

Snowpack Development and Ablation on Glaciers and Alpine Areas in the North Cascades, Washington

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ABSTRACT

In the North Cascade Range, Washington, snowpack depth and snowpack ablation rates vary widely because of local topography and consequent microclimates. To identify the degree to which annual snowpack development and ablation can be accurately estimated from a few sites, the following data sets are utilized: 1) annual glacier mass balance measurements from eight North Cascade glaciers; 2) snowpack ablation on five glaciers, and six Snotel sites; 3) snowpack development at twelve Snotel sites and on two glaciers.

Cross-correlation of annual mass balance (bn) values between the eight glaciers, each with differing geographic characteristics, exceeded 0.85 for every combination. Mean daily glacier ablation for specific periods are: early ablation season May 1–June 10, 2.7–3.3 cm/day; mid-ablation season June 11–August 31, 6.3–7.1 cm/day; late ablation season September 1–30, 3–2.8 cm/day. The correlation in midseason and late season ablation between each glacier exceeds 0.95, indicating the degree to which the similarity of weather conditions across the North Cascades in the summer. The correlation of daily snow water equivalent (SWE) at the three Snotel sites between 1400 m and 1900 m ranges from 0.88–0.99. From 1000–1400 m the correlation coefficient is 0.87–0.99. The correlation between the high elevation and low elevation Snotel sites is 0.63–0.96. These data suggest that despite the mean SWE depth and maximum SWE being widely variable from site to site the annual pattern of development and ablation in response to specific climate conditions is quite similar for each elevation band.

The primary conclusion is that local climate in the North Cascades influences mean snowpack depth

and daily ablation rate, but does not result in significantly different responses to specific annual climate conditions within a specific elevation band. Extrapolation from standard sites to secondary sites can be accomplished, but only when the sites are at similar elevations and the sites have a baseline history documenting the mean accumulation depth and ablation rates. The variation in snowpack depth is consistent, as is summer ablation. However, the variation is not consistent for spring ablation.

Keywords: Snowpack development, ablation, glaciers

INTRODUCTION

The spatial and temporal variation of snowpack accumulation, snowpack ablation and consequent alpine runoff is crucial to determining regional summer water resources in the North Cascades Range, Washington. Glaciers alone provide 750 million m³ of runoff each summer (Fountain and Tangborn, 1985). What is the spatial and temporal variability of accumulation and the ablation across the North Cascades spatially and temporally? Rasmussen and Tangborn (1976) noted a poor relationship between observed annual precipitation and annual runoff. They also noted, in plotting mean annual runoff versus basin mean altitude in 36 basins in the North Cascades, that there was a poor relation between runoff and basin altitude. However, correlation of monthly precipitation and annual runoff is good. These observations demonstrate that precipitation variation is complex and significant in the region and that extrapolations cannot be made from a standard measurement site to a secondary location without

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Table 1. Location of USDA Snotel, USGS, and NCGCP glacier measurements sites.

	<i>Elevation</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Source</i>
Lyman Lake	1805	48 12	120 55	USDA
Rainy Pass	1460	48 33	120 43	USDA
Thunder Basin	1285	48 31	120 59	USDA
Stevens Pass	1245	47 44	121 05	USDA
Stampede Pass	1190	47 17	121 20	USDA
Alpine Meadows	1070	47 47	121 42	USDA
Skookum Creek	1200	47 41	121 36	USDA
Wells Creek	1280	48 51	121 47	USDA
Elbow Lake	1000	48 41	121 54	USDA
Park Creek Ridge	1405	48 27	120 55	USDA
Fish Lake	1030	47 31	121 04	USDA
Miners Ridge	1890	48 10	120 59	USDA
Columbia Glacier	1450–1750	47 58	121 21	NCGCP
Daniels Glacier	2000–2250	47 34	121 10	NCGCP
Sulphide Glacier	1900–2700	48 50	121 36	NCGCP
Lynch Glacier	1950–2250	47 34	121 11	NCGCP
Rainbow Glacier	1350–2250	48 48	121 40	NCGCP
Easton Glacier	1700–2900	48 44	121 50	NCGCP
S. Cascade Glacier	1645–2100	48 21	121 03	USGS
L. Curtis Glacier	1650–1950	48 50	121 37	NCGCP
Neve Glacier	1830–2150	48 39	121 08	NCGCP

some ground truth at the latter location. This paper examines the ability to estimate snowpack development and ablation from standard locations to secondary locations. There is considerable area in the North Cascade Range above 1900 m where snowpack and meteorologic data are not gathered. As the summer progresses streamflow is increasingly dominated by the elevation snowmelt that is not measured by Snotel. NCGCP and the USGS measurements on glaciers can provide the necessary snowpack data in this elevation range for model development and model forecast purposes.

The following data sets are used (Table 1):

1) annual glacier mass balance measurements from eight North Cascade glaciers (North Cascade Glacier Climate Project: NCGCP); 2) snowpack ablation from 1984–1997 on four glaciers (3 by NCGCP and 1 by USGS), and twelve USDA Snotel sites; and 3) snowpack development data from twelve Snotel sites, four of the latter are presented here in detail (USDA).

The necessity of using Snotel sites and glaciers is emphasized by the difference in mean winter accumulation in SWE from 1.17 m at the twelve USDA Snotel sites ranging in altitude from 1000–1900 m and 2.93 m at nine glacier locations ranging from 1650–2200 m. On July 1 at the nine glacier locations SWE still averages 1.3 m, in excess of the mean maximum at Snotel sites.

GLACIER ANNUAL BALANCE MEASUREMENTS

Mass balance measurements were made on the same date each year in August and again in late September, at the end of the ablation season and hydrologic year (Pelto, 1996). Any mass balance changes occurring before the actual accumulation season begins is a measured mass loss or gain for the next hydrologic year. Ice and firn ablation is determined using ablation stakes drilled into the glacier surface and simultaneously checked on the same date in late September. Residual snow accumulation was determined using probing and crevasse stratigraphy on the same date as ablation measurements were completed (Pelto, 1996). The mass balance measurement is thus a composite of the accumulation and ablation processes.

Only accumulation measurements are made above the snow line in the accumulation zone. In the accumulation zone, annual accumulation layer thickness is determined using crevasse stratigraphy, and probing. Measurements are made in August and again in late September. The August measurements are made to determine snowmelt runoff for the late summer period and are not used in the final annual balance assessment. The average density of measurements utilized in this study is 290 points/km².

The accumulation layer thickness is measured at each point to the nearest 0.01 m. Crevasse stratigraphy measurements are conducted only in vertically walled crevasses with distinguishable dirt bands. Crevasses lacking vertical walls yield inaccurate depth measurements. In the North Cascades the ablation surface of the previous year is always marked by a 2–5 cm thick band of dirty firn or glacier ice. We completed more than 100 snowpits from 1984–1986, the range in mean accumulation layer density observed was 0.58–0.63 g/cm². This narrow range indicates that late in the ablation season the density of snowpack on North Cascade glaciers is uniform (Pelto, 1996).

Below the snowline ablation stakes are driven or drilled into the snow or ice. Measurements are made in late July and early August, recording the ablation during the first three months of the ablation season. After re-drilling if necessary in August, ablation measurements are repeated in late September at the designated conclusion of the hydrologic year.

MASS BALANCE RESULTS

The mean accumulation layer thickness at two different elevations during the 1984–1997 period have been monitored on eight glaciers throughout the North Cascades (Table 2). Each of the eight glaciers is at or west of the Cascade Divide. The measurement sites were selected in areas where both avalanching, and wind deposition or erosion are at a minimum. The results indicate consistent snowpack depths west of the divide for the two different elevations, regardless of the year.

Table 2. Snow accumulation in meters of SWE at 6 locations at the start of August. There are two different elevation bands represented, three glaciers at 1650 m and three glaciers at 2200 m. Each depth represents measurements made at the same set of three locations on the same date and using the same methods.

Year	Neve	Lynch	Easton	L.Curtis	Columbia	Rainbow
Elev	2200 m	2200 m	2200 m	1650 m	1650 m	1650 m
1990	1.3	1.2	1.5	0.8	0.6	0.7
1991	2.7	2.6	3.2	1.7	1.9	1.5
1992	0.7	0.9	1.2	0.6	0.3	0
1993	1.0	1.0	1.8	0.6	0.5	0.6
1994	1.0	1.3	1.9	0.8	0.6	0.7
1995	2.0	1.8	2.4	0.8	0.8	0.9
1996	2.4	3.0	3.3	1.7	1.4	1.3
1997	2.8	3.0	3.6	1.8	1.5	1.8

The relation between the two different elevations is often consistent, but in 1990 the accumulation gradient was below average and in 1996 an above-average accumulation gradient was observed. Thus, as one would expect, snowpack depth on a single glacier or between glaciers cannot be accurately assessed from a single elevation.

Ablation is reported for five in the North Cascades: Columbia Glacier, Ice Worm Glacier, and Easton Glacier monitored by NCGCP and on South Cascade Glacier observed by the USGS. The USGS has monitored both ablation and glacier runoff on the South Cascade Glacier since 1955 (Krimmel, 1993, 1994, 1995, 1996, 1997). Monthly ablation season measurements at each of the above glaciers allow determination of the mean ablation rates for different periods of the ablation season, but not specific correlation of daily ablation. In each case, ablation is the change in surface level, measuring loss of snow or ice thickness, which is reported in SWE. Mean daily ablation for specific periods are early ablation season May 1–June 10, 1.8–2.2 cm/day; mid-ablation season June 11–August 31, 3.1–4.0 cm/day; late ablation season September 1–30, 1.7–2.0 cm/day. The mean daily ablation from June 1 through August 31 is noted in Table 3, the variation in between glaciers for each ablation season is less than 10%. This shows that though daily ablation may vary and seasonal ablation totals can be reasonably estimated from glacier to glacier (Table 3).

The correlation in mid and late season ablation between each glacier exceeds 0.95 indicating the degree to which the regional summer climate is consistent across the North Cascades. The early season ablation correlation is a much lower 0.72. Based on

Table 3. Mean daily glacier ablation rates from June 1–August 30 (cm of water equivalent).

	South Cascade cm WE	Columbia Glacier cm WE	Daniels Glacier cm WE	Rainbow Glacier cm WE
1984	Missing	3.3	3.3	3.1
1985	M	3.8	3.7	3.5
1986	M	3.7	3.8	3.6
1987	M	4	3.9	3.8
1988	M	3.6	3.6	3.4
1989	M	3.5	3.4	3.4
1990	M	3.6	3.8	3.5
1991	M	3.8	3.6	3.6
1992	3.6	3.7	3.8	3.6
1993	3.4	3.6	3.5	3.5
1994	3.6	3.4	3.4	3.2
1995	3.6	3.6	3.4	3.3
1996	3.3	3.5	3.2	3.1
1997	M	3.6	3.5	3.4

North Cascade Glacier Mass Balance

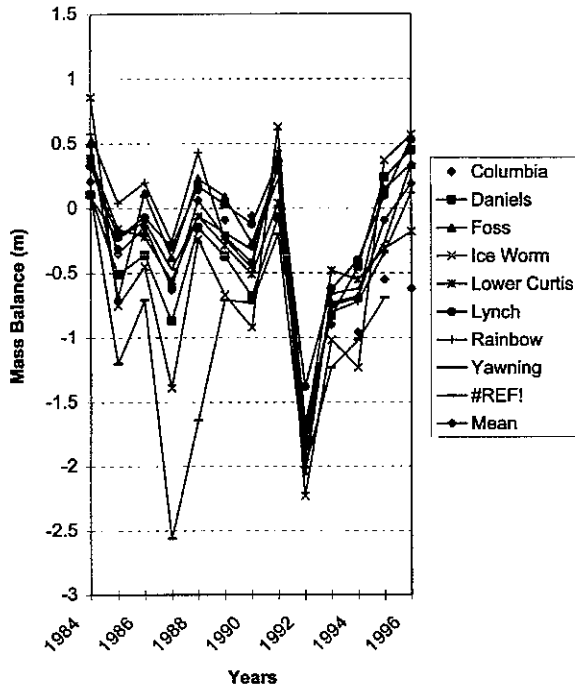


Figure 1. Annual balance of North Cascade glaciers.

field observations on the low elevation ablation sites on Columbia Glacier (1400 m) and higher elevation site Lynch Glacier (2000 m) this is largely due to the crucial impact of the freezing level determining rain or snow events, ablation, or accumulation conditions across the glaciers.

The cross-correlation of annual balance for the eight North Cascade glaciers ranges from 0.83–0.97, indicating the similarity of each glacier’s annual balance response to the annual climate conditions. Figure 1 displays the annual balance of the eight North Cascade glaciers observed by NCGCP from 1984–1994. The similar response of each glacier from year to year illustrates the high cross correlations. The actual range in annual balance between the glaciers for any given year is significant. This is in contrast to Pelto (1988) postulating that the variation in annual balance between glaciers is due to their different geographic characteristics. The high cross-correlation of annual balance for each glacier suggests that the geographic characteristics are of secondary importance to actual climate conditions, but does not suggest that geographic characteristics are unimportant.

The individual glaciers were selected to represent a range of geographic and topographic characteristics. This tendency for small alpine glaciers in the Pacific Northwest to have significantly different mass balance histories and geographic locations, yet

high cross correlation coefficients were previously noted by Letreguilly (1989).

SNOTEL SNOWPACK MEASUREMENTS

The Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA) operates an extensive automated Snotel system to collect snowpack and climatic data in the western United States. Snotel sites have at a minimum a pressure-sensing snow pillow, storage precipitation gage, and air temperature sensor. The snow pillows are envelopes of stainless steel or synthetic rubber containing an antifreeze solution. As snow accumulates on the pillow it exerts a pressure that is measured and converted to a reading of snow water equivalent and telemetered to two NRCS master stations.

There are 12 North Cascade Snotel sites. At these 12 Snotel sites from November 1–February 15 snowpack development is rapid reaching 68–80% of the maximum snowpack water equivalent (SWE). In this study detailed readings from four principal stations, each within 20 km of a monitored glacier are used (Table 1).

However, there are 8 additional stations in the North Cascades that have been evaluated to identify average snowpack development and ablation at specific elevations. From 1000 to 1400 m snowpack development typically ends by April 15. From 1400 to 1700 m snowpack development peaks by May 1. From 1700 m to 1900 m, the lower elevation range of glacier accumulation zones, snowpack depth peaks by May 10. The correlation of daily SWE for the 1989–1997 period at the four Snotel sites between 1400 m and 1900 m ranges from 0.88–0.99. From 1000 to 1400 m the daily SWE correlation coefficient at eight Snotel sites is 0.87–0.99. The correlation between the high elevation and low elevation Snotel sites is 0.63–0.96.

The mean and maximum SWE depth is variable from site to site; however, the annual pattern of development and ablation in response to specific climate conditions is similar for each elevation band. The annual progression of snowpack development and ablation for Lyman Lake provides a typical example of the annual variation in SWE accumulation (Fig. 2). Figure 3 illustrates the variation in snowpack SWE for 1995 winter season at all four stations. Snowpack development was substantial from October 15–February 15 at each site. After mid-February accumulation tapered off reaching an approximate peak by March 15 at all but the highest elevation site, Lyman Lake. Ablation began On April 5 at

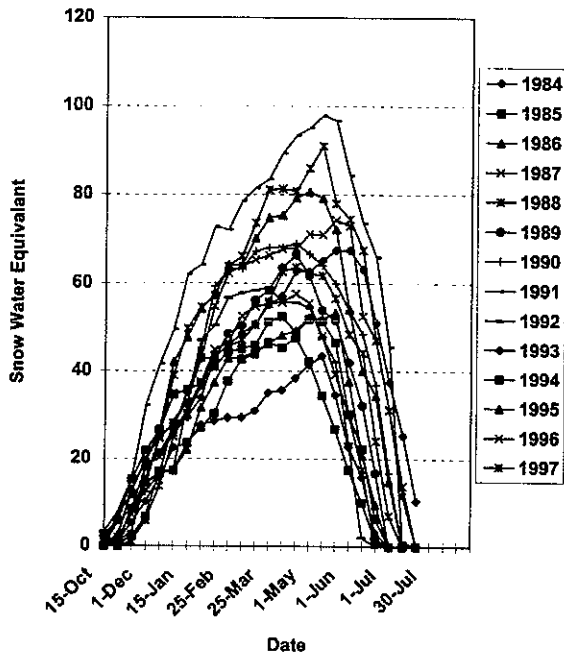


Figure 2. Annual snow water equivalent (inches) development at Lyman Lake USDA Snotel site.

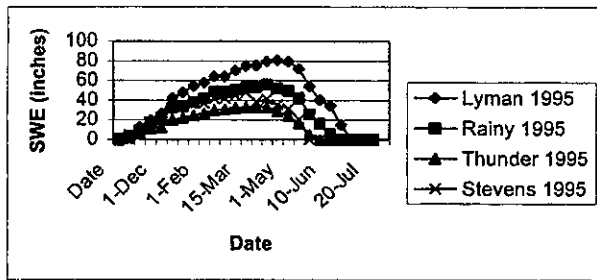


Figure 3. Annual progression of snowpack development in SWE (inches) at four USDA sites in the North Cascades in 1995.

Rainy Lake, Thunder Basin, and Stevens Pass, and began on May 1 at Lyman Lake. The maximum date at Lyman Lake is delayed 30 days from Thunder Basin and Stevens Pass and 10 days from Rainy Pass (Table 4). The maximum SWE date for Lyman Lake has a 0.98 correlation with the beginning of the melt season as marked by the first three consecutive days with mean temperature at Stevens Pass in excess of 6°C. In each year from 1984–1997 the beginning of the ablation season at Stevens Pass occurred within 3 days of the onset of significant ablation at Lyman Lake. This marks the beginning of the ablation season on North Cascade glaciers (Pelto, 1993).

The onset of ablation is also seen in the spring ablation rates at the Snotel sites (Table 5). The early ablation season is marked by freezing levels that

Table 4. Date of maximum SWE accumulation in inches (as reported by USDA) at four USDA North Cascade, Washington, Snotel sites, and the date of maximum SWE accumulation.

Year	Lyman	Rainy	Thunder	Stevens
1984	1-Jun	20-May		15-Apr
1985	10-May	1-May		25-Apr
1986	20-May	20-May		5-Apr
1987	1-May	25-Apr		15-Apr
1988	10-May	25-Apr		15-Apr
1989	1-May	15-Apr	15-Apr	15-Apr
1990	10-May	15-Apr	25-Mar	25-Mar
1991	10-May	1-May	15-Apr	15-Apr
1992	1-May	1-May	25-Mar	15-Mar
1993	10-May	1-May	5-Apr	5-Apr
1994	1-May	25-Apr	15-Apr	5-Apr
1995	10-May	25-Apr	25-Apr	25-Apr
1996	20-May	10-May	5-Apr	5-Apr
1997	10-May	10-May	25-Apr	15-Apr
Mean	10-May	1-May	10-Apr	10-Apr

Table 5. Snowpack ablation rates at four Snotel sites in cm of SWE from May to June 10.

	Lyman Lake	Rainy Pass	Stevens Pass	Thunder Basin
1984	0	0.66	1.5	m
1985	1.83	1.72	3.3	m
1986	2.03	1.72	2.41	m
1987	2.41	2.02	m	m
1988	1.14	1.14	2.97	m
1989	1.83	1.9	2.8	2.4
1990	1.14	1.11	2.28	2.03
1991	1.4	1.72	1.88	1.98
1992	3.3	2.23	m	1.72
1993	1.78	2.36	2.54	1.78
1994	2	2.1	1.78	1.75
1995	2.5	2.3	2.72	2.1
1996	1.8	1.5	2.84	2.06
1997	1.25	1.5	1.85	1.72
Mean	1.74	1.7	2.4	2.41

more frequently result in snowfall at Lyman Lake and rainfall at the lower sites. May ablation rates between Snotel sites are poorly correlated as are the daily ablation rates, correlation coefficients ranging from 0.43–0.76 (Table 6). Average ablation after June 1 is a limited data set in many seasons due to the disappearance of the snowpack at the lower elevation stations. However, at any melt station with snowpack enduring past June 15, the daily ablation rate have been correlated for the entire June–July period when snowpack was present. Ablation rates after June 1 are highly correlated ranging from 0.73–0.92. Average June ablation in SWE is 3.8 cm/day at Lyman Lake, 3.7 cm/day at Rainy Pass, 3.8 cm/day Miners Ridge, 3.7 cm/day at Columbia Glacier, and 3.6 cm/day at South Cascade Glacier. The lack of

Table 6. Annual correlation coefficients between daily snowpack water equivalent for each Snotel site.

	LL-RP	LL-TH	LL-ST	RP-TH	RP-ST	TH ST
1989	0.99	0.9	0.82	0.87	0.76	0.99
1990	0.97	0.83	0.81	0.91	0.89	0.99
1991	0.97	0.82	0.73	0.93	0.87	0.98
1992	0.98	0.92	0.71	0.97	0.81	0.91
1993	0.88	0.96	0.63	0.94	0.9	0.81
1994	0.96	0.93	0.96	0.99	0.99	0.98
1995	0.96	0.85	0.73	0.96	0.89	0.98
1996	0.94	0.78	0.64	0.92	0.96	0.88
1997	0.96	0.88		0.97		

LL=Lyman Lake, RP=Rainy Pass, TH=Thunder Basin, ST=Stevens Pass.

variation between various glacier and Snotel sites contrasts with the sharp variation in accumulation between sites. Thus, within the elevation zone from 1400–2000 m across the North Cascades ablation after June 1 has a low degree of variability. Early season ablation rate varies widely with elevation, but after June 1 ablation rates fall within a narrow range. Accumulation is widely variable and can only be estimated if baseline data are available; ablation rates are similar in the summer season and can be extrapolated from primary to secondary sites without substantial baseline data. The most important ramification is that if the distribution and depth of the snowpack is known on June 1, then summer water resources can be estimated for a wide range of basins from a limited number of primary ablation measurement sites.

CONCLUSIONS

Local climate in the North Cascades influences mean snowpack depth and ablation rate, but does not cause in significantly different responses to annual climate conditions within specific elevation bands. Extrapolation from site to site for accumulation can be accomplished, but only when the sites are at similar elevations and the sites have a baseline history documenting the specific development of snowpack. Ablation rates before June 1 are widely variable with altitude and extrapolations can only be made to secondary sites after baseline data are available. After June 1 Snotel ablation rates are approximately equal from 1400–2000 m regardless of location. This same tendency of nearly identical ablation rates is noted on glaciers in this same altitude band.

To model or directly calculate the timing and magnitude of water resource storage, it is essential to collect baseline data on accumulation at numerous

secondary sites. Once the relationship of these secondary sites can be related to long-term records at primary measurement sites, then the secondary site measurements can be discontinued. This also applies to early season, April–May snowmelt runoff. Ablation rates and consequent runoff can be assessed from a few primary sites at glaciated levels from June 1–August 31. It is also evident that the Snotel system provides an excellent and cost effective means of collecting data on snowpack development from 1000–1900 m in the North Cascades, but does not well represent snowpack accumulation at the average glacier accumulation zones of 2000 m, making accurate summer streamflow estimates impossible without data from glacier sites.

REFERENCES

- Fountain, A., and W.V. Tangborn. 1985. The effect of glaciers on streamflow variations. *Water Res. Res.*, 21, 579–586.
- Krimmel, R.M. 1993. Mass balance, meteorologic, and runoff measurements at South Cascade Glacier, Washington, 1992 balance year. USGS OFR-93-640.
- Krimmel, R.M. 1994. Runoff, precipitation, mass balance, and ice velocity measurements at South Cascade Glacier, Washington, 1993 balance year. USGS OFR-94-4139.
- Krimmel, R.M. 1995. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1994 balance year. USGS OFR-95-4162.
- Krimmel, R.M. 1996. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1995 balance year. USGS OFR-96-4174.
- Krimmel, R.M. 1997. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1996 balance year. USGS OFR-97-4143.
- Letreguilly, A., and L. Reynaud. 1989. Spatial patterns of mass balance fluctuations of North American glaciers. *J Glaciol.*, 35(120), 163–168.
- Pelto, M.S. 1993. Current behavior of glaciers in the North Cascade and effect on regional water supplies. *Washington Geology*, 21(2), 3–10.
- Pelto, M.S. 1996. Annual balance of North Cascade glaciers from 1984–1994. *J. of Glaciology*, 41, 3–9.
- Pelto, M.S. 1996. Recent changes in glacier and alpine runoff in the North Cascades, Washington. *Hydrol. Processes*, 10, 1173–1180.
- Rasmussen, L.A., and W.V. Tangborn. 1976. Hydrology of the North Cascade Region, Washington 1. Runoff, Precipitation, and Storage Characteristics. *Wat. Res. Res.*, 12(2), 187–202.