Chapter 6 - Importance of glacier volume on stream flow

In the Post et al. (1971) inventory, snow and ice melt was compared to precipitation and runoff for August and September for the South Fork Nooksak River, Thunder Creek, and Stehekin River basins for the years 1964 and 1966. These three watersheds were selected because of variations in their glacier cover. South Fork Nooksak has no glacier cover; 3.4 % of the Stehekin watershed was covered by glaciers; and 14.2 % of Thunder Creek watershed was covered. The years 1964 and 1966 were selected because of contrasting snowfall and summer conditions. 1964 had above average snowpack with a cool, wet summer. 1966 had a below average snowfall with a hot, dry summer. By estimating glacier change in each basin using mass balance figures from South Cascade Glacier and stream gage records they concluded that in 1964 the melting of glacier ice contributed 13% to the August - September streamflow of Thunder Creek and 5% to the discharge of Stehekin River. The 1966 glacier melt contributed 34% to the August-September discharge of Thunder Creek and 27% to discharge from Stehekin River. Since the most critical months for Pacific Northwest water users are August and September, these percentages indicate glacier melt is an important part of the water resources of northwestern Washington.

The analysis described in this chapter reexamines these conclusions by comparing glacier volume change for 1957-1997 to precipitation and runoff. For a watershed with glaciers the principle input is precipitation (P) in the form of both snow and rain, outputs include evaporation (E) and runoff (R), and glacier net balance (B) represents changes in storage (equation 6.1)

$$B = P - E - R \qquad \textbf{(6.1)}$$

This equation states that annual precipitation in a watershed without glaciers equals runoff plus evaporation since there is no ice storage in the system. It also assumes that groundwater flow and storage is negligible. In a largely unvegetated watershed that is covered by glaciers that are in equilibrium, precipitation equals runoff since evaporation is assumed to be negligible and there is no change in storage. However, if net mass balance is positive, runoff will be less than precipitation due to a portion of the snow received that year being locked up as ice. On the other hand, when annual net balance is negative, runoff will be augmented by glacier melt (Paterson, 1969).

Glacier melt, precipitation, and runoff in selected basins

The watersheds selected for this analysis (Fig. 6.1) have complete or nearly complete glacier area, runoff, and climate data for the period 1961 to 1990. The period 1961-1990 was based on the averaging period used to compile the digital precipitation maps. While glacier population and area are known for both Thunder and Newhalem Creeks, glacier change in the Stehekin and Cascade basins had to be estimated because the 1998 glacier coverage for the two watersheds was only 50% complete (table 6.1). The lack of aerial photography for significant portions of each basin precluded completing the inventory. The 1958 glacier areas were determined using both the 1958 map layer and additional digitized glacier outlines provided by Mt. Baker-Snoqualmie and Wenatchee National Forest staff. The 1998 glacier areas for these two watersheds were estimated by multiplying their total glacier areas in 1958 by an area change factor for each basin. The area change factor was calculated using the fractional area change for the 50% of the Cascade and Stehekin River basins for which 1998 glacier data exists.

Table 6.1 - Geographic and glacial characteristics of selected watersheds. % coverage is the percentage of each basin that is glacier covered. Errors were not calculated for 1998 area and % coverage for Stehekin and Cascade watersheds since 1998 glacier areas were estimates based on 1998 FAC for less than 50% of the glaciers in each basin.

Watershed Name	Area (km^2)	Glacier Population		Area (km^2)		% coverage	
		1958	1998	1958	1998	1958	1998
Thunder Creek	299	56	56	39.2±0.6	36.8±0.7	13.1±0.2%	12.3±0.2%
Stehekin River	797	94	94	26.4±0.6	24.7	3.3±0.1%	3.1%
Cascade River	483	53	53	16.9±0.3	15.8	3.5±0.1%	3.2%
Newhalem Creek	74	3	3	0.4±0.1	0.4±0.1	0.6±0.1%	0.6±0.1%

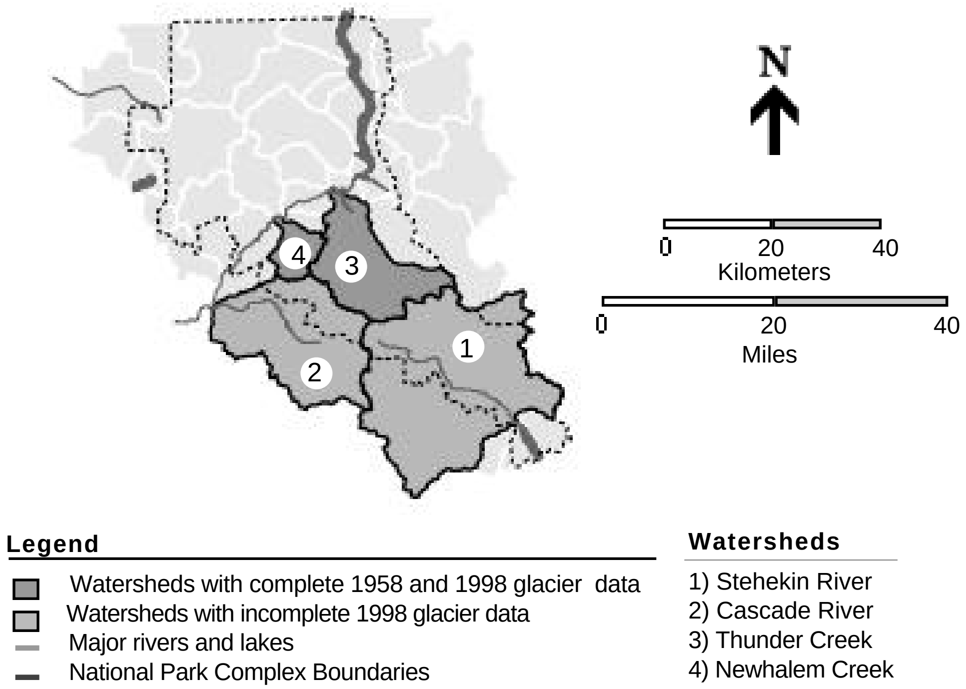

Figure 6.1 - Map of selected watersheds

The relationship of glacier mass wastage to runoff in each basin was determined using equation 6.2 ...

$$\%C = \frac{V_g}{V_{ro}} \tag{6.2}$$

Where V_g is the average net glacier mass loss and V_{ro} is the August-September runoff volume. V_{ro} was derived by averaging August September runoff volumes for the selected watersheds for the period 1961 to 1990. V_g for each watershed was derived from volume changes based on the Bahr et al. (1997) area-volume scaling method. These individual volume changes were summed for each watershed and then averaged over forty years (1958-1998). In doing so, it was assumed that average annual volume loss for the 1958 to 1998 period was roughly equivalent to the loss for 1961-1990. The assumption was also made that all of the glacier loss takes place in August and September after the annual snow pack has melted.

The question of how much glacier mass loss has contributed to August-September precipitation was dealt with using equation 6.3.

$$\%C' = \frac{V_g}{V_{ppt}} \quad \mathbf{(6.3)}$$

where V_{ppt} is the average volume of precipitation received by each basin during August and September. V_{ppt} was calculated using PRISM (Parameter Elevation Regressions on Independent Slope Model) data for average annual precipitation and watershed boundaries drawn by the US Geological Survey. PRISM is based on data from climate stations and digital elevation models to generate gridded estimates of annual, monthly, and event based climatic parameters (Daly et. al., 1994, 2001). The PRISM data were converted from an ASCII gridded data format into a raster map of average annual precipitation for the entire park complex. Watershed boundaries were used to create precipitation maps for each selected watershed. Finally, the precipitation values were summed over the entire area of each watershed to produce annual precipitation volume. The average August-September precipitation volume was estimated by multiplying annual precipitation volume by the fraction of annual precipitation falling during August and September. This fraction was derived by dividing the average August September precipitation from the nearest climate station by the average annual precipitation for that same station.

Results:

Glacier melt contributes between 0.1 and 6.0 % to the August-September runoff of the four watersheds (Table 6.2). This contribution is highest for the watershed with the highest fraction of glacier cover (Thunder Creek). While this trend is consistent with the results of Post et al. (1971), the estimated contributions are significantly lower than those made by them. The major reason for this mismatch is differences in how volume change and precipitation were determined. Post et al. (1971) estimated volume change by scaling from the South Cascade mass balance record, while I estimated this change using

1958 and 1998 areas and area volume scaling techniques. Given the errors calculated for estimates derived by the Bahr et al. (1997) method (chapter 3), it is possible that average annual glacier volume change may be twice the calculated value. In other words, the contribution from glacier melt could range from 1 to 12%, a result that is more in line with that of Post et al. (1971). Post et al. (1971) estimated precipitation using climate station data from specific months, while I used a digital precipitation model based on a more robust calculation of 30 years of annual averages of climate station data. Given the very different ways in which precipitation was calculated, it is inevitable that estimated precipitation would vary widely.

Glacier melt augments August-September precipitation by between 1.0 and 16%. Again, given probable errors in area-volume scaling based estimates of glacier volume change; this augmentation could be as high as 2 to 32%. The significance of this result can be seen by examining differences in precipitation and runoff. During August-September, precipitation accounts for 25 to 35% of the runoff from the four basins. This means that over 65% of the runoff for these two months was from snow and ice melt, with the latter making up between 4 and 7% of the melt derived runoff.

Table 6.2 - Hydrologic characteristics for selected watersheds. %C” is augmentation of precipitation by glacier loss and %C is contribution of loss to runoff. Uncertainties in precipitation and runoff are the standard deviation of both values for 1960-1991.

	Volume (1,000,000 m^3)			
Watershed	Glacier loss	Precipitation	Runoff	%C"
Thunder Creek	7.4 ±0.1	47.0 ±19.7	122.0 ± 17.1	15.7%
Stehekin River	2.5	48.6 ±24.3	194.0 ± 32.0	5.1%
Cascade River	2.0	33.0 ±13.9	121.0 ± 32.0	6.1%
Newhalem Creek	0.1 ±0.0	6.0 ±2.5	17.0 ± 0.0	1.0%

	Specific volume (m)			
Watershed	Glacier loss	Precipitation	Runoff	%C
Thunder Creek	0.75 ±0.10	0.16 ± 0.07	0.41 ± 0.06	6.0%
Stehekin River	0.25	0.06 ± 0.03	0.20 ± 0.04	1.3%
Cascade River	0.25	0.07 ± 0.19	0.33 ± 0.43	1.7%
Newhalem Creek	0.03 ±0.00	0.08 ± 0.01	0.03 ± 0.00	0.4%

Projected changes in glacier cover and runoff for selected watersheds

From 1957 to 1997 glacier mass loss made a small, but significant contribution to runoff from selected watersheds. However, glacier wastage had no discernible impact on the timing of peak flow or the variability of annual runoff from these basins. Nevertheless, if glacier mass loss continues it is a strong possibility that the timing and variability of runoff would be affected. If and when these changes would take place was determined by modeling glacier change for Thunder Creek, Newhalem Creek, Cascade River, and Stehekin River basins based on current rates of glacier change. Rates of glacier change were determined by averaging changes in the combined glacier area for each watershed over a 40 year period (Table 6.3). Rates of glacier change were also calculated for 1976-1998 since this period was a time of accelerated glacier loss which may be more typical of upcoming decades. The 1977-1998 rates were calculated by determining the fraction of the 1958-1998 cumulative mass balance that occurred during 1977-1998. This fraction (92%) was then multiplied by the 1958-1998 area change for each basin and averaged over 23 years. Assuming that these rates remain constant, the number of years until each watershed was some fraction of its 1998 area was calculated using equation 6.4...

$$t = \frac{(A_{1998} * f)}{\Delta A'} \quad \textbf{(6.4)}$$

where t is the number of years, A_{1998} is the combined glacier area of the watershed in 1998, f is the fractional reduction in the glacier area, and $\Delta A'$ is annual rate of glacier area loss for the watershed. The number of years was calculated using annual change rates based on calculated 1957-1998 and estimated 1975-1998 total area changes (Tables 6.4 and 6.5).

Table 6.3 - Rates of glacier change for Cascade, Newhalem, Stehekin and Thunder Creek watersheds...

	Cascade River	Newhalem Creek	Stehekin River	Thunder Creek
Years	Glacier areas (km^2)			
1958	16.90	0.46	26.40	39.17
1998	15.80	0.42	24.66	36.76
Glacier change (km^2) for 1958-1998				
Total	-1.10	-0.04	-1.74	-2.41
Ave	-0.028	-0.001	-0.043	-0.060
Glacier change (km^2) for 1976-1998				
Total	-1.02	-0.04	-1.62	-2.24
Ave	-0.044	-0.002	-0.070	-0.097

Table 6.4 - Estimated years to percent deglaciation based on 1958-1998 rates of glacier change.

% 1998 area	Cascade River		Newhalem Creek		Stehekin River		Thunder Creek	
	Years	% Cover	Years	% Cover	Years	% Cover	Years	% Cover
100	0	3.3%	0	0.6%	0	3.1%	0	12.3%
90	57	2.9%	38	0.5%	56	2.8%	61	11.1%
80	115	2.6%	76	0.4%	113	2.5%	122	9.8%
70	172	2.3%	114	0.4%	169	2.2%	183	8.6%
60	230	2.0%	152	0.3%	226	1.9%	244	7.4%
50	287	1.6%	190	0.3%	283	1.5%	305	6.2%
40	345	1.3%	228	0.2%	339	1.2%	366	4.9%
30	402	1.0%	266	0.2%	396	0.9%	427	3.7%
20	460	0.7%	304	0.1%	452	0.6%	488	2.5%
10	517	0.3%	342	0.1%	509	0.3%	549	1.2%
0	575	0.0%	380	0.0%	566	0.0%	610	0.0%

Table 6.5 - Estimated years to percent deglaciation based on 1976-1998 rates of glacier change.

% 1998 area	Cascade River		Newhalem Creek		Stehekin River		Thunder Creek	
	Years	% Cover	Years	% Cover	Years	% Cover	Years	% Cover
100	0	3.5%	0	0.6%	0	3.3%	0	13.1%
90	19	2.9%	13	0.5%	19	2.8%	20	11.1%
80	39	2.6%	26	0.4%	38	2.5%	41	9.8%
70	59	2.3%	39	0.4%	58	2.2%	62	8.6%
60	79	2.0%	52	0.3%	77	1.9%	83	7.4%
50	98	1.6%	65	0.3%	97	1.5%	104	6.2%
40	118	1.3%	78	0.2%	116	1.2%	125	4.9%
30	138	1.0%	91	0.2%	136	0.9%	146	3.7%
20	158	0.7%	104	0.1%	155	0.6%	167	2.5%
10	177	0.3%	117	0.1%	174	0.3%	188	1.2%
0	197	0.0%	130	0.0%	194	0.0%	209	0.0%

The impact of these changes on stream flow was determined by comparing the coefficient of variation of annual runoff to the fraction of each basin covered by glaciers (Fig. 5.5). Based on this comparison, Thunder Creek would show the greatest change in variability. Currently Thunder Creek has a 12.3% glacier cover, which gives it a coefficient of variability of 0.13. At 1958-1997 rates of glacier change, the basin would be glacier free in 610 years. If the basin were to deglaciate at 1977-1998 rates, the last glaciers would disappear in 209 years. However, noticeable changes in the variability of annual runoff would happen much more quickly. Given 1977-1998 rates, the variation coefficient would increase by 0.02 in less than 83 years. By comparison, the coefficient of variation for the basin increased by only 0.005 between 1958 and 1998. For the other three basins changes in the variability coefficient would happen more rapidly. Given 1977-1998 rates of glacier loss, Cascade River would see a 0.02 increase in the coefficient in 57 years, Cascade River in 61 years, and Newhalem Creek in only 38 years. Furthermore, based on the hydrographs shown in figure 5.2, in less than two centuries the selected basins would shift to flow patterns characteristic of an intermediate altitude basin.

Summary

In four selected watersheds in the North Cascades, average annual mass loss from glaciers contributes between 0.1 and 7.4 million m^3 to average annual August-September runoff. This means that between 0.1 and 6.0 % of runoff during this part of the year is derived from glacier melt. Though this amount may seem insignificant, consider that precipitation accounts for only 25 to 35% of the runoff from these basins. The remaining 65 to 75% comes from snow and ice melt. So as annual precipitation decreases and temperature increases, annual snow pack decreases while glacier melt increases. In other words, increased glacier melt acts to offset decreases in precipitation and snow melt. In the four watersheds examined in this analysis, ice melt augments August-September precipitation by between 1.0 and 15.7%. Given the economics of Northwestern Washington, the impact of this increased glacial melt affects both hydropower and agriculture.

Seven hydroelectric plants draw water from rivers flowing through the National Park Complex. Four of these are owned by Seattle City Light and produce 27% of the electric power that the company provides to its customers (Seattle City Light, 2000). The other three lie just outside the complex on Lake Chelan and Baker Lake and service areas both east and west of the Cascades. These statistics, plus the analysis in this study, support the idea that power production forecasting for basins with significant glacier cover depend on constructing runoff simulations that include glacier change (Tangborn, 1980; Braithwaite and Thomsen, 1989). The same can be said for agricultural water resource management in Central Washington. Several streams, including Stehekin River, drain from the North Cascades to provide water for irrigation to arid areas in Columbia Plateau. Given that peak flow from these streams is highest during the driest part of the year, the relevance of glaciers to Washington agriculture is apparent.

Though glacier change had no detectible impact on the timing or annual variability of regional stream flow, it is a strong possibility that continued glacier loss will impact runoff characteristics in the near future. Assuming the rate of glacier loss continues at the 1977-1998 rates all of the watersheds described in this chapter would be glacier free in 130 to 209 years. During this time glacier melt would continue to offset decreased annual snow melt. At the same time, decreasing glacier cover in each of the watersheds would increase the variability of annual runoff and change the timing of peak flows. Comparisons of projected glacier change to the coefficient of variation of annual runoff indicate that significant changes in the variation and timing of annual flows would occur in less than a century. Furthermore, these changes would occur most rapidly for basins having the smallest percent glacier cover. The effect of this for at least one utility (Seattle City Light) is significant since the basin providing water to the company’s facilities is approximately 1% glacier covered, meaning that detectible changes in the timing and annual variability of runoff could take place in less than fifty years.