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RELATIVE IMPORTANCE OF GLACIER CONTRIBUTIONS TO STREAMFLOW IN A CHANGING CLIMATE

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ABSTRACT

The role of glaciers and snow in climate change-affected runoff is evaluated by taking into account the carryover of runoff and of unmelted snow from one hydrological year to another. This water balance is computed for the present climate and for future climates with changed temperatures and precipitation. With this procedure, the contribution of glaciers to the total runoff and the yearly loss of glacier ice in a warmer climate can be more accurately determined than by just considering the overall increase of annual runoff volume. The Illecillewaet Basin in British Columbia, Canada (1155 km^2, 509–3150 m a.s.l.) was selected for this study because of a significant glacial melt component in the runoff. For a temperature increase of 4°C, an additional $134.2 \cdot 10^6 m^3$ of today's glaciers (in terms of water) in this basin would be melted in a year. This amount would be reduced as the glacier area gradually diminishes in the next decades.

KEY WORDS

Water supply and sustainable use; climate change effects; watershed modelling; remote sensing.

1. Introduction

In earlier studies of hydrological responses to climate change [1],[2], 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 no change of losses (evapotranspiration) was introduced, 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. The snowmelt runoff model (SRM) can also handle climate scenarios involving different changes of temperature and precipitation in the winter and summer half years, as demonstrated by [3]. 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, glaciers, 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. A special study will be necessary to keep track of glacier volumes and corresponding glacier areas in the coming years of global warming based on characteristic regional relationships between glacier area and glacier volume. At present, future glacier areas in a warmer climate are not known and are kept unchanged from the current day in this study.

2. 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 modelling, the basin was divided into four elevation zones listed in Table 1.

Table 1. Elevation Zones and Estimated Glacier Areas in the Illecillewaet Basin.

Elevation Zone	Area km^2	Elevation Range m a.s.l.	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 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 [4] 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.

3. Runoff Modelling

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. Fig. 1 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 [5] where a critical temperature determines whether a precipitation event is rain or snow. The runoff simulation in the hydrological year 1984 is shown in Fig. 2. The predetermined values of the SRM model parameters were in the following range during the snowmelt season:

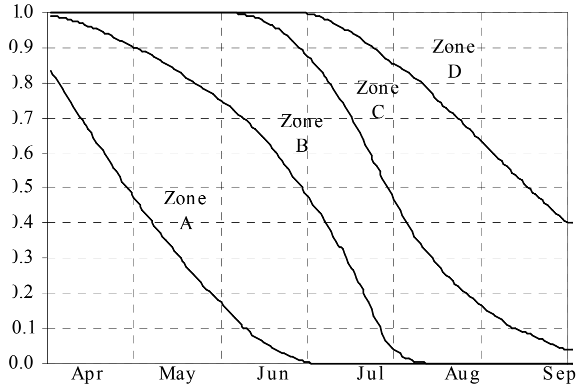

Fig. 1. Depletion curves of snow coverage (CDC) from satellite snow cover mapping, elevation zones A, B, C, and D, 1984 in the Illecillewaet basin.

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 ^{o}C per 100 m altitude
critical temperature (snow/rain) T_{CRIT} = 0.75–3 ^{o}C

In winter, the range was more narrow:

a= 0.2–0.3 cm $^{o}C^{-1}d^{-1}$
c_S and c_R = 0.8–0.9
temperature lapse rate 0.65 ^{o}C per 100 m altitude
critical temperature (snow/rain) T_{CRIT} = 0.75^{o}C

Good values of the statistical accuracy criteria (coefficient of determination R^2 = 0.93, runoff volume difference 0.55%) in Fig. 2 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 [6],[7].

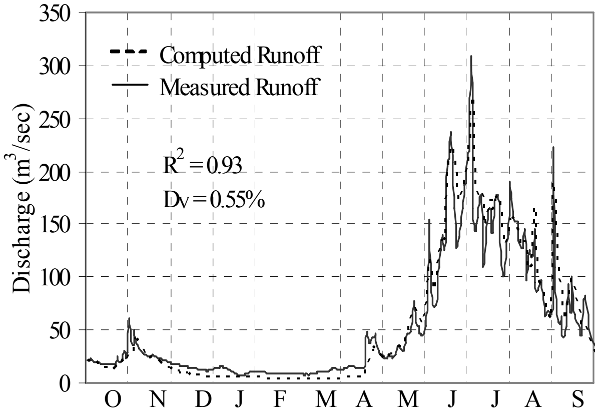

Fig. 2 Measured and computed runoff in the Illecillewaet basin in the hydrological year 1984.

4. Snow Conditions and Runoff for Different Climate Scenarios

The SRM computer program (Martinec et al, 1998) 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^{o}C, precipitation unchanged (T+4^{o}, P)
Scenario B: Temperature increase of 4^{o}C, 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 earlier [8]. 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 eliminated 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. 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 [4]. 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 climate change-affected conventional depletion curves of the snow coverage, $CDC_{CLIM\ WA,}$ which are shown in Fig. 3 for Scenario A. The summer half year is computed using snow-covered areas from $CDC_{CLIM\ WA}$, T + 4^o and unchanged precipitation as input variables. For the winter half year, the snow coverage was estimated as described for the runoff simulation in Fig. 2. The computed runoff (original simulation) for the year 1984 (see also Fig. 2) and for Scenario A is shown in Fig. 4. 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 $CDC_{CLIM\ WA}$ (Fig. 3). The redistribution of runoff and changes in the yearly runoff volume are indicated in Table 2 for the scenarios.

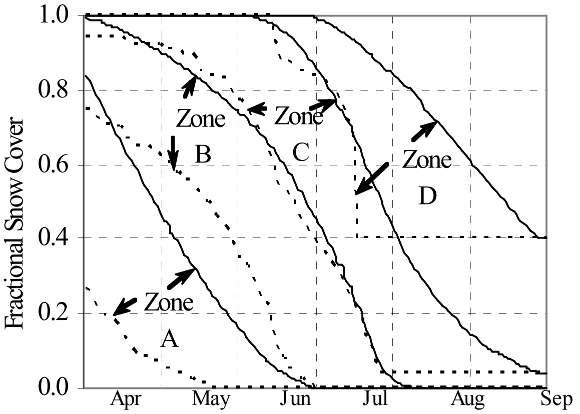

Fig. 3 Original depletion curves (solid lines) of the snow coverage (CDC, see also Fig. 2), and climate-adjusted curves (dashed lines), elevation zones A, B, C, and D for Scenario A.

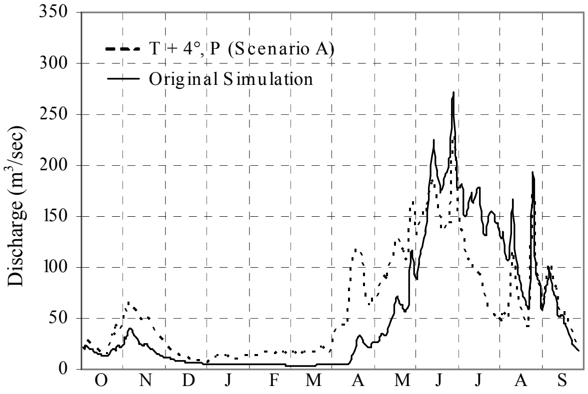

Fig. 4. Computed runoff in the Illecillewaet basin for Scenario A (T+4^o, P) compared with the original runoff simulation for the hydrological year 1984.

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.

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 %**	**Hydrological Year 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

5. 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. In contrast to the seasonal snow cover, the glacier area remains approximately unchanged 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 [9].

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 by $322.1 \cdot 10^6$ 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 10^6m^3	Δ Precip. 10^6m^3	Δ Snow storage 10^6m^3	Δ Carry-over runoff 10^6m^3	Total Δ runoff 10^6m^3	% of Original runoff 10^6m^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.

6. Conclusion

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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