and the rest being carried over to the next year as additional unmelted snow and recession flow.

Table 3 Changes of the yearly runoff volume in response to climate change

Scenario	Δ Glacier melt $10^6 m^3$	Δ Precip. $10^6 m^3$	Δ Snow storage $10^6 m^3$	Carry-over Runoff $10^6 m^3$	Total Δ runoff $10^6 m^3$	% of Original Runoff $10^6 m^3$
A: T+4°, P	+134.2	0	+13.3	-5.4	+142.1	+8.53
B: T+4°, P . 1.2	+108.0	+322.1	+12.9	-7.3	+435.7	+26.17
C: T, P . 1.2	0	+297.6	-3.6	-3.9	+290.1	+17.42

It should be noted that, under conditions of climate change, as soon as glacier areas start to shrink as a result of a continued loss of glacier volume from increased melting, the contribution of glacier melt runoff as a percentage of total runoff will also decline. The relationship between volume and area will have to be determined specifically for glaciers in each basin studied. As a result, the glacier area in this study was held constant until such studies can be performed. The effect of temperature and precipitation changes in a future climate overshadows the other items.

However, it should be noted that by neglecting the differences of the snow storage at the end of the hydrological year, the additional glacier melt in a warmer climate would have been overestimated by 10-12%. The effect of a runoff carryover in the example hydrological year 1984 is relatively small but could be more important in other years.

CONCLUSION

By using a snowmelt runoff model with a transparent structure, such as SRM, contributions of snow, rain, and glacier ice to runoff can be separately computed for a year representing the present climate and one for a future warmer climate. The runoff carryovers and, if applicable, the residual snow reserves at the end of a hydrological year are affected by a changed climate. They serve to establish a balance of the respective components and the yearly loss of glacier ice. The importance of glacier melt as a contributor to total runoff in a warmer climate will at first increase thanks to higher temperatures, but this effect will gradually be reduced when the glacier area in a basin starts to decline as a result of a continued volume loss.

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