THE NET VOLUMETRIC LOSS OF GLACIER COVER WITHIN THE BOW VALLEY ABOVE BANFF, 1951-1993 1/

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ABSTRACT

Three methods have been used to explore the volumetric change of glaciers in the Bow Basin above Banff for the years 1951 to 1993. Using aerial photography, the extent of glacier covers for the two years were mapped at a scale of 1:50,000. The first volumetric calculation of glacier loss was based on inventory criteria (Stanley, 1970); the second a hypsographic curve method based on Young's investigations in Mistaya Basin (1991) and the third; stereo air photogrammetry and DEM comparisons using the computer software package *Surfer*®. These methods were applied to the highly glacierized Hector Lake catchment within the Bow Valley and then extrapolated up to the whole basin above Banff. Reasonable agreement was achieved between the methods and the magnitude of net glacier loss from 1951 to 1993 is estimated to be 1100 to 1650 m^3x10^6. The true value for volumetric change is considered to be towards the upper end of the range given, due to the likelihood for systematic underestimation during the extrapolation up to the basin above Banff.

KEY WORDS: glacier recession; Bow Valley; volume change; water resources.

INTRODUCTION

Since the middle of the nineteenth century, an irregular but general rise in global temperatures has been recorded (IPCC, 1990) and many mountain glaciers have responded by retreating to higher elevations. It is estimated that mountain glaciers globally, have lost on average 11% of their total masses during the last 100 years (Meier in Mcinnis, 1995). A consequence of glacier recession in mountain regions is an augmentation of river flows in excess of the net annual income of precipitation (for example: Meier, 1973 and Young, 1991). Knowledge of the magnitude of flow augmentation over long periods of time is of great interest to water resource managers and planners. It is, therefore, the aim of this paper to investigate the volumetric change of glacier cover within the moderately glacier covered Bow Basin in the Canadian Rockies.

The impact of glacier wastage upon basin water yields in this region of the Canadian Rockies has been explored previously (for example: Henoch, 1971 and Young, 1991). Using observations of glacier recession, and area loss, photogrammetry and mass balance, Henoch calculated that the glacierized area within the Upper North Saskatchewan Basin (1,518km^2) diminished by 10% between 1948 and 1966. Young's paper studied glacier recession between 1966 and 1989 in the Mistaya Basin (247km^2), a sub basin of the Upper North Saskatchewan and just 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 m^3x10^6 of water equivalence for the 23 year study period.

The Bow River rises in a region of relatively high annual precipitation along the Eastern Frontier Range of the Rocky Mountains and flows down into the more arid Prairies (see fig. 1). The Bow Basin above Banff (2226 km^2) has an elevation range from around 1200m up to 3400m on the summit of Mount Hector, and is underlain predominantly by limestone. The average annual temperature at Banff is approximately +3^{o}C but temperatures in this part of the Rockies can dip down to as low as -35^{o}C in winter and up to +35^{o}C in summer (Gadd, 1995). This area was chosen for the study as it is relatively free of development and is an important hydrological source region for a variety of downstream users. In addition, there is extensive aerial photography available covering the glacierized regions for a range of dates.

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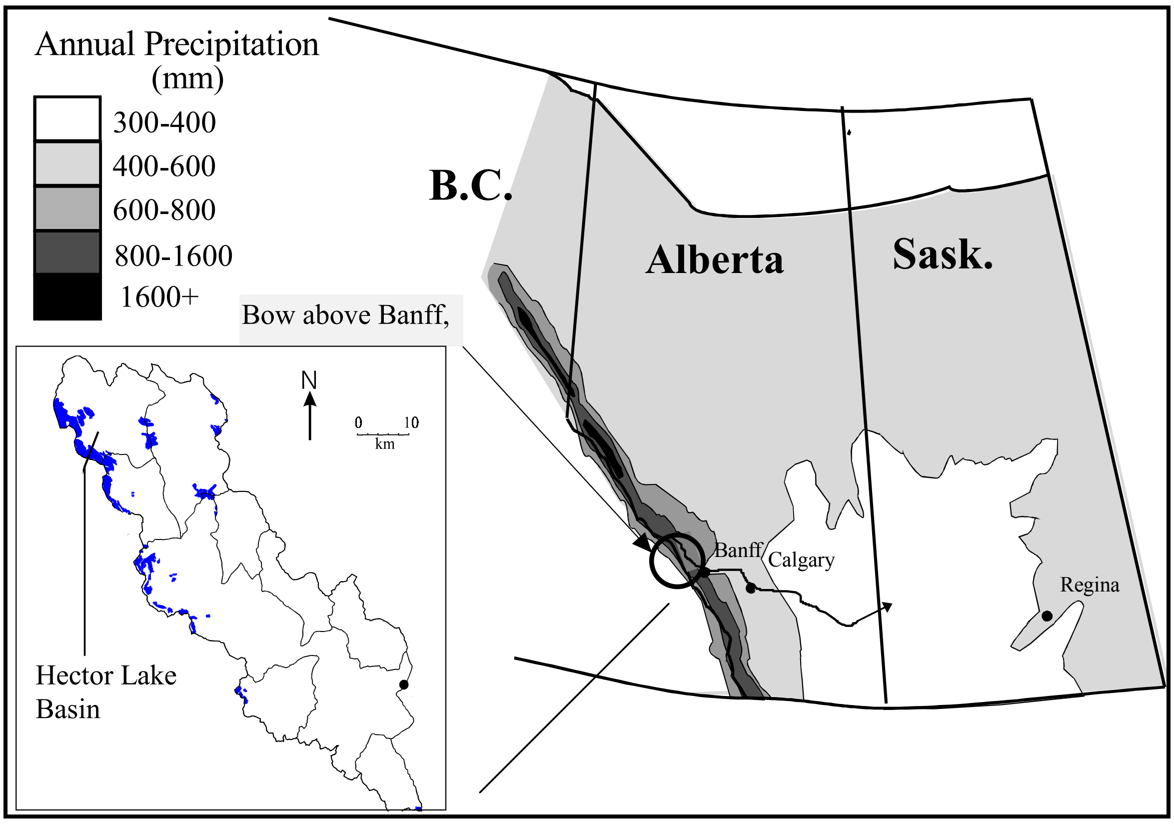

Figure 1. Map showing study area and precipitation zones. Inset is the Bow Valley above Banff showing sub-basins and glacier covers.

The Hector Lake sub basin (276 km^2) is the most northerly and highly glacierized of all the basins within this stretch of the Bow River system and is similar in size and character to the Mistaya Basin. Detailed volumetric analyses have been confined to this catchment due to its dense glacier cover, much of which has been catalogued in the glacier inventory of the Waputik Mountains in the late 1960s (Stanley, 1970). Areal glacier cover in the Bow Valley and its sub-basins has been measured from the national topographic series (NTS) 1:50,000 maps in a report by Young (1995). It was suggested that the Bow above Banff was approximately 3.3% glacier covered in 1977, the time of map update (Department of Energy, Mines and Resources, 1979). The corresponding glacier cover for the Hector sub basin was 11.8%.

METHODS

Prior to estimating volumetric glacier loss, it was necessary to map the areal glacier cover change within the Hector Lake Basin between years of good quality aerial photography that covered the whole sub basin. Based on this criteria, the years of 1951 and 1993 were chosen as the end points for the study. The extents of glacier margins were interpreted manually and transferred to the 1:50,000 NTS map sheet 82N9 and then digitised into the *Mapinfo®* software package. Individual glacier areas were computed automatically within the program.

Three distinct methods have been used to estimate the volumetric change of glacier loss within the Hector Lake Basin. This has facilitated a comparison of the techniques and an increased confidence in the final results. The first method (referred to as the *Inventory Method*) is simply based on the inventory criteria adopted by Stanley (1970). The glacier inventory provides a very approximate estimation of average glacier depth which is based on the glacier type and area. These depths and areas have been combined to provide an estimation of the total glacier volumes for each of the dates. The individual glacier volume values for 1993 have been subtracted from those calculated for 1951 to give the approximate loss. There are more accurate determinations of glacier volume using inventory data (see Ommanney, 1980) but they have not been applied in this study region due to insufficient data describing glacier dimensions and surface slope angles.

The second procedure is referred to as the *Hypsographic Method* and is modelled on the analysis carried out by Young in the Mistaya Basin (1991). It is significantly more sophisticated than the *Inventory Method* in that hypsographic curves of glacier cover and rates of ice melt were used to estimate volume loss per elevation band. The curves were constructed by digitising 100m elevation bands, interpolated from the NTS map, onto the previously constructed glacier extent map within *Mapinfo*. The glacier surfaces of the NTS map are, however, taken from one point in time and not thought to be highly accurate. This has led to the super-imposition of the elevation bands for remaining glacier covers in 1993 onto those of 1951. Observations of surface lowering rates on Peyto Glacier (lying just outside the Hector Lake sub-basin) from 1966-89 (Young, 1991) were linearly extrapolated both forwards to 1993 and backwards to 1951. These rates were then used as the model for elevation dependant melt for each band of the Hector Basin glacier hypsograph.

Digital elevation models have proven useful in a variety of glaciological investigations (for example: Ebner, 1987 and Rentsch, *et al.,* 1990). They were employed to investigate the volumetric change of the Vernagtferner Glacier, Austria (Reinhardt and Rentsch, 1986). This study highlighted the economic gain of such methods over more traditional manual contouring techniques (see Haumann, 1960).

In the third volumetric glacier change procedure adopted (referred to as the *DEM Method*), DEM construction and analysis was confined to the region of glaciers directly upstream of Hector Lake in the Waputik Mountains (see figure 2). This area was considered appropriate for the following reasons : 1) the high proportion of glacier coverage, approximately 59.5% of all glaciers in Hector Basin for both 1951 and 1993; and 2) the range of glacier aspects being over 180^{o} from north through east to south facing (few glaciers have significant westerly facing slopes within the Bow Valley).

Figure 2. Partial aerial photograph coverage of glaciers upstream of Hector Lake

The Cartesian co-ordinates of approximately eleven hundred surface points over the sample glaciers were manually digitised from stereo models using a *Topocart B* photogrammetric stereoplotter. The glacier covers upstream of Hector Lake were divided into three regions with the 1951 glacier margins defining the boundaries of the DEMs for both years. The 1951 glacier surface data were registered and scaled to the 1993 data in the software package *Idrisi*® using 2 known ground control points and 16 reference points which were digitised during the photogrammetric analysis. The surface data for each of the years were then entered into *Surfer*® and raster DEMs with a grid spacing of 5m were constructed using a *triangulation with linear interpolation* algorithm to maintain point integrity (see Golden Software, 1995). The 5m grid spacing was considered fine enough to holistically recreate the terrain being mapped, whilst not leading to unduly large DEM computer grid files. The 1951 and 1993 DEMs for each of the three regions were then overlaid to provide maps of surface and volumetric change.

The volume change estimates for Hector Lake Basin were then linearly extrapolated up to the entire Bow Valley above Banff using Young's (1995) estimates of relative glacier covers. Hector Lake Basin was considered to contain 45.6% of total glacier area within the Bow Valley above Banff, therefore an extrapolation factor of 2.19 was used.

RESULTS & DISCUSSION

The areal extents of glaciers in Hector Lake Basin for 1951 and 1993 are illustrated in figure 3. It was found that in 1951, there was 32.4 km^2 or 11.7% glacier cover within the basin and by 1993 this had reduced to 24.3 km^2 or 8.7%. Although this is only a change of 3% basin cover, it is equivalent to a loss of approximately 25% areal glacier cover.

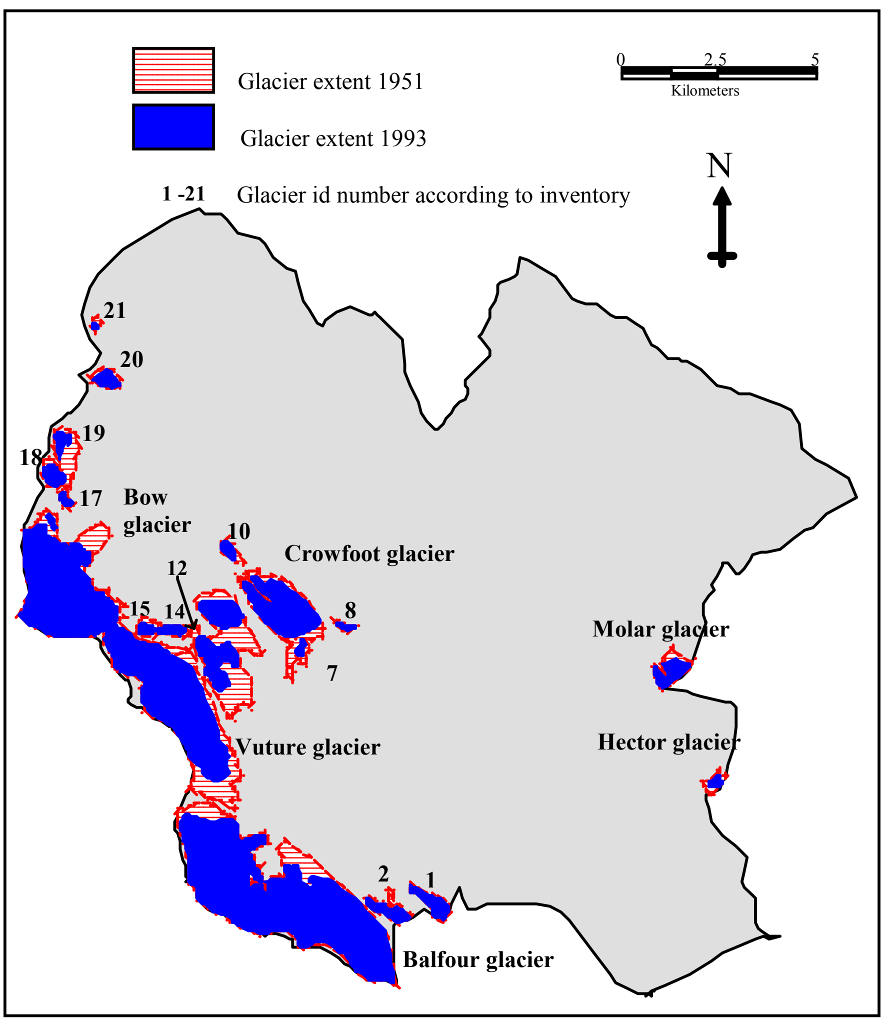

Figure 3. Glacier extents in Hector Lake Basin, 1951-1993.

Using the *Inventory Method,* it was estimated that the glaciers in the Hector Lake Basin lost approximately **566 m^3x10^6** of glacier ice between 1951 and 1993 (see table 1).

Glacier name & number according to 1967 Inventory.		1951			1993		
		Planimetric area estimation (km^2)	Depth estimation (m)	Glacier volume estimation (m^3x10^6)	Planimetric area estimation (km^2)	Depth estimation (m)	Glacier volume estimation (m^3x10^6)
1	Pulpit Glacier	0.33	10	3.3	0.32	10	3.2
2	Waputik Glacier	0.39	10	3.9	0.26	10	2.6
3	Balfour Glacier	6.94	100	694.0	6.07	100	607.0
4	Waputik Icefield	4.20	70	294.0	3.63	70	254.1
5	Vulture Glacier	5.28	100	528.0	3.88	70	271.6
6	Crowfoot Icefield	2.42	50	121.0	0.77	50	38.7
7	Crowfoot Glacier	0.50	25	12.6	0.09	10	0.9
8		0.07	10	0.7	0.05	10	0.5
9	Crowfoot Glacier	2.03	25	50.8	1.66	25	41.5
10		0.17	10	1.7	0.10	10	1.0
11	Crowfoot Icefield	0.80	25	19.9	0.52	25	12.9
12		0.11	10	1.1	0.03	10	0.3
13	Wapta Icefield	2.50	25	62.5	2.15	25	53.8
14		0.20	10	2.0	0.12	10	1.2
15		0.18	10	1.8	0.10	10	1.0
16	Bow Glacier	4.26	70	298.2	3.57	70	249.9
17		0.10	10	1.0	0.06	10	0.6
18		0.50	10	5.0	0.22	10	2.2
19		0.45	10	4.5	0.14	10	1.4
20		0.29	10	2.9	0.19	10	1.9
21		0.05	10	0.5	0.02	10	0.2
	Hector Glacier	0.50	10	5.0	0.35	10	3.5
	Molar Glacier	0.17	10	1.7	0.06	10	0.6
Totals for sample		**32.4**		**2116**	**24.3**		**1550**

Table 1. Hector Basin glacier volume estimations, 1951 & 1993

After collection of the hypsographic glacier cover data for each 100m elevation band within Hector Basin, it was found that the elevation range 2600 to 2700m contained the largest area of glacierization for both 1951 and 1993. The glacier areas, estimated average depths of surface downwasting and calculated volume change per elevation band are given in table 2. Using the *Hypsographic Method,* it is estimated that a net volume of **695 m^3x10^6** of glacier ice was lost in this basin between 1951 and 1993.

Elevation Range (m)	Area (km²) 1951	1993	depth of glacier surface melt (m)	glacier volume loss ($m^3 \times 10^6$)
above 2900	0.70	0.70	0.0	0.0
28-2900	2.69	2.31	9.1	22.8
27-2800	6.02	4.91	13.7	74.9
26-2700	8.90	7.65	16.1	133.2
25-2600	7.05	5.00	28.1	169.3
24-2500	4.18	1.95	38.5	117.9
23-2400	1.39	1.01	78.2	93.8
22-2300	1.10	0.33	101.2	72.4
21-2200	0.31	0.09	45.7	9.1
20-2100	0.12	0.01	18.3	1.1
Total catchment glacier wastage ($m^3 \times 10^6$)				**695**

Table 2. Glacier volume loss estimation using hypsographic and surface melt data

The glacier surface change calculated for the largest of the three DEM regions, the Waputik Icefield, is illustrated in figure 4. The first major observation when studying the surface change between the DEMs is that most of the glacier wastage appears to be on the north side. The maximum depth of surface loss is approximately 100m at an elevation between 2400m and 2500m. It is to be expected that the majority of wastage should be on this side of the model due to its southerly aspect. Proof that south westerly facing glaciers are most likely to undergo recession has been provided by Kasser (1980). Even high up on the Icefield (above 2700m), it is suggested that a large area of downwasting has reached a depth of about 70m. On the south side of the model (NE facing), the changes appear to be more erratic with large areas of little change. On much of the north westerly oriented glacier tongue, a zone of marked recession, the model indicates that over 50m of glacier depth has been lost. In the accumulation zone, patches of surface growth up to 50m are indicated. It is thought that these areas of growth may be due to errors in the DEMs but the possibility of increased depth accumulation at these elevations can not be discounted. For this reason, the volume calculations were performed twice. Surface growth was included in one calculation and not in the other.

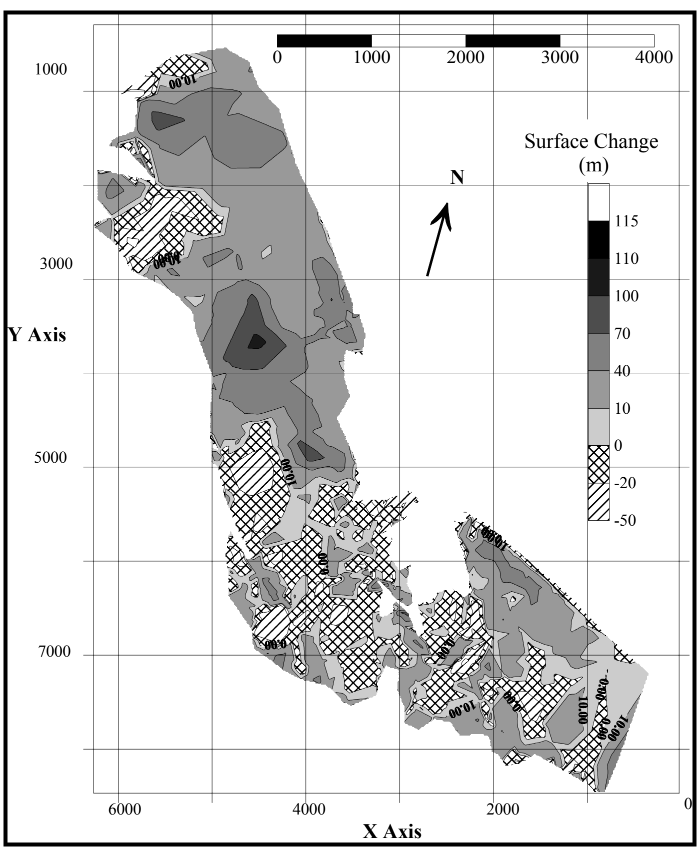

Figure 4. Surface Change between 1951 and 1993 Waputik Icefield DEMs.

The volume calculations between each of the three DEM pairs, performed in *Surfer*®, suggested that the sample of glaciers modelled using stereo air photogrammetry, lost approximately **366 m^3x10^6** of glacier ice if surface growth was included or **423 m^3x10^6** if surface growth was not included. Linearly extrapolating these values up to the entire Hector Lake Basin (based on a 59.5% glacier cover proportion) gives **616 m^3x10^6** and **711 m^3x10^6**, respectively.

A summary of the calculated volumetric glacier losses for Hector Lake Basin with extrapolations up to the Bow Valley at Banff between 1951 and 1993 using the three methods presented is given in table 3. Reasonable agreement is found between the three procedures. However, the validity of the extrapolation up to the larger parent basin using relative glacier areas is questionable.

Volumetric Change Method	Basin (m^3x10^6)	
	Hector Lake	Bow at Banff
Glacier Inventory	566	1239
Hypsographic Curve	695	1522
Photogrammetrical (with surface growth)	616	1350
Photogrammetrical (without growth)	711	1557

Table 3. Glacier volume change calculations for Hector Basin and Bow at Banff.

It was observed in the DEM analysis that wastage volumes can vary significantly from one side of a valley to another. It therefore needs to be ascertained whether or not these large scale variations over short distances are effectively smoothed out when applying the results to a larger area. A test was performed by comparing the volumes of the sample of glaciers used in the DEM analysis, with the volumes calculated for the same suite of glaciers in the Inventory and Hypsographic Methods. If the upward extrapolation method is valid then it would be reasonable to expect that the volumes calculated using the Inventory and Hypsographic techniques for the smaller suite of glaciers should make up approximately 59.5% of the volume calculated for the entire Hector Basin.

In the results of the Inventory method, the sample of glaciers selected were responsible for 84% of the estimated total catchment wastage. This is significantly more than their areal coverage would suggest. However, this was largely the result of one of the more extensive glaciers in the sample reducing its area to just below a depth criteria threshold value which has led to a large volume change estimate relative to other glaciers. Another factor was that many of the glaciers outside the sample were small independent units and, therefore, apportioned shallow depths. For these reasons it was felt that the Inventory Method is not suited to investigating small regions of glacierization where individual glaciers can drastically affect the result.

Using the Hypsographic Method it was estimated that the sample of glaciers were responsible for 62% of all wastage within Hector Basin. This was very close to the 59.5% areal proportion but still suggests that when extrapolating to a larger scale it may be possible to over-estimate the total glacier wastage. The sample of glaciers tested contain relatively large areas of contiguous ice sheet, whereas much of the rest of Hector and indeed Bow Basins, contain larger proportions of dispersed glaciers and glacierettes. This suggests that applying glacier volume losses from one glacierized region to another may be invalid if the two areas have different densities of areal coverage.

However, this test may not be entirely appropriate. The Inventory Method estimates negligible volume changes in areas of small glaciers due to the very shallow depths apportioned. Also, the Hypsographic Curve Method applies shallow depths of melt at the higher elevations where many of the smaller glaciers are found. From the DEM comparisons, it was apparent that surface downwasting at high elevations was generally greater than the depths used in the Hypsographic Method. Thus, both of these methods will probably systematically under-estimate the volume losses of glacial ice from small glacier areas. Intuitively, this makes sense when one considers that small glaciers and glacierettes may be more prone to wastage per unit area than larger ice sheets due to extra longwave radiation and advective inputs from nearby surrounding ground features.

In addition, the glacier hypsographic curve for the entire Bow Valley (in Young, 1995) indicates that there is a slightly higher proportion of glaciers at lower elevations than in the Hector Basin alone. The potential for melt lower down in the basin should, therefore, be greater due to slightly warmer temperatures. The linear extrapolation of glacier volume loss up to the scale of the Bow above Banff, although possibly quite reasonable, is considered more likely to lead to under rather than over-estimation.

The possibility of errors due to invalid glacier and melt depth estimations, poor correspondence between DEMs and uncertainty in the upward extrapolation procedure can not be discounted. The limits on basin wide glacier wastage above Banff are estimated to be **1100 m^3x10^6** to **1650 m^3x10^6** with increased confidence that the true wastage figure is within the upper half of this range.

CONCLUSIONS

In 1993 there was approximately 25% less total glacier area in the Hector Lake Basin than in 1951. The reduction from approximately **32km^2** to **24km^2** translated to a total basin cover change of 3%. There was good corroboration between the glacier volume change calculations using the three methods. Values ranged from **566 m^3x10^6** for the Inventory Method to **711 m^3x10^6** for the DEM comparisons without the inclusion of possible glacier surface growth in the accumulation zone.

It is thought that the Inventory and Hypsographic Methods tend to under-estimate the importance of small high elevation glaciers to total glacier volume losses due to the shallow glacier and melt depths apportioned in both methods. The importance of glacier aspect to surface change was highlighted in the DEM comparisons. South facing areas underwent substantially more wastage than north facing. Thus, in any method constructed to estimate glacier loss through time it is important to factor in glacier slope aspect in addition to area and elevation components.

The linear extrapolation of glacier wastage up to the Bow above Banff is thought to systematically under-estimate the total wastage for the entire basin. This is again due to the higher incidence of small glaciers within the basin above Banff and also because there is a slightly higher proportion of glacier cover at lower elevations than experienced in the Hector Lake Basin. There is reasonable confidence that the true volumetric glacier loss for the Bow Basin is between **1100** and **1650 m^3x10^6** but the possibility of volume under-estimations in the methods and the linear extrapolation suggests that the true value is likely to be toward the upper end of this range.

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