THE IMPACT OF GLACIER RECESSION UPON THE DISCHARGE OF THE BOW RIVER ABOVE BANFF, ALBERTA. 1951-1993 1/

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ABSTRACT

Three methods were used to determine the net volumetric loss (*wastage)* of glacier cover within the Bow Valley above Banff, Alberta between 1951 and 1993 (see Hopkinson, 1997). It was estimated that between 1100 and 1650 $m^3 \times 10^6$ of ice volume was lost during this time period. The median value of 1375 $m^3 \times 10^6$ was converted to a water equivalence value of approximately 1170 $m^3 \times 10^6$ by assuming a glacier ice (including firn and voids) / water ratio of approximately 85%.

The bulk glacier wastage estimate was divided into proportions using the Peyto Glacier mass balance record. Unfortunately, the record began in 1966 and a back-cast to 1952 was necessary. Banff maximum summer temperature and Lake Louise snow course data were used as surrogates for summer and winter glacier mass balance, respectively. Seasonal wastage contributions to river flow were estimated for 1967 to 1974 using modelled values of glacial melt (ice and firn only) generated for Peyto Creek by Young (1982).

An estimate of the temporal variation of glacier recession inputs to the Bow River hydrograph at Banff was facilitated by comparing known basin yields with the modelled wastage values. For 1952 to 1993, the average annual wastage/basin yield ratio is found to be around 2.3%. For the extremely low flow year of 1970 this ratio increases to 12.5%. The proportion of flow derived from glacier recession in August of this year is estimated to be around 53%. It is thought that the mass balance back-cast may slightly under-estimate wastage values in the early part of the time series, therefore, leading to an over-estimation later on.

INTRODUCTION

Observations of glacier recession in the eastern frontier range of the Canadian Rockies have been recorded since 1887 (Meek, 1948). A consequence of glacier wasting (see glossary for a definition of terms) in mountain regions is that river basin yields are augmented more than the net income of annual precipitation (see Meier, 1969). It is to be expected that the warmer and drier the year coupled with a low winter snow cover, then the more glaciers will recede and more important is their role in flow augmentation. However, as glaciers retreat to higher elevations, their areal extents and volumes diminish and their snouts approach the average 0° isotherm. Thus, even though toe recession may continue at a similar or even accelerated rate for some time to come, the potential to shed large volumes of ice through melting will gradually diminish. It is, therefore, the aim of this paper to investigate the relationship between observations of glacier wastage and hydrological basin yields within a glacierized mountain basin.

The area chosen for this study was the Bow River Basin upstream of Banff (2230 km^2), Alberta (see figure 1). The Bow River is regionally important as a water resource for both the permanent and transient populations that live within the basin. It has been suggested that development in the Bow Valley could not have reached such a high level without the assured supply of melt from glaciers (Collier, 1958). (Note the rapid reduction in annual precipitation yields as one travels east from the Rockies to the prairies, figure 1.) The Bow River is the main source of supply to many domestic users, the number of which increases greatly in the summer due to the influx of tourists. In Banff the permanent population numbers approximately 10,000, however, during the summer months of June to September of 1995-96 over 5 million people visited Banff National Park (McMahon, 1997, personal communication). This not only increases domestic usage but also acts to reduce water quality downstream of urban drainage and sewer outfalls (Bow River Water Quality Task Force, 1991) a problem which is heightened during periods of low flow.

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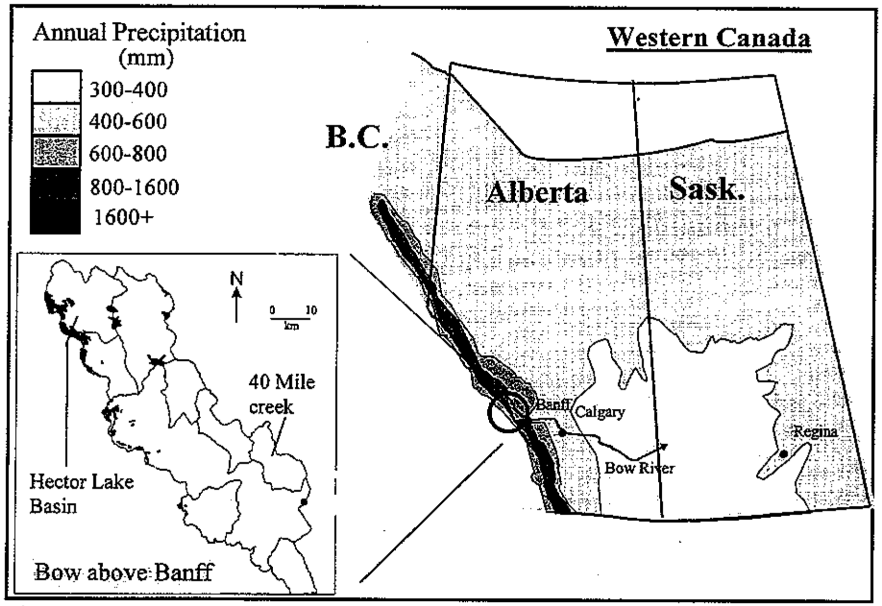

Fig. 1. The study region, showing precipitation zones. Inset is the Bow River Basin above Banff with glacier cover and sub-basins.

During the low flow and high demand year of 1977, approximately 95% of water consumption within the Bow Basin was for irrigation purposes with 4% municipal and 1% industrial (Alberta Environment, 1984). Another important consideration is the provincial government agreement that states at least 50% of the natural flow leaving Alberta via the South Saskatchewan River must be maintained to serve Saskatchewan's needs.

In a region of intense water usage, where demand can sometimes exceed supply (Young, 1995), a knowledge of the relative proportions of contributing hydrological sources is essential. Also, how these sources vary through time and with climate must be researched in order to predict future resource availability. This knowledge can then be used to aid with short term management decisions and, perhaps more importantly, long term policy initiatives. In the Bow Valley, annual river flow is dominated by snow melt, however, it is apparent that during the summer months when demand for water is high the flows derived from glacier melt are at their most influential. Therefore, more learned decisions regarding river management issues will be facilitated if the timing and magnitude of glacier wastage inputs to river flows (past, present and future) can be ascertained.

METHODS

Net Glacier Wastage, 1951 - 1993

It has been estimated that within the Bow valley above Banff the net volumetric wastage of glacier cover was between 1100 to 1650 $m^3 \times 10^6$ from 1951 to 1993 (Hopkinson, 1997). For the purpose of this study the median value of 1375 $m^3 \times 10^6$ has been adopted as the net glacier wastage volume for the 42 year study period. To enable comparison with river basin yields, monitored at Banff by Water Survey of Canada, the glacier volume was converted to a water equivalence. If glaciers comprised of pure blocks of ice, the water equivalence of any volume lost would be around 91%. However, this conversion factor is considered too high for two reasons:

1. Glaciers are not solid; they contain many voids in the form of crevasses, moulins and englacial/subglacial conduits;
2. Within the accumulation zone of glaciers there can be several metres depth of firn with a density between 40 to 80% that of water (Sugden and John, 1991).

A conversion factor of 0.85 glacier volume/water equivalence was, therefore, considered more reasonable and has been adopted in this study.

Annual Glacier Wastage Estimations

Glacier mass balance data are ideally suited to the task of "weighting" the annual proportions of wastage yield calculated over a long time series. The data indicate directly which years did and did not undergo a loss of mass and, also, the relative proportions for each year contained within the dataset. Therefore, the rationale used in this section of the analysis was to assume that the record of net annual mass balance for Peyto Glacier, just to the north of the study basin (obtained from Demuth, 1996, personal communication), would be representative of all glacierized regions of the Bow Valley. For the years prior to 1966, when no records were kept, some method of back-casting the mass balance/wastage proportions was necessary.

The first option considered for a net annual mass balance back-cast was a model proposed by Letreguilly (1988), which demonstrated a strong correlation with mean minimum May to July temperatures at Jasper. Upon further scrutiny, it was considered that this model was inappropriate for this application. For 1952 to 1965 Letreguilly's model suggests a thirteen year net positive mass balance of approximately 0.02m depth of water equivalence over the entire Peyto Glacier surface. Although this is not impossible, it is considered extremely unlikely when observations made by Brunger *et al.* (1967) are taken into account. Their study indicated that the toe of Peyto Glacier receded by almost 450m between 1952 and 1965. Therefore, a much more negative net mass balance for this period would intuitively be expected.

Within the Bow Valley, long time series of climate and winter snow course data exist for a variety of sites (collected by Atmospheric Environment Service and Water Survey Canada, respectively). Thus, an attempt was made to correlate all the long term April 1st snow course data from each site in the Bow Basin with the winter mass balance depth record for Peyto Glacier. It is known that summer air temperatures correlate well with melt water yields from highly glacierized basins (Collins, 1988). Therefore, various combinations of average monthly temperatures at Banff were correlated with the summer balance depths.

The Mirror Lake snow course for April 1st, located approximately centrally within the Bow Basin near Lake Louise at 2030m, was found to have a correlation of around 0.66 with the 1966 to 1993 Peyto winter mass balance record. The correlation improved to 0.81 if only the earlier period up to 1979 was tested (the mass balance trend appears to change between the mid to late 1970s). It was therefore considered that the 1951 to 1965 winter balance / snow course relationship would be reflected better in the 1966 to 1979 data rather than 1966 to 1993; *i.e.* the relationship between in valley snow accumulation and glacier winter mass balance is not stable through time. Declining winter mass balance is considered to play a major role in the overall net balance reduction observed at Peyto since the late 1970s (Demuth, 1996). A regression model of the Mirror Lake snow course and winter mass balance for Peyto was calculated and then run backwards to the winter of 1951/52.

A correlation of 0.70 was obtained between the summer balance and the mean of maximum daily temperatures for June to August for 1966 to 1993. Other combinations of months were explored but this provided the best relationship. Again, if the earlier period up to 1979 were tested the correlation improved to 0.81. Therefore, as with the winter balance, the summer balance was back-casted using a simple linear regression model. The estimated summer and winter balance depths were summed for each year to give the back-casted net balances for 1952 to 1965. The net thirteen year balance for Peyto Glacier, using this method was - 1.24m depth of water equivalence.

The recorded Peyto mass balance record was amalgamated with the modelled data to give a continuous dataset from 1952 to 1993 (balance years). At this stage of the analysis the balance figures were still expressed as a depth. To adequately represent wastage inputs, the changing area of Peyto Glacier during this time must be 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 14.5km^2 and this was assumed to linearly decrease to 11km^2 by 1993.

The annual proportions of glacier wastage were calculated by summing all of the net balance volumes and dividing each year's balance into the total. Thus, the sum of all the proportions would, naturally, be one. In years where the net balance was positive, it was assumed water was being with-held from the system by going into glacial storage and, therefore, the proportions assigned to these years were not included in the "weighting" process. This being for the reason that the sum of all years wastage yields must, of necessity, be equivalent to the net wastage for the forty two year period. The glacier wastage water equivalence was then multiplied by each of the positive proportions within the forty two year time series to give the annual glacier wastage yields for the entire basin.

Seasonal Glacier Wastage Contributions

For the purpose of this analysis it was assumed that seasonal glacier wastage contributions would coincide with and be in proportion to the combined ice and firn melt hydrograph derived from glacierized regions. It could be argued that glacier wastage flows do not commence until the exact time when the winter accumulation and summer ablation are in balance. Any melt water leaving the glacier after this point in time is effectively "shrinking" the glacier. This is a logical argument but is unrealistic as it does not consider the factors causing the excess glacier loss; 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 not be fair to suggest that the conditions late in the season were responsible for this year's wastage. Further, such an assumption would predict that a high proportion (if not all) of such a year's September melt was due to glacier wastage. However, the observed wastage of a glacier is the result of melt throughout the entire season, it is not the cause of melt water discharge at the end of a season. If, then, the monthly proportions of a basin wide glacier melt hydrograph could be generated, the seasonal variation in wastage yield can be estimated.

Hydrographs display the amalgamation of their upstream flow components. Therefore, separating the observed discharge into its contributing aliquots requires complex measurement using tracer techniques or some form of modelling. It was assumed that the shape of the glacier melt hydrograph at Peyto should be very similar to that of the whole Bow Basin. A study carried out by Young (1982) investigating the runoff characteristics within Peyto Basin for the summer seasons of 1967 to 1974 was used for this section of the analysis. In Young's paper, he describes the monthly flow components and explains the model used to generate the hydrograph separation. Hypsographic curves of ground cover types were used in connection with climatic and snow line elevation data to predict the relative hydrological inputs derived from ice, firn, snow and rainfall.

The monthly proportions calculated from this model (table 1) for the years 1967 to 1974 were applied directly to the estimated wastage yields for these years. It can be seen that August is by far the dominant month in terms of glacier melt (and therefore wastage) inputs to the river system. Outside the 1967 to 1974 time period it was impossible to run the model again due to insufficient data. Therefore, a seasonal comparison of glacier wastage and river basin yields was confined to these years only. It was fortunate that the lowest flow year on record for the Bow River at Banff was 1970 and could be investigated.

Year	Monthly melt ($m^3 \times 10^3$)			
	June	July	August	September
1967	16.3	1391.0	4799.1	6144.7
1968	18.9	1390.0	2669.3	1947.6
1969	646.8	3016.4	5818.0	3139.0
1970	1000.5	6327.0	12069.0	852.5
1971	13.9	2144.2	6358.1	1700.0
1972	9.9	1218.8	4409.5	970.0
1973	98.1	2107.9	5405.9	
1974	12.0	1435.0	3420.7	
Av. proportions	1.5%	22.2%	54.6%	21.7%

Table 1. Estimated Peyto Glacier melt 1967-74 (after Young, 1982) with average monthly proportions.

RESULTS

Annual Glacier Wastage Proportions

In table 2 (below) the measured and back-casted mass balance values for Peyto Glacier from 1952 to 1993 are presented. The 1991 value was estimated based on the equilibrium line altitude (ELA) for this year (Demuth, 1996 personal communication) and 1992 is an average of the 1967 to 1991 series. An average value was used for this year so that it would not bias the proportional weightings in any way. These two years currently have no record and could not be modelled due to a lack of data. They do not significantly affect the overall annual glacier wastage proportions. The running totals of modelled and measured net mass balance are given to illustrate the significant divergence between the values after 1979.

Year	Banff Jun-Aug av max temp (^{0}C)	Mirror Lake April 1st snow course (cm w.e.)	Modelled balance (cm w.e.)				Measured bn (cm w.e.)	
			bw	bs	bn	Running total		Running total
1952	19.5	10.7	143	-123	20			
1953	19.7	8.4	121	-129	-7			
1954	18.7	14	174	-97	77			
1955	20.8	9.1	128	-167	-39			
1956	20.8	14.5	179	-164	15			
1957	19	12.4	159	-107	52			
1958	21.8	10.9	145	-197	-52			
1959	19.7	11.9	154	-129	25			
1960	20.9	8.9	126	-168	-42			
1961	23.3	10.4	140	-247	-107			
1962	19.9	10.4	140	-137	3			
1963	20.7	9.1	128	-161	-34			
1964	20.2	9.1	128	-145	-18			
1965	21.1	12.4	159	-174	-15			
1966	19.2	9.4	131	-115	15	*15*	15	*15*
1967	22.8	16	193	-229	-36	*-21*	1	*16*
1968	19.5	10.2	138	-124	14	*-7*	35	*51*
1969	21.4	10.9	145	-186	-41	*-48*	-40	*11*
1970	23.2	7.1	109	-243	-134	*-182*	-170	*-159*
1971	22	11.7	152	-205	-53	*-235*	-41	*-200*
1972	20.6	15.7	190	-158	32	*-203*	-25	*-225*
1973	20.8	9.1	128	-166	-38	*-241*	43	*-182*
1974	20.8	12.4	159	-165	-6	*-247*	24	*-158*
1975	20	8.9	126	-140	-14	*-261*	-57	*-215*
1976	19.1	11.9	154	-111	43	*-218*	64	*-151*
1977	20	6.9	107	-139	-32	*-250*	-21	*-172*
1978	20.6	8.9	126	-159	-33	*-283*	-105	*-277*
1979	21.8	8.7	124	-198	-74	*-357*	-81	*-358*
1980	19.2	10.2	138	-113	25	*-332*	-58	*-416*
1981	20.1	10.9	145	-143	1	*-331*	-113	*-529*
1982	20.3	10.8	144	-149	-5	*-336*	-56	*-585*
1983	20.8	9.8	134	-166	-31	*-367*	-39	*-624*
1984	21.2	9.2	129	-180	-51	*-418*	-58	*-682*
1985	21	8	117	-171	-54	*-472*	-81	*-763*
1986	20.9	12.9	164	-170	-7	*-479*	-47	*-810*
1987	20.6	10	136	-160	-23	*-502*	-62	*-872*
1988	21.1	9.8	134	-175	-40	*-542*	-99	*-971*
1989	21.2	10.2	138	-177	-39	*-581*	-59	*-1030*
1990	21.2	12.3	158	-177	-19	*-600*	-74	*-1104*
1991	21.3	12.9	164	-181	-17		est -50	
1992		8.5	122				av -50	
1993		8	117				-71	

Table 2. Peyto mass balance depths with comparative running totals, actual and modelled. bw = winter balance, bs = summer balance, bn = net balance.

The proportions of wastage assumed to be entering into river flow for each year within the study period above Banff are presented in table 3 (below). The annual proportions of glacier wastage to basin yield reach a maximum value 12.5%. This high wastage input value occurs during the lowest flow year of the study period, 1970. The number of years not displaying wastage early in the time series reflect the apparent trend in the Peyto mass balance record to become continually negative after the mid seventies.

It can be seen in table 3 and figure 2 that years of low yield tend to coincide with substantial wastage. Lowest yield and highest wastage years are highlighted to illustrate this. However, it is a weak trend and two years in particular deviate significantly from this pattern; The year 1981 is one of both high yield and estimated high wastage with 1957 displaying a low yield and no glacier volume loss.

Year	bn volume (m^3 x 10^6)	Annual weights	Wastage ($m^3 x10^6$) Banff	Yield ($m^3 x10^6$) Banff	Wastage / yield Banff
1952				1246	
1953	-1.07	0.0049	5.7	1249	0.45%
1954				1605	
1955	-5.53	0.0254	29.2	1176	2.48%
1956				1252	
1957				*1098*	
1958	-7.28	0.0335	38.4	1262	3.05%
1959				1334	
1960	-5.81	0.0268	30.7	1135	2.70%
1961	-14.59	0.0672	77.0	1359	**5.67%**
1962				1180	
1963	-4.54	0.0209	24.0	1293	1.86%
1964	-2.37	0.0109	12.5	1337	0.93%
1965	-1.98	0.0091	10.4	1457	0.72%
1966				1508	
1967				1539	
1968				1186	
1969	-5.20	0.0239	27.5	1249	2.20%
1970	-21.96	0.1011	116.0	*927*	**12.50%**
1971	-5.26	0.0242	27.8	1230	2.26%
1972	-3.19	0.0147	16.8	1561	1.08%
1973				1151	
1974				1353	
1975	-7.13	0.0328	37.6	*1009*	3.73%
1976				1498	
1977	-2.59	0.0119	13.7	*1044*	1.31%
1978	-12.86	0.0592	67.9	1233	**5.51%**
1979	-9.86	0.0454	52.0	*1003*	**5.19%**
1980	-7.01	0.0323	37.0	1224	3.02%
1981	-13.56	0.0624	71.6	1416	**5.06%**
1982	-6.67	0.0307	35.2	1240	2.84%
1983	-4.62	0.0213	24.4	*1076*	2.27%
1984	-6.82	0.0314	36.0	*1069*	3.37%
1985	-9.45	0.0435	49.9	*1016*	4.91%
1986	-5.44	0.0251	28.7	1422	2.02%
1987	-7.13	0.0328	37.7	*1047*	3.60%
1988	-11.30	0.0520	59.7	1120	**5.33%**
1989	-6.69	0.0308	35.3	1192	2.96%
1990	-8.33	0.0383	44.0	1394	3.15%
1991	-5.58	0.0257	29.5	1429	2.06%
1992	-5.54	0.0255	29.3	*1038*	2.82%
1993	-7.81	0.0360	41.2	*1091*	3.78%

Table 3. Estimated annual proportions of glacier wastage/basin yield for Banff and Lake Louise.

Italics **= Banff yield < 1100 m^3x10^6, shaded = wastage > 50 m^3x10^6, Bolded = wastage/ yield > 5%.**

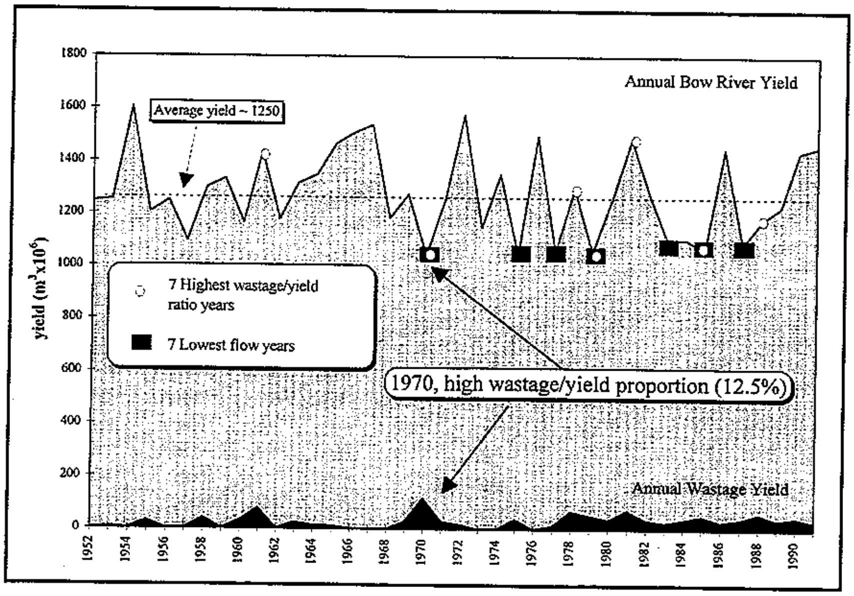

Fig. 2. Annual Basin yield and glacier wastage for the Bow above Banff.

Seasonal Wastage Proportions, 1967 - 1974

The estimated monthly glacier loss / basin yield ratios for 1967 to 1974 are given in table 4. August 1970, is the most notable period of the study. It is estimated that over 50% of the flow upstream of Banff was derived from glacier wastage. The significance of seasonal glacier wastage distribution to the hydrograph at Banff for the years 1969 to 1972 is illustrated in figure 3. Only the years 1969 to 1972 are shown as the years 1967-68, 1973-74 had positive mass balances at Peyto Glacier and thus it was considered that no wastage occurred during these years.

	Glacier wastage / Bow River basin @ Banff			
Year	**June**	**July**	**August**	**September**
1967				
1968				
1969	0.40%	2.67%	8.00%	7.56%
1970	1.99%	18.13%	52.55%	7.55%
1971	0.01%	2.42%	9.26%	4.82%
1972	0.00%	0.91%	5.15%	2.44%
1973				
1974				

Table 4. Monthly glacier volume loss / basin yield for Bow above Banff. Blank cells = years of estimated zero glacier wastage (positive mass balance).

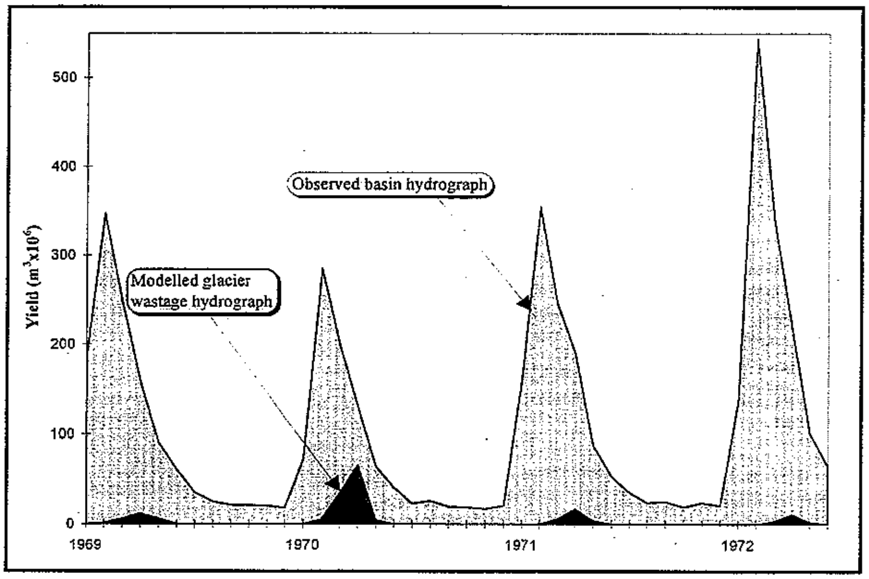

Fig. 3 Observed hydrograph for Bow River above Banff 1969-1972 with modelled wastage flow superimposed.

DISCUSSION

Peyto Glacier Mass Balance

It is interesting to note that wastage inputs are apparently higher in the second half of the time series, after the mid-seventies. This is intuitively not what would be expected if the climate were stable or at least changing in a linear fashion. Observations do not indicate a decline in magnitude of the net balance values despite the rapidly shrinking dimensions of Peyto Glacier. Winter positive balance figures show some tendency to reduce through time (Demuth, 1996) but no discernible trend is apparent in the summer negative values (see figure 4). This can indicate one of two things: 1) the Peyto data set is unreliable or 2) there has been a change in climatic regime. There is some evidence to support the second premise; a shift in the atmospheric circulation pattern at the 700mb level was observed around the mid 1970s (Fountain and McCabe, 1996).

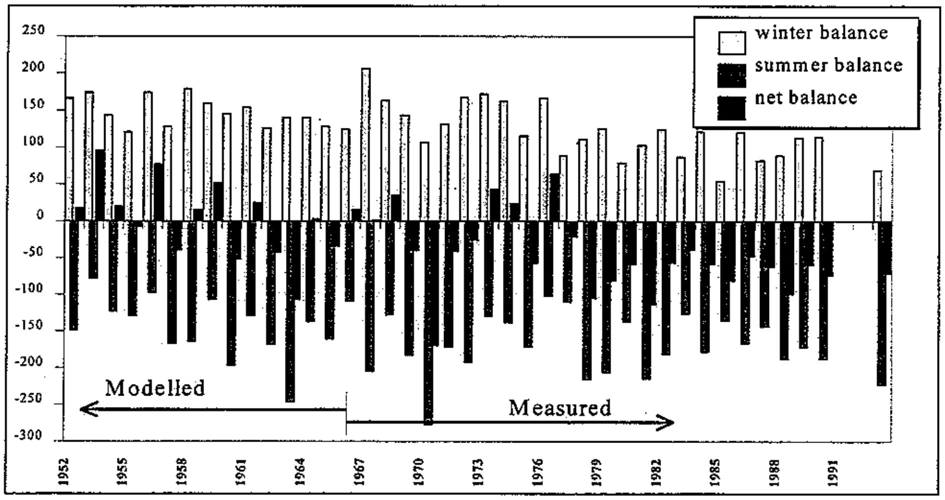

Fig. 4. Peyto Glacier mass balance (depth cm), measured 1966-93, back-casted 1952-65.

It is known that for the early period of the Peyto mass balance data series, the area factor was not changed for at least thirteen years (Young, 1981). More recently the area factor has been updated regularly, perhaps every third year or so (Demuth, 1997 personal communication). The application of this dataset to long term glacier wastage estimations would be improved if the raw field book measurements, for the earlier time period (if available), could be reviewed and the mass balance values recalculated with adjusted area factors at regular time intervals.

Peyto Glacier Mass Balance Back-cast

Local winter snow course and summer maximum temperatures are considered to be reasonable surrogates for winter and summer balances. Maximum temperature is probably a more useful estimator of summer melt than average or minimum temperature because it provides some insight into whether a day was cloudy or very hot. If the maximum temperature for a day is low, then it would be assumed to be cloudy (and possibly wet) with low melt, conversely a high maximum temperature suggests high melt potential. It is more difficult to make the same inferences with only average temperature data. It may be more appropriate to attempt a multiple regression using other climatic parameters such as summer time precipitation, however, comparison of the precipitation records for Banff, Lake Louise and Castle Mountain Village (all within the Bow Valley) indicate a high spatial variability in rainfall patterns within the basin.

Continuing Letreguilly's (1988) mean minimum Jasper May to July temperature model backwards to 1952 led to a thirteen year positive mass balance depth of 0.02m compared to -1.24m for the snow course / maximum temperature model. The negative value better represents the observations of toe recession at Peyto during 1952-65 (Brunger *et al*, 1967) but it could still be significantly conservative. There are several individual years in the Peyto mass balance dataset that show negative balances of over 1.0m. Therefore, to suggest that the glacier can undergo 450m of recession and only lose 1.24m depth of total water equivalence seems highly unlikely.

If it is indeed the case that the annual wastage proportions for the period up to 1965 have been under-estimated then this will lead to a systematic over-estimation of the proportions after this date. Therefore, it is quite possible that annual volumes of wastage calculated for low flow years such as 1970 are too high. Hypothetically, if the 1952-65 balance was actually 5m more negative than calculated (-6.24m), then the annual ratio of wastage to discharge at Banff in 1970 would be slightly below 10% as opposed to 12.5%. The August ratio would also decrease from 53% down to around 40%, still a highly substantial proportion.

An improvement of the back-casted mass balance data series could be facilitated if air photos dating back to the early 1950s were used to map the Peyto Glacier surface. This would enable a comparison with the previously mapped 1966 surface (Inland Waters Directorate, 1975) and an estimate of the volume change between the two dates. The volume change could then be converted to the net balance figure in water equivalence. Monitoring glacier mass balance using aerial photography and sequential mapping has been widely practised with much success in Norway (Østrem, 1986).

The Impact of Glacier Recession on the Flow of the Bow River

It is estimated that the average basin yield above Banff is reduced by 27 m^3x10^6 w.e. from 1244 to 1217 m^3x10^6 w.e. if the influence of glacier wastage is omitted. For 1970, the same drop is 927 to 811 m^3x10^6 w.e. (see table 3). 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 or no glacier wastage. 1961, 1981 and 1990 are interesting for they all show above average basin yields but also a high proportion of flow derived from glacier loss. This demonstrates that, although glacier wastage is hydrologically at its most influential during years of low flow, it can still be an important component of river flow even during some high flow years.

The Low Flow Year, 1970

The 1970 basin yield and modelled monthly wastage contributions for the Bow River at Banff are shown in figure 5. The light section of the bars displays the hydrograph without glacier wastage, the total yield is represented by the entire bar. 1970 produced a high proportion of wastage to yield due to little winter snow fall, low summer precipitation and high temperatures. August of this year had the lowest rainfall of any August during 1952 to 1992 and the average temperature of 15.5 °C was significantly higher than the average August temperature of 14.4 °C. If the climatic regime that persisted during 1970 were to repeat but without any glacier cover, the basin hydrograph would be similar to the graph shown in figure 5 but with a smaller wastage component. The difference between July and August yields would be enhanced with August and September being almost identical. However, the timing and shape of the hydrograph would probably be a little different due to an earlier snow melt peak from more rapid melt of snow in areas that were previously glacier covered and less flow retardation of water draining through glacier systems.

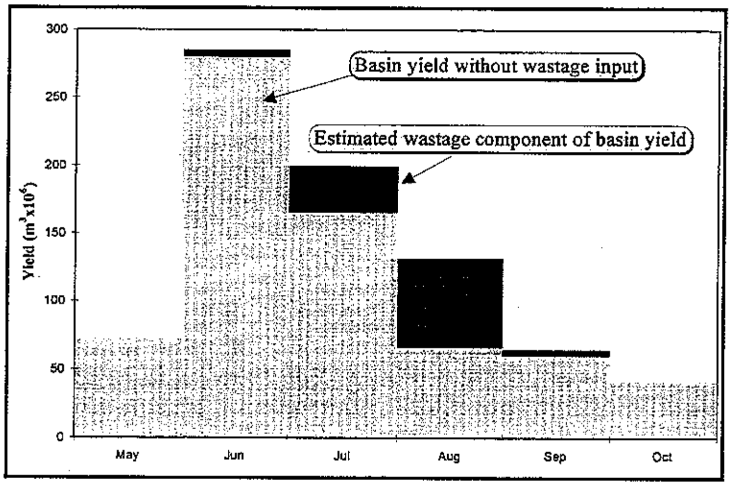

Fig. 5. Monthly wastage proportions at Banff, 1970

It is not known exactly what the proportional glacier coverage was in 1970, but it is known that the areal cover reduced from approximately 11.7% to 8.7% in the most northern basin in the Bow Valley (Hector Lake Basin, 276 km^2) from 1952 to 1993 (Hopkinson, 1997). This 3% reduction in basin wide glacier cover equates to approximately a 25% reduction in total glacier area over the 42 year period. 1970 is near the middle of this time series and (comparing Brunger *et al's.* observations (1967) with the current extent of Peyto Glacier) it can be assumed that approximately half of the recession had occurred after this date. Therefore, from 1970 to 1993 glacier area probably reduced between 10 and 15%. If areal coverage is considered a reasonable surrogate for the ability of glaciers to augment river flows then the following conclusion can be made: If a climatic scenario equivalent to that prior to and during 1970 occurred today, then the amount of flow in the Bow River derived from glacier wastage could be reduced by 10 to 15% of that estimated for June to September, 1970. Therefore, the annual yield could be reduced from 927 to 910 m^{3}x10^6 and the overall flow for August depleted by up to 7.5%.

The Future

Over the last fifty years and indeed probably the entire century, glaciers within Bow Valley have acted as flow regulators, delivering water late in the summer and during dry years when it has been needed most. As glacier areas and volumes shrink, their ability to augment flows in the future will naturally diminish. If the glaciers were to continue receding indefinitely in this part of the Rockies, then it will not be long before they are gone altogether. Hypothetically, if it is assumed that the rate of glacier diminution is linear, then the life expectancy for glacier cover can be calculated. Approximately one quarter of total glacier volume in 1951 was estimated to have been depleted by 1993 (Hopkinson, 1997). Therefore, extrapolating forwards would suggest that there is between 100 and 150 years of cover left. However, this is an extremely unlikely scenario, as rates of recession should reduce as glaciers reach higher and colder elevations.

CONCLUSIONS

Peyto Glacier Back-cast

The back-casting procedure using Mirror Lake April 1st snow course and Banff maximum June to August temperature to predict Peyto Glacier winter and summer mass balance depths, respectively, was felt more appropriate than Letreguilly's model (1988) for the 1952 to 1965 time period, due to it better representing the observations of Peyto recession during this time. However, the net -1.24m balance modelled for this time period is still thought to be quite conservative. If a larger negative balance is more appropriate for the earlier period then the total net balance for the 1952 to 1993 time series will be altered. This would result in apportioning more of the bulk wastage into the pre 1966 period, therefore increasing the wastage/basin yield ratio for years such as 1961 (already a high wastage year) with a commensurate reduction in ratio for the years following 1965.

Impact of Glacier Wastage on the Bow River Hydrograph at Banff, 1951-1993

The Peyto Glacier mass balance annual weighting of the bulk wastage suggests that most of the glacier losses occurred later in the time series, particularly after the mid 1970s. This corresponds with observed lower winter snow accumulations (Demuth, 1996), which could explain why the lowest flow years are also prevalent during this time period. It is found, therefore, that years of high wastage have a tendency to coincide with low annual basin yields. However, the years 1961, 1981 and 1990 all display above average basin yields at Banff with high wastage components also. Thus demonstrating that although low flow years tend to be those most significantly augmented by glacier losses, wastage can make up an important part of basin yield even in a year of above average flow.

1970 was the lowest flow year during the study period and is also estimated to be the year of greatest glacier volume loss. The month of August for this year displayed a particularly low yield at Banff as a result of very low precipitation and high temperatures. Therefore, most of this month's flows were made up of glacier melt and groundwater base flows. Groundwater input was probably depleted for this year due to the very low winter snow accumulation. It is perhaps not surprising, then, that approximately 50% of the August basin yield for the Bow above Banff is estimated to be made up of glacier wastage.

Implications for Future Water Availability in the Bow River above Banff

If glacier recession were a linear process that could be extrapolated forwards in time, then the glaciers in Bow Valley would disappear in around 125 years. However, this is thought unlikely and the augmentation of basin yields during low flow years at Banff will probably continue for quite some time beyond this. However, the magnitude of flow augmentation must diminish if glacier extents and volumes reduce and their snouts retreat to higher and cooler elevations. The fortuitous augmentation of river flows experienced over the past century or so should not be relied upon when planning for future water demands in the Bow River Basin.

It has been calculated that a similar climatic scenario to that witnessed in 1970 occurring today, would result in a reduced annual basin yield of approximately 2%. For the month of August this translates to a monthly yield 7.5% lower than that measured in 1970. If the glacier wastage component is taken out of the hydrograph altogether, then the drop in flow between July and August flows will be very pronounced, with August approaching the flow volume experienced in September. A further consequence of a zero or negligible glacier coverage is the timing of the river hydrograph. Overall basin snow melt may be more rapid, thus, speeding up and increasing the magnitude of spring melt events and leading to an increased risk of flooding. Summer precipitation events will also move more quickly through the basin if the temporary storage facilitated by glaciers and high elevation snowpack is diminished. Therefore, as glaciers recede the system will become increasingly snow melt and precipitation dominant.

These scenarios are based on the assumption that glaciers will continue to retreat as a result of further climatic warming. However, increased air temperatures could lead to a change of the precipitation regime also. It is not inconceivable that at some point in the future the winter accumulation of snow in these glacierized mountain regions could increase. Indeed, a recent advance of some maritime glaciers in Norway due to greater winter accumulation has been observed while the majority of continental Norwegian glaciers have been receding due to increased summer ablation (Bogen, *et al.*, 1989).

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