

The influence of a debris cover on the mid-summer discharge of Dome Glacier, Canadian Rocky Mountains

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Abstract Meltwater discharge patterns of two glacierized mountain basins in the Canadian Rocky Mountains are compared over the same 25-day period in 1994 and 1995. The glaciers under study are the Dome and Athabasca; both situated in the Columbia Icefield. The two glaciers lie adjacent to one another and are similar in size, orientation, and range in elevation. They differ however, in their surficial characteristics. While the ablation zone of the Athabasca Glacier is mostly debris free, the ablation zone of the Dome Glacier displays an extensive debris cover. It is postulated that this debris cover significantly influences the diurnal discharge patterns of the Dome Glacier's meltwater stream producing different discharge patterns to those observed in the Athabasca Glacier meltwater stream. Results indicate that the debris cover on the Dome Glacier acts as a regulator of streamflow producing annual variances of volumetric discharge of only 1.0% between 1994 and 1995 as compared with 24% for the debris-free Athabasca Glacier.

INTRODUCTION

It has long been known that significant portions of the world's glaciers carry either a partial or complete debris cover that masks their ablation zones. It is hypothesized that this debris cover significantly influences the discharge characteristics of the meltwater streams emerging from these glaciers through the alteration of surficial energy fluxes. The purpose of this paper is to test this hypothesis by comparing and contrasting the meltwater discharge characteristics of a debris-free glacier and a debris-covered glacier over two contrasting field seasons.

REVIEW

During the summer of 1989, a 14% difference in meltwater discharge between the Dome and Athabasca Glaciers was measured (in favour of the Athabasca), despite their similarities in size (Mattson, 1990). It was postulated that this difference could possibly be attributed to the debris on the Dome Glacier. Mattson *et al.* (1993) illustrated that a debris cover can significantly influence the surficial ablation process where, after a threshold thickness of approximately 0.02 m, ablation rates decreased in comparison to "clean" glacier surfaces. They found that the greatest mean ablation rate occurred beneath a debris cover of about 0.01 m. Those areas with less than 0.01 m of debris exhibited relatively lower ablation rates. Similar results had been obtained for

other debris-covered glaciers through out the world, (e.g. Østrem, 1959; Loomis, 1970; Nakawo & Takahashi, 1982; Khan, 1989). This hyperbolic relationship occurs because a thin layer of debris, rather than insulating the underlying ice, decreases albedo, thereby increasing absorbed shortwave radiation which in a thin debris cover is transmitted to the ice interface contributing to rapid ablation (Mattson & Gardner, 1989).

The thermal properties of thick debris covers (>0.03 m) are of critical importance in determining the rate of heat transfer to the debris/ice interface. Mattson & Gardner (1989) found a three-fold increase in the percentage of absorbed surface energy reaching the debris/ice interface of the Rakhiot Glacier when the debris cover was moistened by rainfall. This occurs because of an increase in thermal conductivity. With the continuous fluctuation of the temperature gradient within the debris profile resulting from the variability of the net rate of heat exchange at the surface, the phase and condition of water located within the profile will alter. As a result, the debris cover will not display a continuous conductivity but rather, a series of conductivity's depending on the moisture conditions (Mattson, 1986).

STUDY SITES

The two basins chosen for this study are the Athabasca (52°11'N, 117°15'W) and the Dome (52°12'N 117°17'W), both of which are located in the Columbia Icefield (Fig. 1). These adjacent basins contain the streams that form the headwaters of the Sunwapta River which, in turn, flows via the Athabasca, Slave, and Mackenzie Rivers to the Arctic Ocean. The factors considered in the selection of the basins relate to the degree of similarity between them as well as the relatively easy access to the sites.

The Athabasca basin displays a general northeast orientation. It covers an area of roughly 28 km². Of this area about 65% or 18 km² is covered by glacial ice. There are four glaciers situated within this basin, three of which are relatively small cirque glaciers: the Sunwapta, the AA, and the Andromeda. In total these three glaciers cover an area of 3.7 km². The Athabasca Glacier accounts for the remaining 14.3 km² of ice cover.

The drainage divide for the Athabasca basin is defined by a series of peaks and connecting ridges that encompass it. Along the southeast perimeter Mount Athabasca (3491 m) and Mount Andromeda (3445 m) form the divide. The southern perimeter of the basin is difficult to define because it is located in the greater Icefield. Mount Snow Dome (3456 m) and Little Dome (2750 m) define the northwest perimeter. The mouth of the basin is located along its northeast end. The Sunwapta River emerges from the toe of the glacier and it is from this stream that discharge measurements were derived.

The Dome basin also displays a general northeast orientation. In total, the basin covers an area of about 15 km² and of this about 68% or 10 km² is ice. There is a single cirque glacier associated with the Dome basin; it is situated on the divide between the two basins. This small glacier, known as the Saddle Dome, covers an area of 0.25 km² and is thought to contribute an insignificant amount of meltwater to the basin due to its small size and high elevation. The Dome Glacier accounts for the remaining 9.75 km² of ice cover.

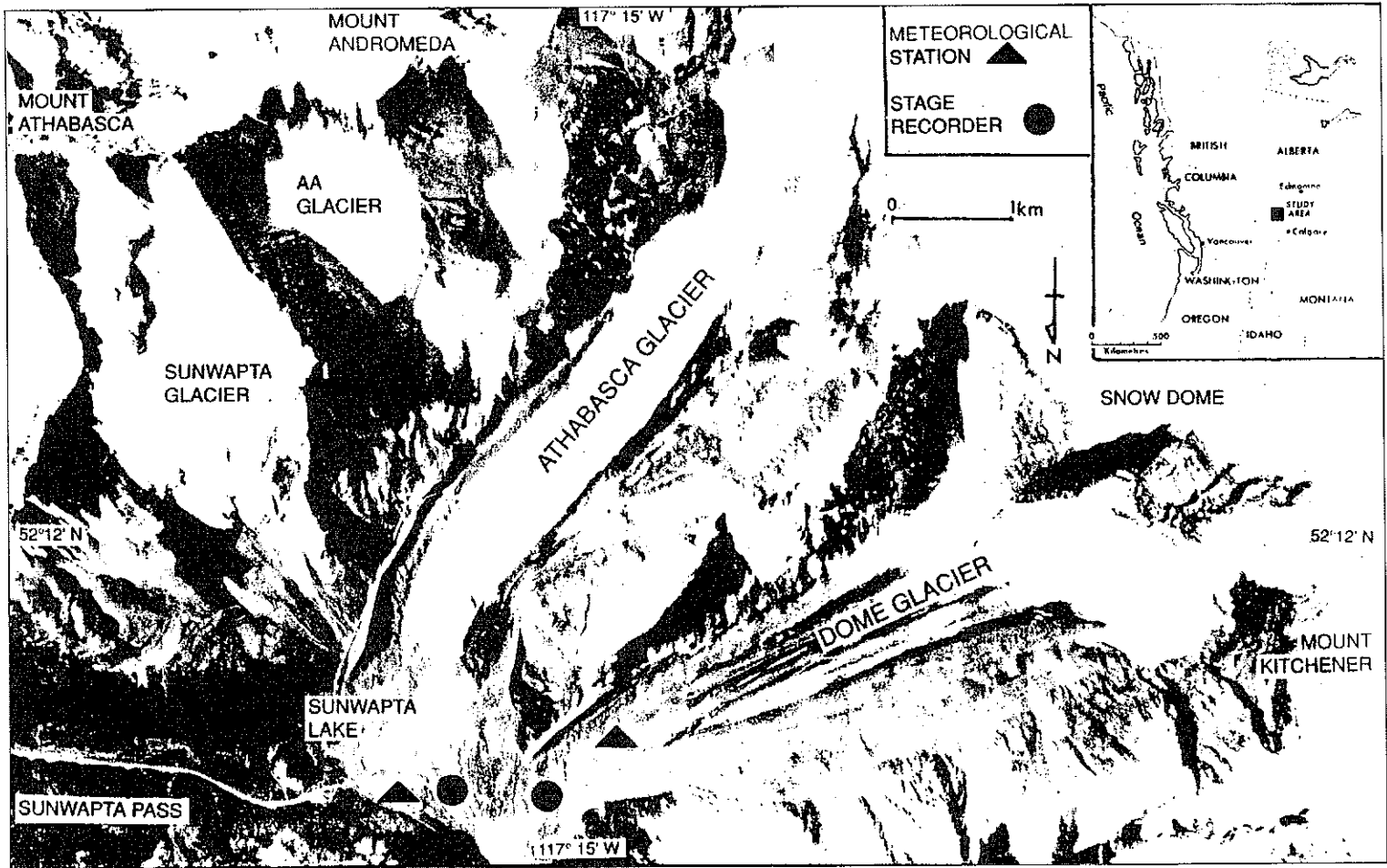


Fig. 1 Study site and measurement locations.

The drainage divide for the Dome basin is also defined by a series of peaks and the ridges. Little Dome marks the southeast perimeter, Mount Snow Dome marks the southern perimeter, and Mount Kitchener (3490 m) marks the northwestern perimeter. The mouth of the basin is located at the northeast end. There is a single meltwater channel, the Dome River, which flows out of the basin and into the Sunwapta River, 1.5 km below the terminus of the Dome Glacier.

The Dome and Athabasca basins are composed predominantly of sedimentary rock from the Palaeozoic era. These rocks have been disturbed and contorted by folding and faulting in response to tectonic activity. The lithologies present are mainly fine-grained mudstone, limestone and dolomite. Green conglomerate, quartzite and shale are also present. It is unknown if either basin is watertight with respect to the subsurface exiting of groundwater.

A list of the morphometric, morphologic and dynamic characteristics of the Dome and Athabasca Glaciers is presented in Table 1. It indicates that the two glaciers are very similar with regards to all physical attributes. The extensive debris cover is the most evident characteristic that differentiates the Dome from the Athabasca Glacier. Debris thickness were interpolated for the surface from a series of spot depth measurements, including manually dug pits where thickness could not be visually estimated. The debris cover extends completely over the glacier surface from the terminus to a distance of 625 m upglacier. From this point on, to a distance of 3.5 km from the terminus, the debris cover dominates the surface of the glacier with only a thin strip of "clean" ice extending up the centre. There is a general tendency for the debris-cover thickness to decrease from the lateral margins to the centre axis of the glacier. The debris is up to 0.5 m thick along the margins of the glacier. Summer field observations since 1984 indicate that debris sources include: snow and ice avalanches off the north face of Mount Snow Dome (as many as 21 per day), high-frequency low-magnitude rockfalls from adjacent slopes (as many as 100 per day), and the emergence of englacial debris derived from subglacial erosion.

Table 1 Morphologic, morphometric, and dynamic characteristics of the Dome and Athabasca Glaciers.

Physical attributes	Dome	Athabasca
Glacier length (m)	8.5	5.4
Maximum elevation (m a.s.l.)	3460	3460
Terminus elevation (m a.s.l.)	2000	2000
Altitudinal range (m)	1460	1460
Average gradient	1:6	1:4
Firn line elevation (m a.s.l.)	2500	2500
Area of accumulation zone (km ²)	8.3	4.9
Area of ablation zone (km ²)	6.0	5.5
Ice thickness at base of icefall (m)*	300	-
Velocity at base of icefall (m year ⁻¹)†	75	35
Year of maximum Holocene extent‡	1843	1846
Rate of retreat (1721–1953) (m year ⁻¹)§	4.7	4.7
Rate of retreat (1738–1960) (m year ⁻¹)	28	19

* Cited in Kite & Reid (1977).

† Cited in Paterson & Savage (1963).

‡ Cited in Luckman (1988).

§ Cited in Deaton (1975).

DATA COLLECTION

Meltwater discharge was monitored for both years from 11 July to 9 August for the Dome Glacier basin. Discharge data derived from this basin include both instantaneous stream discharge, calculated on the basis of measurements of water velocity (using an Ott model 10-152 current meter) and cross-sectional area and continuous stage records which have been translated to hourly readings of discharge through a rating curve. The rationale for employing this technique, though not recommended for streams displaying unstable hydraulic conditions, was to maintain consistency with the data set collected by the Federal Government for the Sunwapta River. Discharge measurements were taken over a 12-h period (06:00–18:00 h) at 15-min intervals resulting in 48 readings. Regression analysis between stage and discharge revealed an r^2 value of 0.98 and 0.97 for 1994 and 1995, respectively. Discharge data for the Sunwapta River (Athabasca basin) were obtained from Inland Waters of Environment Canada and are stated to contain less than 5.0% error. Figure 1 indicates the location of the Sunwapta and Dome River stage recorders.

Meteorological measurements were collected from a standard meteorological station situated near the confluence of the two basins at an elevation of 1950 m (Fig. 1). Specific variables measured included relative humidity, air and surface temperature, precipitation as well as incident solar and net radiation. Readings were recorded at 5-min intervals through the employment of a Squirrel data logger. These values were then averaged over hourly periods resulting in a record of over 5000 readings per field season. Additional meteorological information was obtained from the Columbia Icefield Information Centre operated by Parks Canada.

OBSERVATIONS

Because of the high contrast in meteorological conditions, the 1994 and 1995 field seasons turned out to be ideal for this study. The 1994 field season was predominantly warm, with clear skies and air temperatures averaging 12.1°C. The maximum and minimum temperatures recorded were 22.5°C and 2.5°C, respectively. Cloud cover, measured three times a day, ranged from 0 to 10 tenths but averaged 3 and rain only occurred on 7 days resulting in a total of 30.5 mm.

Conversely, the 1995 field season was characterized by cool, wet conditions. The mean air temperature averaged 9.5°C, a difference of 2.6°C from the previous year. The maximum and minimum temperatures recorded were 18.8°C and 1.3°C, respectively. Cloud cover ranged from 0 to 10 tenths but averaged 9 and rain occurred on all but 2 days resulting in a total of 60.9 mm.

The 1994 and 1995 hydrographs of the Sunwapta and Dome Rivers (Figs 2 and 3, respectively) were characterized by a series of oscillating waves typical of most proglacial streams described in the literature. This basic pattern consists of a diurnal cycle of rising and falling limbs superimposed over a more consistent baseflow. The baseflow is derived primarily from a combination of groundwater and subglacial melt however the percent contribution of each is unknown to the author. The superimposed daily pattern is primarily controlled by the individual components of the diurnal energy

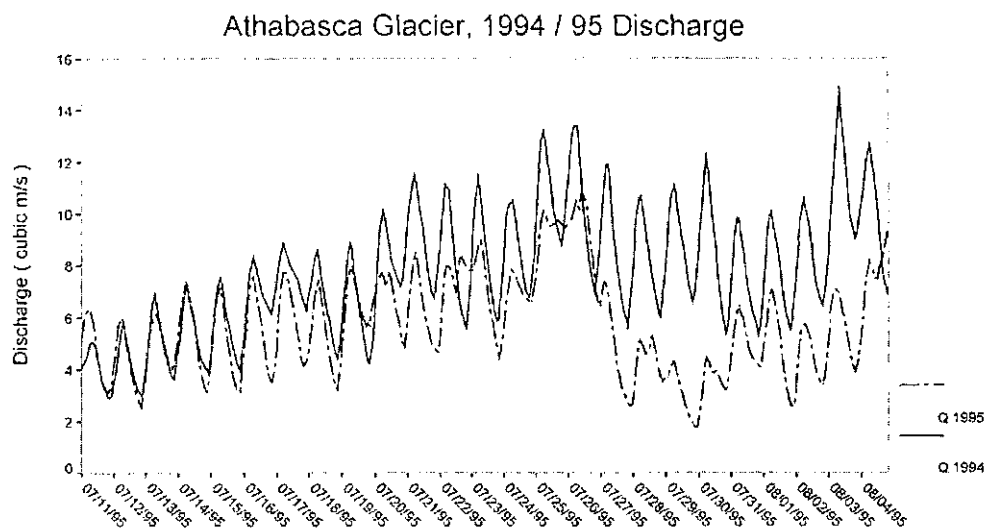


Fig. 2 Discharge for the Sunwapta River from 11 July to 5 August 1994 and 1995.

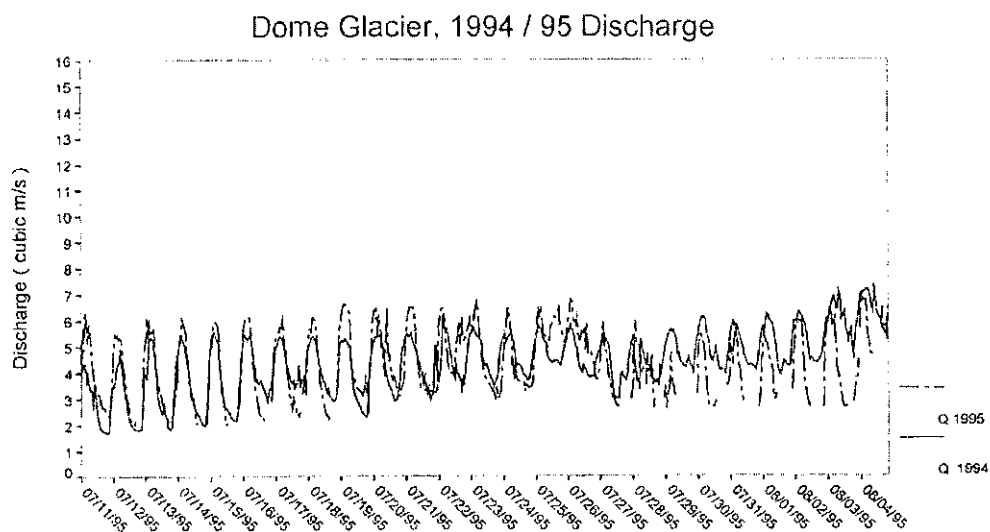


Fig. 3 Discharge records for the Dome River from 11 July to 5 August 1994 and 1995.

exchange that exists between the atmospheric boundary layer and the surface of the glacier. The energy exchange includes the turbulent fluxes of latent and sensible heat, net radiation, conductive heat flux and precipitation heat transfer. This energy exchange controls the amount of surficial ablation which, in turn, determines the amount of meltwater production from the surface of the glacier.

It is evident that the quantities of water released by both basins are of the same order of magnitude. However, a significant difference does exist. The mean discharge for the Sunwapta River during the 1994 field season was $7.79 \text{ m}^3 \text{ s}^{-1}$ resulting in an average runoff of $0.28 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ for the Athabasca basin. The total volume of

meltwater produced over the sampling period was $16.74 \times 10^6 \text{ m}^3$. The mean seasonal discharge for the Dome River for the same period was only $4.40 \text{ m}^3 \text{ s}^{-1}$ resulting in an average runoff of $0.29 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ for the Dome basin. The total volume of meltwater produced over the sampling period was $9.45 \times 10^6 \text{ m}^3$; $7.28 \times 10^6 \text{ m}^3$ less than that of the Athabasca basin.

The 1995 discharge pattern of the Dome River was similar to that experienced for the same sampling period in 1994 with the exception of an obvious increase in the amount of "noise" experienced. An examination of the meteorological record reveals that these minor spikes in the discharge record correspond with rainfall events. A lag of approximately 1 h exists between the initiation of rainfall and an abrupt increase in discharge indicating the time in which it takes for water to travel through the glacial system. The reason for the absence of the same phenomenon on the discharge record for the Athabasca basin is due to the fact that Sunwapta Lake, a small proglacial lake (Fig. 1) lies between the glacier and the stage recorder. The lake acts as a buffer to these events which results in a much smoother hydrograph. Discharges greater than the 1994 maximum were also due to rainfall events.

The mean discharge of the Dome basin in 1995 was approximately $4.41 \text{ m}^3 \text{ s}^{-1}$ resulting in an average runoff of $0.29 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$. The total volume of water produced from the basin was $9.48 \times 10^6 \text{ m}^3$. The 1995 mean seasonal discharge for the Sunwapta River was $5.84 \text{ m}^3 \text{ s}^{-1}$ resulting in an average runoff of $0.21 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$. The total volume of water produced from the basin was $12.55 \times 10^6 \text{ m}^3$; $3.08 \times 10^6 \text{ m}^3$ more than for the Dome over the same period.

In comparing the basins on an individual basis over the two years one can see that large differences exist. Volumetric discharge derived from the Dome Glacier between the 1994 and 1995 field seasons varied by $0.002 \times 10^6 \text{ m}^3$ which translates to a difference of less than 1.0%. On the other hand, the volumetric discharge derived from the Athabasca Glacier for the same period differed by $4.18 \times 10^6 \text{ m}^3$ or 24%.

DISCUSSION

Lower volumes of meltwater derived from the Dome basin, when compared to the Athabasca basin, can be easily explained by the fact that it is smaller in size and contains less ice cover. More specifically, the Dome basin is smaller by 13 km^2 and contains 8 km^2 less ice cover. When the areas of each basin are taken into consideration, and specific discharge or runoff is calculated for each, the two almost equate. This is not surprising considering the fact that the basins lie adjacent to each other and experience the same meteorological conditions.

What is of greater interest is the large variation in discharge for the Athabasca basin between the two field seasons compared to that for the Dome basin which varied little. One possible explanation for this could be due to the absence or presence of a debris cover. In the case of the Athabasca Glacier, which displays primarily a debris-free surface, all of the energy being absorbed through the latent, sensible, and radiative heat fluxes is used directly to melt the exposed ice. No energy is lost through the conductive heat flux into the glacier due to the fact that the ice is at its pressure melting point. During the 1994 field season, which was characterized by warm, clear sky conditions, ample energy was available to promote ablation which, in turn, led to the

production of large quantities of meltwater. However, during the 1995 field season, which was characterized by cool, overcast conditions, less energy was available to promote ablation leading to significantly less runoff.

In the case of a relatively thick debris cover, such as that found on the Dome Glacier, the situation is quite different. During the 1994 field season the debris cover became very dry and much of the energy being absorbed at the debris surface could not reach the underlying ice. A large portion of the energy was expended in increasing the surface and subsurface temperature of the debris cover. This energy was then lost back to the atmospheric boundary layer through the emission of longwave radiation and sensible heat. Only a fraction of the absorbed energy could be transferred to the debris/ice interface because of the low conductivity associated with the dry debris. The wet conditions associated with the 1995 field season exerted a tremendous influence on the physical properties of the debris cover by increasing its thermal conductivity. Although less energy was being absorbed at the atmosphere/debris interface a greater proportion of it was being transferred to the underlying ice to promote ablation. The two-fold increase in precipitation would also add to the volume of water leaving the Dome and Athabasca basins over the 1995 field season but would not account for the differences in variation between the two.

CONCLUSIONS

This study indicates, by way of presenting volumetric discharge data, that a debris cover may play a significant role in glacier hydrology. Results suggest that the debris cover on the Dome Glacier acts as a regulator of streamflow producing annual variances of volumetric discharge of only 1.0% between 1994 and 1995 as compared with 24% for the debris-free Athabasca Glacier. This most likely occurs because of the changes of moisture content within the debris cover between field seasons. When atmospheric conditions are warm and dry, and ample energy is available for melt, the debris cover retards the transfer of energy to the ice because of its low thermal conductivity. When atmospheric conditions are cool and wet, and little energy is available for melt, the debris cover promotes the transfer of energy to the ice because of its increased thermal conductivity. This implies that a debris-covered glacier may not be as sensitive to changes in climate as would be a debris-free glacier, however, further research is required in order to substantiate this claim.

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