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Skykomish River, Washington: Impact of ongoing glacier retreat on streamflow

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Abstract:

Glacier retreat and changes in summer runoff have been pronounced in the Skykomish River Basin, North Cascades, Washington from 1950 to 2009. An analysis comparing USGS streamflow records for the 1950–1985 to the 1985–2009 period indicates that during the recent period the Skykomish River summer streamflow (July–September) has declined 26% in the watershed, spring runoff (April–June) has declined 6%, while winter runoff (November–March) has increased 10%. The minimum mean monthly August discharge from 1928 to 2010 occurred in 2003 and 2005 when streamflow was 15·1 and 15·2 m^3s^{-1}, respectively. From 1929 to 1985, streamflow was less than 14 m^3s^{-1} during the glacier melt season on a single day in 1951. From 1986 to 2007 there were 217 days with discharge below 14 m^3s^{-1} with 9 periods lasting for 10 consecutive days. In the Skykomish River watershed from 1958 to 2009, glacier area declined from 3·8 to 2·1 km^2. Columbia, Foss, Hinman and Lynch Glacier, the primary glaciers in the basin, declined in area by 10, 60, 90 and 35%, respectively, since 1958. Annual mass balance measurements completed from 1984 to 2009 on Columbia, Foss and Lynch Glacier indicate a mass loss of 13·1 m w.e. Despite 15% higher ablation rates during the 1985–2009 period, the 45% reduction in glacier area led to a 38% reduction in glacier runoff between 1958 and 2009. The 38% reduction in glacier runoff did not lead to a significant decline in the percentage summer runoff contributed by glaciers under average conditions; the contribution has remained in the range of 1–3% from July to September. The glacier runoff decline impacted river discharge only during low flow periods in August and September. In August 2003 and 2005, glacier ablation contributed 1·5–1·6 m^3s^{-1} to total discharge, or 10–11% of August discharge. While declining glacier area in the region has and will lead to reduced glacier runoff and reduced late summer streamflow, it has limited impact on the Skykomish River except during periods of critically low flow, below 14 m^3s^{-1} when glaciers currently contribute more than 10% of the streamflow. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS glacier runoff; glacier retreat; snowpack; stream discharge; North Cascades

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INTRODUCTION

Glaciers act as natural reservoirs storing water in a frozen state instead of behind a dam. Glaciers modify streamflow releasing the most runoff during the warmest, driest periods and summer, when all other sources of water are at a minimum (Fountain and Tangborn, 1985). Annual glacier runoff is highest in warm dry summers and lowest during wet cool summers (Rasmussen and Tangborn, 1976). The loss of glaciers from a watershed than poses the hazard of reducing streamflow the most during minimum flow periods (Nolin *et al*., 2010). The amount of glacier runoff is the product of surface area and ablation rate (Pelto, 2008). The North Cascade Glacier Climate Project (NCGCP) began an annual monitoring program of North Cascade glaciers in 1984 (Pelto, 1996). Mass balance is observed annually on ten glaciers. The cumulative mass balance loss has been 20–30% of the entire glacier volume in 25 years (Pelto, 2010). All 47 observed glaciers have retreated significantly since 1984, 5 have disappeared (Pelto, 2010). North Cascade glaciers provided 800 million m^3 of runoff each summer in the past, but today this contribution is declining as glacier area available for melting declines (Bach, 2002; Pelto, 2008).

In the Skykomish River Basin, mean summer streamflow declined 35% during the 1950–2006 period (Pelto, 2008). The minimum monthly mean August streamflow occurred in 2003 and 2005. The minimum monthly mean streamflow for September was observed in 1998. The recent increase in number of minimum flow events during the late summer low flow season just when glacier runoff is at its peak raises the question of the role of glacier runoff decline for the low flow periods in the Skykomish River Basin. The USGS sought feedback on the causes of the summer 2003 minimum streamflow to understand potential impacts on salmon. NCGCP monitors the mass balance of the three largest glaciers in the basin comprising 83% of the total glaciated area in 2006 and provides a direct measure of the glacier melt contributing to streamflow in the basin. The combination of USGS discharge data and glacier mass balance data allows direct determination of the percent of flow contributed by glaciers to the Skykomish River. The aim of this paper, therefore, is to determine the impact of extensive glacier retreat on glacier runoff and summer streamflow in the Skykomish River Basin.

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Table I. Discharge data is from the Skykomish River at Gold Bar, USGS gaging station 12134500

	Jul	Aug	Sep
Discharge 1950–1984 (m^3/s)	106·0	41·8	40·3
Discharge 1985–2009 (m^3/s)	79·4	31·0	29·4
Discharge minimum 2003 and 2005(m^3/s)		15·1	
Glacier runoff 1950–1965 period (m^3/s)	1·2	1·3	0·8
Glacier runoff 2000–2009 period (m^3/s)	0·8	0·9	0·5
Glacier runoff August 2003 (m^3/s)		1·6	
Glacier runoff August 2005 (m^3/s)		1·5	
Glacier contribution 1950–1965 period (%)	1·1	3·1	2·0
Glacier contribution 2000–2009 period (%)	1·0	2·9	1·7
Glacier contribution 2003 (%)		10·6	
Glacier contribution 2005 (%)		9·9	

Glacier runoff determined from direct observations of ablation on three glaciers in the basin for the 2000–2009 period. The 1950–1965 period assumes a 15% decline in ablation from the 2000–2009 period applied to a 45% greater glacier covered area.
The glacier flow for August 2003 and 2005 is from direct ablation measurements.
The last four rows are the percent of glacier contribution for the different periods. Each is calculated by dividing glacier runoff by discharge.

METHODS

In this study, we utilize streamflow records from the USGS Skykomish River gaging station at Gold Bar, which is the only continuous gaging station on the river. The record extends from 1928 to 2010. The table of mean monthly discharge for the 1950–2009 period is the dataset for Discharge in Table I. For minimum flow periods, the mean daily flow records were also utilized. The United States Department of Agriculture-SNOTEL program has one station in the basin at Stevens Pass at 1200 m that has discharge records dating back to 1946 that are utilized. The principal annual SNOTEL snow water equivalent (SWE) measurement used for hydroclimatological analysis is the April 1 SWE. This measurement is compared to seasonal cumulative precipitation recorded at Stevens Pass to determine the ratio of SWE to precipitation. From 1984 to 2009, NCGCP has monitored the mass balance from Columbia, Foss and Lynch Glacier in the Skykomish Basin. The methods utilized in this extensive, ongoing program are detailed by Pelto (1993, 2008, 2009). Accumulation and ablation measurements are completed on each glacier each year at a density of over 150 points/km^2 each summer, and changes in glacier area are assessed at least every 3 years. Direct measurement of ablation using ablation stakes and changes in snow depth from probing measurements as part of the mass balance program directly measures snow and ice ablation and resultant glacier runoff (Pelto, 2008). These data including the specific glacier area is reported annually to the World Glacier Monitoring Service (WGMS). The program relies on consistent methods applied to the same network of 250–300 data points on the glaciers each year. The maximum monthly glacier runoff occurred in August 2003 and August 2005 reported in Table I is the product of directly measured mean ablation and the total glacier covered area. The percent contribution in Table I is the observed glacier runoff divided by observed discharge at Gold Bar.

SKYKOMISH WATERSHED HYDROGRAPH

The Skykomish River watershed drains the west slope of the North Cascades (Figure 1). The basin has an area of 1386 km^2, the average elevation of the basin is 1050 m. This gauging station is downstream of the confluence of the North Fork and South Fork of the Skykomish River located where the river exits the Cascade Mountains. The watershed has sub-watersheds that are dominantly pluvial, nival and glacial. The pluvial segments have peak flows in the winter due to the winter storm events

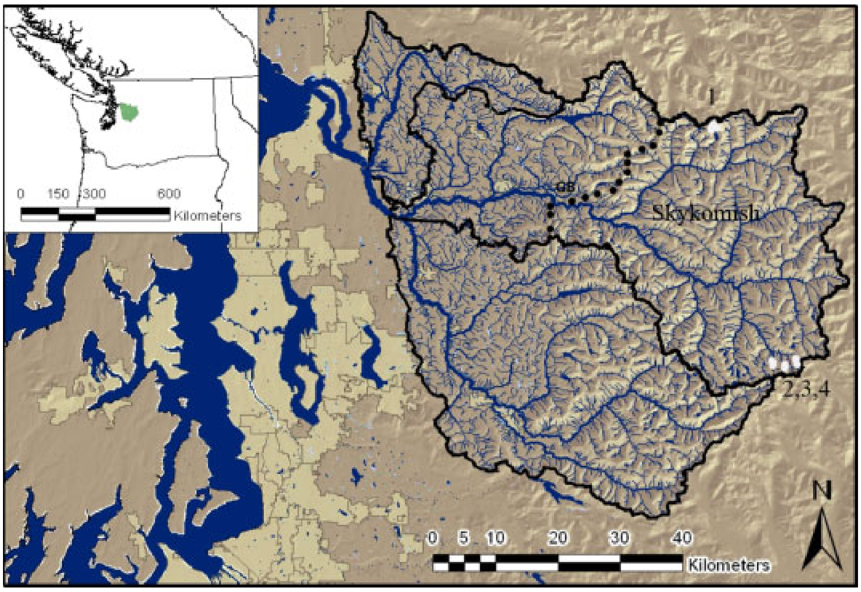

Figure 1. The Skykomish River Basin indicating gaging station (GB) and glaciers (in white) and watershed boundary for the Gold Bar (dotted line). 1 = Columbia, 2 = Hinman, 3 = Foss and 4 = Lynch

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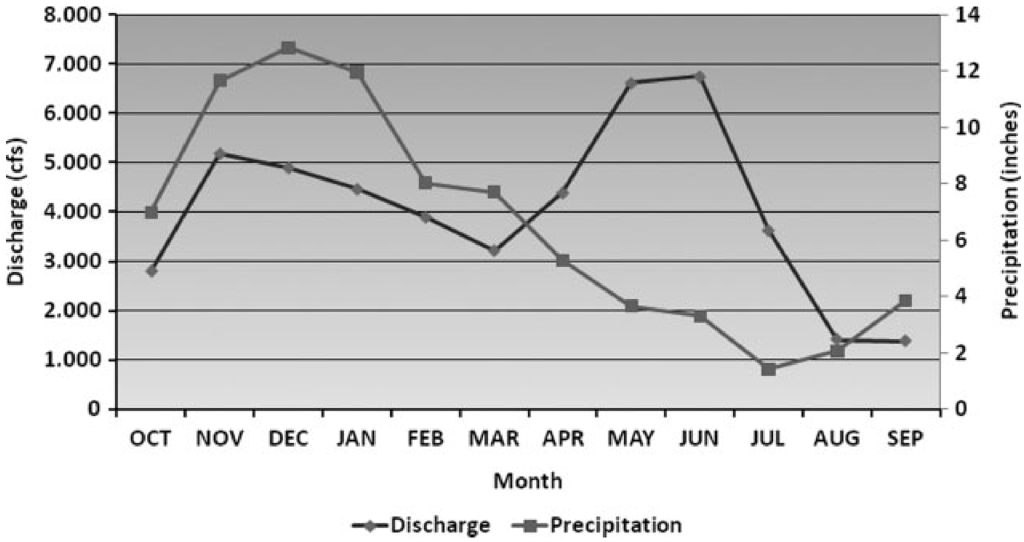

Figure 2. Annual precipitation and hydrograph for the Skykomish River Basin. Runoff is at the USGS gaging station on the river at Gold Bar. Precipitation data is from Stevens Pass 1210 m at the headwaters of the basin

(Gersib R *et al*., 2009) (Dery *et al*., 2009). Nival streams peak in May and June with the high snowmelt, and glacially fed streams peak in July and August during peak snowmelt (Fountain and Tangborn, 1985; Dery *et al*., 2009). The Skykomish River as a whole is a hybrid basin with the various segments reaching a maximum discharge at different times, which reduces the magnitude and duration of the summer minimum flow period. The period from October to March is a storage period with precipitation exceeding discharge, and from April to August is a period of excess runoff release (Bach, 2002; Dery, *et al*., 2009) (Figure 2).

Alpine runoff throughout the mountain range from the 1950–1984 period to the 1985–2009 period has increased by 10% in winter (November–March). This increase is more pronounced in the Skykomish Basin during the1985–2009 period (Figure 3) and is the result of more frequent rain on snow events that enhance melting and reduce snow storage (Mote, 2003; Mote *et al*., 2008; Pelto, 2008). The tendency for increased winter flows and larger maximum flows in the winter is consistent with the trends in British Columbia and in the Pacific Northwest (Zhang *et al*., 2001; Stahl and Moore, 2006; Mote *et al*., 2008). The earlier release of meltwater in the North Cascades due to warmer spring conditions and reduced winter snowpack has become more pronounced since 1990 as documented by Pelto (1993). Stewart *et al*. (2005) noted a coherent shift toward earlier runoff in snow-fed basins across the western US, one reflection of this is the 10–30-day earlier shift in the date of the centre of mass of annual flow (CT) for each water year. Total spring runoff (April–June) has declined 7% in Skykomish Basin, from the 1950–1984 period to the 1985–2009 period, many North Cascades basins have not seen a significant spring change (Pelto, 2008). The lower mean altitude of the Skyomish River Basin versus others examined by Pelto (2008) emphasizes the earlier snowpack melting leading to greater contributions to runoff from snow melt during the winter. Mote *et al*. (2008) noted that it is low-elevation snowpack reductions that have been most pronounced and that much of this snowpack is lost before spring. In contrast to the winter, summer runoff has decreased markedly in all six North Cascade basins examined (Pelto, 2008) and in neighbouring BC (Stahl and Moore, 2006). The 26% decline in summer runoff for Skykomish River from the 1950–1984 period to the 1985–2009 period is the largest of the six basins examined by Pelto (2008) (Figure 3). Luce and Holden (2009) examining changes in streamflow at 43 Pacific Northwest gaging stations found the most significant changes in streamflow to be attributed to decreases in streamflows for the lowest 25th percentile of flows.

For the Skykomish Basin, glacier runoff is most significant in August and September after the loss of most non-glacier alpine snowpack. From 1928 to 2009, 6 of the 10 lowest mean August flows have occurred since 1985, with 2003 and 2005 having the lowest mean flow

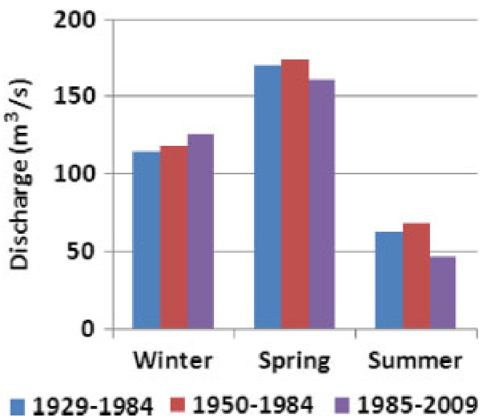

Figure 3. Changes in mean seasonal runoff in the Skyomish River Basin 1929–1984 and 1950–1984 compared to 1985–2009. Streamflow data is from the USGS gaging station on the Skykomish River at Gold Bar. Winter streamflow increased 7–10% for the 1985–2009 period. Spring streamflow decline is 6–8% for the 1985–2009 period. Summer streamflow declined 26–31% for the 1985–2009 period

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at 15·1 and 15·2 $m^3 s^{-1}$, respectively. In September, 6 of the 10 lowest flows have occurred since 1985 with 1998 being the lowest at 13·2 $m^3 s^{-1}$. This recent tendency for lower minimum flows fits the widespread pattern noted by Luce and Holden (2009) and is made more likely by an earlier shift in the CT (Stewart *et al*., 2005). The minimum flows are occurring during the low-flow season just when glacier runoff is at its peak and the potential for declining glacier runoff due to declining glacier area is most pronounced.

The decline in summer runoff is apparent in the change in its fraction of the total annual runoff. Rasmussen and Tangborn (1976) noted that the basin had a summer fraction of runoff of 43% for May–September for the 1929–1973 period. From 1985 to 2009, the summer fraction of runoff has declined to 36% of the total runoff. This is indicative of an earlier timing of the CT (Stewart *et al*. 2005). Annual precipitation has risen during this same period in the region and in the basin (Pelto, 2008; Mote et. al., 2008). The most likely cause of the decline in summer fractional flow is the reduced snowpack storage efficiency, which is the ratio between April 1 SWE and winter precipitation (Mote, 2003). Mote (2003) in examining 40 stations in the Washington and British Columbia noted that substantial declines in SWE coincide with significant increases in temperature, and occur in spite of increases in precipitation. This has been the larger trend across the western US (Knowles *et al*., 2006). A key ratio that can be used to identify the relationship between the snowpack and precipitation is the ratio between April 1 SWE and winter total precipitation (November–March). An increasing ratio indicates a greater percentage of precipitation is falling and remaining as snow. A declining ratio indicates that greater percentages of precipitation occur as rain instead of snow and/or that melt of winter snowpack is increasing. Mote *et al*., (2008) noted that the fraction of the precipitation from November to March retained as snow on April 1, had declined by 28% overall in the Cascades of Washington, and 19 and 20%, respectively, at the two stations closest to the Skykomish River from 1950 to 2006. Pelto (2008), in examining the snowpack record at Stevens Pass in the Skykomish River Basin, noted a decline in snowpack storage efficiency of 30% from 1950 to 2006.

GLACIER CHANGE

There are four principal glaciers in the basin comprising 90% of the glacierized area: Columbia, Foss, Hinman and Lynch Glaciers. In the Skykomish River watershed from 1958 to 2009, glacier area has declined from 3·8 to 2·1 km^2, a 45% decline (Pelto, 2010). Annual mass balance measurements have been completed from 1984 to 2009 on Columbia, Foss and Lynch Glaciers, yielding a balance loss of −13·3, −14·2 and −11·7 m, respectively. This is an average of 14 m of ice thickness (Figure 4). The glacier areas have declined 10, 60, 90 and 35%, respectively, since the 1958 USGS mapping glacier area estimates. This compares to changes in area of −22% noted by Granshaw and Fountain (2006) for South Cascade Glacier from 1958 to 1998. A qualitative examination of the USGS orthophoto images of the glaciers from 1958, 1960 and 1964 indicate that the USGS-mapped glacier boundaries were accurate in 1958. The recent glacier retreat (1958–1998) has exposed new alpine lakes.

Lynch Glacier is on the north side of Mount Daniels, the highest point in the Skykomish Watershed, and drains into the South Fork Skykomish River. According to the 1960 USGS map of the region, the glacier flows north into a basin with a modest fringe of water (Figure 5). This lake, referred to locally as Pea Soup Lake, expanded rapidly between 1978 and 1983, as the portion of the glacier occupying this basin disintegrated, and by 1988 the lake basin was fully open water (Figure 5). Lynch Glacier retreated 390 m from its 1950 terminal position to 1979, with most of its retreat occurring in a rapid breakup of the glacier in Pea Soup Lake. From 1979 to 2009, the glacier had retreated 132 m from the lake shore. Annual mass balance measurements indicate the loss of 13 m of ice thickness on average. More importantly in 2003, on the upper west section of the glacier a bedrock ridge and scattered outcrops were exposed by the melting. The width of the glacier at this elevation has been reduced by 135 m, 15%. The bedrock features have continued to expand, indicative of thinning of the glacier in what was its accumulation zone. Note the rock outcrop on the upper right portion of the glacier in 2007 in the right image of Figure 5. This is an indicator of a glacier that cannot survive for long under current warmer and wetter environmental conditions; a glacier cannot survive without a consistent and persistent accumulation zone (Pelto, 2010). Lynch Glacier has lost 35% of its area since 1958.

Hinman Glacier is on the west side of Mount Hinman and drains into the South Fork Skykomish River. This

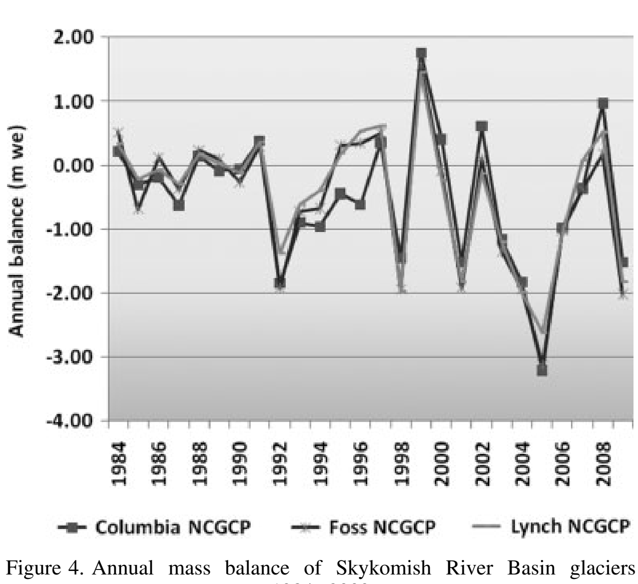

Figure 4. Annual mass balance of Skykomish River Basin glaciers 1984–2009

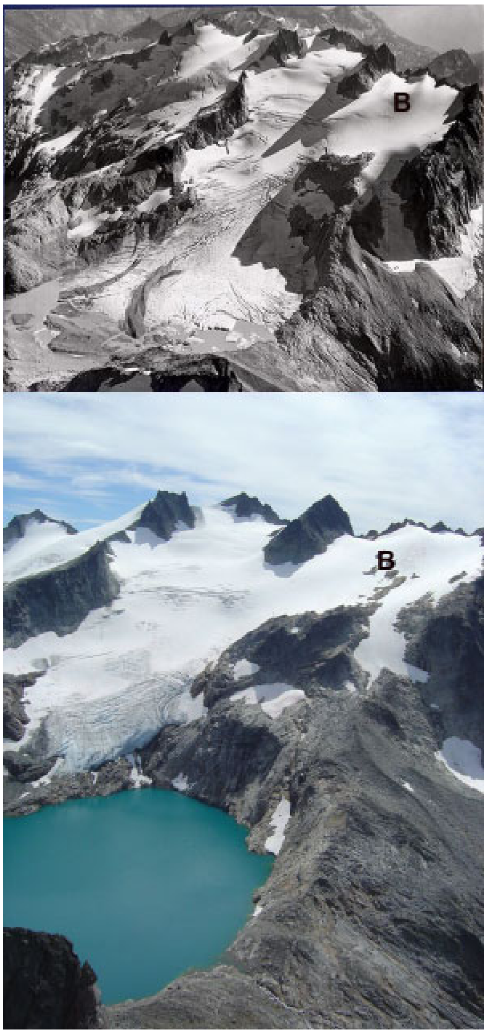

Figure 5. Lynch Glacier, North Cascades in 1960 (Austin Post, USGS) and 2007 (below). There are new rock outcroppings in the accumulation zone on the right side (west side) of the glacier (B), the width of exposed rock on the ridge on the right side of the glacier has expanded

was the largest glacier in the North Cascades south of Glacier Peak 50 years ago. Today it has all but disappeared. The unofficially named Hinman Lake has taken the place of the lower portion of the former glacier, which still has a couple of separated relict ice masses. The new lake is 1 km long. In the USGS map, based on 1958 photographs, the glacier extends from the top of Mount Hinman at 2300 meters to the bottom of the valley at 1525 meters (Post *et al*., 1971). The western extent of Hinman Glacier in 1988 separated into a group of four ice masses, three are significant in size till today. The largest relict had an estimated area of 0·05 km^2 in 2009. A 2009 view from the far end, north end of Lake Hinman up the valley and mountain side that was covered by the Hinman Glacier, shows it is now 90% gone compared to 1958 (Figure 6). In 2009, there is no longer a glacier and only a few relict pieces of thin remnant ice remain in view from the 1958 terminus location.

Foss Glacier is on the northeast side of Mount Hinman and drains into the South Fork Skykomish River. As recently as 1984, this glacier covered the majority of this mountain face. Today the glacier is rapidly thinning, separating into smaller ice bodies and retreating. By the middle of August, Foss Glacier had lost all its snow cover in 1992, 1993, 1994, 1998, 2003, 2005 and 2009. This has led to significant thinning of the upper reaches of the glacier. This thinning of the upper section of the glacier, i.e. the accumulation zone, is an indicator of a glacier that cannot survive current climate (Pelto, 2010). The lower section of the glacier detached from the upper section in 2003 and fully ablated in 2009. Figure 7 illustrates the change in the areal extent from 1988 to 2009. In the latter two images the snowpack has disappeared from this dying glacier. Annual balance measurements indicate a loss of over 15 m of average ice thickness, which for a glacier that averaged 30–40 m in thickness represents 40–50% of the volume of the glacier lost between 1984 and 2009. The estimated reduction in glacier extent is 40% between 1984 and 2009, and 60% between 1958 and 2009.

Columbia Glacier occupies a deep cirque above Blanca Lake ranging in altitude from 1460 to 1720 m and is the headwaters of the North Fork of the Skykomish River. Kyes, Monte Cristo and Columbia Peaks surround the glacier with summits over 2200 m. This glacier has the lowest mean altitude of any substantial glacier in the North Cascades. The glacier is the beneficiary of locally heavy precipitation and orographic lifting over the surrounding peaks causing cooling of the air mass greater than that expected from the elevation of the

Figure 6. Above: Hinman Glacier from the west in 1988 is a group of four separated ice bodies; three are still significant in size. Two ice masses, A and B, are indicated. Below: A 2009 view from the far end, north end of Lake Hinman up the valley and mountain side that was covered by the Hinman Glacier, now 90% gone compared to 1958. Photograph taken from near the 1958 terminus position, arrow indicates terminus. The lake did not exist in 1958

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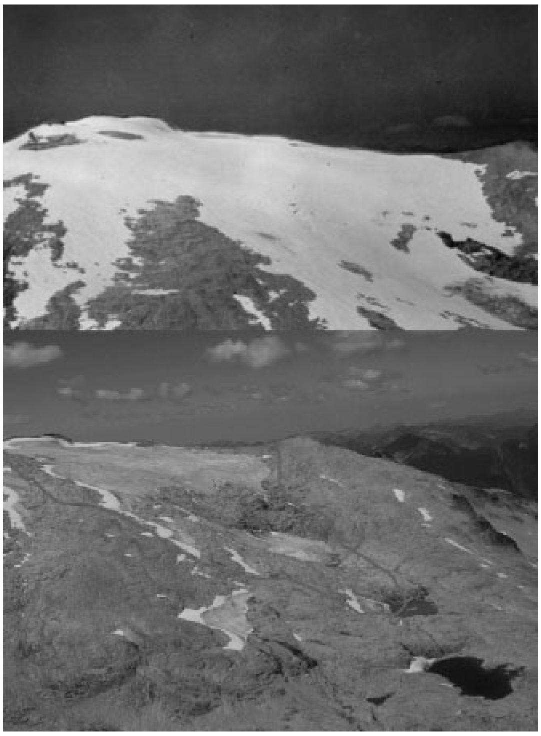

Figure 7. Foss Glacier, North Cascades 1988 and 2005 indicating the change in the extent of the glacier. There is substantial marginal retreat in the accumulation zone and new rock outcroppings in the accumulation zone

glacier. During the winters storm winds sweep from the west across Monte Cristo Pass precipitating snow in the lee on Columbia Glacier. Avalanches frequently deposit mass from the mountain snowpack above onto the Columbia Glacier. The avalanche fans created by the settled avalanche snows are up to 6 m deep even late in the summer. Facing southeast, the Columbia Glacier is protected from afternoon sun, however, Columbia Glacier has retreated 134 m since 1984. The head of the glacier has retreated 90 m. The key issue is that the glacier is thinning as appreciably in the accumulation zone in the upper cirque basin as at the terminus (Pelto MS 2006). This indicates a glacier that is in disequilibrium with current climate and will melt away with a continuation of the current climate conditions. Despite this disequilibrium, and the glacier losing some 15 m in thickness since 1984, the Columbia Glacier will likely remains a thick glacier, of over 75 meters in the upper basin, and will not disappear quickly (Pelto, 2010). In 2003, 2004, 2005 and 2009 there was a nearly complete loss of all snow cover on the glacier. This exposed more than 50 annual layers in 2005 (Figure 8) indicating that the glacier no longer has a consistent or persistent accumulation zone.

GLACIER RUNOFF

Direct measurement of ablation using ablation stakes and changes in snow depth from probing measurements from July to September as part of the mass balance program directly measures potential glacier runoff (Pelto, 2008).

Figure 8. Accumulation zone of the Columbia Glacier from the headwall. Notice the number of annual horizons exposed on 1 August 2005. This is the third consecutive year of significant negative annual balances, and follows 2004 when the AAR dropped below 20

Sublimation has a negligible role in ablation on mid-latitude temperate glaciers such as the North Cascades and runoff is considered an accurate proxy for ablation (Tangborn, 1980; Fountain and Tangborn, 1985). For the three glaciers in the basin monitored from 1984 to 2010, mean August glacier runoff is 75 000 m^3 day^{-1} in the basin. Mean August total ablation has varied from a high of 2·0–2·2 m SWE in 2003, 2005 and 2009 to a low of 1·0–1·1 m SWE in 1995, 2007 and 2010. The high ablation periods tend to be during the dry weather low-flow periods in the Skykomish River, the low glacier ablation periods during higher flow periods in the Skykomish River.

Annual glacier runoff is the product of annual ablation and glacier area. A 15% increase in summer mass balance loss has been observed for the 1959–1983 period compared with the 1985–2005 period on South Cascade Glacier (Bidlake *et al*, 2007). This summer balance is reported in loss per unit area, not overall volume, and hence is a measure of the mean summer ablation on a glacier. The correlation coefficient in annual balance for the 1984–2005 period exceeds 0·8 between each glacier pair of South Cascade, Columbia, Foss and Lynch Glacier (Pelto, 2007). This suggests that the 15% increase in summer ablation rate is applicable to the Skykomish Basin glaciers. The product of a 15% increase in summer ablation for the 1985–2005 period from the 1959–1983 period and a 45% reduction in glacier area in Skykomish River Basin from 1958 to 2005 yields a 38% reduction in total glacier runoff currently, compared with the 1958 estimates. This represents a 45 000–50 000 m^3 day^{-1} reduction in mean August glacier runoff from 1958.

For the Skyomish River at Gold Bar, the two lowest mean August streamflows are for 2003 and 2005, which were two of the highest ablation rate periods. The mean monthly streamflow was 15·1 and 15·2 m^3s^{-1}, respectively, in 2003 and 2005. In 2003 and 2005, measured ablation generated 1·5 and 1·6 m^3s^{-1} of runoff (Table I). Glacier runoff during the August 2003 and

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2005 flows of the Skykomish River provided 10–11% of the monthly streamflow at Gold Bar, with weekly values exceeding 15% (Table I). If the same peak ablation period observed in 2003 and 2005 had occurred in 1958, when the glaciers were 45% larger, glacier runoff would have been 2·7–2·9 m^3s^{-1}. Given recent minimum flows observed 13·2 m^3s^{-1} in September and 15·1 m^3s^{-1} in August. The 1·1–1·4 m^3s^{-1} decline in late summer glacier runoff during high ablation periods will cause a minimum flow decline in excess of a 10% from current minimum streamflows.

Glacier volume loss can contribute to changes in streamflow, leading to an increase in overall streamflow if the volume loss is sufficiently large (Stahl and Moore, 2006). In the North Cascades in general, the glacier volume loss has contributed up to 6% of the August–September streamflow (Granshaw and Fountain, 2006). The observed net glacier volume loss in the Skykomish River Basin has been a source of runoff, which is observed as a portion of the ablation. The −0·50 m a^{-1} annual glacier mass balance loss spread over the July–September period, when maximum glacier volume loss occurs, yields a volume loss of approximately1 000 000 m^3a^{-1}. This represents a 0·12–0·25 m^3s^{-1} increase of discharge in Skykomish River, which is less than 1% of the mean summer streamflow. Therefore, glacier volume loss has not been compensating for summer low flows in the basin as it has in other more heavily glaciated basins. Change in glacier runoff is dominated by the area of glacier lost. Of greater importance than volume is the reduction in glacier area. Stahl and Moore (2006) noted that glacier-fed streams in British Columbia have exhibited a decreasing trend for August streamflow with significant glacier area losses. This has been the case for the Skykomish River.

IMPACT ON SUMMER MINIMUM STREAMFLOW

Simultaneous with the observed declining summer glacier runoff, overall summer streamflow has declined and late summer minimum flows in the basin have also declined. The result of an overall streamflow reduction is similar in effect to the impact from a reduction in glacier meltwater runoff in that the mean percentage of streamflow contributed by glaciers changes little from the 1950–1984 period to the 1985–2009 period (Table I), despite the reduced glacier area. However, the magnitude of the flow contributed by glaciers during late summer minimum flow periods is diminishing. This decline in glacier runoff, following substantial glacier mass loss, has played a pivotal role in the Skykomish River Basin's low-flow regime leading to a reduction in minimum monthly flows late in the summer.

The reduction of the glacial melt component augmenting summer low flows is already resulting in more low-flow days in the North Cascade region (Luce and Holden, 2009). A key threshold of in-stream flow levels considered insufficient to maintain short-term survival of fish stocks is below 10% of the mean annual flow (Tennant, 1976). For the Skykomish River, 10% of mean annual flow varies from 12 to 14 m^3s^{-1} depending on the interval of years utilized. For this analysis, we will utilize the 14 m^3s^{-1} as the critical 10% threshold. In the Skykomish River from 1950 to 2009, there have been 476 days with flow less than 10% of the mean annual flow, 357 or 75% of the low-flow days since 1985. Of the 476 days, 219 have occurred during the glacier melt season, 218 of those since 1985. Before 1985 only one day, 23 September 1951, had a streamflow less than 14 m^3s^{-1}. Of more concern for aquatic life is the occurrence of extended periods of low flow (Tennant, 1976). From 1929 to 2009 there have been 8 years where streamflow dropped below 14 m^3s^{-1} for 10 consecutive days during the melt seasons in 1986, 1987, 1992, 1998, 2003, 2005, 2006 and 2007. In August 2003 and 2005, there were low-flow periods on at least 10 days when glacier ablation measurements indicated glacier melt yielding 1·5–1·6 m^3s^{-1} and streamflow averaged 11·2 and 13·2 m^3/s, respectively. Glacier runoff contributed 11–14% of the flow to the river during these lowest-flow periods. The low-flow periods typically coincide with high ablation periods on the glaciers and low discharge from non-glacier sources. It is during these low-flow periods that glacier loss particularly affects streamflow. The complete loss of glaciers in the basin would approximately double the observed decline in glacier runoff to date, reducing minimum flows by a further 1–1·5 m^3s^{-1}. This will further increase the number of days that fall below the 14 m^3s^{-1} threshold.

CONCLUSIONS

The continued loss of glacier area will lead to an ongoing decline in late summer glacier runoff and streamflow in the Skykomish Basin. This will accentuate the trend toward lower minimum flows late in the summer that have been observed with increasing frequency since 1986. The 26% decrease in total summer runoff for the 1985–2009 period, compared with the 1950–1984 period, is accompanied by a 38% reduction in glacier runoff that has resulted in a 1·5–2·0% decline in total streamflow. Only when streamflow is at critically low levels, below 14 m^3s^{-1} for the Skykomish River at Gold Bar, does the glacier runoff contribution increase above 10% of streamflow, compared to 17% in 1958. The low-flow periods generally occur in August–October; August and September coincide with the peak glacier runoff season, and low flows are augmented by the contribution from glacier runoff of 1·5–1·6 m^3s^{-1}.

Hinman Glacier and Foss Glacier continue to lose area and volume rapidly and will cease to exist within 20 years with a continuation of present environmental conditions. Columbia Glacier and Lynch Glacier do not have a persistent accumulation zone, but remain thick and will persist and provide runoff to the basin for some time. The loss of glacier area will continue to reduce glacier runoff to the Skykomish River, significantly reducing streamflow during minimum flow periods.

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