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The effect of glacier wastage on the flow of the Bow River at Banff, Alberta, 1951–1993

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Abstract:

A surface area/volume relationship was used to estimate total glacier volumes for the highly glacierized Hector Lake Basin (281 km^2) in the Canadian Rockies in the years 1951 and 1993. The change in volume was calculated and this value then extrapolated up to the Bow Basin at Banff (2230 km^2) based on relative proportions of glacier cover. The mean net glacier volume loss estimate of 934×10^6 m^3 was divided into annual proportions of glacier wastage and storage using a local mass balance record collected at Peyto Glacier in the Mistaya Valley, contiguous to the Bow Basin. Unfortunately, the record began in 1966 and a hind-cast to 1952 (hydrological year) was necessary. Banff maximum summer temperature and Lake Louise snow course data were used as surrogates for summer and winter glacier mass balance, respectively. Monthly wastage proportions were estimated for 1967–1974 by using modelled values of glacial melt as a template. Glacier wastage inputs to and storage held back from the Bow River hydrograph at Banff were compared with known basin yields to assess the hydrological effects of glacier volume change. For 1952–1993, the average annual wastage/basin yield ratio was found to be around 1·8%. For the extremely low flow year of 1970 this ratio increased to 13%. The proportion of flow derived from glacier wastage in August of this year was estimated to be around 56%. Although the results tend to confirm the regulatory effect of glaciers on stream flow, it was found that in some years of low flow this situation has been aggravated by water being held in glacial storage.

KEY WORDS glacier wastage; Bow River; volume change; water resources; basin yield; climate change

INTRODUCTION

Since the middle of the nineteenth century, an irregular but general rise in global temperatures has been recorded (IPCC, 1995) and many mountain glaciers have responded by retreating to higher elevations. The consequences of glacier wastage (see Glossary) are an increase of stream flow above the net income of annual precipitation and rises in global sea level (Meier, 1984). It is to be expected that in warmer and drier years, especially if coupled with low winter snow accumulation, the more glaciers will retreat (net negative mass balance) and the more significant will be their role in stream flow augmentation and sea level rise (Dyurgerov and Meier, 1997). Conversely, in years of high snow fall and/or little melt, glaciers may 'grow' (net positive mass balance) and hold back water from the downstream hydrological system. For these reasons glaciers are generally considered to be efficient stream flow regulators (e.g. Meier, 1969, 1973; Fountain and Tangborn, 1985).

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Fountain and Tangborn (1985) attempted a quantification of the influence of glacier storage and wastage to stream flow by comparing discharge records from glacierized and non-glacierized basins in south-east Alaska and the North Cascades of Washington. From their study of 49 river basins they found that for a net glacier mass balance of -1 m and a mean specific annual runoff of 2 m (typical in this maritime region), a river basin with 20% glacier cover would yield 10% more runoff than a similar non-glacierized basin (Fountain and Tangborn, 1985). However, glacial–hydrological systems vary in character with latitude and continentality, and relationships developed in one region may not be applicable elsewhere. The influence of climate change and resultant glacier fluctuations to water resources is a topic of global concern and much research effort (e.g. Chen and Ohmura, 1990; Kaser *et al*., 1990; Young, 1991; Zhenniang and Xiaogang, 1992). The study presented here is original in that it focuses on one mesoscale temperate basin of limited (approximately 3%) glacier cover and examines the interactions between climate, glacier variation and stream flow at a variety of temporal scales within a 42-year period. A major thrust of this study is to ascertain to what extent such a small areal glacier cover has affected and regulated interannual stream flow and how continued glacier loss might influence the water resource in the future.

The objectives of this paper are to estimate the net glacier volume loss within the Bow Valley above Banff, Alberta, Canada (Figure 1) between the hydrological years of 1952 and 1993, and to convert this volumetric change into annual wastage and storage components using local glacier mass balance data. Seasonal wastage contributions are also investigated for a few years in the middle of the time-series. The effect of glacier wastage/storage to the Bow River at Banff is assessed by comparing wastage with measured basin yields and comparing the variability of interannual stream flow with and without the influence of glaciers. Emphasis is placed on glacier wastage rather than storage for two reasons: (1) it is clear from observations of glacier recession in this area (Brunger *et al*., 1967) and from local glacier mass balance data (M. Demuth, NHRI, 1996, personal communication), that glacier wastage has been more prevalent than storage and (2) the importance of glaciers to the water resource increases during years of glacier wastage (Meier, 1969).

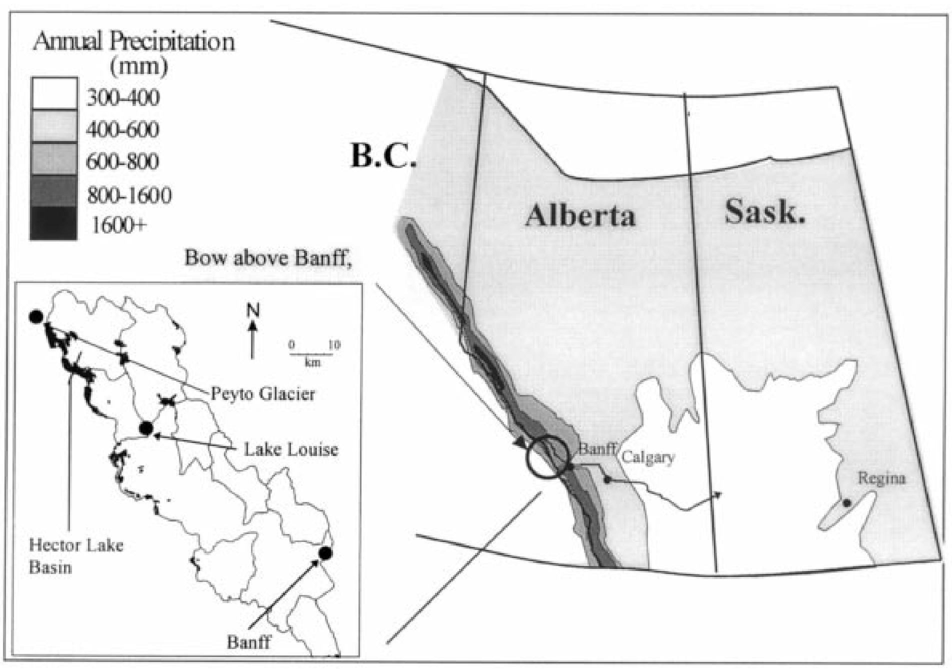

Figure 1. Map showing study area and precipitation zones. Inset is in the Bow Valley above Banff showing sub-basin boundaries and glacier covers

THE STUDY AREA AND DATA AVAILABILITY

The Bow River above Banff was chosen for this study as it is relatively free of development, is an important hydrological source region for a variety of downstream users and has the highest upstream gauging station with a continuous discharge record dating back to 1910. The river rises in the Eastern Front Range of the Rocky Mountains (Figure 1), has a region of high annual precipitation relative to the more arid Prairies, which it feeds. The Bow Basin above Banff has an elevation range from 1200 m to 3400 m, and is underlain predominantly by limestone. The average annual temperature at Banff is approximately $+3\,^{\circ}C$ but temperatures in this part of the Rockies can dip down to as low as $-35\,^{\circ}C$ in winter and rise up to $+35\,^{\circ}C$ in summer (Gadd, 1995). The Bow River is regionally important as a water resource, particularly during summer months for water supply and Prairie irrigation. Further downstream, the importance of the resource has been recognized in the provincial agreement guaranteeing that at least 50% of the natural flow leaving Alberta via the South Saskatchewan River must be maintained to serve Saskatchewan's needs (Alberta Environment, 1984).

Observations of glacier recession in the Eastern Front Range of the Canadian Rockies have been recorded since 1887 (Meek, 1948) and the effect of glacier wastage upon basin water yields in this region has been previously explored (Collier, 1958; Henoch, 1971; Young, 1991). Using photogrammetry and observations of glacier recession and mass balance, Henoch calculated that glacier loss within the Upper North Saskatchewan Basin (1518 km^2) between 1948 and 1966 equated to 4% of the total basin yield (Henoch, 1971). Young's paper studied glacier loss between 1966 and 1989 in the Mistaya Basin (247 km^2), a sub-basin of the Upper North Saskatchewan and immediately north of the Bow Valley. Young calculated that total glacier area reduced from 12·1% of total basin cover in 1966 to 10·8% in 1989. This areal loss was considered to equal approximately 340×10^6 m^3 of water equivalence, or 6·0% of basin yield. For the extremely low flow year of 1970, it was also calculated that approximately 25% of the annual basin yield was derived from glacier wastage (Young, 1991).

Data sources

Glacier cover in the Bow Valley and its sub-basins has been digitized from the national topographic series (NTS) 1:50 000 maps and the individual basin-wide glacier areas measured (Young, 1995). The Bow above Banff was approximately 3·3% glacier covered with an area of 73 km^2 in 1977, the time of map update (Environment Canada, 1979). The hydrological process that dominates annual runoff is spring snowmelt. This is evidenced by the observation that the average basin yield for all months of June, taken from the 82-year record at Banff, is 27% of the average annual yield (Young, 1995). July and August show declining proportional contributions of 22 and 14%, respectively. If icemelt input were dominant then it would be logical to expect higher proportions of flow in July and August (Meier, 1969).

The Hector Lake sub-basin (281 km^2) is the most northerly and highly glacierized of all the basins along this stretch of the Bow River and is similar in size and character to the Mistaya Basin studied by Young (1991). Volumetric analyses have been confined to this catchment because of its relatively dense glacier cover, much of which has been catalogued in the glacier inventory of the Waputik Mountains in the late 1960s (Stanley, 1970). According to the 1977 NTS maps, there was 33·2 km^2 of glacier surface area in the Hector Lake Basin at this time. Therefore, approximately 45% of the entire glacier cover for the Bow Valley above Banff was found in the Hector Lake Basin. A good selection of aerial photographs is available covering the Waputik Mountains at a variety of dates containing a large area of glacier cover in a few images. The years of highest quality imagery for this area were found to be 1951 and 1993 (Figure 2). Photographs taken in 1966 would have been useful, to coincide with the implementation of the mass balance programme on Peyto Glacier, but the quality and coverage of these images was comparatively low.

In order to investigate temporal variations of glacier wastage it has been necessary to find a local surrogate for interannual and seasonal glacier behaviour within the study area. Peyto Glacier lies just outside the boundary of the Bow Basin and drains into the adjacent Mistaya River to the north. Although lying outside

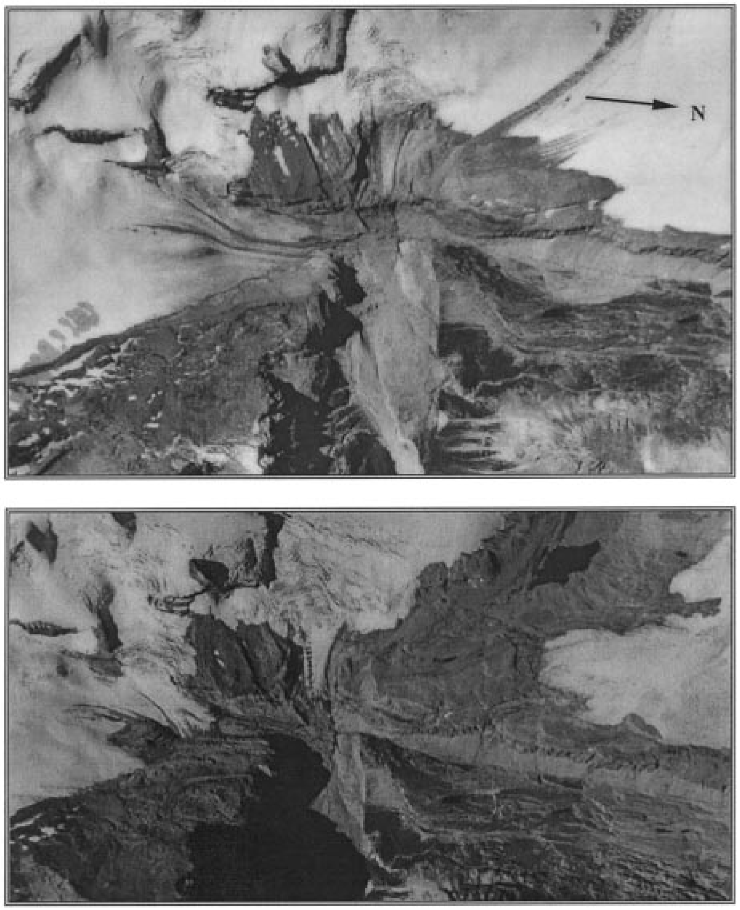

Figure 2. Partial aerial photograph coverage of glaciers in the Waputik Mountains upstream of Hector Lake in 1951 (top) and 1993 (bottom)

the Bow Valley, Peyto Glacier is considered fairly representative of glaciers in this region. It spans the elevation range of virtually all glacier cover in the Bow Basin, it lies on the north-eastern facing slopes of the Waputik Mountains, as do most glaciers in the Bow above Banff and it would be expected to be influenced by the same synoptic meteorological conditions. Evidence that glaciers in the rest of the Bow Valley are influenced by similar climatic conditions as those experienced at Peyto has been provided by Young (1977). Summertime temperatures and end of winter snow courses, permanently monitored at Lake Louise, approximately 60 km to the south and in the middle of the Bow Basin, were found to correlate favourably with Peyto Glacier summer and winter mass balances, respectively. In addition to the mass balance programme, discharge records with modelled hydrograph separations are available form 1967 to 1974 (Young, 1982).

CALCULATING GLACIER WASTAGE AND STORAGE

Volumetric change from 1951 to 1993

It was decided that the simplest way to estimate net volumetric loss of glacier cover from 1951 to 1993 would be to use a surface area/volume relationship. Such statistical relationships have been developed and

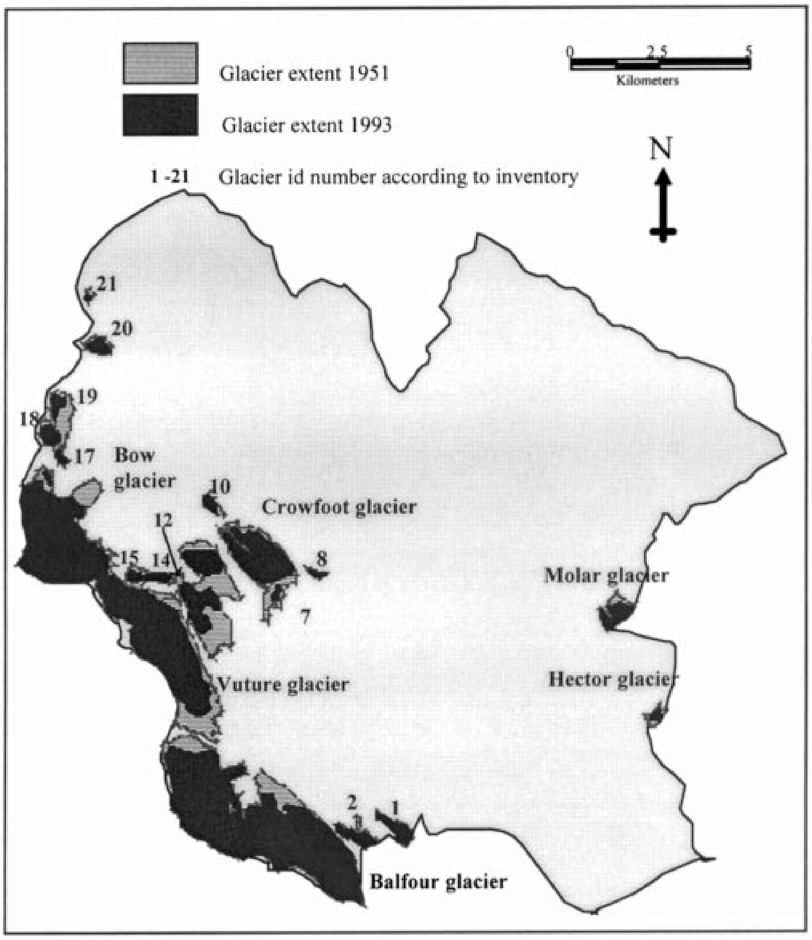

Figure 3. Glacier extents in Hector Lake Basin, 1951–1993

used in various studies and glacier inventory applications (e.g. Brückl, 1970; Paterson, 1970; Chen and Ohmura, 1990). It was therefore necessary to map the extents of all glacier surfaces in the Hector Lake Basin for the two dates. The glacier margins were interpreted manually and transferred to the 1:50 000 NTS map sheet number 82N9 and then digitized using the Mapinfo® software package. Individual glacier areas were computed automatically within the program. The relative areal extents of glacier cover for 1951 and 1993 in the Hector Lake Basin are illustrated in Figure 3.

It was found that in 1951, there was 32·4 km^2, or 11·7% glacier cover, within the Hector Lake Basin, and by 1993 this had reduced to 24·3 km^2, or 8·7%. Although this was only a change of 3%basin cover, it was equivalent to a loss of 25% areal glacier cover. It was apparent that the area calculated from the aerial photographs for 1951 was less than that calculated for 1977 from glacier areas illustrated on the NTS map. After examining the photographs used for map making (Environment Canada, 1979), it was found that poor image quality and low snow-line had led to some areas of snow being mapped as glacier surface. This is not thought to invalidate the relative approximate glacier proportions for Hector Lake and the Bow above Banff, but it did mean that glacier areas calculated for 1951 and 1993 could not be compared directly with those of 1977.

Table I. Hector Lake Basin glacier area and volume estimations, 1951 and 1993

Glacier name and number according to 1967 inventory (Stanley, 1970)	1951		1993	
	Area (km^2)	Glacier volume ($\times 10^6$ m^3)	Area (km^2)	Glacier volume ($\times 10^6$ m^3)
1 Pulpit Glacier	0·33	6·5	0·32	6·1
2 Waputik Glacier	0·39	8·1	0·26	4·7
3 Balfour Glacier	6·94	469	6·07	389
4 Waputik Icefield	4·20	232	3·63	189
5 Vulture Glacier	5·28	319	3·88	207
6 Crowfoot Icefield	2·42	107	0·77	21·5
7 Crowfoot Glacier	0·50	11·7	0·09	1·0
8	0·07	0·7	0·05	0·4
9 Crowfoot Glacier	2·03	83·4	1·66	62·8
10	0·17	2·6	0·10	1·2
11 Crowfoot Icefield	0·80	22·3	0·52	12·1
12	0·11	1·5	0·03	0·2
13 Wapta Icefield	2·50	112	2·15	90·4
14	0·20	3·2	0·12	1·6
15	0·18	2·8	0·10	1·2
16 Bow Glacier	4·26	236	3·57	184
17	0·10	1·3	0·06	0·6
18	0·50	11·6	0·22	3·6
19	0·45	10·0	0·14	1·8
20	0·29	5·5	0·19	3·0
21	0·05	0·4	0·02	0·1
Hector Glacier	0·50	11·5	0·35	6·9
Molar Glacier	0·17	2·6	0·06	0·6
Total	32·4	1660	24·3	1189

Chen and Ohmura (1990) presented a range of possible power function equations to relate glacier surface area (S) to volume (V) of the form

$$V = Z_0 S_1^z \tag{1}$$

where Z_0 and Z_1 are coefficients. The general equation given was derived from a sample of 63 Northern Hemisphere mountain glaciers of a wide range of surface area, up to 20 km^2. The range of typical glacier surface areas found in the Bow Valley is generally between 0·05 and 7 km^2 (see Table I). The most appropriate power relationship equation given in Chen and Ohmura (1990) was considered to be one developed from a sample of 32 glaciers (collected by Driedger and Kennard, 1986), mostly in North America and in the area range of 0·1 to 11 km^2

$$V = 30{\cdot}834 S^{1{\cdot}405 \pm 0{\cdot}071} \tag{2}$$

The assumed errors in volume estimation were contained in the range of Z_1. The maximum and minimum possible volume change for the 42-year period was calculated to be in the range of 207–744 $\times$ 10^6 m^3. However, the glaciers studied in the analysis presented here did not belong to the sample from which the relationship was derived and it is therefore difficult to estimate the true range of error. In addition, this range is computed by comparing the maximum volume in 1951 with the minimum in 1993 and vice versa. These are thought to be unlikely scenarios, as an underestimation or overestimation of volume for one set of imagery is thought likely to be repeated for the other. If alike maximum and minimum volumes were compared, the range of error reduced to between 419 and 532 $\times$ 10^6 m^3. Furthermore it was noted by Chen and Ohmura (1990) that errors in volume calculation using this method are greatest for larger glacier areas. Fortunately,

Table II. Glacier volume loss estimations for Hector Lake Basin and Bow at Banff

Basin		Volumetric loss ($\times 10^6$ m^3)
Hector Lake	Glacier ice	472
	Water equivalent	425
Bow at Banff	Glacier ice	1038
	Water equivalent	934

the majority of glacier cover in the study sample is made of small areal units (see Table I). Owing to the inherent difficulties associated with assessing the error in glacier volume calculation, the average volumetric change of 472×10^6 m^3 was used in the subsequent stages of analysis.

The wastage estimates were converted to a water equivalent by assuming a glacier ice to water ratio of approximately 0·9 (a value adopted in various studies, e.g. Reid and Paterson, 1973; Tangborn *et al.*, 1975; Young, 1991) and then applied to the entire Bow Valley above Banff using a multiplication factor of 2·2 (Table II). This extrapolation factor was based on the knowledge that in 1977 Hector Lake Basin contained 45% of the total basin glacier cover and the assumption that this ratio has remained approximately constant from 1951 to 1993.

Basin-wide annual glacier mass balance

To investigate interannual glacier wastage and storage and their effect on river flow, it was necessary to divide the estimate of net volume loss into annual increments of basin-wide glacier mass balance. It has already been noted that mass balance data already exists for Peyto Glacier from 1966 to the present and, because of its proximity to and representative aspect and elevational range for glaciers in the Bow Valley, it should be a suitable proxy indicator of overall mass balance in the Bow Basin. The record of summer, winter and net annual balance depths averaged over the entire surface of Peyto Glacier were obtained directly from the National Hydrology Research Institute. Values for 1991 and 1992 were not available and have been estimated based on observations of equilibrium line altitude (M. Demuth, 1996, personal communication).

A significant problem exists in filling the gaps for the balance years of 1952 to 1966. Young (1977) noted that summertime (June–August) average temperatures and end of winter (1 April) snow courses measured at Lake Louise were suitable surrogates for mass balance on Peyto Glacier and could be used to reconstruct the record for previous years. All temperature and snow course depths (mm water equivalent) collected at Lake Louise (and Banff) were therefore obtained directly from source (Environment Canada, 1995) in order to attempt a mass balance hind-cast. Three snow courses at Lake Louise were found to have continuous records from around 1940 to 1995: Bow River (1580 m.a.s.l.), Pipestone (1615 m.a.s.l.) and Mirror Lake (2030 m.a.s.l.). Mirror Lake data were chosen for the hind-cast of winter mass balance as this is the only site not found in the bottom of the Bow Valley and it is located at an elevation that should be more representative of winter snow accumulation on glacier surfaces. In addition, the Pearson product–moment correlation coefficients for 1 April snow course depth and Peyto winter mass balance (1966–1990) for the Bow River, Pipestone and Mirror Lake sites were found to be 0·62, 0·47 and 0·66, respectively ($n = 25$).

A low correlation coefficient between snow course and winter balance of 0·66 does not instil confidence in this method and the standard error of estimate was found to be 34 cm. It is known that the net mass balance at Peyto has decreased dramatically since the mid to late 1970s (Demuth, 1996) and this has been attributed to a shift in the atmospheric circulation pattern at the 700 mb level (Fountain and McCabe, 1996). It was therefore tested to see if the relationship between winter mass balance and snow course depth improved if only the earlier parts of the time-series were compared. Although the number of years in the sample was reduced to 14 and the resulting statistical confidence diminished, a better correlation coefficient of 0·81 and a standard error of estimate of 20 cm were obtained for the years 1966–1979. Mirror Lake snow course depths

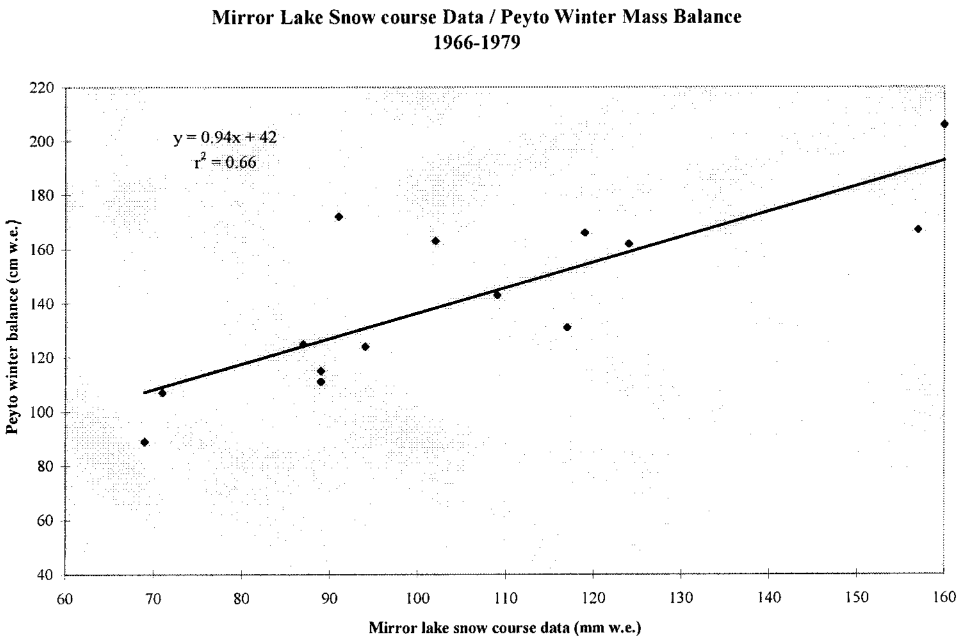

Figure 4. Mirror Lake 1 April snow course/Peyto winter mass balance, 1966–1979. Coefficient of determination, $r^2 = 0{\cdot}66$; standard error of estimate = 20 cm; $n = 14$

were therefore plotted against Peyto winter balance for 1966 to 1979 and the linear relationship calculated (Figure 4).

In order to hind-cast the summer balance at Peyto Glacier, simple correlation coefficients were calculated between balance and July to August mean, mean maximum and mean minimum daily temperatures at both Lake Louise and Banff for the time period 1966 to 1990. The best relationship obtained was with mean maximum daily temperatures at Banff, with a correlation coefficient of 0·70 and standard error estimate of 31 cm. Again, if the earlier period up to 1979 were tested the correlation coefficient improved to 0·81 and the standard error of estimate remained at 31 cm despite a smaller sample size. Therefore, as with the winter balance, the summer balance was hind-casted using a simple linear regression model (Figure 5). The estimated summer and winter balance depths were summed for each year to give the hind-casted net balances for 1952 to 1965.

The recorded Peyto mass balance record was amalgamated with the modelled data to give a continuous data set for the balance years 1952 to 1993. At this stage of the analysis the balance figures were still expressed as an average depth over the whole glacier area. To represent volumetric wastage and storage adequately , the changing area of Peyto Glacier during this time was considered and the depths converted to volumes. The balance volumes were calculated by multiplying the annual balance depths by the changing area of the glacier. In 1951, the area was approximately 14·4 km^2, 13·4 km^2 in 1966 and around 11 km^2 in 1993, suggesting an approximately linear decrease in area with time. The measured and modelled balance depths and volumes for Peyto are given in Table III. For the model calibration period, 1966–1979, the measured and predicted net glacier mass balance had a coefficient of determination (r^2) of 0·59 and a standard error of estimate of 42 cm. The greater change in correlation coefficient and standard error in the winter balance relationship suggests that winter accumulation patterns in this region have changed more dramatically than the summer melt regime.

Before comparing glacier wastage and storage values with stream flow for the Bow above Banff, it was necessary to convert the mass balance values for Peyto into annual proportions of the estimated volumetric glacier loss of 934×10^6 m^3. These annual proportions were calculated by summing all of the net positive

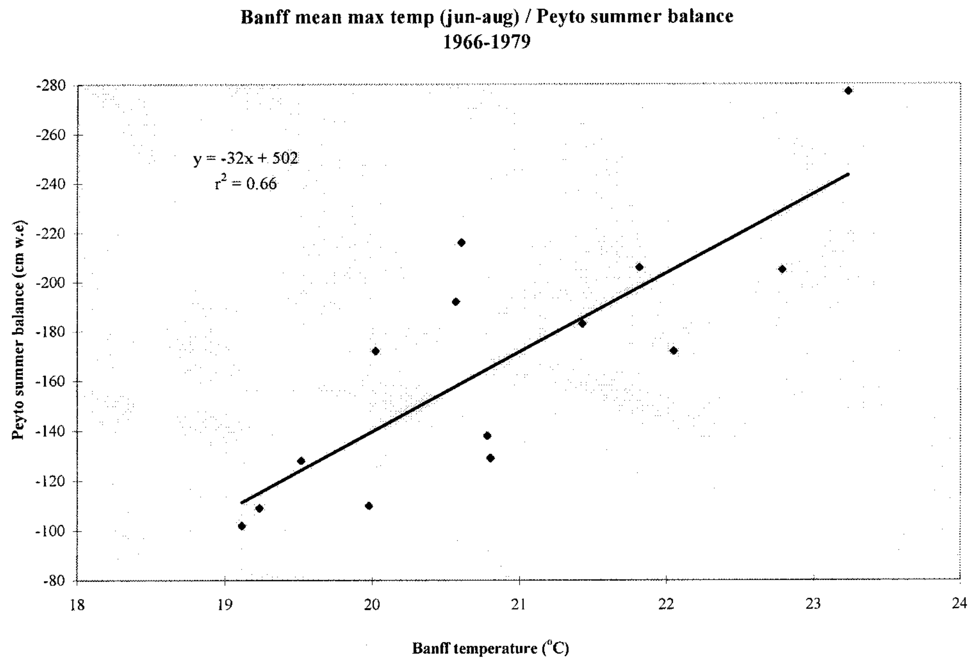

Figure 5. Banff average maximum June to August temperature/Peyto Glacier summer mass balance, 1966–1979. Coefficient of determination, $r^2 = 0{\cdot}66$; standard error of estimate = 31 cm; $n = 14$

and negative balance volumes for Peyto and dividing each year's balance into the total. Each proportion was then multiplied by the total volumetric loss to give a value of either glacier wastage or storage for each year (Table IV). Basin-wide glacier wastage and storage (negative wastage) were summed for the 42-year period, resulting in totals of 1215 and 281×10^6 m^3, respectively. This emphasizes the dominance of glacier loss over growth.

THE EFFECT OF WASTAGE AND STORAGE ON BASIN YIELD

Comparing annual basin yield with glacier wastage and storage

Discharge data for the Bow River at Banff for 1952 to 1993 were obtained directly from Water Survey Canada in the form of daily averages. These data were then aggregated into annual average volumetric water yields and compared directly with the estimates of glacier wastage and storage (Table IV and Figure 6). The average annual basin yield at Banff was found to be approximately 1249×10^6 m^3. The proportions of net wastage, total wastage and growth to the total 42-year basin yield were 1·8, 2·3 and −0·5%, respectively (glacier growth is expressed as a negative percentage as it acts to reduce basin yield). If the influence of net glacier wastage is omitted, the average basin yield drops by over 22×10^6 m^3 to 1227×10^6 m^3. It can be seen in Table IV and Figure 6 that years of below-average yield tend to coincide with wastage years. Conversely, above-average yields were common during years when water was entering into glacier storage.

The regulatory capability of the small glacier cover in the Bow Valley was tested by comparing the coefficients of variation for the total basin yield (C_B) with basin yield–wastage yield (C_w) for the 42 years

$$C = \sigma / R \tag{3}$$

where σ = standard deviation of runoff and R = mean. Using the coefficient of variation to glacier area relationship calculated by Fountain and Tangborn (1985), it was estimated that in a basin with no glacier

Table III. Peyto measured and modelled mass balance depths and volumes. bw = winter balance, bs = summer balance, bn = net balance. Bold values = balance model calibration period, 1966–1979

Year	Banff Jun–Aug ave max.temp (°C)	Mirror Lake 1 April snow course (cm w.e.)	Modelled mass balance (cm w.e.)			Measured net balance (cm w.e.)	Approx. area (km^2)	Est. bn volume ($\times 10^6$ m^3)
			bw	bs	bn			
1952	10·5	10·7	143	−123	20		14·4	2·9
1953	19·7	8·4	121	−129	−7		14·4	−1·0
1954	18·7	14·0	174	−97	77		14·3	11·0
1955	20·8	9·1	128	−167	−39		14·2	−5·5
1956	20·8	14·5	179	−164	15		14·1	2·1
1957	19·0	12·4	159	−107	52		14·1	7·3
1958	21·8	10·9	145	−197	−52		14·0	−7·2
1959	19·7	11·9	154	−129	25		13·9	3·5
1960	20·9	8·9	126	−168	−42		13·8	−5·8
1961	23·3	10·4	140	−247	−107		13·8	−14·6
1962	19·9	10·4	140	−137	3		13·7	0·4
1963	20·7	9·1	128	−161	−34		13·6	−4·6
1964	20·2	9·1	128	−145	−18		13·5	−2·4
1965	21·1	12·4	159	−174	−15		13·4	−2·0
1966	19·2	9·4	**131**	**−115**	**15**	15	13·4	2·0
1967	22·8	16·0	**193**	**−229**	**−36**	1	13·3	0·1
1968	19·5	10·2	**138**	**−124**	**14**	35	13·2	4·6
1969	21·4	10·9	**145**	**−186**	**−41**	−40	13·1	−5·2
1970	23·2	7·1	**109**	**−243**	**−134**	−170	13·0	−22·0
1971	22·0	11·7	**152**	**−205**	**−53**	−41	12·9	−5·3
1972	20·6	15·7	**190**	**−158**	**32**	−25	12·8	−3·2
1983	20·8	9·1	**128**	**−166**	**−38**	43	12·7	5·4
1974	20·8	12·4	**159**	**−165**	**−6**	24	12·6	3·0
1975	20·0	8·9	**126**	**−140**	**−14**	−57	12·5	−7·1
1976	19·1	11·9	**154**	**−111**	**43**	64	12·4	7·9
1977	20·0	6·9	**107**	**−139**	**−32**	−21	12·3	−2·6
1978	20·6	8·9	**126**	**−159**	**−33**	−105	12·3	−12·9
1979	21·8	8·7	**124**	**−198**	**−74**	−81	12·2	−9·9
1980	19·2	10·2				−58	12·1	−7·0
1981	20·1	10·9				−113	12·0	−13·6
1982	20·3	10·8				−56	11·9	−6·7
1983	20·8	9·8				−39	11·8	−4·6
1984	21·2	9·2				−58	11·8	−6·8
1985	21·0	8·0				−81	11·7	−9·5
1986	20·9	12·9				−47	11·6	−5·4
1987	20·6	10·0				−62	11·5	−7·1
1988	21·1	9·8				−99	11·4	−11·3
1989	21·2	10·2				−59	11·3	−6·7
1990	21·2	12·3				−74	11·3	−8·3
1991	21·3	12·9				est −50	11·2	−5·6
1992		8·5				ave −50	11·1	−5·5
1993		8·0				−71	11·0	−7·8

cover (C_W) should have a coefficient of variation of around 0·20. For a basin of 3% cover C_B dropped to 0·18. From the total basin and wastage yield data generated in this study, it was found that $C_W = 0{\cdot}16$ and $C_B = 0{\cdot}14$. The coefficients of variation are slightly smaller than those estimated from Fountain and Tanghorn's model but the difference in values is the same. The reason for the smaller C values in the Bow Basin may be explained by the lower specific annual runoff of 0·55 m compared with around 2 m in the sample tested by Fountain and Tangborn (1985). A further factor may be that the Bow River is also

Table IV. Estimated annual proportions of glacier wastage (negative values = storage due to positive mass balance) and basin yield for the Bow at Banff

Year	Annual proportions	Wastage (10^6 m^3) (Banff)	Yield (10^6 m^3) (Banff)	wastage/yield (Banff) (%)
1952	−0·017	−16·1	1246	−1·3
1953	0·006	5·6	1249	0·4
1954	−0·066	−61·4	1605	−3·8
1955	0·033	30·9	1176	2·6
1956	−0·013	−11·8	1252	−0·9
1957	−0·044	−40·7	*1098*	−3·7
1958	0·043	40·5	1262	3·2
1959	−0·021	−19·3	1334	−1·5
1960	0·035	32·3	1135	2·8
1961	0·088	<u>81·8</u>	1359	**6·0**
1962	−0·002	−2·3	1180	−0·2
1963	0·027	25·7	1293	2·0
1964	0·014	13·5	1337	1·0
1965	0·012	11·2	1457	0·8
1966	−0·012	−11·1	1508	−0·7
1967	−0·001	−0·7	1539	0·0
1968	−0·027	−25·6	1186	−2·2
1969	0·031	29·1	1249	2·3
1970	0·132	<u>122·9</u>	*927*	**13·2**
1971	0·032	29·4	1230	2·4
1972	0·019	17·8	1561	1·1
1973	−0·033	−30·5	1151	−2·6
1974	−0·018	−16·9	1353	−1·2
1975	0·043	39·9	*1009*	3·9
1976	−0·048	−44·5	1498	−3·0
1977	0·016	14·5	*1044*	1·4
1978	0·077	<u>72·0</u>	1233	**5·8**
1979	0·059	<u>55·1</u>	*1003*	**5·5**
1980	0·042	39·2	1224	3·2
1981	0·081	<u>75·9</u>	1416	**5·4**
1982	0·040	37·3	1240	3·0
1983	0·028	25·8	*1076*	2·4
1984	0·041	38·1	*1069*	3·6
1985	0·057	<u>52·9</u>	*1016*	**5·2**
1986	0·033	30·5	1422	2·1
1987	0·043	39·9	*1047*	3·8
1988	0·068	<u>63·2</u>	1120	**5·6**
1989	0·040	37·4	1192	3·1
1990	0·050	46·6	1394	3·3
1991	0·033	31·2	1429	2·2
1992	0·033	31·0	*1038*	3·0
1993	0·047	43·7	*1091*	4·0

Italics = Banff yield $< 1100 \times 10^6$ m^3; underline = wastage $> 50 \times 10^6$ m^3; bold = wastage/yield > 5%.

somewhat regulated by significant slow routing of snowmelt and rainfall through groundwater (Grasby, 1997).

It is interesting to note that during the six years that experienced approximately −1 m net mass balance at Peyto, i.e. 1961, 1978, 1979, 1981, 1985 and 1988, the wastage to yield ratio always lies between 5 and 6%, despite the range in total basin yield for these years ($1003–1416 \times 10^6$ m^3). Adopting another model developed by Fountain and Tangborn (1985) to estimate the level of flow augmentation in a basin of 3%

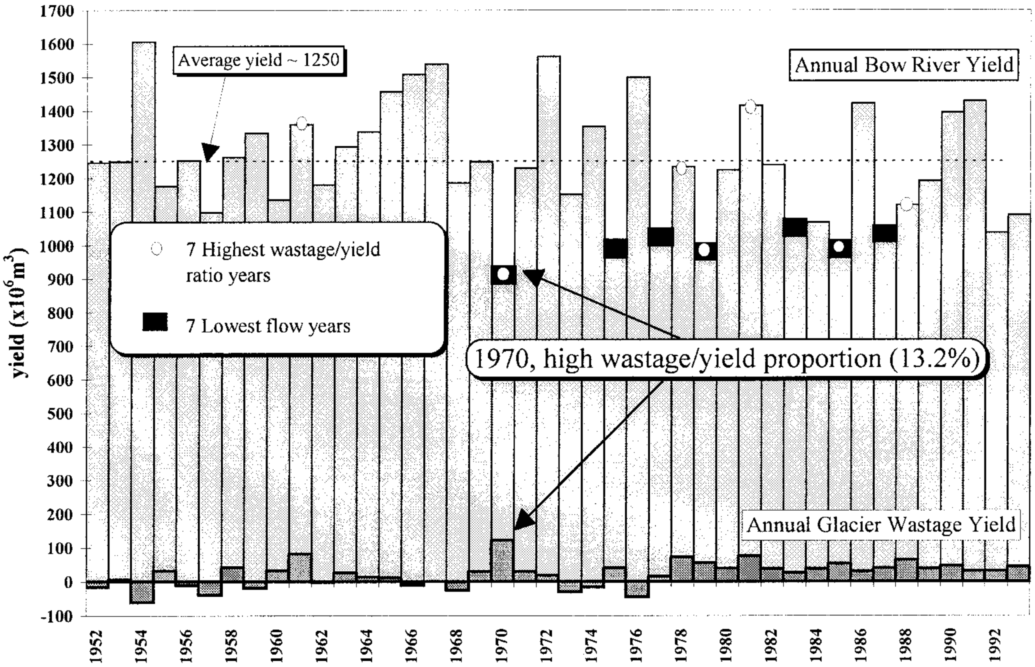

Figure 6. Annual Bow River Basin yield with glacier wastage and storage superimposed

glacier cover, with a specific annual runoff of 0·55 m during a year of −1 m net mass balance, it is calculated that annual yield should increase by approximately 6%. Thus the results of this analysis concur with those of Fountain and Tangborn (1985) despite the differences in methodology. This observation can also be used as further evidence that Peyto is representative of glaciers in the Bow Valley.

In Figure 7, the weak trend for river basin yield to reduce with increasing wastage inputs is illustrated (coefficient of determination = 0·2 and correlation coefficient = −0·39). The low flow years of 1970, 1979, 1983–85, 1987–88 and 1993 all show relatively high wastage inputs with most of the high flow years displaying very little wastage or some water going into storage. The two extremes in this relationship were found in 1954 and 1970. In 1954, the highest basin yield (1605×10^6 m^3) during the study period was recorded and this corresponded to the year of greatest estimated glacial storage ($61{\cdot}4 \times 10^6$ m^3). This can be partially explained by the relatively high winter accumulation experienced during this year and reduced summer temperatures (see Table III). The lowest basin yield was recorded in 1970 (927×10^6 m^3) owing to very low accumulation and high summer temperatures and glacier wastage was estimated to be at its highest (123×10^6 m^3). The proportion of wastage to basin yield was at its maximum of 13·2% for this year. Subtracting wastage from the Bow River Basin yield for 1970, left a remainder of 804×10^6 m^3, approximately half of the maximum yield in 1954. This clearly demonstrates the regulation capability of small glacier covers but does not tell the whole story. Considerable scatter exists around the trend line in Figure 7 and there are numerous outlying points.

The five years 1952, 1957, 1962, 1968 and 1973 all experienced below-average basin yields, while at the same time water was being held back in glacier storage. This was particularly marked in 1957, when it is estimated that up to 4% of the low annual basin yield of less than 1100×10^6 m^3 was being withheld from river flow. *Thus, it is apparent that glaciers do not always augment river discharge during low flow years.* For 1957, the low summer temperatures suggest that it was probably a low melt year and precipitation data, collated by Young (1995), indicate that there were below-average atmospheric hydrological inputs. Examining the results further, it is also evident that years of high flow can be made even higher because of

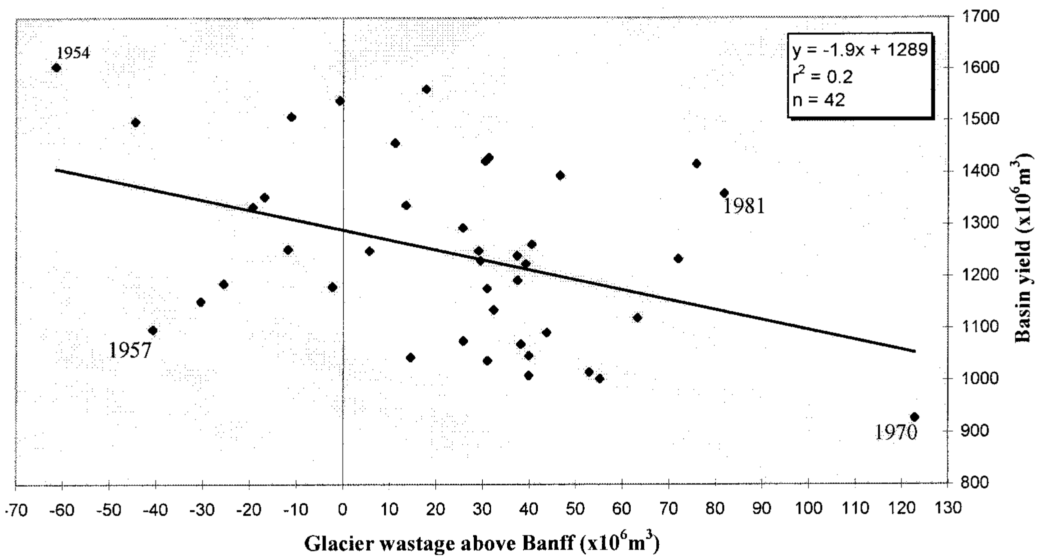

Figure 7. Bow River Basin yield/glacier wastage (negative values = storage)

the input of water from glacier wastage. The years 1961 and 1981 both experienced high flows of around 1400×10^6 m^3. However, they also both experienced wastage volumes of approximately 80×10^6 m^3. *Therefore, although it is generally the case that glaciers do regulate river flow in the Bow Basin, some years may deviate quite markedly from this pattern.* In 1961, the high summer temperatures indicated conditions conducive to high melt rates and thus basin yield, but in 1981 winter accumulation was near average and summer temperatures apparently slightly below average. This further illustrates that the climate, glacier and stream flow inter-relationships are more complex than simple empirical models suggest.

Seasonal glacier wastage contributions

It has been demonstrated that wastage effects of the small area of glacier cover in the Bow Valley above Banff have had a noticeable, and sometimes marked, influence on annual basin yield. However, in the Canadian Rockies, glacier melt is largely confined to the summer months of June to September and, therefore, the influence of glacier wastage must be confined to these four months. An attempt is made in this section to assess the seasonal effect of glacier wastage for 1967 to 1974, years containing both high (greater than 1500×10^6 m^3) and low flow (below 1000×10^6 m^3) at Banff. Seasonal glacier storage was not considered here as its estimated effect on basin yield has generally been much less than that of wastage.

It was assumed that seasonal glacier wastage contributions would be synchronous with the combined ice and firn melt hydrograph derived from glacierized regions. A logical argument against this assumption may be that glacier wastage does not commence until the winter accumulation and summer ablation are in balance [see Meier (1973) for a discussion of the concepts of accumulation, ablation and the interaction with mass balance]. Any meltwater leaving the glacier after this point in time is effectively 'shrinking' the glacier. However, this is unrealistic as it does not consider the factors causing wastage. For example, if the ablation season of any given year had an exceptionally hot and dry June but a cool and damp August, it would be incorrect to suggest that the conditions late in the season were responsible for most of that year's wastage. If, then, the monthly proportions of a basin-wide glacier melt hydrograph could be generated, the seasonal variation in wastage yield could be estimated.

There are no data available for monthly glacier melt in the Bow Basin. Therefore, it was decided to continue the assumption that Peyto was representative of local glacial response and modelled glacier melt

Table V. Estimated Peyto Glacier melt 1967–1974 (after Young, 1982) with average monthly proportions (n.d. = no data)

Year	Monthly melt ($\times 10^3$ m^3)			
	June	July	August	September
1967	16	1390	4800	6140
1968	19	1390	2670	1950
1969	647	3020	5820	3140
1970	1000	6330	12070	850
1971	14	2140	6360	1700
1972	10	1220	4410	970
1973	98	2110	5410	n.d.
1974	12	1440	3420	n.d.
Ave proportions (%)	1·5	22	55	22

Table VI. Monthly glacier wastage/basin yield for Bow above Banff

Year	Glacier wastage/total basin yield (%)			
	June	July	August	September
1969	0·4	2·8	8·5	8·0
1970	2·1	19	56	8·0
1971	0·0	2·6	9·8	5·1
1972	0·0	1·0	5·4	2·6

values, calculated by Young (1982) for Peyto Glacier for 1967 to 1974, were used as a proxy record. The model computed glacier melt values using hypsographic ground cover, meteorological and snow-line data collected on the glacier (Young, 1982). The estimated monthly glacier melt for June to September, for 1967 to 1974, is presented in Table V. It can be seen that the month of August and the year 1970 display high glacier melt at Peyto. Further years could not be modelled owing to insufficient data.

The glacier melt values at Peyto were then divided into the total for the four months to give a monthly melt proportion that could be applied to the Bow above Banff. Only the years 1969 to 1972 displayed glacier wastage and the two years either side could not be examined. The annual wastage values for each of the four years were then multiplied by these proportions to provide an estimate of monthly wastage contribution to the Bow River. Monthly glacier wastage values were compared with total monthly basin yields and the relative proportions calculated (Table VI and Figure 8). It should be noted that glacier wastage and glacier melt are not synonymous (see glossary) as glacier melt will occur in any year, whether it displays a positive or negative mass balance. Therefore, the calculated values of monthly glacier wastage for the Bow at Banff, although considered synchronous to glacier melt contribution, may have different absolute values.

Figure 8 illustrates that maximum glacier wastage (and melt) inputs do not coincide with maximum basin yields. Proportional glacier inputs are greatest in August when the basin yield is receding. The proportional values for September (Table VI) suggest that in some years flow during this month may also be significantly augmented. Of particular interest is the observation that during 1970, the lowest flow on record at Banff, approximately 56% of basin yield for August was derived from glacier wastage. A high annual proportion of wastage to yield was displayed in 1970 owing to little winter snow fall, low summer precipitation and high temperatures (Environment Canada, 1995). August 1970 had the lowest rainfall of any August during the 42-year study period and the average temperature of 15·5 °C was significantly higher than the average August temperature of 14·4 °C.

A potential problem with the seasonal comparison presented is that basin yields measured at Banff have been considered synchronous with glacier wastage often taking place over 100 km upstream. Melt at a

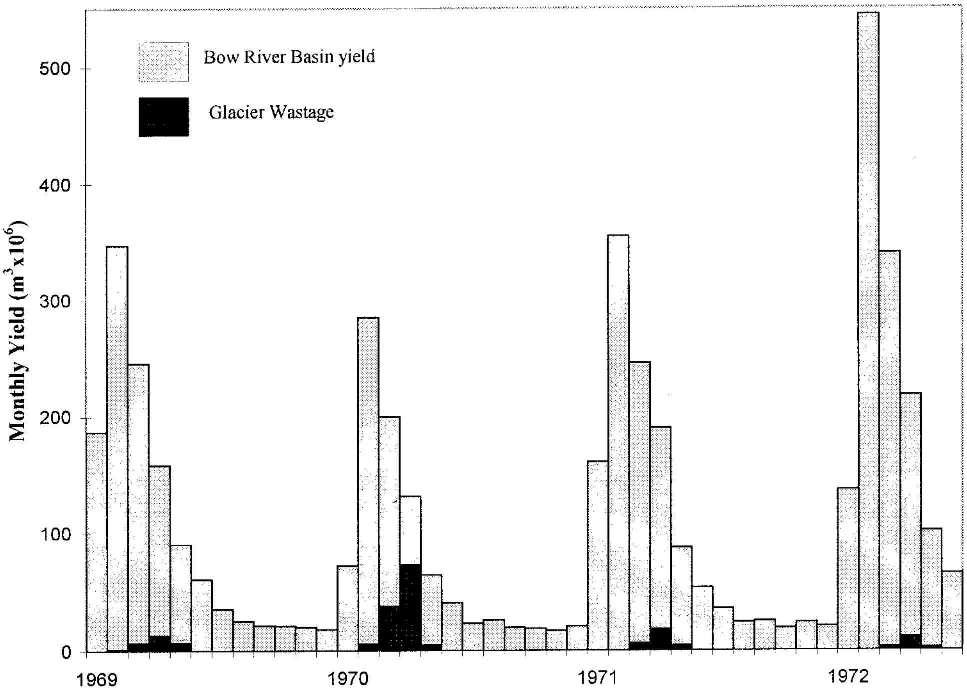

Figure 8. Observed monthly hydrograph for Bow River above Banff 1969–1972 with modelled wastage flow superimposed

glacier surface can enter into temporary storage and then be delayed by days or even weeks before entering into the downstream river system (Stenborg, 1970; Tangborn *et al.*, 1975). There are also over 15 km^2 of lakes in the Bow Valley which are predominantly located in the upper reaches directly downstream of glaciers. The lakes will have the effect of retarding flow (Hutchinson, 1957) and losing a large volume of water to evaporation (Starosolszky, 1987). In addition, evaporative losses are enhanced in the sort of turbulent mountain streams typical in the upper sections of the Bow, where spray is sent into the air (Raudkivi, 1979). The influence of these processes may act to slightly reduce the total amount of glacier wastage reaching Banff but, perhaps more importantly, lag wastage flows and raise the proportion of wastage/basin yield later in the season.

THE EFFECT OF CONTINUED GLACIER LOSS

The importance of glaciers to the local water resource in years and months of warm, dry weather has been highlighted. It is inevitable that as glacier areas and volumes shrink, their ability to augment flows will diminish. In this section, inferences are made as to the effect of continued glacier wastage in the future and the effect of a warm dry year, such as that experienced in 1970, recurring today.

Possible consequences of a warm, dry year occurring today

In order to assess the effect of similar climatic conditions to 1970 occurring today, it was first necessary to estimate how the relative glacier cover for the Bow Basin changed between 1970 and today (for the purpose of this test 1993 is considered to reflect the coverage of today). The glacier area and volume contained within the Bow basin in 1970 was not known. However, it has been estimated that the areal cover in Hector Lake Basin (and probably for the whole Bow Basin) reduced by approximately 28% from 1951 to 1993. 1970 is near the middle of this time-series and, considering that most of the wastage has occurred since 1970, it was assumed that more than half of the glacier volume loss occurred after this date. Therefore, from 1970 to 1993 glacier volume has probably diminished by over 15%. Glacier volume was considered a reasonable surrogate for the ability of glaciers to augment river flows. Therefore, if a climatic scenario equivalent to that prior to and during 1970 occurred today, the annual yield could be reduced from 927 to 908 $\times$ 10^6m^3 and the overall flow for August depleted by over 8%.

Implications for the future

At some time in the future it is conceivable that glacier extent will reduce to zero in the Bow Basin. This could possibly be the case in about 150 years from now if the rate of glacier diminution remains constant. In a situation of zero glacier cover, the specific yield for those basins that are currently glacierized, such as Hector Lake, will reduce during summer and may become similar in character to nearby non-glacierized basins. Dry months and years, when water supply is most critical, would no longer be augmented and the occurrence of low flows would increase while their magnitude would decrease.

In future warm and dry years, similar in character to 1970, the basin hydrograph may be the same as that shown in Figure 8 but with the wastage component subtracted. The difference between July and August yields would be enhanced, with August and September being almost identical. However, the shape of the hydrograph may change and display greater precipitation dominance. Higher proportions of exposed rock and bare ground in the areas of prior glacier cover may lead to more rapid rises in snow-line elevation (Young, 1982). If this is combined with a lack of meltwater storage, facilitated by slow routing through firn and englacial/subglacial environments (Elliston, 1973), river flows in spring may be higher than previously experienced and potentially result in flood events.

CONCLUDING REMARKS

During the period 1951 to 1993, there was approximately 934 $\times$ 10^6 m^3 w.e. (water equivalent) change in net glacier volume in the Bow Valley above Banff, resulting from 1215 $\times$ 10^6 m^3 total wastage, offset by 281 $\times$ 10^6 m^3 storage (with most of the storage concentrated early in the study period and most of the wastage later). During the 42 years studied, net glacier wastage has made up only 1·8% of total basin yield. However, wastage is clearly an important component of river flow during times of low flow. In 1970, the lowest flow year on record, it was estimated that approximately 13% of the annual yield and 56% of the monthly yield for August were derived from glacier wastage. The demonstrated augmentation ability of glaciers in this region will inevitably decrease if glacier dimensions continue to diminish. Indeed, it has been estimated that if similar climatic conditions to those experienced in 1970 were repeated today, then the basin yield at Banff may be reduced by a further 2% as a result of the reduction in glacier cover.

Although the main thrust of this study has been to quantify the regulatory capability of the relatively small glacier coverage in the Bow Valley, it has also been shown that even during above-average flow years, inputs from glacier wastage can still be high. Conversely, glacier storage can sometimes hold back flow during low flow years when water is most needed to supply downstream users. *It is therefore apparent that the interaction between basin-wide glacier mass balance and river flow is not simple and glaciers are not the ideal flow regulators they are often thought to be*.

Development in and downstream of the Bow Basin at Banff (and other glacierized regions of the world) during the last century has occurred at a time of almost continual glacier recession. The baseline stream flow data collected at Banff since 1910, useful for planning future water resource availability and consumption, inevitably lead to overestimations of future stream flow and therefore, promote a false sense of security. Glacier cover in the Bow Valley, as elsewhere, will tend towards zero if the current rates of loss continue. The results of this will likely be generally lower summer flows, possible enhanced spring runoff and an increased likelihood of water shortages.

GLOSSARY

Glacial hydrological terms are often used ambiguously. The following glossary is provided to avoid misinterpretation.

Basin yield The total volume of river runoff leaving the basin in question during the time period of interest.

Glacier melt The melted ice and firn draining from a glacier basin. For the purpose of the analysis presented here, *glacier melt* does not include melted snow that has fallen on to a glacier's surface within the same hydrological year.

Glacier recession The apparent visual shrinkage of glacier dimensions.

Glacier wastage The volume of glacier loss measured over a period of time. *Wastage* is considered analogous to a negative mass balance for the glacier or suite of glaciers being studied. Thus for any given year, *wastage* occurs if the glacier shrinks in volume and water leaving the glacier exceeds hydrological inputs.

Glacier storage The opposite of glacier *wastage*. *Storage* is considered analogous to a positive glacier mass balance and acts to withhold water from river flow.

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