Current Behavior of Glaciers in the North Cascades and Effect on Regional Water Supplies

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The North Cascade Glacier Climate Project (NCGCP) was established in 1983 to monitor the response of North Cascade glaciers to changes in climate. NCGCP receives its funds from numerous sources, primarily the Foundation for Glacier and Environmental Research. Each summer, NCGCP hires several students from Pacific Northwest colleges as assistants. Between 1984 and 1990, NCGCP observed the behavior of 117 glaciers; 47 of these were selected for annual study (Fig. 1). NCGCP has collected detailed information (terminus behavior, geographic characteristics, and sensitivity to climate) on 107 glaciers in every part of the North Cascade region. Annual mass balance measurements have been made on twelve glaciers and annual runoff measurements on four. Because most glaciers are in wilderness areas, researchers used simple equipment that could be transported in backpacks. This ensured a "light tread", minimized expenses, and allowed us to monitor many glaciers in a short time. With a glacier monitoring network now firmly established, our emphasis has shifted to providing natural-resource managers with information on fluctuations in glacier runoff.

The North Cascades of Washington extend from Interstate Highway 90 north to the Canadian Border. They are bounded on the west by the Puget Lowlands and on the east by the Columbia and the Chewuch (formerly Chewack) Rivers. This area supports 750 glaciers (Post and others, 1971) that store as much water as all of Washington's lakes, rivers, and reservoirs combined and provide approximately 230 billion gallons (87 million m^3) of water each summer (Meier, 1969). Nearly all this water is used for irrigation and power generation.

From 1944 to 1976, North Cascade glaciers were in good health: a majority of them advanced, and mean glacier runoff was high (Tangborn, 1980). Now, North Cascade glaciers are in retreat. This has been caused by a climate change, documented by records at eight North Cascade weather stations (Fig. 1). Mean winter precipitation for 1977 to 1992 has been 12 percent less than the long-term (1951–1980) mean for these stations. During the 1980s, NASA reported that the mean global temperature was 0.7°C (1.2°F) above the 1940–1978 mean. In the North Cascade region, most of the warming up to 1984 occurred during the winter (Trenberth, 1990). Mean summer temperature has been 1.0°C (1.8°F) above the long-term mean from 1985 to 1992.

HISTORIC TERMINUS BEHAVIOR

Since the end of the last ice age, three principal periods of alpine glacier advance have been identified in the North Cascades: Neoglacial (2,500–3,500 years ago), Little Ice Age (A.D. 1500–1800), and the recent advance (1944–1976) (Miller, 1969; Easterbrook and Burke, 1972; Hubley, 1956). The Neoglacial and Little Ice Age advances were of approximately the same magnitude; snowlines descended 100 to 150 m (330–490 ft) and all glaciers advanced substantially. The recent advance was much smaller, and only 50 to 60 percent of the North Cascade glaciers advanced (Hubley, 1956; Meier and Post, 1962).

During the Little Ice Age mean annual temperatures were 1.0 to 1.5°C (1.8–2.8°F) cooler than at present (Burbank, 1981; Porter, 1981). Depending on the glacier, the maximum advance occurred in the 16th, 18th, or 19th century, with little retreat prior to 1850 (Miller, 1969; Long, 1956). The temperature rise at the end of the Little Ice Age led to ubiquitous and rapid retreat from 1880 to 1944 (Hubley, 1956). The average retreat of Mount Baker glaciers from their Little Ice Age maximum to their present positions was 1,440 m (4,725 ft). In contrast, the average retreat of all North Cascade glaciers during this period was 550 m (1,800 ft); the range was from 1,600 m (5,250 ft) on Honeycomb Glacier to 100 m (325 ft) on Lower Curtis Glacier. The amount of recently deglaciated terrain in this area indicates that the climate change at the end of the Little Ice Age eliminated approximately 300 glaciers and approximately 30 percent of the total glacier area.

PRESENT TERMINUS BEHAVIOR

Advances and retreats are the best measures of long-term glacier health. With the exception of those on Mount Baker, few North Cascade glacier termini were observed prior to 1949. From 1951 to 1956, Richard Hubley of the University of Washington monitored terminus changes of North Cascade glaciers by taking aerial photographs of the glaciers each summer. This survey was continued by Austin Post of the U.S. Geological Survey (USGS) during the next decade. In the early 1970s, only glaciers on Mount Baker and Glacier Peak were observed by the USGS, and although some photographs were taken, since 1975 only the Klawatti and South Cascade Glacier termini have been analyzed (Tangborn and others, 1990). The only other terminus measurements since 1975 have been made by NCGCP.

For each glacier in the program, NCGCP crews determined terminus position change by measuring with a tape from fixed benchmarks at three locations beyond the glacier terminus—one at the center of the glacier and one each halfway from the center to the lateral margins of the terminus. Each measurement was made approximately perpendicular to the glacier front. The terminus change was the average of the three measurements.

Hubley (1956) demonstrated that North Cascade glaciers began to advance in the early 1950s, after 30 years of rapid retreat, in response to a sharp rise in winter precipitation and a decline in summer temperature beginning in 1944. Approximately half the North Cascade glaciers advanced during the 1944–1978 period of glacier growth (Hubley, 1956; Meier and Post, 1962; Muller, 1977). Advances of Mount Baker glaciers ranged from 120 to 800 m (395–2,625 ft) (Harper, 1992) and culminated in 1978 (Heikkinnen, 1984).

By 1984, all Mount Baker glaciers were retreating. In 1990, NCGCP measured the retreat of nine Mount Baker glaciers from their recent maximum positions. The average retreat was 50 m (165 ft) (Fig. 2, Table 1).

[1] In this article, the first unit of measurement given is the reporting unit, and the conversion is of approximately equal precision.

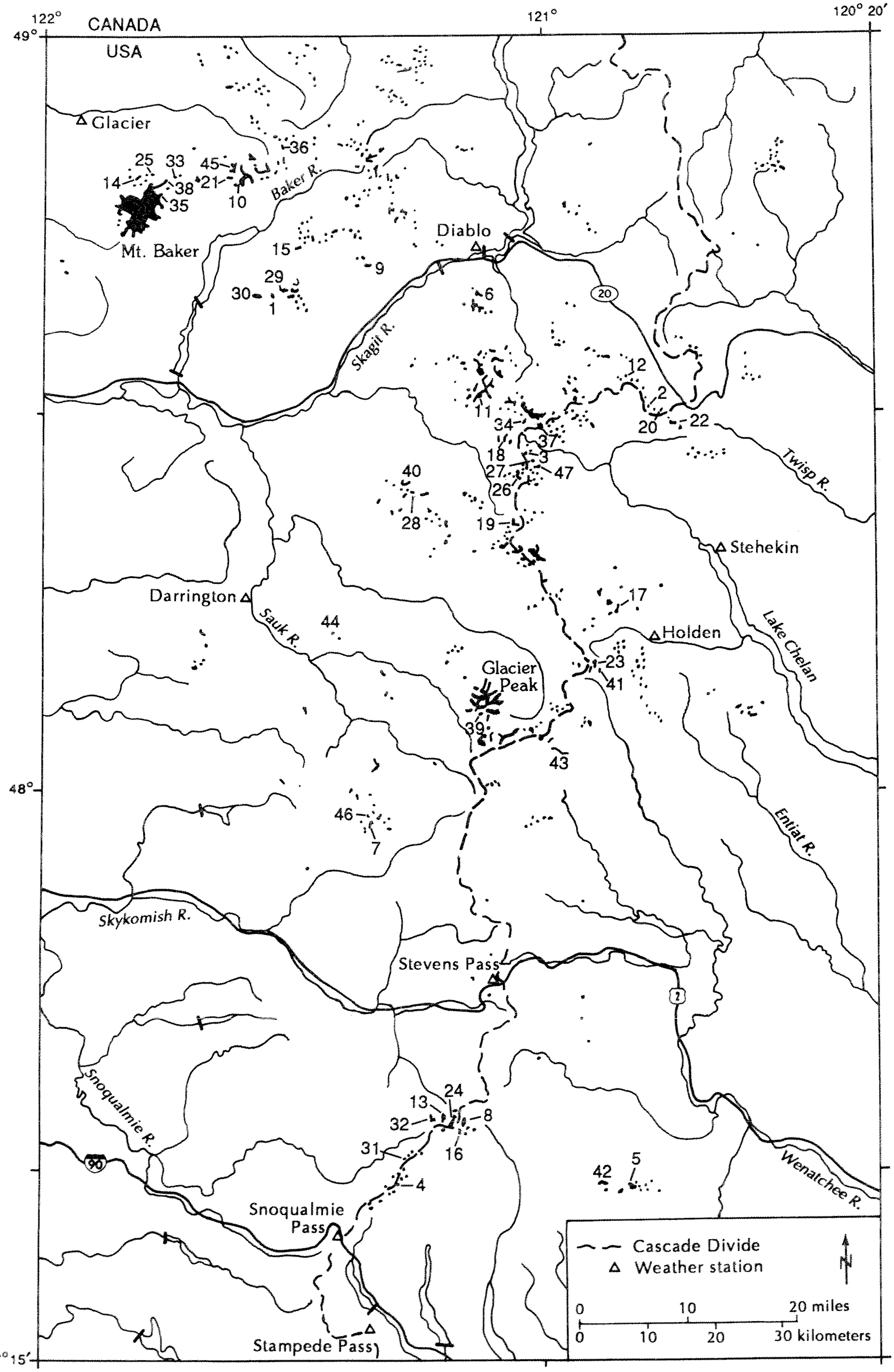

Figure 1. Locations of the 47 North Cascades glaciers studied by the NCGCP. Area weather stations also shown.

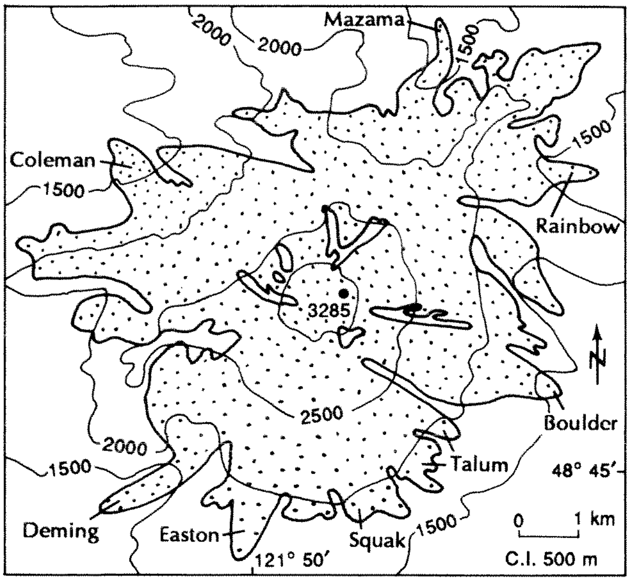

Figure 2. Glaciers on Mount Baker that have been part of the NCGCP study. See data in Table 1.

From 1984–1988, 91 of the 107 glaciers observed by NCGCP retreated significantly, 3 advanced, and 13 were in equilibrium. Of the 49 glaciers observed in 1992, 47 were retreating, and only LeConte Glacier on Sentinel Peak and Walrus Glacier on Clark Mountain were in equilibrium. Table 2 summarizes the terminus behavior of North Cascade glaciers from 1955 to 1992, and Table 3 lists the overall change in terminus position of 47 glaciers between 1984 and 1991 or 1992.

The recent retreat is due largely to a decrease in winter precipitation that began in 1977 (Fig. 3). At that time, the mean winter position of the Aleutian Low shifted southeast, resulting in more precipitation in Alaska and less precipitation in the Cascades (Trenberth, 1990; Pelto, 1990). The trend of North Cascade glacier retreat is typical of alpine glaciers around the world during the 1980s. In 1980, more than 50 percent of all small alpine glacier around the world were advancing (Haeberli, 1985), but in 1990 only 18 percent were advancing (Pelto, 1991).

One can also determine the current health of a glacier terminus by simply observing its profile and the number of crevasses (Meier and Post, 1962), as illustrated in Figure 4.

MASS BALANCE

For a glacier to survive, snow accumulation must equal or exceed snowmelt. Annual mass balance for a glacier is the difference between the amount of snow and ice accumulated and the amount of snow and ice melted during a hydrologic year (October–September). If there is more accumulation than melt, a positive balance results, and if net accumulation continues for several years, the glacier will advance. Where melting exceeds accumulation, a negative mass balance leads to glacier retreat.

For this discussion, estimates of mass balance are made from comparisons of annual snowline positions. The snowline, defined as a line above which the past winter's snow still covers older firn and ice, rises throughout the summer. Its position at the end of the hydrologic year (September 30) is the annual snowline position. The percentage of a glacier's total area that is above the snowline is a good indication of its mass balance (Meier and Post, 1962; Armstrong, 1989). The snowline can occur as a line at a specific altitude as it does at Mazama Glacier on Mount Baker, or it can be a patchwork of bare areas as at Eldorado Glacier near Cascade Pass.

Table 1. Minimum estimated advance of Mount Baker glaciers between 1949 and 1978 (Long, 1953, 1956; Muller, 1977) and the observed retreat of these glaciers from their 1979 maximum to 1990

Glacier	Advance (m) 1949–78	Retreat (m) 1979–90
Boulder	575	55
Coleman	610	73
Deming	510	53
Easton	440	8
Mazama	450	38
Rainbow	215	60
Squak	275	35
Talum	305	78

Factors Affecting Mass Balance

North Cascade glaciers are sensitive to four climatic variables: summer temperature, summer cloud cover, winter precipitation, and freezing levels during May and October precipitation events (Porter, 1977; Tangborn, 1980; Pelto, 1988). Glacier behavior is also influenced by geographic characteristics that affect how much snow accumulates and melts: orientation (the direction the glacier faces), glacier altitude, accumulation sources, radiational shading, and location with respect to the Cascade Crest. For example, a southern orientation and few surrounding peaks lead to increased sun exposure and more summer melting. A westward orientation results in reduced wind drift accumulation compared to an eastern orientation because most storms come from the southwest. Glacier altitude is the mean altitude of the glacier with respect to the mean local annual glacier snowline. Radiational shading is a combination of glacier orientation and the shading provided by the surrounding peaks. All these factors except accumulation sources can be identified from map analysis.

Accumulation sources are direct snowfall, wind drifting, and avalanching. To determine accumulation sources requires direct examination of the snowpack on the glacier. Avalanche accumulation can be recognized by the uneven, and in places blocky, nature of the surface where avalanches have deposited snow. Wind drift accumulation can be recognized by rapid changes in snow depth in the lee of ridges and changes in glacier slope. Direct snowfall has a fairly consistent depth for a given altitude and few rapid changes in snow depth.

From a comparison of annual mass balance measurements and from observation of the area of accumulation above the annual snowline, both completed annually on 11 glaciers and at least once on 37 other glaciers, the area of accumulation above the annual snowline necessary for equilibrium could be estimated.

In the North Cascades, if avalanche accumulation is received, then between 60 and 65 percent of a glacier's area

Table 2. Terminus behavior of North Cascade glaciers as noted in 1955 by Hubley (1956), in 1961 by Meier and Post (1962), in 1967 by Post and others (1971), in 1975 by the USGS (Muller, 1977), and by the North Cascade Glacier Climate Project in 1988 and 1992. Data reported as percentage of the total number of glaciers observed

Year	Glaciers examined	Advancing (%)	Stable (%)	Moderate retreat (%)	Rapid retreat (%)
1955	63	61	21	5	13
1961	137	2	46	48	4
1967	22	32	36	18	14
1975	13	69	8	8	15
1988	107	3	15	60	22
1992	48	0	4	41	51

must be in the accumulation zone above the snowline, at the end of the summer for it to be in equilibrium. If a glacier does not receive avalanche accumulation, then 65 to 70 percent must be above the snowline for equilibrium.

NCGCP has monitored the snowcovered area on 47 glaciers annually at the end of the hydrologic year (Pelto, 1987, 1988). From 1985 to 1992, only 49 percent of the average North Cascade glacier remained snow covered at the end of September. This indicates significant negative balances, which have resulted in glacier retreat.

Characteristics Affecting Glacier Health

Glaciers cease to exist when there is not enough accumulation to support flow. Glaciers that have an insufficient accumulation zone to survive the present climate regime usually have several of the following characteristics: southern orientations, poor radiational shading, direct snowfall accumulation only, a location east of the Cascade Crest, and a low altitude with respect to the local snowline. Any glacier with three of these characteristics is likely to disappear in the next few decades. A survey of North Cascade glaciers indicates that between 120 and 140 glaciers have three of the aforementioned characteristics. East of the Cascade Divide most glaciers have these characteristics and are likely to disappear soon. Glaciers that fall into this category now have thin concave termini and accumulation zones of limited extent and limited altitude range.

By comparing the retreat rate of 107 North Cascade glaciers for which these geographic characteristics are known, the effect of each characteristic on glacier health is evident. A location west of the Cascade Crest, a northward orientation, multiple accumulation sources, a high mean altitude, and substantial radiational shading are geographic characteristics that tend to slow retreat. A location east of the Cascade Crest, direct snowfall accumulation only, poor radiational shading, and a low mean altitude are associated with more rapid retreat.

GLACIER RESPONSE TO CLIMATIC WARMING

At the end of the Little Ice Age, warming of only 1.2°C (2.1°F) (Burbank, 1981) led to an average North Cascade glacier retreat of 550 m (1,800 ft), the disappearance of approximately 300 glaciers, and a minimum loss of 30 percent of the volume of North Cascade glaciers.

The USGS defines glaciers as any perennial snow-ice mass larger than 0.1 km^2 (0.03 mi^2). This means that aerial photographs can be used to distinguish glaciers (Post and others, 1971). Between 1990 and 1992, NCGCP confirmed by field measurement of glacier area that 17 of the 756 glaciers identified by the USGS in 1969 no longer meet the definition.

Of the 107 glaciers first observed by NCGCP in 1984, three no longer exist. Lewis Glacier near Rainy Pass stagnated in 1987 and melted away in 1989. Klenhi Glacier on Mount Daniel melted away in 1992. David Glacier on the north side of Mount David disappeared in the late 1980s.

In the Cascade Pass area, two small glaciers in Torment Basin and two beneath the Triplets and Cascade Peak have altitude ranges of less than 500 ft (150 m). In 1985, 1987, 1990, and 1992, these glaciers were entirely in the ablation zone. If present conditions continue, they will disappear.

In the Mount Stuart area, 15 glaciers existed in 1969; today 12 are left, and of these, 4 are on the verge of vanishing. At the turn of the century, Snow Creek Glacier comprised three ice masses separated by narrow bedrock ridges and covered 2.0 km^2 (about 0.8 mi^2). Today, there are nine ice masses covering just 0.4 km^2 (0.15 mi^2), and three of these ice patches are not moving.

In 1971, Hinman Glacier on Mount Hinman was listed as the largest glacier between Mount Rainier and Glacier Peak. It had an area of 1.3 km^2 (0.5 mi^2) (Post and others, 1971). By 1992, the glacier had separated into three masses with a total area of just 0.4 km^2 (0.15 mi^2). A new 0.4-km^2 lake has appeared where the glacier is still shown on USGS topographic maps.

On the current (1965 edition) USGS topographic map of the Mount Daniel area, Lynch Glacier is shown with an area of 0.9 km^2 (0.35 mi^2) and occupying the basin that now holds Pea Soup lake. Lynch Glacier receded out of the basin in 1983. By 1992, air-photo mapping showed that Pea Soup lake had an area of 0.35 km^2 (0.13 mi^2) and Lynch Glacier had shrunk to 0.5 km^2 (0.19 mi^2).

If our climate warmed 2.0°C (3.6°F) in the near future (as is typically projected for a greenhouse warming), then, on the basis of observed lapse rates of temperature (Porter, 1977), the average glacier snowline would rise nearly 300 m (975 ft). For example, Sahale Glacier near Cascade Pass extends from 7,350 to 8,600 ft, an altitude range of 1,250 ft (380 m). It has a fairly uniform slope and a present annual snowline at 8,100 ft (2,470 m). With this snowline elevation, the glacier will be in equilibrium at half its present size. If the

Table 3. Change in terminus position of 47 North Cascade glaciers between August 1984 and August 1991(*) or August 1992. Glacier locations are indicated in Figure 1

Loc. no.	Glacier	Terminus change (m)	Latitude	Longitude
1	Bacon Creek	-13	48 40	121 30
2	Black	-14*	48 32	120 48
3	Cache Col	-29	48 27	121 03
4	Chimney Rock	-21	47 30	121 17
5	Colchuck	-24	47 29	120 50
6	Colonial	-38	48 40	121 08
7	Columbia	-31	47 58	121 21
8	Daniels	-45	47 34	121 10
9	Davis	-25	48 44	121 12
10	East Curtis	-22	48 49	121 37
11	Eldorado	-17	48 31	121 08
12	Fisher	-27	48 33	120 51
13	Foss	-48	47 34	121 12
14	Hadley	-18	48 49	121 49
15	Hidden Creek	-17	48 44	121 30
16	Ice Worm	-41	47 34	121 10
17	Isella	-33	48 14	120 52
18	Johannesburg	-22	48 28	121 06
19	LeConte	+10*	48 22	121 02
20	Lewis	-82	48 31	120 48
21	Lower Curtis	- 4*	48 50	121 37
22	Lyall	-39	48 29	120 45
23	Lyman	-62	48 10	120 54
24	Lynch	-46	47 34	121 11
25	Mazama	-47*	48 48	121 48
26	Middle Cascade	-41	48 25	121 03
27	Mixup	-29	48 27	121 02
28	Mutchler	-18	48 24	121 15
29	Noisy Creek	-26	48 40	121 32
30	North Watson	-33	48 39	121 34
31	Overcoat	-24	47 30	121 18
32	Hinman	-141	48 34	121 14
33	Ptarmigan	-33	48 49	121 45
34	Quien Sabe	-53	48 30	121 03
35	Rainbow	-68	48 48	121 46
36	Ruth	-16*	48 52	121 32
37	Sahale	-31	48 49	121 02
38	Shoales	-28	48 49	121 46
39	Sitkum	-51	48 07	121 08
40	Snowking	-12	48 25	121 17
41	Spider	- 8	48 10	120 53
42	Stuart	-36	47 12	120 54
43	Walrus	0*	48 03	120 58
44	White Chuck	-32*	48 13	121 25
45	White Salmon	-24	48 50	121 37
46	Wilman	-19	47 58	121 22
47	Yawning	-20	48 27	121 02

snowline rises to 8,300 ft (2,530 m), however, the accumulation zone will be too small to sustain the glacier. Any glacier on which the difference in elevation from the present day annual snowline to the upper accumulation zone is less than 300 m (980 ft) will not survive.

Approximately 60 North Cascade glaciers could survive 2°C (3.6°F) warming. The remaining 690 would disappear within 40 years. Thus, within a few decades, half the North Cascade glaciers could disappear if the greenhouse warming follows the anticipated trend.

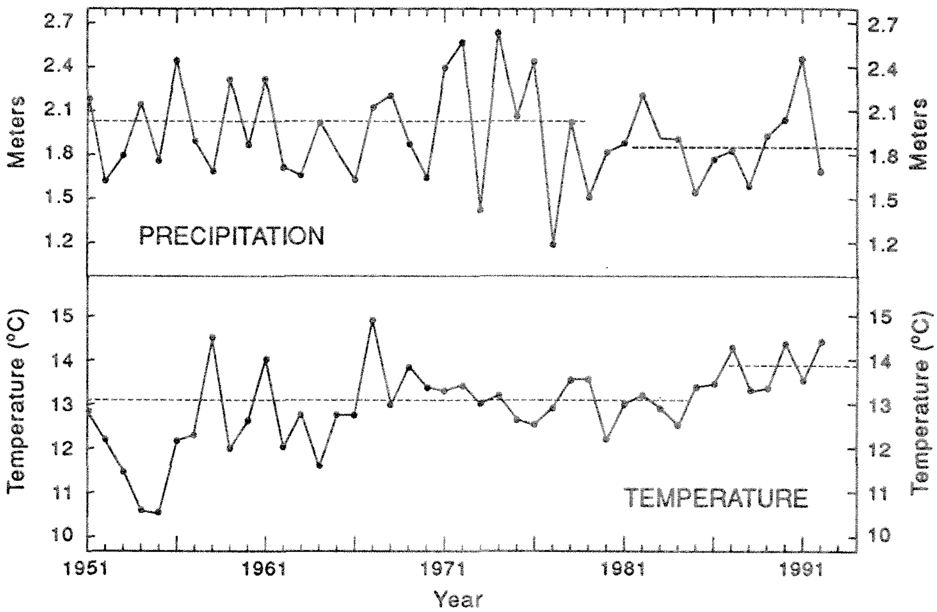

Figure 3. Mean annual ablation season temperatures (May–September) and annual accumulation season precipitation values (October–April) at Stampede Pass. The dashed lines represent the mean for the different periods. Note the decline in precipitation beginning in 1977 and rise in summer temperature in 1985.

MELTWATER STORAGE

During spring and early summer, accumulated layers of snow and firn on a glacier act as an unsaturated aquifer, soaking up (Bazhev, 1986) and holding approximately 50 percent of all meltwater generated on the glacier (Krimmel and others, 1973). The larger this aquifer, the more meltwater it can store and the longer the delay in release of glacier runoff. The size of the aquifer is determined by measuring the thickness and extent of the snow and firnpack (Bazhev, 1986). The other factor affecting delay is the weather during the melt season.

Table 4 indicates that, in an average year, peak spring runoff from basins with a significant percentage of glacier cover is delayed by 4 to 6 weeks relative to peak spring runoff from unglaciated basins (Pelto, 1992; Fountain and Tangborn, 1985). Water retention in glaciers also reduces peak spring flows and lengthens the high spring-summer runoff period. This offers opportunities for water managers to more efficiently use the runoff. However, in 1986, 1987, 1990, and 1992, thin snowpack led to a delay in glacier runoff of only 2 weeks. This situation raised flood danger because peak glacier runoff overlapped peak non-glacier snowmelt runoff.

More important to water supply management is the reduction in summer glacier runoff due to glacier retreat. As glaciers shrink, the surface area available for melting is reduced and the volume of glacier runoff must decline. Initially, higher than normal melt rates cause retreat, and the increased runoff may offset the runoff decline due to the loss of glacier area.

Comparing Basins Types

During dry summers, glacier runoff is typically higher than normal and can buffer the effects of low summer flows. This is illustrated by runoff measurements in neighboring lightly and heavily glaciated basins (Table 5). Newhalem Creek and Thunder Creek basins were chosen because their climatic conditions and geographic characteristics are similar. During droughts, stream flow at the USGS gaging station on Newhalem Creek, whose basin is lightly glaciated, drops on average 34 percent below the long-term mean. In contrast, an 18 percent drop is noted at the USGS gaging station on Thunder Creek, which drains a heavily glaciated basin. Droughts were defined as periods when winter precipitation was below the long-term mean and the combined mean July and August precipitation was less than 6 cm (2.3 in.) at the eight North Cascade weather stations.

Comparing runoff measured at stream gages placed by NCGCP on neighboring glaciated and unglaciated basins of the North Fork Skykomish River, Stehekin River, and Baker Lake indicates that between July 15 and September 15, water release averaged 0.22 m^3/m^2 in glacier-free alpine areas, whereas it reached 2.1 m^3/m^2 in glacier-covered areas, or 950 percent more runoff for glaciated areas than for unglaciated areas. This means that a basin with 1.5 percent glacier cover, for example, receives approximately 14 percent of its mid- and late-summer supply from glacier runoff.

Regions recently deglaciated are still in high alpine areas with substantial snowpack. Thus, runoff should be higher there than for most glacier-free alpine areas. To determine the actual runoff decline due to decreased glacier area, runoff was monitored from the Lewis Glacier basin at a gage placed 100 m (330 ft) beyond the terminus. This small outlet stream was fed only by glacier melt; no other snow patches existed in the basin. In August 1985, Lewis Glacier had an area of 0.09 km^2 (0.04 mi^2) and released 0.15 million m^3 (5.3 million ft^3) of runoff. By August 1990, Lewis Glacier had disappeared, and runoff dropped to 0.04 million m^3 (1.4 million ft^3), just 27 percent of the glacial flow despite approximately the same monthly precipitation.

Baker Lake: A Case Study

Baker Lake is fed by 60 glaciers that have a total area of 15.3 km^2 (5.9 mi^2). (See cover photo.) Glacier runoff was determined from direct measurement of glacier ablation on four glaciers in this basin. The 60 glaciers released an average of slightly more than 25 billion gallons (9.4 million m^3) to Baker Lake between May 15 and October 1. This is 40 to 45 percent of the total summer runoff into Baker Lake (Pelto, 1991). If glacier retreat continues at its present pace, within 15 years summer glacier runoff in the basin will have declined by 4 to 6 billion gallons (1.5–2.3 million m^3).

The U.S. Army Corps of Engineers buys a certain amount of reservoir storage in Baker Lake each spring; this volume is left empty to hold any floodwaters. If the recent trend of early glacier runoff continues, more storage will have to be bought

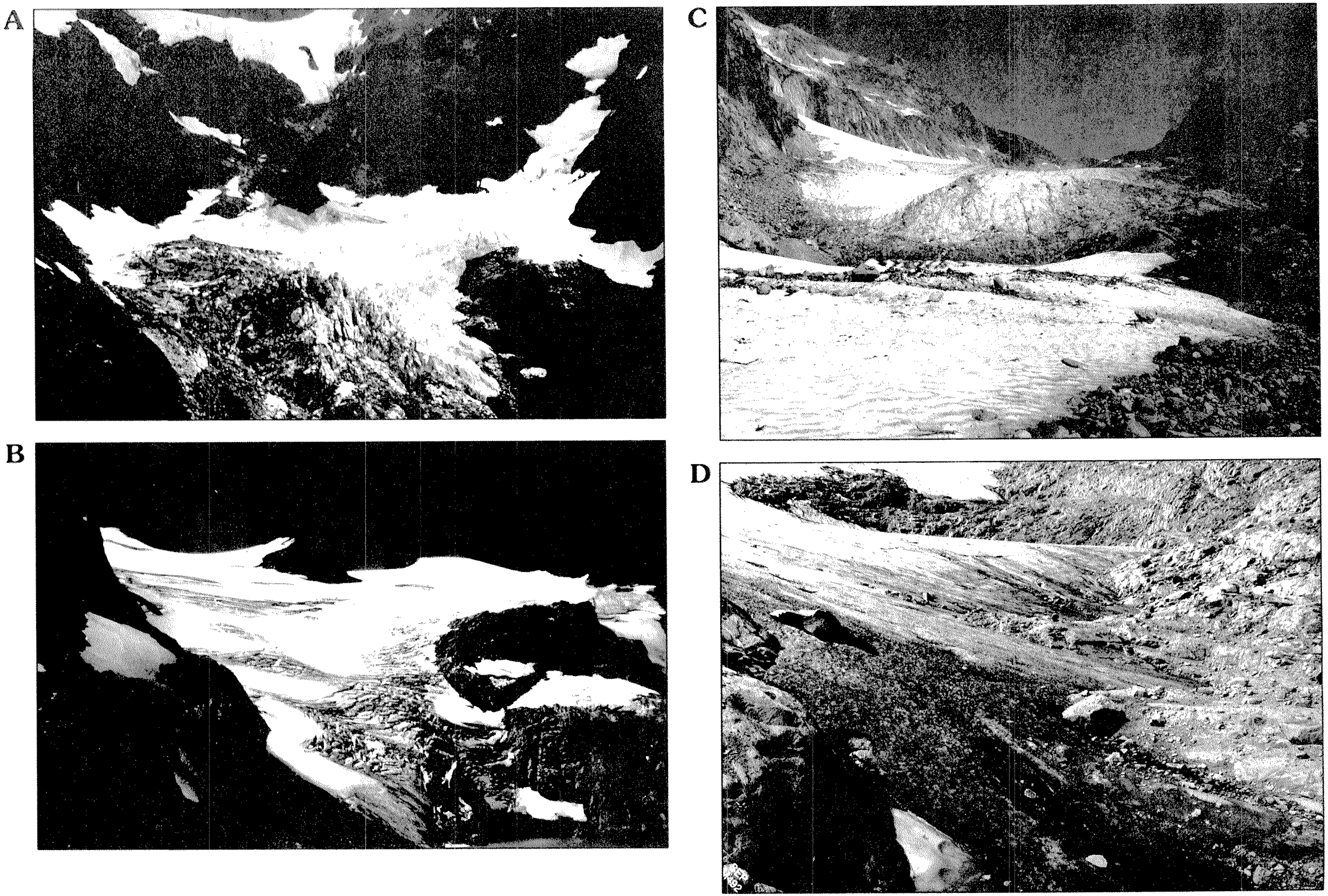

Figure 4. A glacier's front is active when it is advancing or in equilibrium. A, Lower Curtis Glacier on Mount Shuksan, 1985 – an active front distinguished by extensive crevassing and a rapid increase in thickness upglacier from the terminus, resulting in a strongly convex shape. B, Lynch Glacier on Mount Daniel, 1986 – a moderately active front, indicative of slow retreat, that has limited crevassing and a moderately convex surface at the terminus. C, Columbia Glacier at Monte Cristo in 1986 – a moderately retreating terminus that has few crevasses and a thin, flat terminus. D, Foss Glacier, Mount Hinman, 1986 – a rapidly retreating terminus that is not crevassed and has a flat or even concave surface at the thin terminus.

in some years to protect against flooding. If the glaciers are monitored, managers will be prepared to purchase more storage when a warm summer (reducing glacier snow and firn pack) is followed by a moderately wet winter. During dry winters, low snowpack accumulation in unglaciated areas would not significantly augment the early peak in glacier runoff. The magnitude of the decline in glacier runoff and summer runoff would dictate how much additional water needs to be stored early in the summer to maintain sufficient late summer streamflow in the Baker River. NCGCP has in place a program to determine the changing contribution of runoff from glaciers to Baker Lake.

WATER SUPPLY FROM NORTH CASCADE GLACIERS

North Cascade glaciers are an important natural resource because they contribute 20 to 25 percent of the region's total summer water supply. We rely heavily upon glacier runoff to meet basic water demands, including hydropower generation, irrigation, and fisheries. In the past, water resources have been sufficient, regardless of climate. However, the continued rapid development in the Puget Sound region has increased demand. At the same time, average annual precipitation has been 15 percent below the long term mean since 1977, reducing water supply. Mean streamflow from July 1 to October 1 at the USGS gaging station on the Stehekin River at Stehekin was 46.3 m^3/s (1,635 ft^3/s) for the years 1951 to 1976; for 1977 to 1990, it was 36.5 m^3/s (1,290 ft^3/s), a 22 percent decline. The consequence was water shortages in the North Cascades area, necessitating rationing in some areas in 1985, 1987, and 1992.

Summer glacier runoff is the product of the mean ablation on these glaciers and their total area. Runoff rates are highest from June through September when the glaciers normally release approximately 230 billion gallons (87 million m^3) of water (Meier, 1969; Pelto, 1992). Glacier runoff is highest during warm, dry summers when the total water supply is low. This also is the period when precipitation and non-glacier runoff are lowest. Glacier runoff was comparatively stable and high from 1944 to 1980 (Tangborn, 1980), possibly lulling many into ignoring the role of glaciers in the water supply of the North Cascades.

The amount of runoff in a given year is determined primarily by annual precipitation. However, the timing of release of 230 billion gallons (87 million m^3) of summer glacier runoff to North Cascade streams is determined by the volume of glaciers, the volume of glacier aquifers, and weather conditions. Shrinking glaciers result in reduced runoff. Low flow in the late summer now threatens aquatic life in streams and lakes during dry years. Given present climate trends, this problem will become more severe.

Table 4. First day of peak spring discharge (defined as the first day of the highest 4-day total discharge) from three North Cascade basins with different percentages of glacier cover. Runoff data from USGS gaging stations

Year	Newhalem	Stehekin	Thunder
1984	May 29	May 29	June 20
1985	May 17	May 14	May 18
1986	May 18	May 19	May 26
1987	Apr 28	Apr 29	May 7
1988	Apr 13	Apr 14	May 11
1989	Apr 5	Apr 15	June 1
1990	Apr 11	Apr 14	June 16
Mean	Apr 30	May 2	May 28
% of basin area glaciated	0.4	3.1	14.1

Table 5. Stream flow at USGS gaging stations on Newhalem Creek (lightly glaciated basin) and Thunder Creek (heavily glaciated basin) during drought conditions and percent depletion in streamflow from mean flow conditions; mean August flow is for 1955–1990

Date	Newhalem (m^3/s)	Thunder (m^3/s)
Aug. 1969	2.0	20.1
Aug. 1970	1.7	23.4
Aug. 1979	1.8	27.3
Aug. 1985	1.8	22.0
Aug. 1987	1.9	22.6
Mean Aug. flow	2.8	28.1
Depletion	34%	18%

With the increasing demand for water, all available information will be needed to make water management decisions that will best serve the needs of the area's population and aquatic ecosystems. The rapid changes in runoff occurring in the Skykomish, Stehekin, and Baker Lake basins emphasize the futility of managing our water resources without considering the changing influence of glaciers. If demand for water from the region's rivers continues to increase, then maintaining the present flow levels through the summer will require different water-management practices and must include analysis of glacier fluctuations.

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Note: Because the glaciers are rapidly changing, NCGCP is establishing an archive of photographs of North Cascade glaciers to serve as a record of glacier variations. The collection will be duplicated and housed in both Sedro Woolley and Seattle under the aegis of the National Park Service and will be annually updated. Though the project cannot compensate you for the photographs, you will be fully credited in the archive. Please send contributions, with as much documentation as possible, to NCGCP. ■

Surficial Geologic Map of Seattle Now Available

Geologic map of surficial deposits in the Seattle 30′ x 60′ quadrangle, Washington, by J. C. Yount, J. P. Minard, and G. R. Dembroff, has been released as U.S. Geological Survey Open-File Report 93-233. It is comprised of two oversize sheets, scale 1:100,000.

It sells for $12.75 paper; $1.50 microfiche. Order from:

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Hecla Honors Republic Unit Workers for Outstanding Safety Record

Hecla Mining Company's underground hardrock gold mine in northeast Washington set a safety record by going the entire year of 1992 without a lost-time accident. The last lost-time accident at the Republic unit was in September 1991, bringing the total length of the safety record to nearly 18 months.

Each of the Unit's 124 employees was awarded a ¼-ounce pure gold medallion for the accomplishment. The medallions were designed by the Unit's draftsman, Shannon Sheridan, and show the Republic mill on one side, with the Republic decline, headframe, and front-end loader on the other side. The safety medallions were made from gold mined and milled at the Republic unit.

Ron Clayton, Republic Unit manager, said it's very rare for an underground hardrock mine or any other industrial operation to go more than a year without any lost-time accidents. Clayton said the record is not due to luck. "It takes a lot of hard work to get to this point," he said. "We have a full-time safety supervisor who works with all department heads. Each department has its own safety committee, which reviews accident reports, talks about how those accidents could be prevented and makes sure the employees are very safety conscious. These people meet on their own time, and we have many more people ready to volunteer as members on the committees." Clayton said safety is the most important piece of everything done at the Unit. "People watch out for themselves and each other...that's part of their job. Our employees readily accept this responsibility and deserve the credit for this significant accomplishment."

Hecla Mining Company is headquartered in Coeur d'Alene, ID. During its 102-year history, Hecla has been a leading producer of silver and lead, and more recently, a significant supplier of gold and industrial minerals.

(From a March 11, 1993, Hecla press notice)