Hydrological relationships in a glacierized mountain basin

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Abstract
A description is given of the runoff from a small highly glacierized basin for an eight-year period. Components of total runoff are estimated for glacier ice and firn, seasonal snow-packs and summer precipitation. While the presence of the glacier is seen to have a regulatory influence on total runoff and while the progression of events is similar from one year to another, the timing of events is markedly different resulting in summer hydrographs of quite different shapes. The interplay between terrain types, precipitation events and energy receipt is complex. The response time of the basin and the relative importance of ice and firn melt to total flow is closely linked to the timing of the progression of the transient snowline up glacier.

Introduction
The purpose of this paper is to describe for a small glacierized basin the temporal variability of runoff for an eight-year period. An attempt is made to break down the runoff into its various components; for the glacier itself ice melt and firn melt are calculated and for both glacier and non-glacier areas estimates are made of snowmelt derived from winter snow-packs and runoff derived from summer precipitation. The smallest temporal unit considered is the day; diurnal variations in runoff, although recognized as important indicators of runoff derivation, are not the subject of this paper. The paper is not concerned with prediction of runoff although some of the relationships outlined are considered essential in formulating predictive models.

A comprehensive review of the hydrology of glaciers has been given by Meier (1973); Krimmel & Tangborn (1974) have illustrated the important regulatory role exerted by glaciers in a basin; lag effects have been considered by Stenborg (1970). An outline of the important factors controlling runoff is given in the following paragraphs, since variation in such factors from one basin to another or from one time to another will explain variation in runoff.

Within a glacier basin a number of terrain types are usually found. The primary distinction between glacier and non-glacier areas can be extended for the non-glacier area into rock, moraines and snow-patches and for the glacier area into glacier ice and firn zones. The relative proportion of these zones, their spatial and vertical distribution can vary greatly from basin to basin; the sizes and shapes of basins also vary. These terrain factors play an important role in accumulation and melt processes and on the time taken for...
water to travel through the basin. Precipitation inputs to a basin vary greatly in quantity and regime from one mountain range to another. Within basins redistribution of snow by wind can have great influence on subsequent runoff regime; the mix of rainfall and snowfall events through time and the freezing elevation during storms clearly are variable and clearly have an important influence on the timing of runoff.

The seasonal variability in energy inputs available for melt in general increases towards the poles; the difference between "summer" and "winter" is minimized at the equator. Superimposed on this large-scale variability is the smaller scale, but often highly important, variability resulting from variety of aspect within a basin. The differences in energy receipt on north- and south-facing slopes can be critical in influencing the timing of runoff. Albedo, so greatly influenced by the persistence of winter snow cover and the occurrence of summer snowfalls, will be shown to have a very important effect on melt rates, most especially the melt rates of glacier ice.

This outline of the important factors in determining the runoff in glacier basins and the stress on variability has been given to put the events described in the study area into better perspective.

THE STUDY AREA

The Peyto Glacier basin, covering 22.8 km$^2$ of which 61% is glacier covered, lies on the eastern slope of the Rocky Mountains at long. 116° 33'W, lat. 51° 41'N. Standard meteorological, hydrological and glaciological measurements have been made as described by Østrem & Stanley (1969). A comprehensive review of work conducted on Peyto Glacier during the International Hydrological Decade is given by Young & Stanley (1977). The most significant contributions to understanding the runoff processes within the basin have been given by Derikx (1973, 1975), Derikx & Loijens (1971), Föhn (1973), Goodison (1972), Loijens (1974) and Munro & Davies (1977).

HYDROLOGICAL RELATIONSHIPS WITHIN THE PEYTO BASIN

The hydrology of the basin is described and accounted for by reference to a series of diagrams and a table which attempt to illustrate salient features of the processes and interrelationships involved. The difficulty in conceptualizing complete-basin hydrology lies in the fact that there are several dimensions involved.

The surface characteristics of the terrain vary in plan and with elevation (Fig.1). Movement of the snowline on the glacier tends to be slow and fairly uniform; in contrast the snowline movement on the non-glacier surface is much faster and much less uniform. Although there are broad similarities from year to year in the progressive stages through which the terrain changes take place, there are significant differences in detail from one year to another. The way in which liquid water is routed through the glacier system consequently follows a similar progression from year to year but the timing of the transition from one stage to another in the progression is again different from year to year.
A glacierized mountain basin

Meteorological inputs, first during the winter to set the scene for summer ablation, and secondly during the summer melt season itself, vary significantly between years and in detail it is still somewhat debatable which particular components of the meteorological inputs are most critical for the hydrological response of the glacier.
The hydrographs for the years 1967-1974 are illustrated in Fig. 2 and a breakdown of the components of discharge is shown in Table 1. While there is not a marked difference in total volume of discharge between summers (glacier melt compensating for lack of snow in dry years), there is considerable variation in the detailed form of the hydrographs and the contribution of glacier ice and especially glacier firn melt varies greatly between years.

![Figure 2: Hydrographs 1967-1974. Mean daily flow in $m^3/s$ are shown for total discharge, ice melt and firn melt.](image)

For the months of June, July and August total volume of runoff and the ice and firn melt volume are given in $m^3 \times 10^5$. The summer season is divided into three periods: 1 when the whole glacier is snow covered, 2 when the transient snowline is on glacier ice, 3 when the transient snowline is above the firn line.

The years 1970 and 1974 are highlighted to illustrate hydrological relationships in more detail. 1970 a year of light winter snowfall and very warm summer is in distinct contrast to 1974. These years are taken to illustrate the extreme conditions (for the eight-year set). Specific annual yields over the basin are illustrated in Fig. 3. It clearly emerges that the lack of snow in 1970 results in low yields from the non-glacier area and increased yields on the glacier. The reverse holds in 1974. Further, specific yield increases with elevation off the glacier and decreases with elevation on the glacier. Transposing what is illustrated here for Peyto Glacier to glacier basins in general: total basin yield will depend on the curves of specific yield being applied to basins having differing proportions of glacier cover and different area/elevation curves for both glacier and non-glacier parts of the basin.
<table>
<thead>
<tr>
<th>Glacier derived runoff</th>
<th>Non-glacier derived runoff</th>
<th>Discharge</th>
<th>Net Mass Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice (a)</td>
<td>Snowmelt (f)</td>
<td>Calc. (i)</td>
<td></td>
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<tr>
<td>Firn (b)</td>
<td>Summer precip. (d)</td>
<td>Measd (j)</td>
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<tr>
<td>Snowmelt (c)</td>
<td>Total (e) = (a)+(b)</td>
<td></td>
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<tr>
<td>Summer precip. (d)</td>
<td>+ (c)+(d)</td>
<td></td>
<td></td>
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<tr>
<td>Total (h) = (f)+(g)</td>
<td></td>
<td></td>
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</tbody>
</table>

1967 7.96(14.5) 1.99(3.6) 17.41(31.8) 11.30(20.6) 38.66(70.6) 8.86(16.2) 7.27(13.3) 16.13(29.4) 54.78 41.89 +0.13
1968 5.34(10.9) 0.81(1.7) 11.14(22.7) 15.09(30.8) 32.38(66.0) 7.00(14.0) 9.66(19.7) 16.66(34.0) 49.04 37.84 +4.69
1969 7.34(14.9) 3.11(6.3) 14.09(28.5) 11.31(22.9) 35.85(72.6) 6.10(12.6) 7.34(14.9) 13.54(27.4) 49.40 40.33 -5.36
1970 10.17(18.8) 12.72(23.3) 14.23(26.3) 7.47(13.8) 44.59(82.3) 4.68(8.7) 4.88(9.0) 9.56(17.7) 54.15 55.67 -2.28
1971 6.98(15.4) 3.13(6.9) 12.91(28.5) 10.04(22.1) 33.06(62.9) 5.74(12.6) 6.58(14.5) 12.32(27.2) 45.37 48.51 -5.49
1972 5.95(9.5) 2.27(3.6) 17.55(28.0) 17.78(28.3) 43.55(89.4) 7.41(11.8) 11.78(18.8) 19.19(36.0) 62.71 44.67 -8.04
1973 6.17(13.5) 0.87(1.9) 10.22(22.3) 12.93(28.2) 30.19(65.9) 7.36(16.1) 8.24(18.0) 15.60(34.1) 45.80 39.14 +5.76
1974 4.99(11.5) 0.92(2.1) 12.67(29.1) 10.90(25.0) 29.48(67.7) 7.04(16.2) 7.05(16.2) 14.09(32.3) 43.57 51.96 +8.39
Mean 6.86(13.6) 3.23(6.4) 13.78(27.2) 12.10(23.9) 35.97(71.1) 6.79(13.4) 7.85(15.5) 14.64(28.9) 50.61 45.25 -5.36
St. dev. 1.67 3.95 2.65 3.17 5.81 1.25 2.09 2.94 6.33 6.36 9.16

TABLE 1 Derivation of streamflow 1967-1974. All figures are m³ x 10⁶ with % of calculated discharge in brackets. Summer is defined as May to September inclusive. Snowmelt (c) and (f) is melted winter snow. Summer precipitation (d) and (g) are rainfall and snowfall which subsequently melt. (a), (b) and (c) from stake measurements on glacier; (d) from precipitation measurements at base camp distributed vertically with the same lapse as measured winter snow accumulation; (f) is inferred from (c) with the assumption that, at a given elevation, snow accumulation on rock will be half as much as on ice; (g) summer precipitation at a given elevation assumed equal on and off glacier; (i) is the summation of (e) and (h); (i) and (j) are often significantly different mainly reflecting measurement inaccuracies, but also the mean difference between (i) and (j) is about 5 x 10⁶ m³ which is about the expected difference if evaporation were to average 200 m a⁻¹ over the basin.
Some of the more important interrelationships between hydrographs and meteorological characteristics and the state of the basin are illustrated in Fig. 4. Movement of the transient snowline is singled out as a very important determinant of hydrological response. The contrast between 1970 and 1974 is apparent—snowline movement being delayed and less rapid in 1974. Differences in snowline movement are attributed to the combined effect of the differences in (a) winter mass balance (1970 specific winter balance 1.07 m, 1974 specific winter balance 1.62 m), (b) summer weather conditions (1970...
mean June-August temperature at base camp 8.6°C contrasting with 7.2°C for 1974; the temperature differences were associated with differences in cloud cover - 1970 had an average of 5.8 tenths cloud cover for the summer, 1974 had an average of 6.2; while precipitation totals for June-August were about the same (1970: 183 mm at base camp, 1974: 173 mm; more precipitation fell as snow in 1974 resulting in snowline lowering).

While the overall mix of proportions of runoff from different sources depends on general meteorology and snowline movement, day to day basin response is clearly linked to fluctuation in daily temperature and to precipitation input (especially to extensive snowfalls which greatly reduce runoff in the short term). Basin response to rises in temperature tend to be slow when the snowline is low (i.e. when snow-packs are relatively deep and liquid water can be retained) and response is usually very fast when the snowline is high.

METHODS USED TO DERIVE COMPONENTS OF DISCHARGE

In describing the derivation of the hydrographs as much use as possible has been made of field measurements. The measurements used (and illustrated in Figs 2 and 4) were (a) total discharge measured

FIG. 4 Snowline movement, meteorology and discharge relationships, 1970 and 1974.
at the gauging station, (b) temperature and precipitation measurements made at base camp and (c) measurements of accumulation and ablation measured at stake locations on the glacier. From these measurements inferences and assumptions can be made which permit the estimation of discharge components as shown in the graphs (Figs 2, 3 and 4) and in Table 1.

In the winter period (October to April inclusive) it is assumed that, at a given elevation, net specific accumulation on the glacier is double that on non-glacier surfaces. In the summer, when any snow that falls is usually too wet to be redistributed, it is assumed that, for a given elevation, precipitation is equal on and off the glacier and that precipitation is distributed vertically with the same lapse rate as measured winter snow accumulation. These assumptions are somewhat arbitrary and are a source of considerable uncertainty for Table 1.

The elevation of the transient snowline, shown in Fig.4, was derived by two procedures. A smoothed elevation/time curve was established by fitting a logarithmic curve to the dates at which measurement stakes at known elevations became snow free. The smooth curve, which is an approximation especially in late summer, is punctuated by temporary depressions caused by summer snowfalls. The freezing level during precipitation events was calculated from the mean daily temperature at base camp lapsed for altitude change with an environmental lapse rate of $6.5 \times 10^{-3}\degree C m^{-1}$.

Having established curves for the movement of the transient snowline, it was then possible to calculate areas of snow-free ice and firn. An empirical question linking specific ice melt to mean daily temperature was derived by the author (Young, 1980). It is of the form:

$$Smr = 1.56 + 5.338 \text{mdt}$$

where $Smr = \text{specific melt rate (mm d}^{-1})$, mdt = mean daily temperature ($\degree C$), ($r = 0.78$; standard error = 6.61 mm).

Specific melt per day was calculated for snow-free areas of ice and firn for points on a square grid (grid interval = 100 m) using the environmental lapse rate to determine temperature at each point and then applying equation (1). Melt in firn areas was estimated as 85% of ice melt for the same elevation (based on melt measurements at stake locations).

Further assumptions were made in deriving the ice-melt and firn-melt discharge curves in Figs 2 and 4. It was assumed that all water derived from ice melt passed the stream gauge the same day. It was also assumed that only half of the melt from the firn area exited the basin on the same day as it was produced (the other half was added to half the calculated firn melt of the next day). It is considered that these assumptions are very reasonable for a glacier the size of Peyto Glacier; however, the lags might have to be modified for much larger glaciers.

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REFERENCES


Fohn, P.M.B. (1973) Short-term snow melt and ablation derived from heat- and mass-balance measurements. J. Glaciol. 12 (65), 275-289.


