Glacier Change in the North Cascades National Park Complex, Washington State USA, 1958-1998

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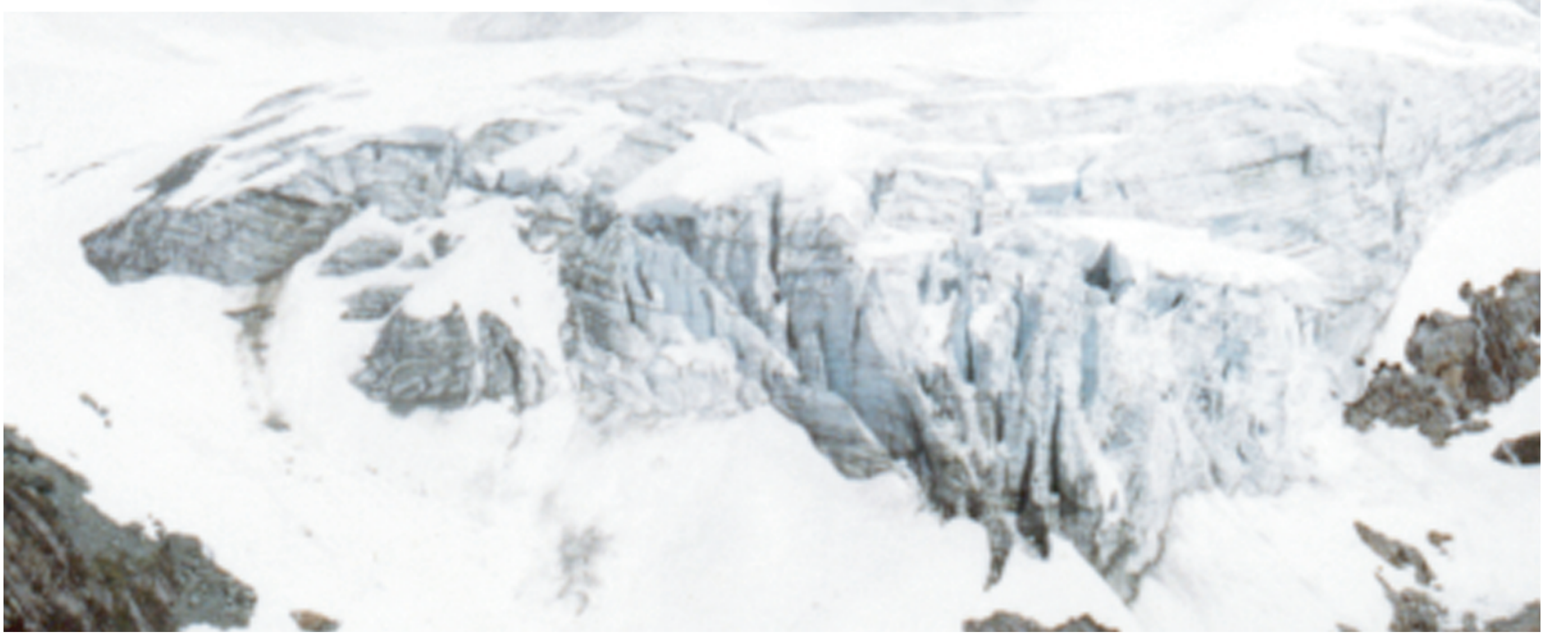

THESIS APPROVAL

The abstract and thesis of Frank D. Granshaw for the Master of Science in Geology were presented December 7, 2001, and accepted by the thesis committee and the department.

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ABSTRACT

An abstract of the thesis of Frank D. Granshaw for the Master of Science in Geology presented December 7, 2001.

Title: Glacier Change in the North Cascades National Park Complex, Washington State USA, 1958 to 1998

The North Cascades National Park Complex contains 25% of the glaciers of the contiguous United States. In addition to their ecological and scenic value, these glaciers are a major water resource for northwestern Washington. Despite their importance, little information about glacier change in the complex exists. To address this problem an inventory of all glaciers in the complex was constructed for 1958 and for 1998. Data from this inventory, regional climate data, and streamflows for selected watersheds were used to determine the extent of glacier change, the causes of that change, and the impact of glacier change on regional water resources.

From 1958 to 1998 the glacier population of the complex dropped from 321 to 316 and combined glacier area decreased by 7.0%. Total glacier volume loss is estimated at -0.8±0.1 km^3. This reduction resulted from the disappearance of five small glaciers and mass loss from 80% of the remaining glaciers. This change was due to a warming, drying trend in regional climate, particularly during the period 1977-1997. Rates of change for individual glaciers were primarily influenced by area, but unaffected by other topographic characteristics. During the period 1958-1998, glacier mass loss contributed less than 1.0 km^3 to the total stream flow of the Skagit, Nooksak, and Stehekin Rivers. Though this contribution may seem insignificant, average annual glacier mass loss accounts for 0.1 to 6.0% of the runoff during the two driest months of the year, August and September. Alternately, average mass loss augments precipitation by as much as 16%.

A comparison of the topographic characteristics of five regularly monitored or "index" glaciers to the regional database revealed that only one of these glaciers, Sandalee Glacier, is representative of the typical glacier in the complex. The changes in the index glaciers to area / volume changes in the bulk of the glaciers show that index glaciers can not be used to accurately infer the magnitude of the regional change in glacier cover. However, the index glaciers can be used to infer the rate of change over time.

GLACIER CHANGE IN THE NORTH CASCADES NATIONAL PARK COMPLEX, WASHINGTON STATE USA, 1958 TO 1998

by

FRANK D. GRANSHAW

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Chapter 1 - Introduction

Alpine glaciers make up less than 3% of the earth's ice cover. Yet, despite their spatial insignificance, the mass loss of small glaciers accounts for approximately 20 to 50% of the 10-15 cm rise in sea level that took place during the last century (Dyurgerov and Meier, 1997; Kuhn, 1993; Meier and Bahr, 1996, Oerlemans and Fortuin, 1992). Furthermore, small glaciers are highly sensitive to changes in temperature and precipitation (Meier, 1984; Oerlemans et al. 1998), making them important indicators of regional climate change. Volume loss of alpine glaciers produces changes in the area and distribution of alpine and subalpine biological communities (Hall, 1994). Variations in glacier mass affect stream flow volume and timing which in turn affect hydroelectric power production, irrigation, and domestic water supplies (Post et al., 1971, Tangborn, 1980; Østrem, 1991). Consequently, the monitoring of alpine glaciers is an important component of resource planning and climate change evaluation.

My research area is the North Cascades National Park Complex, which contains approximately one quarter of the glaciers in the contiguous United States (Meier, 1961). Because of this large population, glaciers play a significant role in the hydrology, ecology, and economy of both the complex and of northwestern Washington. For instance, two of the three major watersheds in the complex, Skagit and Stehekin Rivers, contain five hydroelectric facilities providing power for Seattle, Tacoma, and Chelan, Washington. The production cycle of these facilities is highly dependent on the timing and volume of stream flow which is in turn influenced by patterns of snow and ice melt (Tangborn, 1980b). Furthermore, the National Park Complex is visited by over 600,000 tourists annually (Riedel, U.S. National Park Service, personal communication, 2001). Since the glaciers are a major feature within the complex they are important to the recreational economy of the region. Finally, significant portions of the complex are alpine and subalpine ecosystems which are dependent on the water flow from these glaciers. Thus, the loss of glacier mass would have a strong impact on the biological character of much of the complex (Hall, 1994).

Project Description

The aim of this thesis is to determine the extent of glacier change within the North Cascades National Park Complex. An updated glacier inventory would contribute to the growing database of global glacial change being assembled by the World Glacier Monitoring Service. The specific goals of this project are:

1. Define the population and area of glaciers in the North Cascades National Park complex in 1958 and 1998, and the areal and volume changes that took place between those two years.
2. Determine whether the changes of the regional benchmark glacier (South Cascade) and four "indicator" glaciers inside the complex reliably represent change in the general glacier population of the complex.
3. Calculate the contribution of glacier volume loss to regional stream flow.
4. Examine the relationship between glacier volume changes and climatic changes during the 1958-1998 period.

Previous work

Techniques for Glacier Monitoring

Glacier monitoring includes mapping and measuring the characteristics of individual glaciers as well as mapping and cataloging groups of glaciers with the aim of determining glacier change over time (Fountain et al., 1997). Glacier monitoring has been conducted in some form since the early 1700's (Østrem and Haakenson, 1993). The earliest of these studies were limited to recording changes in the terminal position of a few glaciers. Up until recent times glacier monitoring was difficult because of the inaccessibility of many glaciered areas. With the advent of aerial photography it became feasible to construct comprehensive maps and database for regions with glaciers (glacier inventories). By the 1980's the rapid development of satellite imaging, geographic information systems, computer technology, and global positioning systems made it possible to compile detailed inventories relatively quickly.

Glacier monitoring typically involves ground-based measurements, aerial reconnaissance, and satellite imaging. Ground-based measurements include surveying termini positions, glacier topography, and mass balance (Østrem and Brugman, 1991; Haeberli et al., 1989; Ommanney, 1970). Aerial reconnaissance consists of taken oblique and vertical photographs usually during late summer when snow lines reach their highest altitudes revealing the maximum extent of perennial ice. Oblique photography is often taken without precise positional information so the quantitative information from this imagery is often quite limited. However, when used in conjunction with detailed topographic maps, changes in the position of major glacial features can be re-mapped in relation to stable bedrock or other non ice features (LaChapelle, 1962). Vertical aerial photography with ground control, on the other hand, provides a quantitative base for accurate mapping of surface features. Increasingly, aircraft based laser altimetry (Favey et al, 1999; Echelmeyer et al. 1996) and LIDAR (Krabil et al., 1995) is being used to rapidly construct topographic profiles and maps of glacier surfaces.

Satellite imagery used in glacier monitoring includes both multi spectral and radar imaging (Williams and Halls, 1998; Sidjak and Wheate, 1999; Li et al., 1998; Williams, 1987; Champoux & Ommanny, 1986) . Because of its high altitude, a satellite can image a large section of the earth's surface in a single image. Furthermore, the image is coded in such a way that the image can be digitally manipulated to extract geospatial information (Campbell, 1996). The primary limitation to using satellite imagery to analyze long-term glacier changes is the lack of systematic and repetitive data acquisition. Furthermore the current cost of satellite data limits the amount of data that can be acquired and archived (Williams, 1991).

Geographic information system (GIS) technology is a useful tool for compiling glacier data. Glacier maps can be digitally linked to extensive databases containing spatial and nonspatial glacier information including descriptions of map or data quality (metadata). Once in a GIS, digital maps of different information can be manipulated to derive additional information, such as glacier orientation, population, and total glacier area of selected watersheds.

Glacier monitoring on the global scale

Worldwide collection of information on glacier change was begun in 1894 with the formation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland. Eventually the commission was replaced with the World Glacier Monitoring Service (WGMS), under the auspices of the International Commission on Snow and Ice and the Federation of Astronomical and Geophysical Data Analysis Services under UNESCO. The tasks of the WGMS are to (1) collect and publish data on glacier fluctuations every five years, (2) to complete and continuously upgrade an inventory of the earth's glaciers, (3) to publish data from selected reference glaciers every two years, (4) to produce global coverage of the earth's glaciers using satellite imagery, and (5) periodically access global glacier change (Haeberli and Hoelzle, 2000). The current World Glacier Inventory (WGI) was first published in 1989 and includes data on 67,000 glaciers. The inventory is a compilation of data from 80+ separate inventories from every continent, as well as satellite imagery collected since the late 1970's . WGMS has also collected and published data from several hundred reference glaciers to produce a picture of glacier fluctuations for 1959 to 1990 (Haeberli et al. 1989).

Haeberli and others argue that nearly a century of systematic observations clearly demonstrate shrinkage of mountain glaciers on a planetary scale (Haeberli, 2000, Dyurgerov and Meier, 2000). Examination of the contribution of mass loss from small glaciers to global sea level suggest that the total volume of small glaciers may have decreased between 8 and 11% between 1900 and 1961 (Kuhn,1993; Meier and Bahr, 1996). Though there have been brief periods of advances, the rate of shrinkage appears to have accelerated toward the end of the twentieth century (Dyurgerov and Meier, 2000). For instance in the European Alps, alpine glacier volume dropped 50% between 1850 and and the mid 1970's. However, between 1980 and 1990 20% of the ice remaining in 1980 melted (Haeberlie and Hoezle, 1995). Based on current trends Meier (1984) estimated that a rise in global air temperature of 1.5 to 4.5°C could increase the annual rate of glacier wastage 4 to 11 times the average rate from the twentieth century.

One difficulty with estimating and predicting glacier change is that these projections are frequently based on detailed observations from a small number of the world's 36,000 glaciers (Haeberli et al., 1989). As an example, Meier and Dyurgerov (2000) examined global glacier change for 1960-1999 using a network of only 260 glaciers. In addition to the small sample size, analysis was further complicated by the extremely variable behavior of the individual glaciers. For instance, seven glaciers in North America, Europe, and Asia showed significant losses, while glaciers in Scandinavia and the Alps actually gained mass (Dyurgerov and Meier, 2000). These difficulties indicate a strong need for a regional analysis of glacier change to test the practice of estimating global glacier change using observed changes from individual glaciers.

Glacier monitoring in the United States

In the first half of the twentieth century glacier monitoring was largely nonexistent in the United States. By the beginning of the twenty-first century, limited monitoring programs were in place throughout the western United States (Fountain et al., 1997). In Washington State alone (Meier 1961) there are eight glacier inventories that are completed or in process for Mt. Rainier (Mennis, 1997; Nylen, in process), the Olympic Range (Spicer, 1986), Mt. Adams and Mt. St. Helens (Pinotti, in process), and the North Cascades (Meier, 1961; Post et al. 1971; this thesis). Likewise, regular measurement of terminus position or mass balance has taken place on Mt. Rainier, Blue Glacier in the Olympic Range, and fifty-two glaciers in the North Cascades. Similar monitoring has been done done in California, Wyoming, Montana, Colorado, Oregon, and Alaska (Haeberli et al., 1986).

To provide a structure for glacier monitoring in the United States, the U.S. Geological Survey (Fountain et al., 1997) proposed a three tiered program for glacier monitoring to improve the accuracy of glacier monitoring in a cost-effective way. For instance the cost of any regional monitoring program is greatly reduced by intensively monitoring only a few glaciers and using the data to estimate regional glacier glacier change. Likewise the accuracy of these estimates is improved by comparing the data to less detailed information for the entire region. In the first tier of the program, single glaciers within major glaciered regions in the United States are regularly monitored. These glaciers, called “benchmark” glaciers, are selected for their similarity to other glaciers in the region, ease of access, and extent of previous information. Measurements taken at benchmark glaciers include detailed measurement of mass balance, stream flow, and climate. The benchmark glacier for the North Cascades Range is South Cascade Glacier, which has been monitored since 1958. Tier 2 glaciers, or “secondary” glaciers, are limited to annual measures of mass balance and terminus position. The U.S. National Park Service has been monitoring four such glaciers in the North Cascades since 1993 - Sandalee, North Klawatti, Silver Creek, and Noisy Creek glaciers. The final tier proposed by Fountain et al.(1997) is the intermittent monitoring of areal changes for all of the glaciers in a region by aerial photography and satellite imaging. The Post et al. (1971) inventory and the work described in this report depend heavily on this approach.

Glacier monitoring in the North Cascades

Because of the difficulty of travel in the North Cascades, very few of the glaciers in the region have been monitored on a regular basis. The first official report on the glaciers of North America (Russell, 1885) mentions glaciers on the volcanic peaks of the Cascade Range, but none in the North Cascades. Russell later corrected this omission by including in his 1897 report the statement that “some glaciers *(are found)* in the non-volcanic mountains of the North”, but he did not list specific glaciers. However, it was not until the mid-twentieth century that systematic surveys of glacier change were initiated (Hubley, 1956; LaChapelle, 1962).

Before this thesis, there were only two inventories of glaciers in the North Cascades. The first is a census of glaciers in the contiguous United States (Meier, 1961), that lists 519 glaciers in the entire North Cascades Range. Because of the scope of that project, its listing of glaciers in the North Cascades was incomplete. The second inventory (Post et al.,1971) listed and described all ice masses in the North Cascades

Range that were larger than 0.1 km^2. The report included 756 glaciers having a combined area of 267 km^2. It also included analyses of the hydrologic significance and spatial characteristics of these glaciers. In part, this thesis is an update to the Post et al. (1971) inventory. Like this earlier work it is a census of ice masses larger than 0.1 km^2 and an analysis of glacier spatial characteristics and hydrologic significance. Unlike Post et al. (1971) it looks at glacier change while discussing the climatic and spatial factors causing that change as well as the impact of that change on regional stream flow.

Any analysis of glacier change in the North Cascades must look at data available from regularly monitored glaciers. The only glacier in the region having a detailed long term record is South Cascade Glacier which is located southwest of the National Park Complex. The glacier has been monitored every year since 1958 by the U.S. Geological Survey. Reports generated by this program (Meier, 1964; Meier et. al., 1971; Meier and Tangborn, 1965; Tangborn et al.,1977; Krimmel, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000) include data for seasonal and annual mass balance, local climate, and stream flow from South Cascade Basin. Other monitoring programs in the region have included mapping changes in glacier termini on Mt. Baker (Harrison, 1970; Harper 1992) and measuring terminus positions and net mass balance on 47 other glaciers spread throughout the range (Pelto, 1988). More recently, in 1993, the US National Park Service began a program of annually monitoring four glaciers in the National Park Complex for seasonal and annual mass balance, local climate, and doing subglacial topographic surveys (Riedel et al., 1997).

Significant glacier retreat is a consistent theme derived from all of these programs. These results have frequently been used to determine the extent of glacier change for the entire region. Only South Cascade Glacier has a long term record, estimates of long term regional glacier change have been inferred from trends for that single glacier. By looking at area and volume changes for every glacier in a selected area, this thesis examines the validity of this procedure and makes recommendations for using the results from monitoring individual glaciers to better estimate regional change.

Setting

General description

The North Cascades National Park Complex is located in the northern half of the North Cascades (Fig. 1.1), and is administered by the US National Park Service. The complex consists of three different administrative districts that include the North Cascades National Park, Ross Lake National Recreation Area, and Lake Chelan National Recreation Area. The National Park is largely undeveloped wilderness, while the two National Recreation areas contain several small towns, major roads, four hydroelectric plants, and a major power transmission network. This topography is characterized by steep relief, dense forest cover at low to middle elevations, and considerable exposed rock, snow, and glacier ice in the upper elevations. The complex covers an area of 2757 km^2 located between 120°33' W / 48°14'N and 121°39'W / 49°N. It straddles the crest of the North Cascades and ranges in altitude from less than 100 to over 2800 meters (Becky, 1995a, 1995b).

The northern park unit extends from the Canadian border to the Skagit River. It is bounded on the east by Ross lake and extends westward to Mt. Shuksan and Baker Lake. This area is a series of glacially carved valleys having significant relief. The floors and lower walls of the valleys are covered with dense evergreen forest that give way to subalpine vegetation at approximately 1300 meters. The upper valley walls are a collection of cirques and hanging valleys that contain small lakes, glaciers, or perennial snow fields. Razor like ridges separate the valleys from one another. Large clusters of glaciers appear on the slopes of eight peaks, most notably Mt. Shuksan and Mt. Redoubt. Another major cluster is located on the crest of the Picket Range situated in the center of the northern unit.

The Ross Lake / Skagit River valley is a glacial trough that trends south along the eastern edge of the complex before turning west between the two park units. The entire corridor is the merger of two large glacial valleys formed during the late Pleistocene (Waitt, 1977). Ross Lake lies north of Ross Dam and extends a few kilometers into

Canada. This lake was formed by the construction of Ross Dam which flooded the Upper Skagit River up to the Canadian Border. West of Ross Dam, the Skagit River is again impounded by a hydroelectric dam forming Diablo lake. After passing Diablo Dam, the Skagit flows unobstructed into the Puget Sound.

The southern park unit excluding the Stehekin River basin is bordered on the north by the Skagit River and to the south by the Cascade divide. It is similar to the north unit in that it consists of a network of densely forested glacial valleys fringed by glacier clad peaks. One of the largest of these valleys, Thunder Creek, has over 12% of its total area covered by glaciers (Fountain and Tangborn, 1985) and contains the largest glaciers in the North Cascades. All the streams in this part of the unit flow northward in the Skagit River.

The Lake Chelan / Stehekin River basin is located east of the Pacific Crest. The centerpiece of the basin is a deep post glacial valley fringed by heavily forested mountains and glaciered peaks reaching over 2800 meters. Eight major streams drain into the Stehekin river, which eventually empties into Lake Chelan near the town of Stehekin, Washington. Lake Chelan, a natural lake formed by morainal damming of a glacial trough, extends some 80 kilometers southwest of Stehekin.

Geology

Bedrock in the complex consists almost exclusively of Mesozoic and Paleozoic metamorphic, intrusive, and sedimentary rock of the Western, Metamorphic Core, and Methow domains (Tabor et al., 1989). The structure of the rock underlying the complex is dominated by two north and northwest trending fault systems (Tabor et al., 1989; Tabor and Haugerud, 1999). These two systems, the Straight Creek Fault and the Ross Lake Fault System lie at boundaries of the three rock domains. Several smaller faults intersect these systems at oblique to nearly right angles clearly appear in aerial photographs of exposed rock adjacent to glaciers.

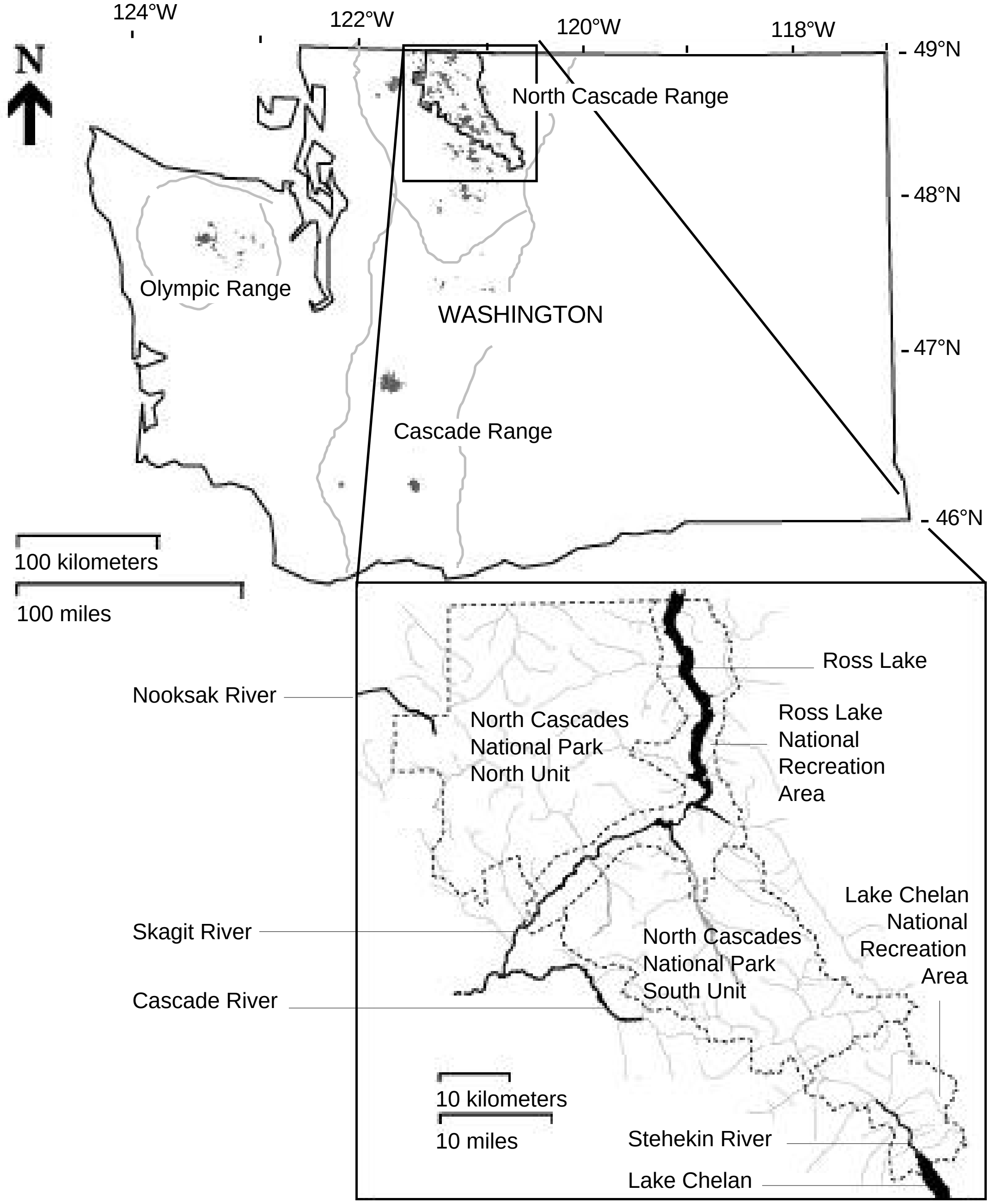

Figure 1.1 - Location of study site, glaciered mountain ranges, and glaciers in Washington State. Glaciers appear as gray areas located in each of the mountain ranges.

Between 800 thousand years ago and the present there were four major glaciations in Western North America (Driedger and Kennard, 1984; Easterbrook, 1986). These glaciations played a significant role in shaping the topography of the North Cascades. During the Pleistocene, North Cascade alpine glaciers frequently expanded until they coalesced with the Cordilleran Ice Sheet. The advancing glaciers which formed in preexisting stream valleys, eroded the valleys into deep U-shaped troughs. At the same time, up glacier erosion produced a complex system of arêtes, horns, and cirques. In several instances, glaciers altered the course of major streams (Waitte, 1977). Between 10 ka and the present, glacier advances occurred at ~7 ka, 2-3 ka, and during the last 700 years (Easterbrook, 1986). The last of these periods, known as the Little Ice Age, ended in the late 19th century.

Climate

Three principal factors shaping the climate of the North Cascades are location, regional air flow, and topography: The latitude of the North Cascades and their proximity to Pacific Ocean are responsible for seasonal variations in regional temperature and precipitation. Because the range is located in the northern mid latitudes it experiences regular changes in insolation and is affected by fluctuations in the position of the northern polar front. The Pacific ocean moderates temperatures in the region, while providing it with an ample supply of moisture. Average total annual precipitation in the complex ranges from 120 to 325 cm, with the greatest amounts falling in the high mountains and the lowest values recorded in the low lying valleys and east of the Cascade divide (Post et al., 1971). Likewise, snowfall is highest in the upper elevations, giving the complex a range of less than 5 to over 10 m for average total annual snowfall. (Jackson, 1985) .

Throughout the year, prevailing westerly winds bring significant amounts of marine air into the Pacific Northwest. During winter, a semi-permanent low pressure, the Aleutian Low, resides over the North Pacific, while a semi-permanent high pressure center lies to the southwest of California (Fig. 1.2). This causes air from the Pacific to flow from the southwest over Washington State (Jackson 1985). When this cool, moist marine air meets colder, drier continental air, cyclonic storms are produced that move eastward over the Northwest. During summer, the Aleutian low dissipates, while the high pressure center migrates northwest to settle over the central North Pacific. As a result, air flow into Washington, changes direction flowing from the Northwest. The oncoming cool, yet drier marine air flow contributes to mild summer temperatures west of the Cascades with a marked decrease in precipitation (Jackson, 1985).

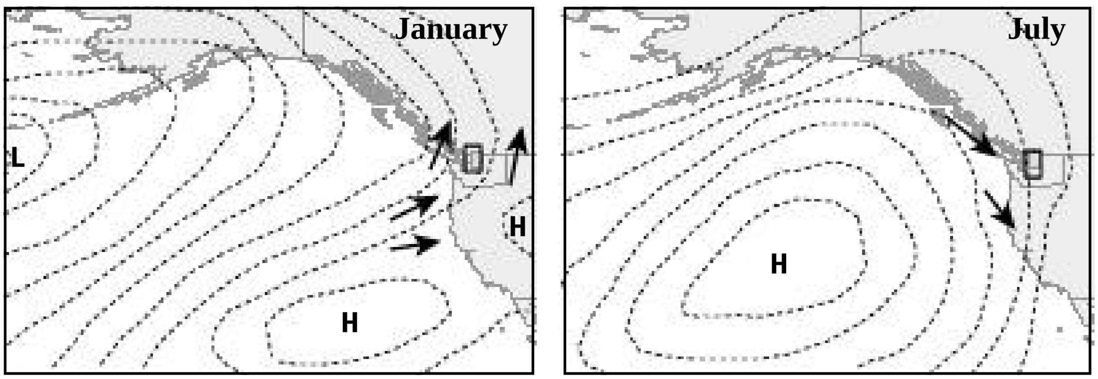

Figure 1.2 - Generalized air flow over the Pacific Northwest for January and July. The rectangle in the upper right quadrant of each frame marks the location of the National Park Complex. The Aleutian Low appears in the northwest quadrant of the January air flow map (After Jackson, 1985)

Marine air approaching the North Cascades flows around or over the Olympic Range (Mass 1985; Mass et al. 1986). Air that flows over the Olympics loses some its moisture due to orographic lifting, while that which flows around the range arrives in the Puget Sound retaining much of its original moisture. Upon leaving the Puget Sound this air is again forced upward, this time over the North Cascades, producing the heavy cloud cover and precipitation that is a hallmark of the range (Fig. 1.3). Because of the high relief and the north south orientation of the range, precipitation is significantly greater in the upper elevations and greatest on the west side of the mountains. Additionally, the relief of the range creates large spatial variations in temperature that occur over a short distance. As a result, storms throughout much of the year deposit significant amounts of rain in the lowlands and snow at higher altitudes.

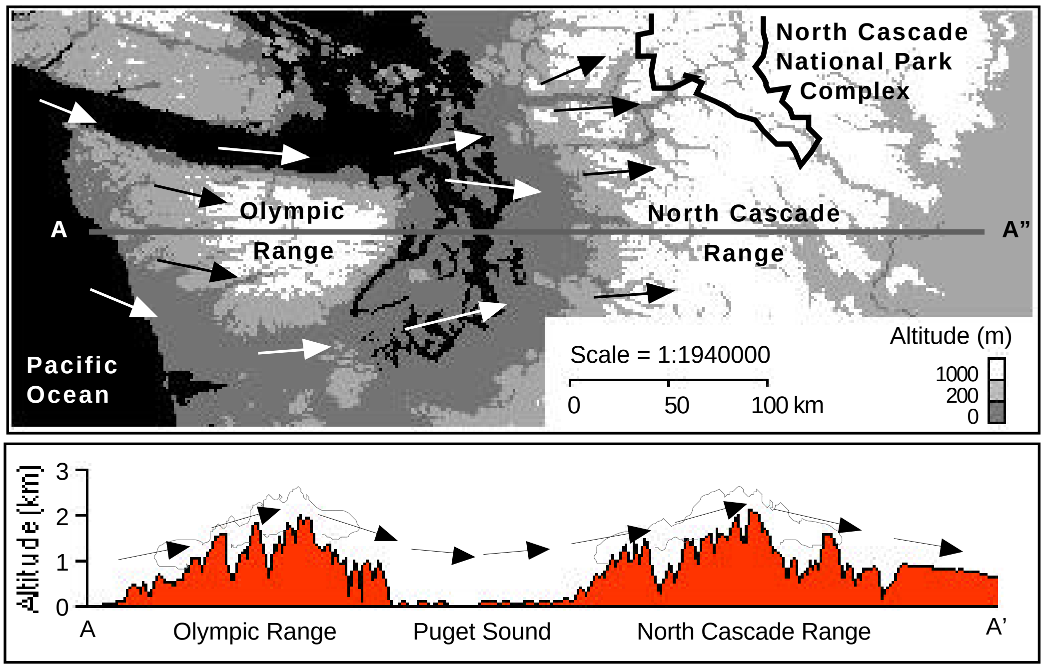

Figure 1.3 - Generalized air flow through northwestern Washington state. The arrows on the map above show typical air flow (after Mass, 1981). The black arrows represent air rising over the Olympic and North Cascades range. White areas are above 300 m, while gray areas lie below this elevation. The profile at the bottom of this figure shows air flow in cross section.

Hydrology

The park complex contains portions of four major watersheds, the Skagit, Stehekin, Nooksak, and Cascade Rivers. Since maximum snow accumulation sometimes exceeds 10 m (Rassmussen and Tangborn, 1976a, 1976b) and nearly 4% (118 km^{2}) of the total area of the complex is covered by glaciers (Post et al., 1971), snow and ice melt are major contributors to regional stream flow. This conclusion is supported by the fact that average monthly discharge is highest during May through July when precipitation is lowest and air temperature is highest (Fig. 1.4). The role of groundwater in the hydrology of the region is poorly understood since no groundwater studies have been found for the area. However, the presence of a significant fault system and extremely visible jointing in bedrock (Tabor and Haugerud, 1999) suggests that groundwater flow could be important.

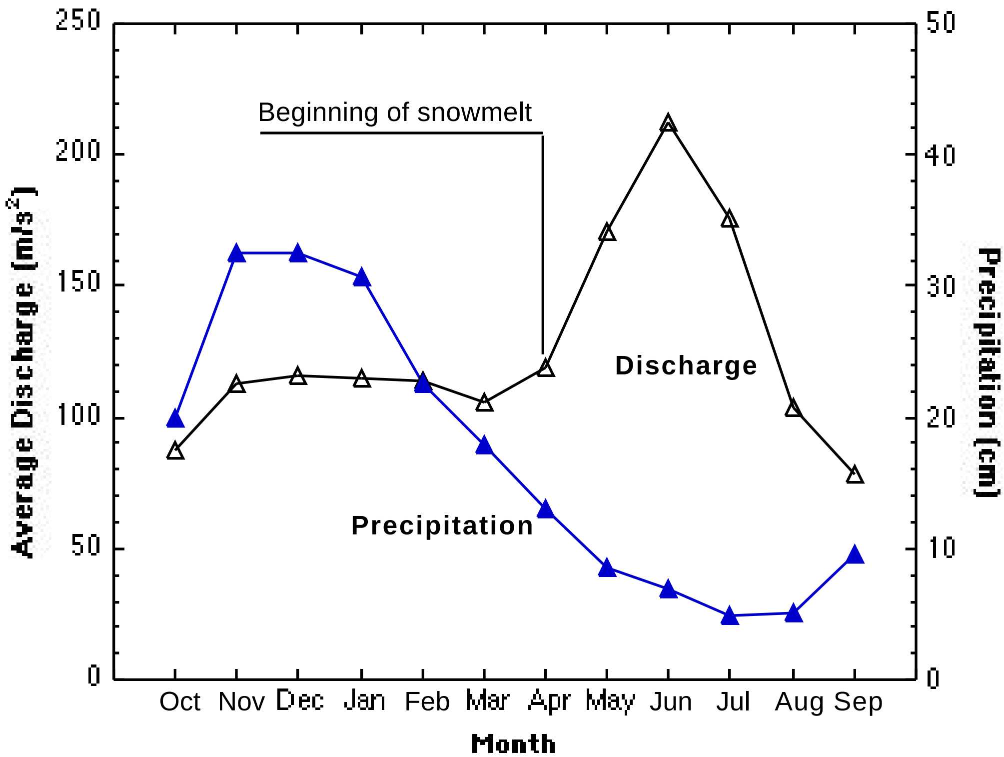

Figure 1.4 - Average daily discharge for the Skagit River and average monthly precipitation at Newhalem, Washington.

Chapter 2

Spatial characteristics of National Park Complex glaciers

A foundation for this study is the glacier inventory of the North Cascades compiled by Post et. al. (1971). The authors cataloged all of the glaciers in the North Cascades Range south of the U.S. /Canadian border. In so doing, they provided insight into the relationship between glaciers and climate and the role of glaciers in the hydrology of the region. However, because of a lack of prior information on glacier spatial characteristics, they could not quantify either glacier change or the impact of that change. By updating this inventory, I aim to quantify glacier change and the impact of that change on streamflow. Three specific questions that were asked in doing this are:

1. What was the population, area, volume, and principle characteristics of glaciers found in the complex in 1958 and 1998?
2. How did the population, area, and volume of these glaciers change between, 1958 and 1998?
3. How did the size, orientation, elevation, debris cover, and terminus condition of a glacier influence rates of change for individual glaciers?

Regional glacier characteristics

Post et al. (1971) identified, mapped, analyzed, and described all of the glaciers in the North Cascades Range during the late, 1950s. They used both vertical and oblique aerial photography taken during late summer, and planimetric maps produced by the U.S. Forest Service to create a catalog of characteristics and map of glacier cover of the entire range. The catalog includes area, length, average elevation, location (latitude /longitude), and type for each glacier based on a modified version of a glacier inventory guide recommended by the International Commission on Snow and Ice (UNESCO /IASH, 1970).

In my study, I reexamined the characteristics of all glaciers in the national park complex (Fig. 2.1) by constructing digital maps of these glaciers for both 1958 and 1998. Like Post et al. (1971) glacier maps were used to determine area, volume, slope, orientation, and elevation for each glacier in the region. Unlike their work, I calculated glacier change and analyzed climatic and topographic factors producing this change. Furthermore, the use of GIS technology and digital data derived from larger scale maps produced an inventory having greater numerical detail than Post et al. (1971). The digital maps were created for both 1958 and 1998 using GIS software ArcView 3.1 for Windows (ESRI) and MFworks 2.6 for MacOS (Thinkspace Inc.). These maps were produced using digitized glacier outlines and topography, as well as vertical aerial photography.

The 1958 glacier layer was produced by converting digitized outlines of snow and ice into an ArcView data format called a shape file. These outlines were digitized from USGS 1:24,000 topographic maps by National Park Service staff. Since Post et al. (1971) were regarded as the authorities on North Cascade glacier cover in 1958, the shape file was compared to paper maps used by Post et al. (1971). Features in the file that also appeared in their maps were tagged with names and hydrologic ID codes. Features that did not appear in the inventory were deleted from the shape file. This and other map layers (streams and lakes, administrative boundaries, elevation contours, and physical relief) were assembled into a digital map collection. These additional layers were used to construct the 1998 layer and do analysis of glacier characteristics and change.

The 1998 map was produced by creating and altering a copy of the 1958 layer to show 1998 glacier extents. This was done by first superimposing the copy onto a shaded relief map generated from 30 meter Digital Elevation Models (DEMs). The boundaries of each glacier were than moved to their 1998 positions using stable non-ice features appearing in both the 1998 aerial photography and the digital relief map as reference marks. LaChapelle (1962), after using a similar method to map boundaries for glaciers in the North Cascades and Olympic Ranges of Washington, claimed that glacier changes could be determined with an accuracy of 10% where good maps exist.

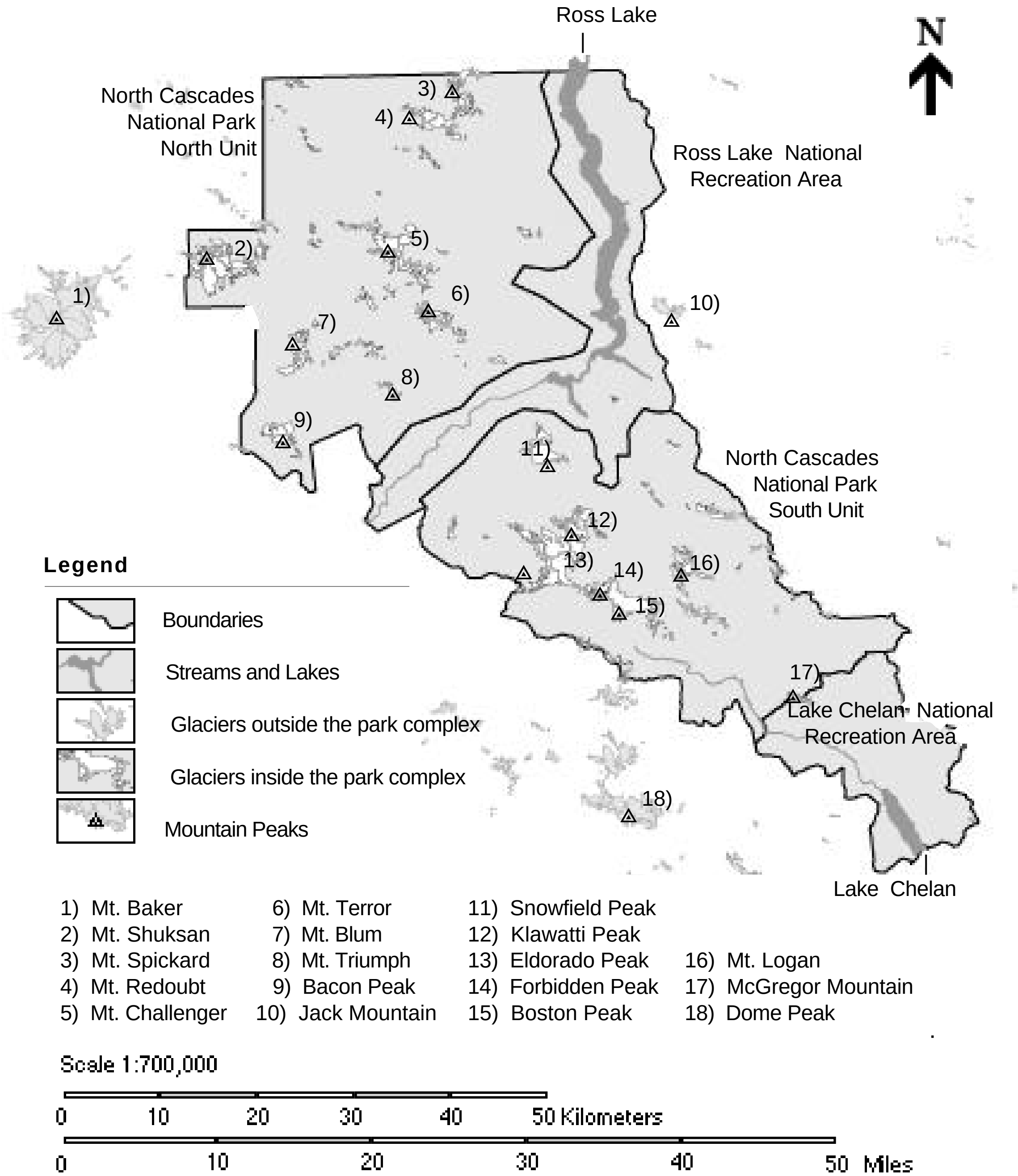

Figure 2.1 - Distribution of glaciers in and major administrative units of North Cascade National Park National Park Complex.

Besides being used to calculate area and area change, the 1958 and 1998 digital maps were utilized to investigate the relationship between selected glacier characteristics. The primary reason for doing so was to determine the impact of topography on glacier distribution and change. Three such characteristics, average elevation, orientation and slope, were calculated for every glacier in the park complex using the digital glacier maps and a 30 meter DEM of the complex. Glacier areas were automatically calculated by ArcView. Average elevation, orientation, and slope were determined using a raster based GIS (MFworks) to create maps of each characteristic. Maps of average glacier elevation were produced by performing a score operation on the DEM. This operation determines the average, maximum, or minimum value of all the cells within a selected region of the map(Thinkspace, 1998). The glacier boundaries were used to select the regions of the DEM being averaged. Maps of average slope were constructed by conducting a grade operation on the DEM and then averaging the slope values for each glacier using the score operation and the glacier maps. A grade operation calculates the slope of each cell in a DEM by calculating the slopes of lines that run through the cell from neighboring cells and averaging them (Thinkspace, 1998). Finally, glacier orientation maps was created by performing an orient operation on the DEM and then using the score operation to average the orientation values for each glacier. The orient operation uses elevation data to produce a map where the value in each cell represents the surface orientation of that cell. Cell orientation is calculated using elevation differences between the cell and its neighbors (Thinkspace, 1998). Elevation, orientation, and slope were derived for 1958, but not 1998, since topographic data is complete only for 1958. These values, as well individual glacier areas were exported from the tables accompanying each map into a single Excel 2000 spreadsheet to create a glacier catalog for the entire complex.

Debris cover for 1998 and terminus condition for 1958 and 1998 were also determined for each glacier. Debris cover, the percentage of each glacier covered by rock was estimated using the 1998 air photos. Terminus condition, the distance of glacier termini from a lake into which it may once have calved, was determined by using

ArcView to select glaciers within 0.1, 0.2, 0.3, 0.4, and 0.5 kilometers from lakes. These data were manually entered into the glacier catalog for the complex.

Finally, the relationship between average glacier elevation and position was analyzed by using ArcView 3.1 to reduce each glacier to a single point (centroid) representing its position. The map containing the centroids was imported into MFworks 2.6 and merged with an elevation map to produce a table containing the UTM coordinates and average elevation of each glacier. This information was then used to create plots of average elevation versus location (east /west or north /west location).

Determining uncertainties in population and area

The accuracy of the digital maps involved three issues: the date represented by the data, glacier population, and glacier area. Map date was easily resolved for the 1998 layer since the aerial photographs used to create the layer were clearly labeled August, 1998. Confirming the date of the 1958 layer was more difficult. To create this layer I used glacier outlines digitized by national park service staff from 1:24,000 USGS topographic maps. Since many of the maps that were digitized were labeled "Topography by photogrammetric methods from aerial photographs taken 1958", I assumed that the glacier outlines in the digital version represent the state of the glaciers in 1958. I tested this assumption by comparing aerial photography from different dates to these outlines and found that glacier photos taken during August 1958 were the best match to the digital outlines.

Population accuracy was determined using two approaches. The first assumed that Post et al. (1971) had the technology to correctly identify all glaciers consistent with their own standard that any ice mass larger than 0.1 km^2 is a glacier. The second approach assumed they did not. In the first approach, the accuracy of the 1958 glacier map was determined by comparing the map to tables and maps produced by Post et al (1971). In the event of a mismatch, the digital map was adjusted to correspond with their maps. The population accuracy of the 1998 layer was calculated by counting ice features that were difficult to classify. Classification was done using color, surface texture, and size as criteria. To begin this classification, the smallest ice features (those less than 0.1 km^2) were all regarded as either snow fields or glaciers. If such a feature had a uniformly smooth, white surface it was identified as a snow field. If it had crevasses and/or patches of blue or gray (exposed ice) it was classified as a glacier. The number of potential snow fields counted in this way then became the population uncertainty. In the second approach the uncertainty in the glacier population was calculated by counting the number of glaciers smaller than 0.1 km^2 for both 1958 and 1998.

Errors in area were determined by assessing the accuracy of the original paper maps, and the procedures used to digitize these maps. The accuracy of the paper maps used to produce the 1958 layer was estimated by assuming that National Mapping Standards adopted by the U.S. Geological Survey apply. These standards for horizontal position require that 90% of 20 or more points surveyed in the field fall within 1/50th of an inch of the same identifiable points on the map (USGS, 2001). For a 1:24,000 topographic map this is an accuracy of 12.2 m. This uncertainty represents a minimum error since it is questionable how well National Mapping Standards apply to maps of mountainous areas. The digitizing error was calculated by measuring the width of the glacier boundary line on the paper 1:24,000 map. This measurement produced a positional uncertainty of 2.4 m for the glacier boundary. Again, this figure represents a minimum uncertainty since no additional information about digitizing error was available from the National Park Service. The total positional error (e_p) for each glacier was calculated using equation 2.1 (after Baird, 1962).

$$e_p = \sqrt{e_m^2 + e_d^2} \qquad \textbf{(2.1)}$$

where e_m is the error of the original paper maps and e_d is the digitizing error. For each glacier, e_p was multiplied by the perimeter of the glacier yielding the area uncertainty (e_g). The area uncertainty (e_{58}) for the entire 1958 glacier cover was determined by using equation 2.2 (after Baird, 1962)...

$$e_{58} = \sqrt{\sum e_g^2} \qquad \textbf{(2.2)}$$

The area uncertainty of the 1998 glacier layer was determined from two factors: the area error fraction (e_f) between glaciers in the 1998 map and the same glaciers in a Digital Orthoquad (DOQ) of the Cascade Pass Quadrangle and positional uncertainty based on National Mapping Standards and digitizing error (e_p). The Cascade Pass Quadrangle was used since at the time of analysis it was the only one that was available that was based on 1998 aerial photography. The area error fraction was determined by creating a digital map of selected glaciers in the quadrangle from the DOQ. Area error fractions (e_f) were calculated using equation 2.3.

$$e_f = \frac{(A_{98} - A_{doq})}{A_{doq}} \qquad \textbf{(2.3)}$$

A_{98} is the area of each glacier appearing in the 1998 layer and A_{doq} is the area of this group as drawn from the 1998 DOQ. Area uncertainty (e_g) based on boundary uncertainties was determined by creating a buffer around each glacier having a width equal to the uncertainty in 1:24:000 maps (e_p) and then determining the area of this buffer. The width of the buffer is based on the fact that in the National Mapping Standards positional uncertainty is the same for both 1:24000 topographic maps and DOQs. The area uncertainty for each glacier (e_{98}) was calculated by inserting e_f and e_g into equation 2.4.

$$e_{98} = \sqrt{e_g^2 + ((e_f)(A_{98}))^2} \qquad \textbf{(2.4)}$$

Finally, since the 1998 glacier outlines were constructed by adding or subtracting area from their 1958 outlines, the uncertainty of the area change for each glacier was determined by calculating the area of a buffer around the glacier having a width equal to the positional uncertainty for 1:24,000 topographic maps.

Results

Assuming that Post et al. (1971) had correctly classified all the glaciers within the complex, in 1958 there were 321 glaciers having a combined area of 117.3±1.0 km^2. Approximately 29% of the population had areas less than 0.1 km^2. This means that 93 ice masses did not fit Post et al's criteria for a glacier. A probable cause of this mismatch is the scale of the maps they used and the technology they used to analyze them. Post et al. (1971) used 1:38,000 scale maps, while the 1958 layer in this project was digitized from 1:24,000 maps. This means that the 1958 map layer was built on more detailed spatial information than the maps of Post et al (1971). This was confirmed by superimposing a map digitized from paper maps used by Post et al. (1971) on to the 1958 layer. Glacier outlines in the Post et al. (1971) layer are coarser than those in the 1958 layer. Furthermore, areas and other dimension values derived by GIS software are significantly more precise than those derived by mechanical planimeters. However, since one of the questions asked in my study is how glacier change impacts stream flow, it is important to map and examine ice units in the study area, even if they do not follow a strict definition of a glacier.

Based on Post et al.'s (1971) classification (including glaciers > 0.1 km^2) the average glacier area in 1958 was 0.37 km^2 with the smallest glacier being 0.02±0.01 and the largest, 6.83±0.18 km^2. Most of the population (93%) had areas less than or equal to 1.0 km2 and accounted for 56% of the total glacier area (Fig. 2.2). The smallest group of glaciers, those having areas less than 5.0 km^2, made up approximately 1% of the population but accounted for 10% of the combined area (Fig. 2.3). Average glacier elevation was 2011 m with the lowest glacier being at 1375 m and the highest at 2457 m (Fig. 2.4). A plot of average elevation versus east /west position (Fig. 2.5a) shows that elevation tended to increase to the east. A similar plot for elevation versus north /south position (Fig 2.6b) showed a slightly more complex pattern, where elevation decreases moving from the Canadian border to the Skagit River and then rises again farther to the south. Average glacier slope was 34° with a range of 12 to 62° (Fig. 2.6). Most of the glaciers (67%) were located on slopes oriented northeast, north, or northwest (Fig. 2.7). Sixteen of the glaciers (5%) terminated in lakes. No data were available for debris cover for 1958.

By, 1998 the glacier population was 316 with a combined area of 109.1±1.1 km^2. Average glacier area was 0.3 km2 with a range of 0.02±0.01 km2 to 6.53±0.20 km2. Approximately sixty of glaciers identified in the 1998 photography were marked as uncertain, meaning that they may have been snowfields rather than glaciers. These were included in the 1998 map for the same reason that glaciers smaller than 0.1 km^2 were included in the 1958 map. Glacier slope, average elevation, and orientation for, 1998 could not be calculated since elevation data were absent for all but four of the glaciers in the complex. Nine glaciers calved into lakes and 52 others had termini within a half kilometer of a lake. Only 23 had any noticeable debris cover and all but six of these had less than 25% of their surfaces covered.

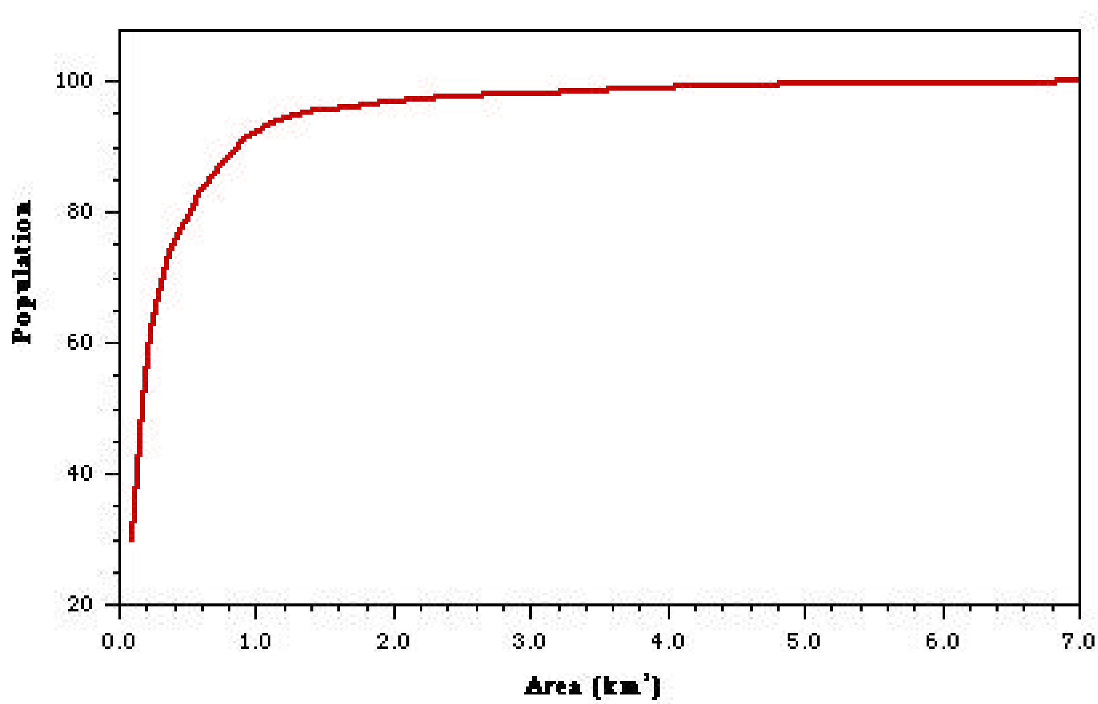

Figure 2.2 - Fraction of glacier population versus area for 1958. Glaciers are grouped into 0.1 km^2 intervals.

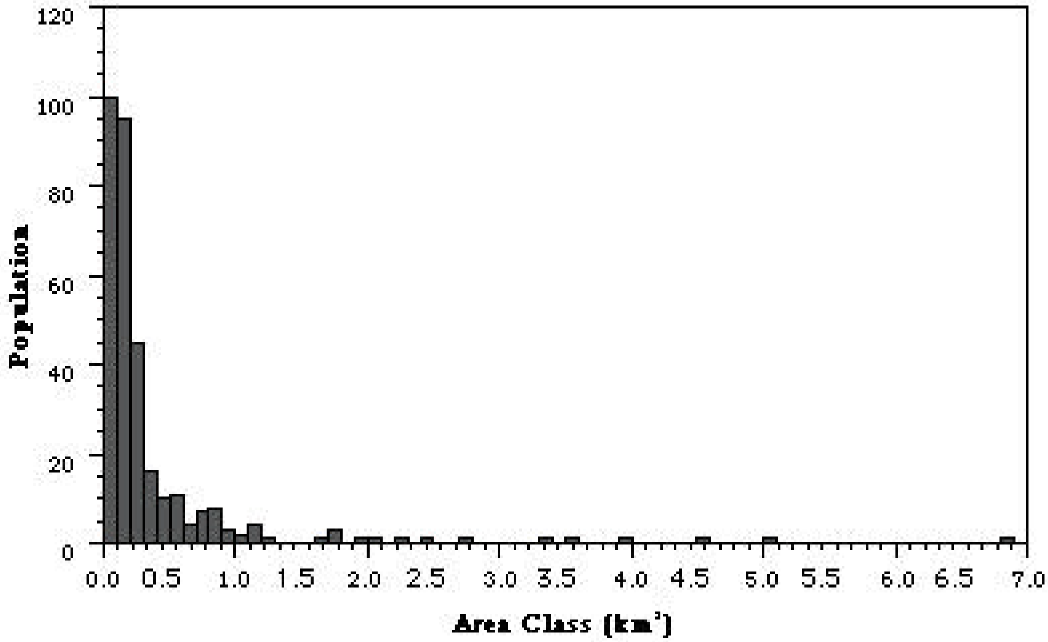

Figure 2.3 - Number of glaciers versus area for 1958. Glaciers are grouped into 0.1 km2 intervals.

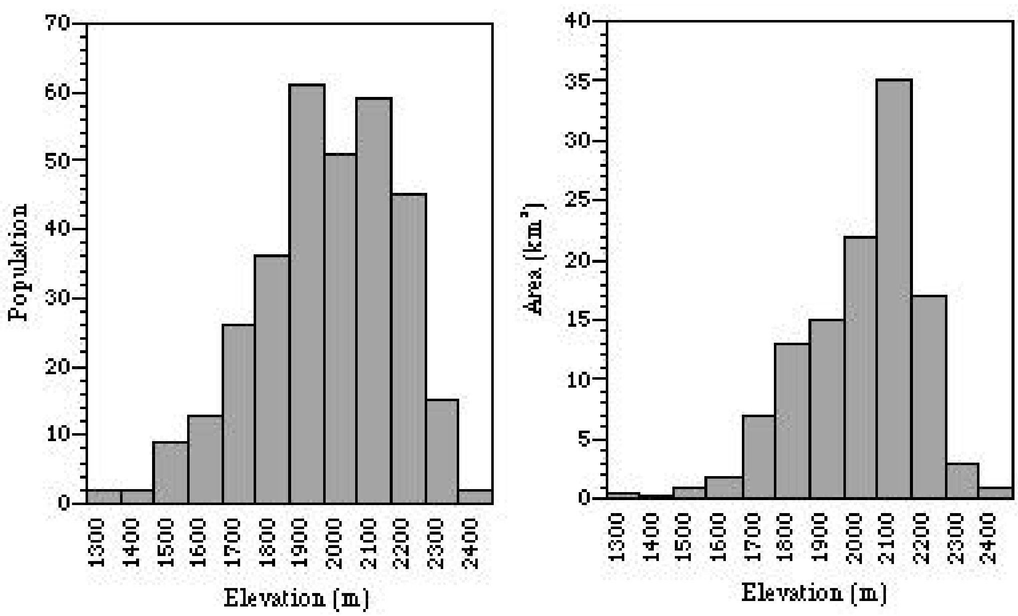

Figure 2.4 - Glacier population and area versus average elevation for 1958. Glaciers are grouped into 100 m intervals. For instance, the 1800 m group includes all glaciers between 1800 and 1899 m.

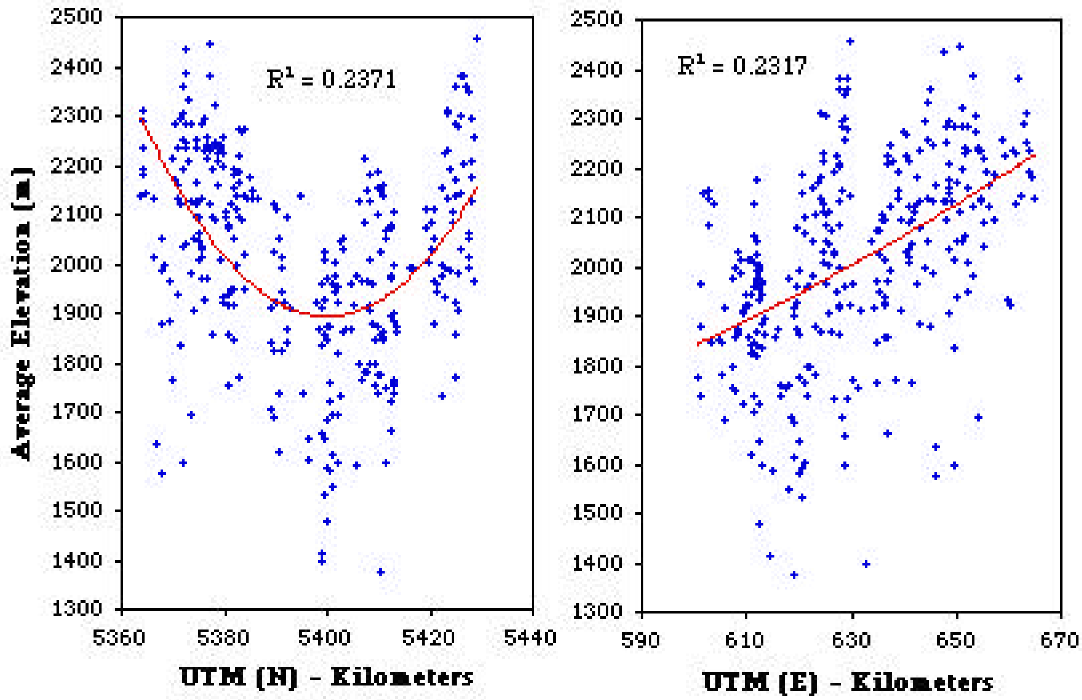

Figure 2.5 - Glacier elevation by north /south and east /west position for 1958.

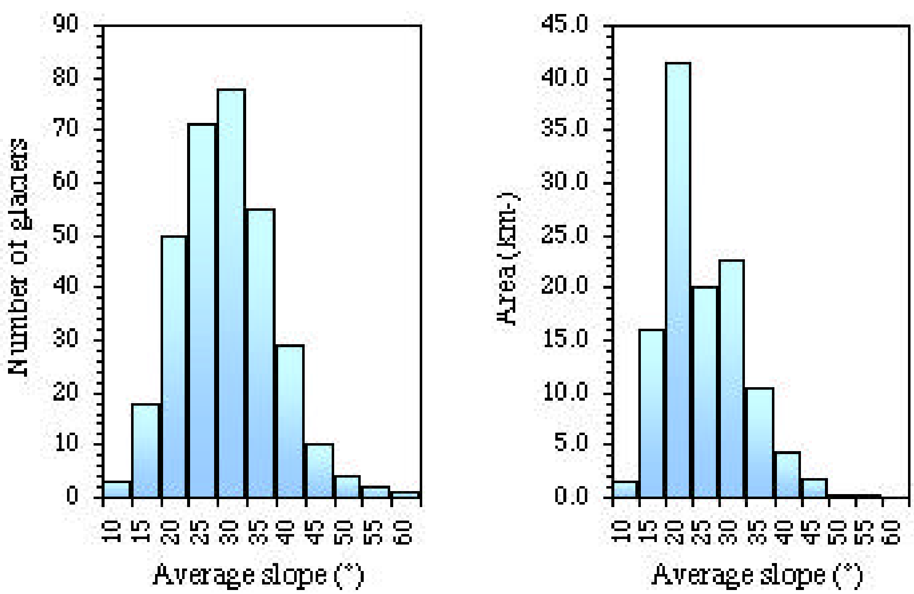

Figure 2.6 -Glacier population and area versus average slope for 1958. Glaciers are grouped into 10° intervals.

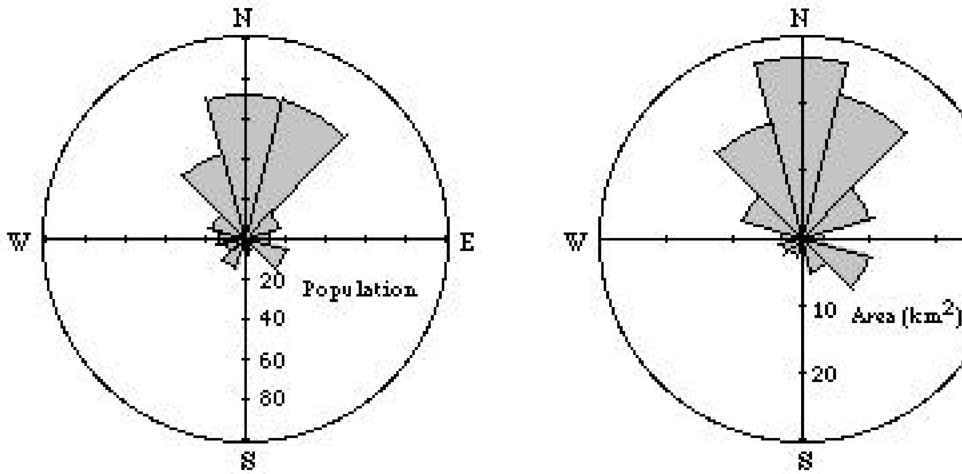

Figure 2.7 - Glacier population and area versus average orientation for 1958. Glaciers are grouped into 30° intervals.

Estimating glacier volume

Methods for estimate glacier volume

A common problem encountered in determining the volume of a glacier is how to calculate this volume if no surface or basal topographic data exists for the glacier. Post et al. (1971) addressed this problem by grouping all the glaciers in the North Cascades into five area classes, assigning an average thickness to each class, and then multiplying these averages by the area of the glacier. The area classes and the assumed thicknesses they used are shown in the table below.

Table 2.1 - Thickness by area class (Post et al., 1971)

Area class (km^2)	< 0.5	0.5-1.0	1.0-2.0	2.0-5.0	> 5.0
Assumed average thickness (m)	20	40	60	90	120

The thickness' assigned to each class were based on the mean thickness of South Cascade Glacier in the North Cascades and Blue Glacier in the Olympic Mountains of Washington, as well as assumed values for small glaciers given in Canadian (Ommanney et al., 1969 after Post et al., 1971) and Russian inventories (Avsiuk and Kotlyakow, 1967 after Post et al, 1971).

A more refined approach to estimating the volume of individual glaciers is to scale area by established values via the general relationship...

$$V = \beta A^{\gamma} \qquad \textbf{(2.5)}$$

Values for β and γ are derived by using either theoretical or empirical methods.

An example of an empirical approach is that of Chen and Ohmura (1990), who derive β and γ by analyzing the relationship between the area and volume of 63 glaciers in North America, Europe, and Asia. These 63 glaciers were chosen because their volumes were known from topographic surveys and radio-echo sounding. By doing a regression analysis on an area versus volume plot of the glaciers, they derived the values for β and γ (Table 2.1).

Two alternative approaches based on theoretical methods are that of Bahr et al. (1997) and Driedger and Kennard (1986). Bahr et al. (1997) use a scaling analysis of mass and momentum conservation equations to derive β and γ (Table 2.2). They did this by taking into account the width, slope, side drag, and mass balance of individual glaciers and then testing their results against known values of volume and area for 144 glaciers. Like Bahr et al. (1997), Driedger and Kennard (1986) derived b and g (Table 2.2) by examining the relationship between glacier flow and geometry. They related known geometric elements (area and slope) to measurable or easily calculated values such as ice density and basal shear stresses. The resulting area volume relationship was then modified using the results of regression analysis of areas and volumes for 25 glaciers in the Washington and Oregon Cascades. They found their relationship to be appropriate for small alpine glaciers less than 8500 ft (2.6 kilometers) long and to be between ±20 and 25% accurate.

Table 2.2 - Values for β and γ derived by various authors

	β	γ
Chen and Ohmura (1990)	28.50	1.396
Bahr et al. (1997)	0.90	1.396
Driedger and Kennard (1986)	3.93	1.124

Determining the uncertainty in estimates of glacier volume

Uncertainty in estimated glacier volume was established by determining uncertainty based on area errors for each glacier, and by comparing estimated volume changes derived by area /volume scaling to volume changes calculated for glaciers having detailed topographic information for both 1958 and 1998. Uncertainties in the estimated volume and volume change of individual glaciers based on area and area change errors were calculated by considering how these errors propagate through power relationships. According to Baird (1962), the error in an equation of the form $z = x^n$ is $z(dz) = nx^{n-1}dx$. Based on this argument the equation used to derive the error for estimated volume is of the general form

$$\delta V = (\gamma - 1)\beta A^{\gamma-1}\delta A \qquad \textbf{(2.6)}$$

with the values $(\gamma\text{-}1)\beta$ and γ-1 for each method being as follows:

Table 2.3 - Values for $(\gamma\text{-}1)\beta$ and γ-1

	$(\gamma-1)\beta$	$\gamma-1$
Chen and Ohmura (1990)	38.7	0.357
Bahr et al. (1997)	1.25	0.396
Driedger and Kennard (1986)	4.42	0.375

To fully determine glacier volume and volume error it was necessary to determine which of the three area /volume scaling techniques used in this study provide the best estimate of actual glacier volume. This was accomplished by comparing volume estimates to changes for South Cascade and the other four index glaciers calculated using topographic data. These glaciers were selected since detailed topography exists for these glaciers for both 1958 and the late to middle 1990s. Volume change, rather than volume, was calculated since no accurate basal topography is available for any of the five glaciers. Furthermore, calculating volume change is more relevant to the glacier /streamflow questions discussed later in this thesis. Volume change for the index glaciers was calculated by superimposing surface maps for each glacier and its immediate surroundings for the 1990's on top of a maps for the same area during 1958. The volume bounded by the two surfaces is the volume change between the time periods represented by each surface. Surface maps were constructed using both TIN (Triangular Irregular Network) and GRID methods. Though TIN derived volumes were selected as the standard based on arguments about the accuracy of TIN versus Grid surfaces (DeMers, 1997; Pinotti, in progress), volume changes based on Grid surfaces were calculated to cross check TIN derived values, since volumes derived by each method should closely agree with one another.

A Grid or raster model is a means of representing a surface using a two dimensional array of cells. Each cell in the array is assigned three numbers, two to identify its location and a third which is a single attribute value (DeMers, 1997). For instance, a DEM is an array in which the position values associated with cells are coordinates such as longitude and latitude and the attribute value is elevation. In this way, the DEM represents a three dimensional surface. One of the primary advantages of a Grid model is that it can be easily manipulated to calculate volume, slope, orientation, and other surface statistics. For this research MFworks 2.6 software and 10 meter resolution DEMs were used to create surface models of each of the five index glaciers. The 1958 surfaces for all five glaciers were created by using 1958 glacier outlines to extract ice surfaces from 10 meter SDTS DEMs. The 1990's surfaces for the four index glaciers inside the complex were created by converting contour maps in computer assisted drafting (CAD) format to raster format and then interpolating them to produce continuous surfaces. Since point rather than contour data were available for South Cascade Glacier, a 1998 DEM was created by interpolating point data over the entire, 1998 surface of the glacier. The CAD data were provided by the National Park Service and are based on Park Service ground surveys. Point data for South Cascade Glacier were provided by USGS Survey's Water Resource Division in Tacoma Washington and is based on photogrammetry of vertical aerial photography (Krimmel, U.S. Geologic Survey, personal communication, 2000).

Using the Grid method, volume change was calculated by subtracting the value for each cell in the 1958 grid from its counterpart in the 1998 grid. The value of each cell (the average change in elevation for that cell) was multiplied by the area of the cell, and the products summed for the entire glacier. In other words, each cell of the elevation change map was treated as a rectangular box having a volume equal to elevation change for that location times the area of the cell. The volume change for the entire glacier is then the sum of all the volumes (Fig. 2.8a).

A TIN model represents a surface using triangular facets. Like the Grid method, each node is assigned an x, y position and an elevation. Unlike the Grid method, nodes can be as close together and as far apart as the user wishes, making the TIN model a more efficient and more accurate means of representing a surface (DeMers, 1997).

The TINs for the 1958 surface of the four glaciers in the park complex were created by importing a 10 meter DEM into ArcView 3.1. Each of the surfaces was then converted into TINs using Spatial Analyst 1.0. TINs for the 1998 surfaces of these same glaciers were created by importing contour maps in CAD file format into ArcView 3.1 and converting these imported files in TINs using Spatial Analyst 1.0. Again since a different type of data was available for South Cascade Glacier the method for producing the 1958 and 1998 TINs was different than it was for the other four glaciers. The TINs for South Cascade for both years were constructed by importing elevation grid data into ArcView, and then converting the point map into a TIN surface. Once TINs were constructed for all five glaciers, volume change was determined by first calculating the volume bounded by the glacier and an underlying plane having a fixed altitude was computed for both years. Volume change for each glacier was then determined by subtracting the 1958 from, 1990's volume (Fig. 2.8b).

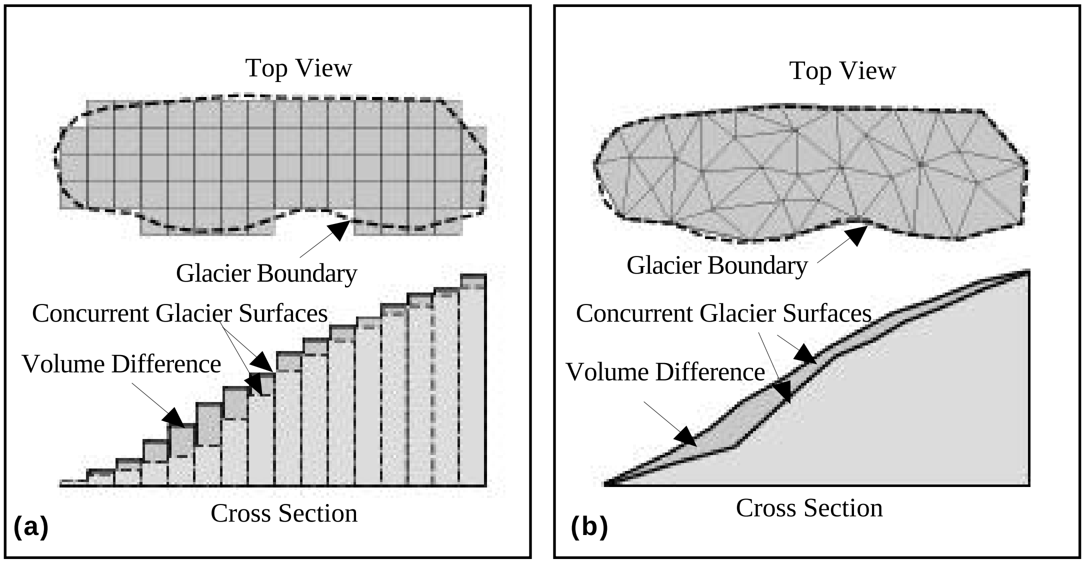

Figure 2.8 - Illustration of Grid method (a) and TIN method (b) for calculating volume change

The decision of which volume estimation scheme is most accurate was based on comparing topographic derived volume changes for the five index glaciers to volume changes derived by area volume scaling. This was done by calculating the volume error fraction via the relationship...

$$e_f^{'} = \frac{(\Delta Vs - \Delta V)}{\Delta V} \qquad \textbf{(2.7)}$$

Where ΔVs is volume change based on the scaling techniques and ΔV is volume change derived from either the TIN or Grid methods**.**

Results

Estimates for combined glacier volume for 1958 and 1998 are 10.1±0.2 km3 and 9.3±0.2 km^3. These estimates was derived using both Bahr et al. (1997) and Chen and Ohmura (1990). Both methods were used since estimates based on Chen and Ohmura (1990) worked best for larger glaciers such as South Cascade and North Klawatti, while estimates based on Bahr et al. (1997) were more accurate for smaller glaciers (Table 2.4).

Therefore, the total glacier volume of the complex was calculated by adding the sum of the volume of glaciers with areas larger than 1.0 km^2 based on Chen and Ohmura (1990), to the sum of the volume of glaciers with areas smaller than or equal to 1.0 km^2 based on Bahr et al (1997).

Table 2.4 - Volume error using TIN derived volume change as a standard

Technique	S. Cascade	N. Klawatti	Noisy Creek	Silver Creek	Sandalee
Chen & Ohmura (1990)	-61.20%	-49.50%	-59.20%	-46.90%	-72.90%
Driedger & Kennard (1986)	-80.00%	-71.70%	-72.70%	-63.20%	-75.80%
Bahr et. al (1997)	**29.30%**	**-19.20%**	**-39.10%**	**13.20%**	**-16.80%**

Regional glacier change

Methods for analyzing glacier change

Two issues were examined in the analysis of glacier change. First is the extent of that change for the region and for individual glaciers. Second is how the topography of a glacier influences its rate of change. The first issue was dealt with by subtracting total and individual glacier areas and volumes for 1998 from their 1958 counterparts. The uncertainty in the volume change of each glacier was calculated using equation 2.5, while the uncertainty in the total glacier volume was determined using equation 2.2.

Fractional area change (FAC) for the entire complex and for individual glaciers was computed by dividing raw area change by 1958 area. To determine the influence of topographic characteristics, FAC was plotted as a function of area, average elevation, orientation, slope, percent debris cover, and distance of terminus from a lake into which it might once have calved. Plotting and analysis was done for the entire glacier population and for selected groups of glaciers. Glaciers were grouped to isolate the impact of each characteristic on FAC. For instance by plotting FAC versus orientation for those glaciers less than 0.2 km^2 that also had average elevations less than, 1900 m, the impact of orientation should be clearer since the influence of area and average elevation was minimized.

Results

Between 1958 and 1998, the glacier population decreased from 321 to 316, total area decreased from 117.3±1.0 to 109.1±1.1 km^2 (an FAC of 7.0%), and total volume dropped from 10.1±0.2 to 9.3±0.2 km^3 (a volume decrease of 7.9%). FAC for individual glaciers ranged from 10.3% to -100%, with an average FAC of -11.4%. Based on FAC the glaciers fell into four groups. Group 1 glaciers (less than 2% of the population) grew between 1 and 11%. Group 2 (19% of the population) showed no discernible change. Group 3 (79% of the glaciers) lost less than 60% of their 1958 area. Finally, group 4 consisted of five small glaciers that were missing in the 1998 aerial photography. Based on estimated volume, the net mass balance for the entire complex for 1958 to 1998 was -6.1 mwe. Net balance for individual glaciers ranged from 4.6 to -40.5 mwe, with an average balance of -5.1 mwe.

Changes in the FAC relative to selected spatial characteristics were investigated to determine what role topographic setting played in glacier changer. A plot of FAC versus glacier area (Fig. 2.9) showed that smaller glaciers had higher FACs than did larger glaciers. Plots of FAC versus orientation, slope, average elevation, location, terminus condition, and average elevation revealed no discernible trends. No relationship was found between FAC and debris cover, distance of terminus to lake, or slope. Determining averages for each group was more instructive (Table 2.5). Group 4 had the lowest average elevation, while group 1 had the highest. Furthermore, all the group 1 glaciers were oriented to the northwest, north, or northeast, while group 4 glaciers were randomly oriented.

Table 2.5 - Characteristics of glaciers grouped by FAC

Group	FAC	Number in group	Ave. Area (km2)	Ave. Elevation (m)	Ave. Slope (°)	Number of glaciers Oriented N	E	S	W
1	> 0%	6	0.23	2061	33	4	2	0	0
2	0	63	0.18	2025	33	33	13	10	7
3	< -60%	247	0.43	2008	31	124	76	19	28
4	-100%	5	0.11	1879	25	1	1	2	1

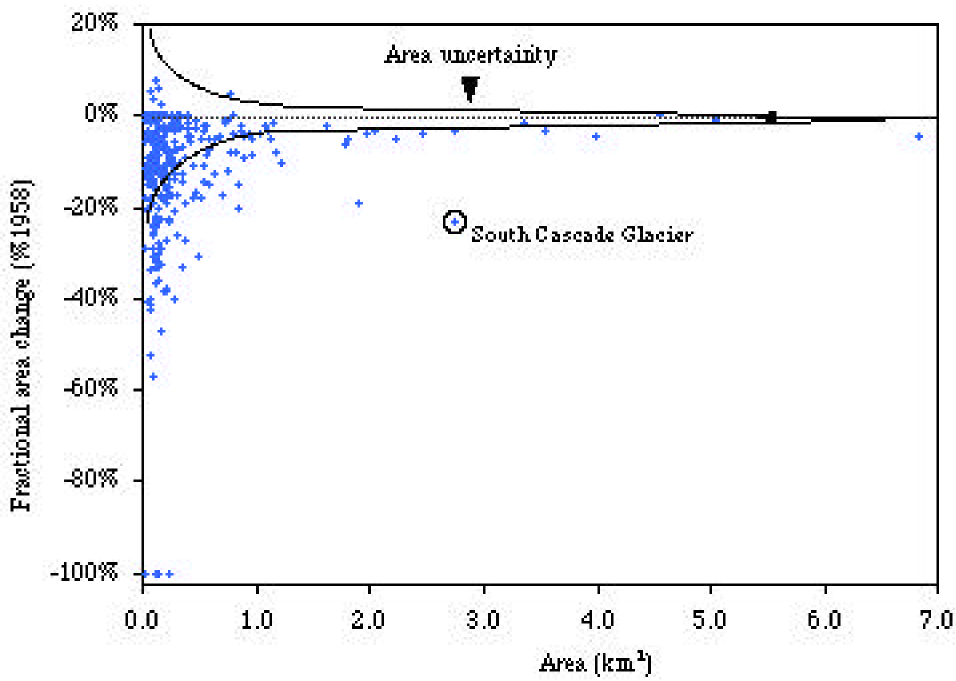

Figure 2.9 - Individual glacier FAC versus area.

The large number of glaciers that lost mass indicates that variations in regional climate is the principle control on glacier change. The general increase in FAC with decreasing area is likely the result of energy exchange rates between the glacier and its local environment. Calculations of area to volume ratios using equation 2.8 demonstrate that smaller glaciers have a larger ratio than do larger glaciers.

$$A/V = A / (\beta A^{\gamma}) \qquad \textbf{(2.8)}$$

Since energy exchange takes place at the glacier /environment interface (Paterson, 1969) it stands to reason that a small glacier will have a larger energy exchange relative to its volume than a large glacier. Consequently, for the same climatic conditions causing net mass loss, smaller glaciers should shrink faster than larger ones. Furthermore, a small glacier should receive proportionally more longwave radiation from adjacent rock walls than a large glacier. This is because the amount of longwave radiation received by the glacier is highest along the perimeter of the glacier. So for a large glacier, the percentage of the glacier surface receiving significant amounts of radiation is small, while this percentage is higher for a smaller glacier. Finally, the five glaciers that disappeared may not have been glaciers because were originally classified as snow and ice patches and because they fell below the Post et al. (1971) size criteria for a glacier.

The glaciers that gained mass were, on average, the highest of the groups. But why other glaciers, of similar altitude did not grow is uncertain. A large number of glaciers (19%) were in equilibrium. We speculate that the enlarging of glaciers and those in equilibrium are in topographically advantageous positions and receive a significant contribution to their mass accumulation from avalanches.

Summary

Based on the creation and analysis of digital maps of all the glaciers in the National Park Complex, the following conclusions were reached:

1. *Spatial characteristics* - There are currently over three hundred glaciers in the National Park Complex ranging in area from less than 0.1 km^2 to nearly 7.0 km^2. The majority of these glaciers (90%) are less than 1.0 km^2, oriented to the northwest, north, and northeast, have slopes of 50 to 60°, average elevations of between 1800 and 2100 meters, and have less than 25% of there surfaces covered by debris. Average glacier elevation tended to rise from east to west.
2. *Extent of glacier change in the complex* - The population of the complex dropped from 321 to 316 between 1958 and 1998. During this same period total glacier area shrank from 117.3 ± 1.0 km^2 to 109.1 ± 1.1 km^2, representing a loss of 8.3 ± 0.1 km^2 (7.0% of the 1958 combined area), while the total glacier volume dropped by 0.8±0.1 km^3. Fractional area change for individual glaciers varied from +10.3 to -100% of their 1958 areas. Based on FAC, the glaciers fell into four groups. Group 1 glaciers gained mass, group 2 glaciers did not change, group 3 glaciers lost area, and group 4 glaciers were missing in 1998. All five of the group 4 glaciers were less than 0.25 km^2 and four of these were classified as snow and ice patches in the Post et

al. (1971) inventory, meaning that their continued existence was precarious even in 1958.

3. *Topographic influences on glacier change* - In general, rates of glacier change were influenced by glacier area and average elevation. However, area was not found to have any statistically significant correlation with magnitude of change. Generally, smaller glaciers tended to have higher fractional area changes. This relationship is probably the result of increased energy exchange rates resulting from the large surface area to volume ratio of smaller glaciers. Local conditions, such as topographic characteristics that favor avalanching, may be responsible for keeping some glaciers in equilibrium.

Chapter 3

Index glaciers: Do they represent the glaciers of the region?

Five glaciers in the North Cascades are monitored by the US Geological Survey (USGS) and the U.S. National Park Service (NPS) each year for mass balance. One of these glaciers, South Cascade, has been extensively monitored since 1958 and includes measurements of climate and streamflow, as well as a photographic record of glacier position back to 1928. Though this glacier resides outside of the National Park Complex, it is important for understanding glacier change in the complex since it has been used by the USGS as the benchmark for the entire North Cascades for nearly 40 years (Fountain et al., 1997). The other four glaciers, Silver Creek, Noisy Creek, North Klawatti, and Sandalee, have been monitored since the early 1990's by the NPS. Previous estimates of North Cascade glacier change, and the impact of those changes have been made largely on the basis of data from South Cascade (Post et al., 1971; Tangborn, 1980a). Even with the addition of the four glaciers now monitored by the NPS and data from other glaciers (Pelto, 1988), the variation of a small number of glaciers is used as an indicator of the population at large. The goal of the analysis described in this chapter is to test the validity of using index glaciers to estimate regional glacier change by determining how the area, volume, orientation, type and area /volume changes of the five index glaciers compare with the spatial statistics for the entire complex.

Spatial characteristics

Characteristics of the index glaciers:

Four of the five index glaciers are located in watersheds that are part of the Upper Skagit River Basin (Fig. 3.1). The fifth, Sandalee Glacier, is located in a watershed inside the Stehekin River Basin. The distribution of the five glaciers is generally representative of the entire complex, though the central part of the north unit is not represented, and South Cascade actually lies outside the complex. Four of the five index

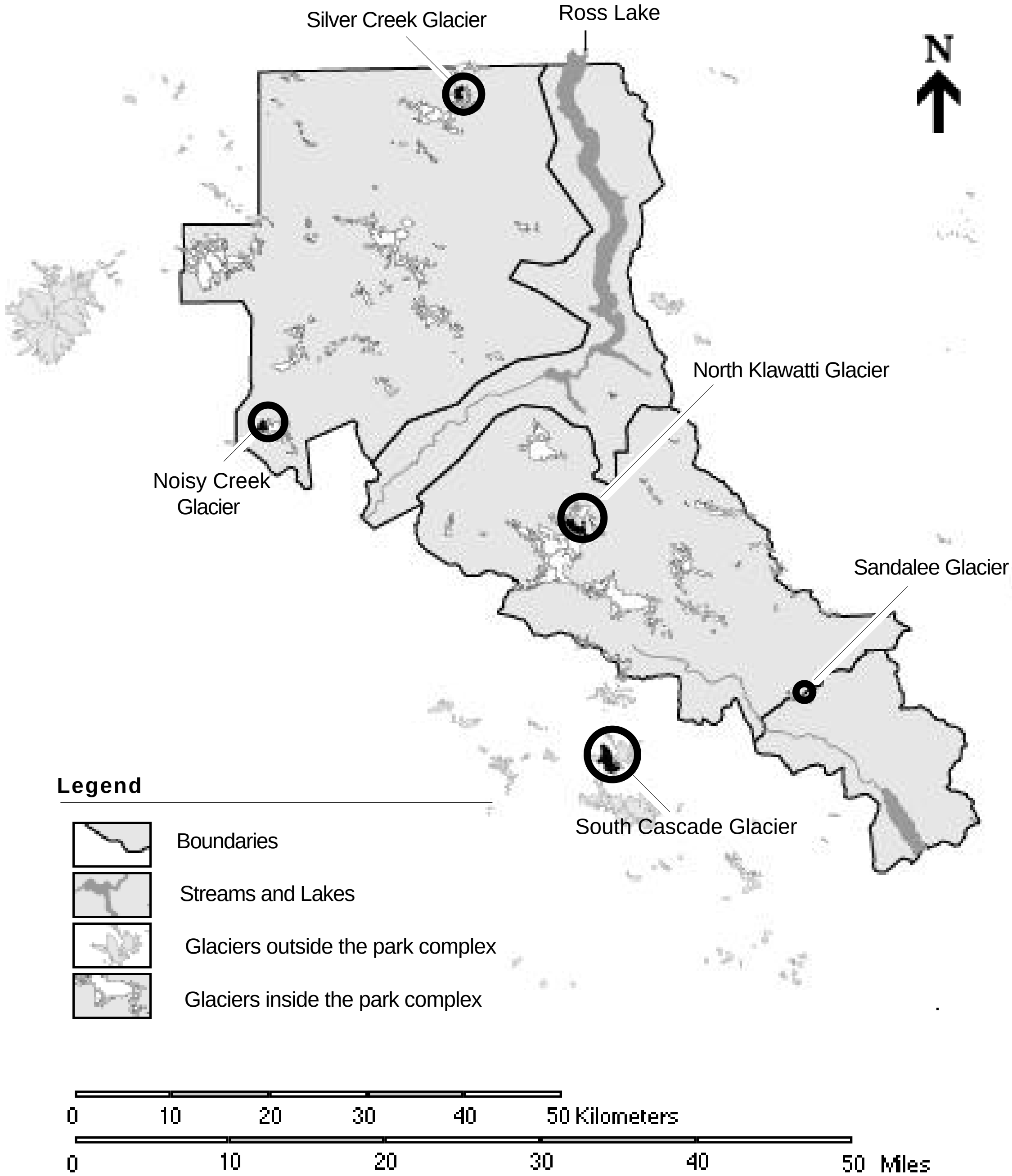

Figure 3.1 - Location of Index Glaciers

glaciers are valley glaciers. The fifth, Sandalee, is a cirque glacier. Glacier areas in 1958 ranged from 2.6 km^2 (South Cascade Glacier) to 0.2 km^2 (Sandalee Glacier) in 1958 and 2.1 to 0.2 km^2 in 1998 (Fig. 3.2). Four of the glaciers are oriented north, while North Klawatti is oriented to the east. During 1958 average glacier slopes varied from 11° to 25° and average glacier elevation ranged from 1896 to 2283 m (Table 3.1). According to area-altitude plots of the glaciers for 1958 (Fig. 3.3), Silver Creek is the highest glacier and Noisy and South Cascade glaciers the lowest. Noisy Creek and South Cascade glaciers had the lowest equilibrium line altitudes and Silver Creek the highest. Three glaciers had altitude ranges of nearly 600 meters. The other two, Noisy Creek and Sandalee glaciers, spanned less than 4000 meters. Slopes in the mid 1990's remained unchanged, while average elevations rose between 13 and 70 m. Major snow accumulation for all the glaciers was from direct snowfall and minor drift (Post et al, 1971). South Cascade and Silver Creek, terminated in lakes during 1958. The other three terminated on gentle slopes. By 1998, all five glaciers terminated on bedrock.

Table 3.1 - Characteristics of indicator glaciers

Glacier	Watershed	Latitude	Longitude
South Cascade	Cascade River / Skagit River	48°23'N	121°08'W
North Klawatti	Thunder Creek / Skagit River	48°34'N	121°55'W
Noisy Creek	Noisy Creek / Skagit River	48°10'N	121°15'W
Silver Creek	Silver Creek / Skagit River	48°59'N	121°32'W
Sandalee	Bridge Creek / Stehekin River	48°25'N	120°48'W

	Area	Altitude (m)			Orientation	Slope
Glacier	(km^2)	Ave.	Min.	Max	Ave.	Ave.
1958						
South Cascade	2.6	1896	1613	2176	340°	11°
North Klawatti	1.8	2134	1692	2436	75°	19°
Noisy Creek	0.8	1883	1673	2121	345°	27°
Silver Creek	0.8	2283	2061	2695	315°	25°
Sandalee	0.2	2151	1920	2304	345°	20°
1990s						
South Cascade (98)	2.1	1916	1641	2176	340°	11°
North Klawatti (92)	1.4	2146	1726	2436	75°	19°
Noisy Creek (92)	0.7	1860	1666	2121	345°	27°
Silver Creek (93)	0.6	2313	2084	2695	315°	25°
Sandalee (95)	0.2	2157	1942	2304	345°	20°

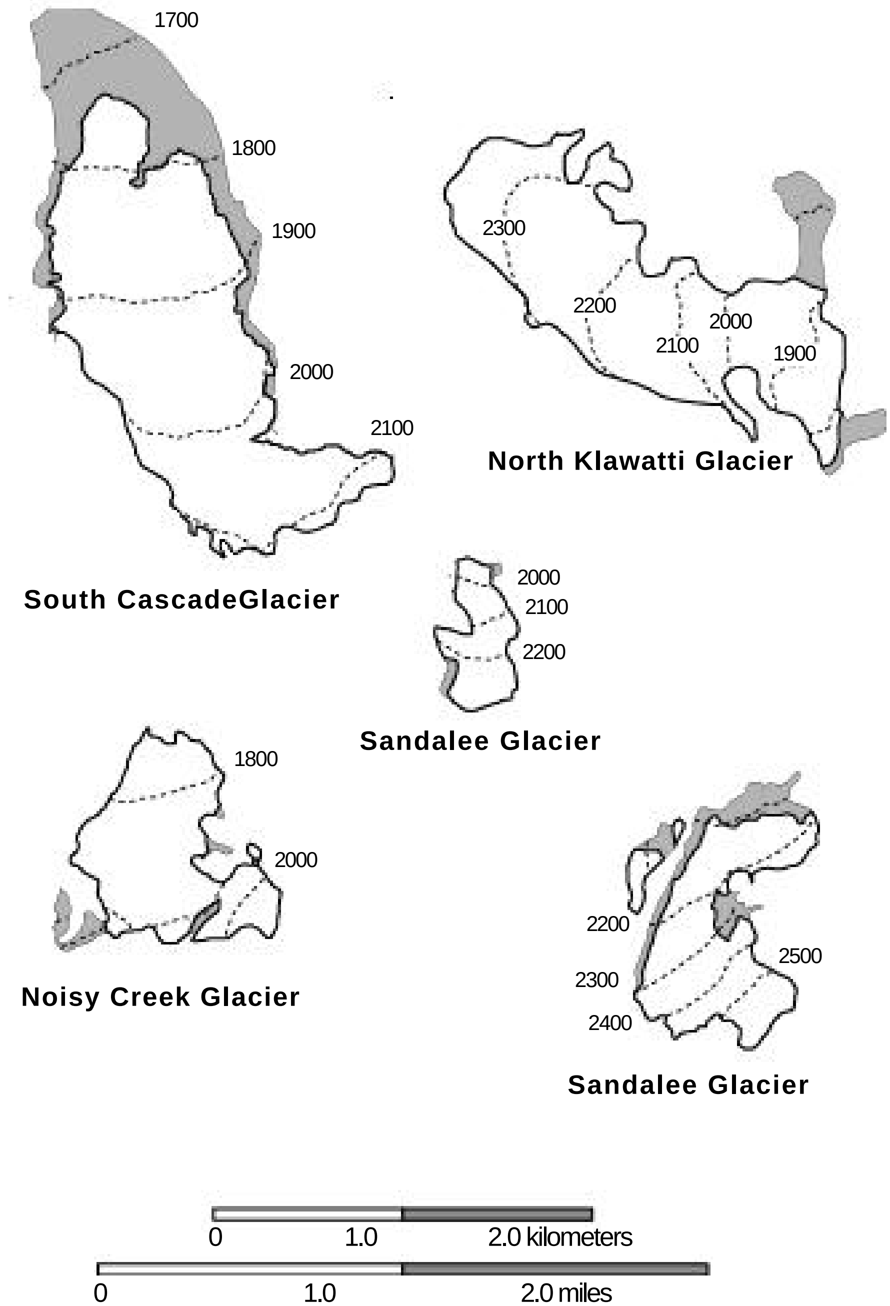

Figure 3.2 - Boundaries of Glaciers in 1958 and 1998. Contours are for 1958 and have a contour interval of 100 meters. Shaded areas are the 1958 extents, and the white areas are the 1998 extents.

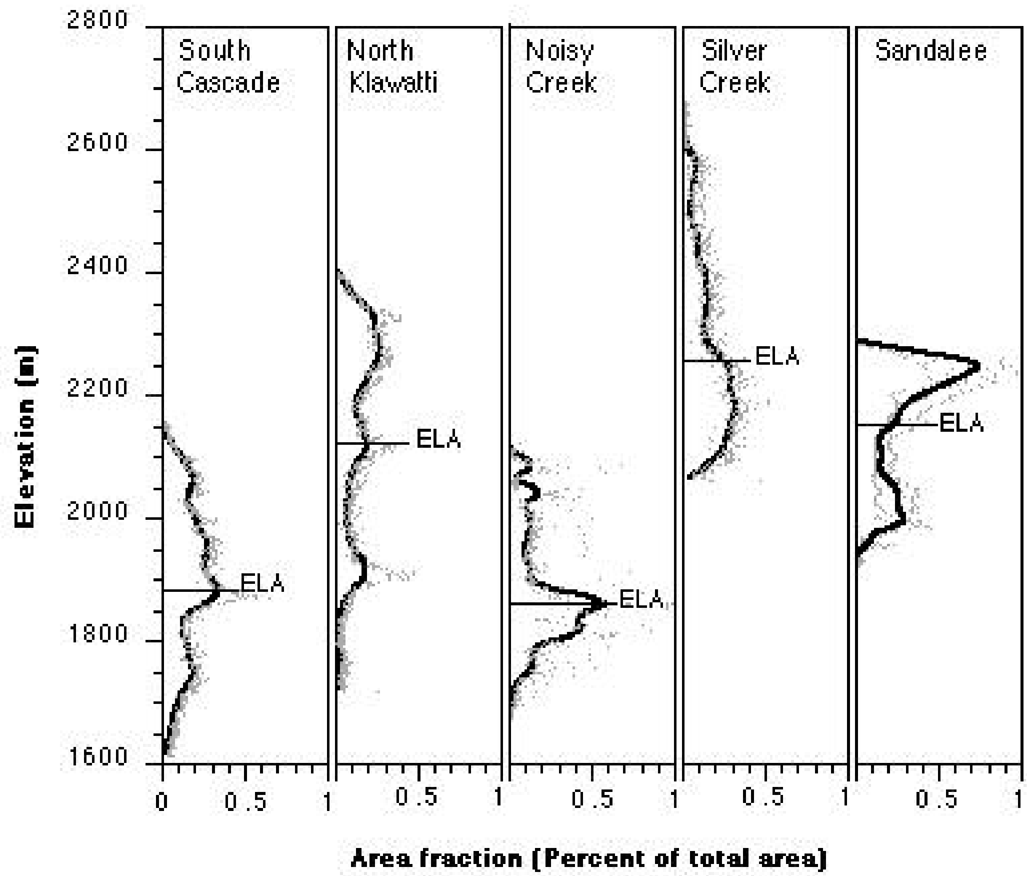

Figure 3.3 - Area altitude (0-1%) distributions for index glaciers for 1958. The light gray dots represent the fraction of the area of each glacier at each altitude. The heavy black line is a10% weighted smoothing of each data set. The steady state ELAs are estimates based an assumed accumulation area of 60% of the glacier (Meier and Post, 1962; Porter 1975; Torsnes et al. 1993).

Comparing the index glaciers to other glaciers in the complex:

In terms of glacier area, only one glacier, Sandalee, is close to the 1958 regional area average of 0.3 km^2. The other four index glaciers fall into the top 15% of the population of the complex (Fig. 3.4). The slopes of all five glaciers are significantly less than the regional average of 32°. With the exception of North Klawatti, the orientation of the index glaciers is the same as 60% of population (340 to 40° azimuth). During 1958 four of the five glaciers fell within 150 m of the regional average elevation of 2011 m. The fifth, Silver Creek Glacier, was 272 m higher than the regional average. Both South Cascade and Noisy Creek glaciers, were lower than the average.

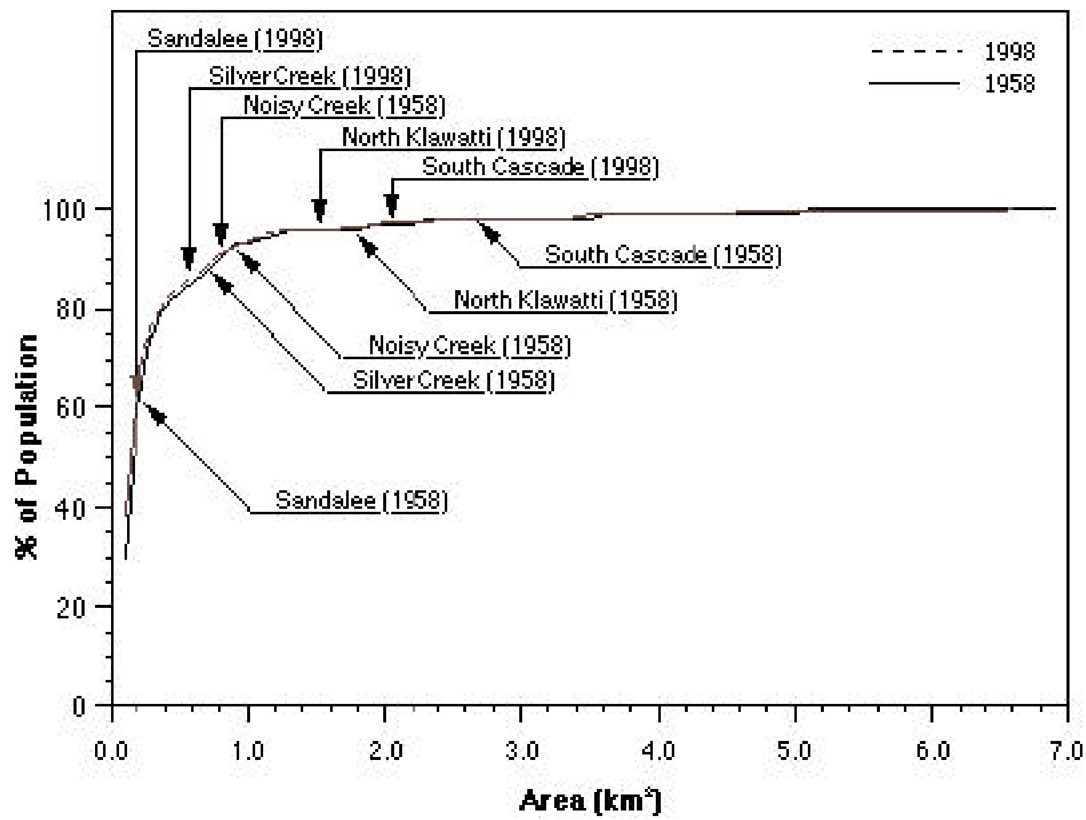

Figure 3.4 - Plot of cumulative glacier population for 1958 and 1998 versus size and position of indicator glaciers within this distribution.

Glacier change

Between 1958 and 1998, area loss for the index glaciers varied from -0.03 to -0.61 km^2, fractional area loss (FAC) ranged from 12 to 22% (Table 3.2), and volume losses ranged from 0.748 to 0.002 km^3. In all three cases South Cascade Glacier had the largest loss, while Sandalee had the smallest. North Klawatti and Noisy Creek glaciers had FACs similar to South Cascade. Silver Creek Glacier had a FAC similar to that of Sandalee.

A comparison of index glacier FAC to the FAC for the general population (Fig. 3.5) shows three of the five index glaciers (South Cascade, North Klawatti, and Silver

Creek) have high FACs for their area class. Furthermore, three of the five glaciers have significantly higher FACs than the regional average of 13%. The other two, Sandalee and Silver Creek fall within 0.5 and 1.1% of the average.

Table 3.2 - Spatial characteristics of the five index glaciers. Area change is shown in km2 and in percentage of 1958 area.

Glacier	Area (km^2)		Change		Volume (km^3)
	1958	1998	Area	FAC	Change
South Cascade	2.71±0.16	2.10±0.13	-0.61±0.06	-22.5±2.2%	-0.0748±0.007
North Klawatti	1.81±0.10	1.45±0.12	-0.36±0.03	-19.9±1.5%	-0.0263±0.002
Noisy Creek	0.91±0.06	0.72±0.06	-0.19+0.01	-20.9±1.1%	-0.0111±0.006
Silver Creek	0.78±0.06	0.67±0.06	-0.11±0.01	-14.1±1.2%	-0.0122±0.001
Sandalee	0.24±0.02	0.21±0.02	-0.03±0.01	-12.5±4.2%	-0.002±0.0007

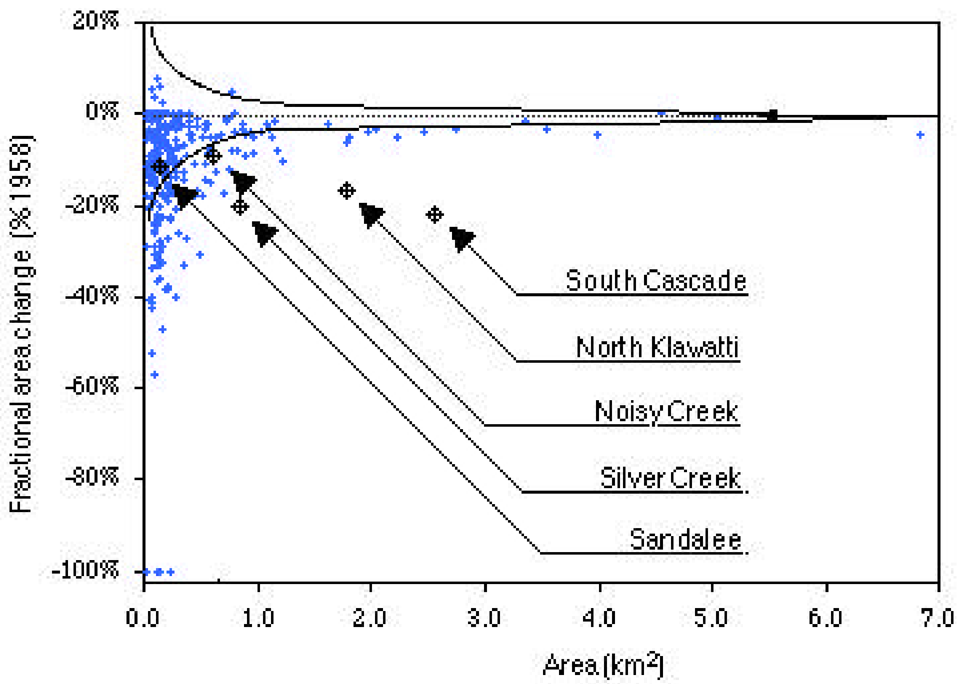

Figure 3.5 - Individual glacier FAC versus area showing location of index glaciers within the population. The two solid lines show the error in FAC for each area class.

Index glaciers as representative of regional characteristics and change

Determining whether the index glaciers are representative of the general population of the complex was done by considering what an "ideal" index glacier is and then investigating how the characteristics of the selected glaciers fit these criteria. From a purely statistical point of view, an ideal benchmark glacier would have the same characteristics as the modal glacier in the region. Based on this approach, Sandalee glacier would be the best representative. It is closest to the modal glacier area (0.1 km^2), has the same orientation as the bulk of the population, and had a FAC closest to the regional mode (-5%). Conversely, South Cascade is the least representative since it is significantly larger, lower, and had a FAC nearly four times that of the modal FAC.

Using statistics alone for evaluating an index glacier is severely limited in that it does not recognize the diversity of the population of the complex or take into account hydrologic considerations. While Sandalee may represent the largest group of glaciers in the complex, it is not representative of a smaller, but still significant group of larger glaciers. While only 10% of the population is larger than 1 km^2, these large glaciers represent more than 47% of the total glacier area and 60% of the combined volume. This means that a small number of large glaciers constitute a major portion of the water stored in the regional ice cover. Therefore, using a single small glacier to represent the characteristics and behavior of the entire population leads to serious difficulties when calculating streamflow on the basis of estimated glacier change. The primary reason for this is that small glaciers respond more quickly to climate change, producing estimates of glacier contribution to regional stream flow that are higher than actual. Therefore, South Cascade and North Klawatti should be good index glaciers because of their size and the fact that they lie in basins with well defined hydrologic boundaries simplifying streamflow monitoring.

However, while South Cascade and North Klawatti glaciers are good index glaciers from a hydrologic point of view, they are inaccurate from a statistical perspective.

Both are larger and have a higher FAC than the regional norm.   For this reason, the strategy of monitoring several glaciers of different sizes provides a more accurate means of estimating glacier change within the complex.   However, even estimates of regional change based on the behavior of all five glaciers produce a somewhat distorted picture of that change for two reasons. First, changes in the index glaciers give the impression that it is the largest glaciers that are most responsive to climatic change. The regional database says exactly the opposite. Second, even the glacier most representative of the modal FAC, Sandalee Glacier, had a fractional change twice that of the modal value. Hence, estimates of regional change from index glacier behavior must be adjusted by regional glacier data to produce an accurate portrait of that change.

Mass balance and index glaciers

The issue of how detailed data from a few selected glaciers can be used to estimate change for an entire region is discussed by examining the balance between ablation and accumulation (mass balance) for the five index glaciers in relation to regional area and volume changes. The mass balance of all five glaciers are estimated from ground-based methods (Reidel et al.; 1997, Krimmel, 2001). Of the five index glaciers, South Cascade has the longest record (1958-2000) based on stake measurements made twice a year (Krimmel, 2000). According to this data set, yearly net balance for 1958 through 1998 varied from -2.6 to +1.6 meters water equivalent (Fig. 3.6a). From 1957 to 1976, the number of negative balance years were roughly equal to the number of positive balance years. From 1977 to 1997, negative balance years become significantly more frequent (McCabe and Fountain, 1995).   This trend can also be seen in the plot of cumulative mass balance for South Cascade. For the entire 1957-1997 period cumulative mass balance decreases by 21 mwe. Most of this change takes places during 1977-1997 (Fig. 3.6b).

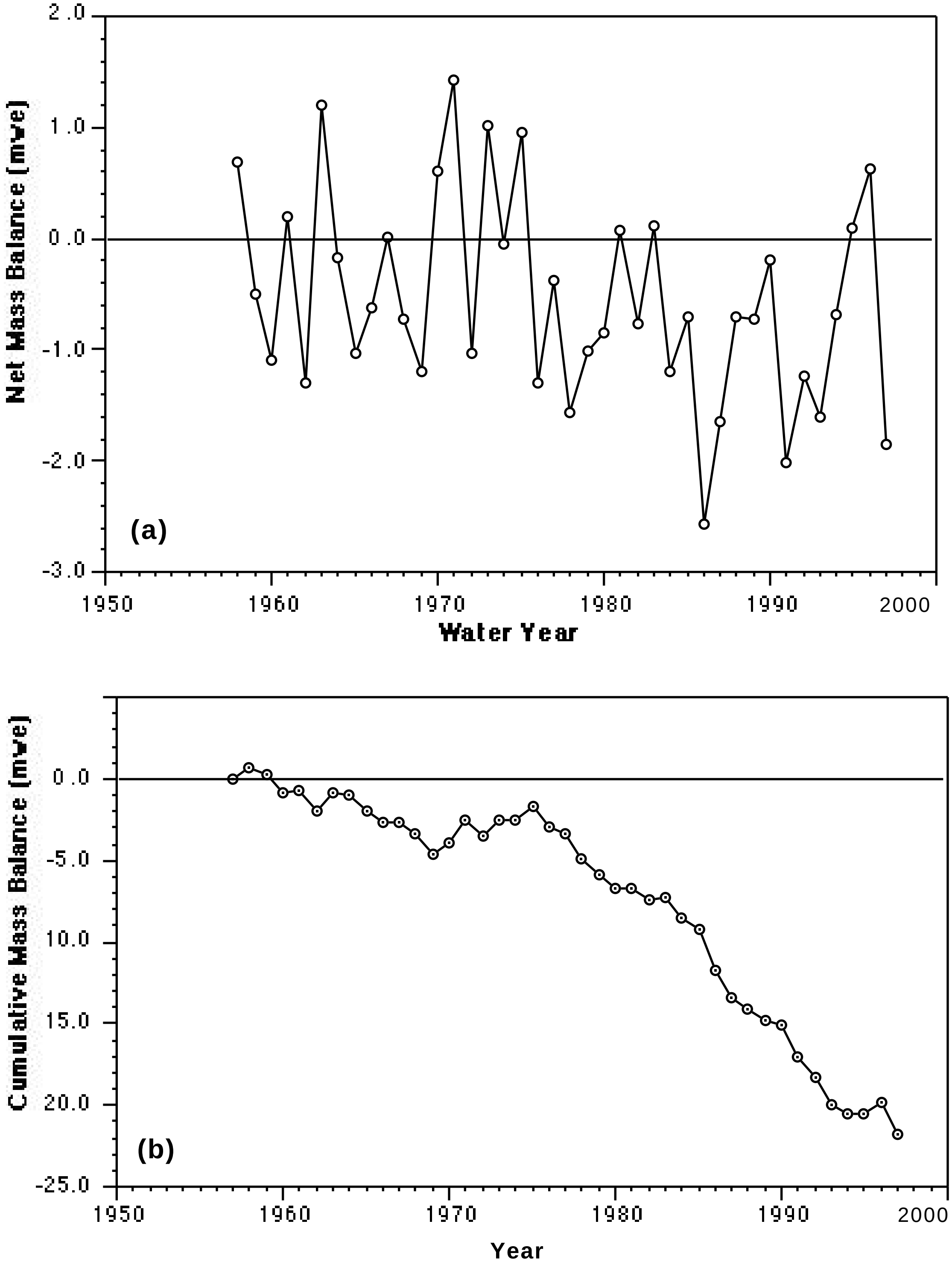

Figure 3.6 - Net mass balance (a) and cumulative balance (b) (in meters water equivalent - mwe) for South Cascade Glacier from 1958 to 1998

The mass balance records of the index glaciers are significantly shorter than that of South Cascade. Three of the glaciers (Noisy, Silver Creek, and North Klawatti) have measurements from 1992 to 1998 and the fourth, Sandalee, has a 1994 to 1998 record. In comparing field derived mass balance for all five glaciers (Fig. 3.7a and 3.7b) three major trends appeared. First, Silver Creek and Sandalee glaciers generally had the highest net balances, while North Klawatti, Noisy Creek, and South Cascade had the lowest. Second, the first two glaciers has positive cumulative balances. The last three, Silver Creek and Sandalee, had negative cumulative balances, indicating that they grew between 1992 and 1998, while North Klawatti and Noisy Creek shrank. Finally, while the cumulative balance curves for the five glaciers were significantly different, variations in net balance were similar. In other words, net balance increased and decreased in tandem for all four glaciers. The similarity in net balance indicates a consistency in the climate changes experienced by each glacier. The differences in their cumulative balances point to topographic characteristics that either enhance precipitation or reduce melt.

The impact of topography on mass balance was determined primarily by looking at elevation (Table 3.3). Area was disregarded as a factor due to the anomalous behavior of the five glaciers (larger glaciers having a larger FAC than small glaciers). Likewise, slope and orientation were ignored due to the similarity of the glaciers to one another. Generally, the glaciers with negative cumulative balances had the lowest average and minimum elevations, as well as the lowest ELAs. The two glaciers with positive balances, Silver Creek and Sandalee, had the highest ELA and average and minimum elevations.

Table 3.3 - Cumulative mass balance (cmb) and elevation for index glaciers.

Glacier	cmb	Elevation (m)			
	(mwe)	Ave	ELA	Min	Max
South Cascade	-4.7	1896	1871	1613	2176
North Klawatti	-1.6	2134	2102	1692	2436
Noisy Creek	-0.9	1883	1847	1673	2121
Silver Creek	0.5	2283	2207	2061	2695
Sandalee	0.2	2151	2150	1920	2304

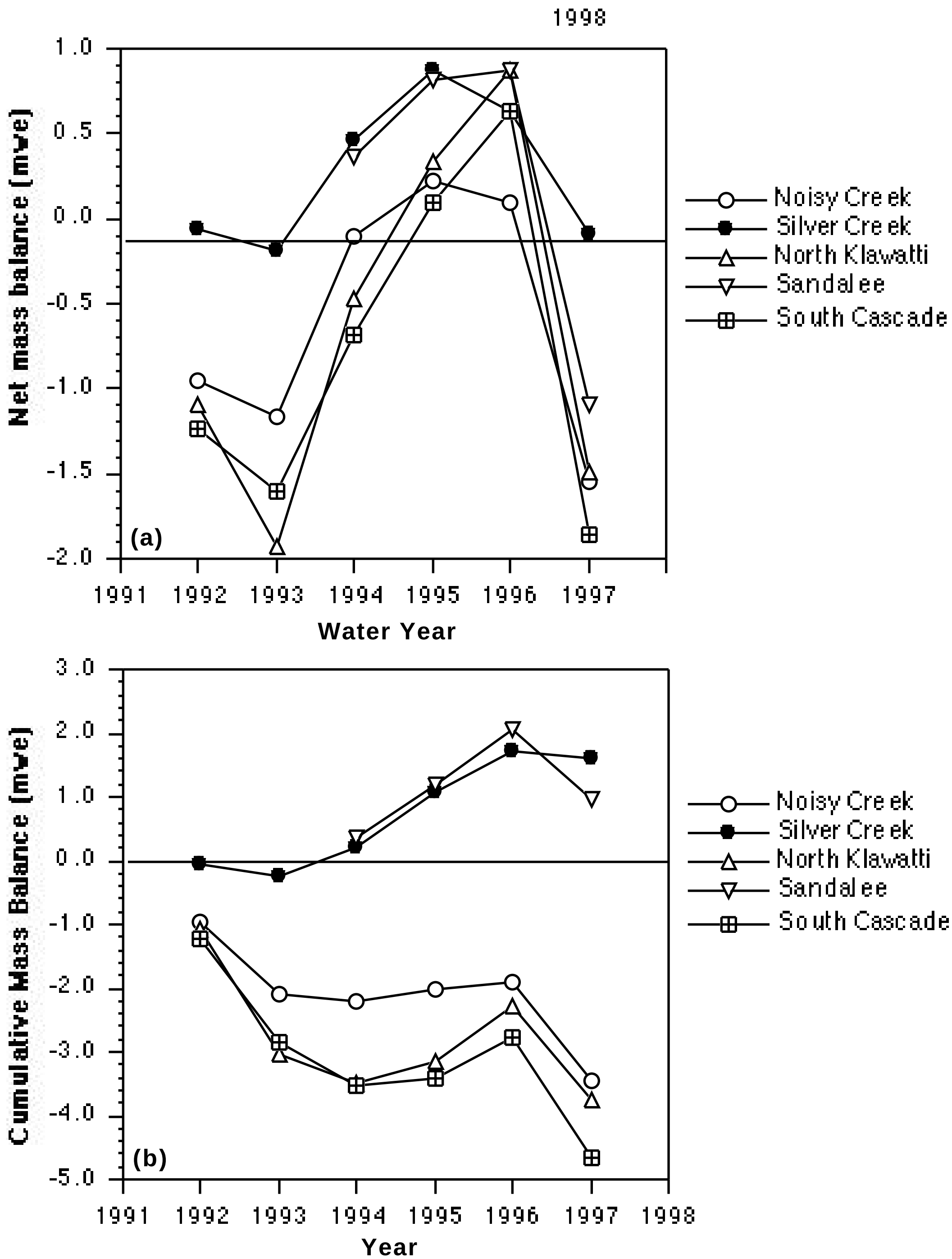

Figure 3.7 - Net (a) and cumulative (b) mass balance by water year for benchmark and secondary glaciers.

One explanation for this is that in a time of increasing temperature and precipitation, the lowest glaciers would have decreased snowfall and increased melt. However, the higher glaciers would have increased snowfall due to increased precipitation which would offset any increase in melt rate.

A comparison of the balance of all five glaciers suggests that it is possible to create a more extensive balance history for the NPS index glaciers and the bulk of the glaciers in the park complex using the mass balance for South Cascade. This suggestion is derived from the observation that between 1992 and 1998, variations in net balance for South Cascade were similar to variations for the other index glaciers (Fig. 3.7a). Therefore, I presume that the mass balance variation for any other glacier in the complex would also be similar.

The mass balance for the other glaciers can be estimated by scaling the cumulative balance for South Cascade using the equation...

$$b_x = \frac{\Delta V}{A} b_s \qquad \textbf{(3.1)}$$

where mb is the mass balance of the glacier for which a history is being constructed, ΔV is its volume change, A is its 1958 area, and b_S is the mass balance of South Cascade Glacier. To create a complete balance history for each of the four NPS index glaciers ΔV was calculated for 1958-1998 using the Bahr et al. (1997) scaling technique and each glacier's 1958 area. The plot generated using equation 3.1 (Fig. 3.8a) showed Sandalee having the smallest cumulative balance and South Cascade having the largest.

This strategy was tested by estimating 1992-1998 net and cumulative balances for the four NPS index glaciers, and comparing them to their field derived counterparts. Estimated net balance was derived using equation 3.1 with 1992 or 1994 areas for A (maps for all the glaciers but Sandalee were compiled in 1992) andvolume changes derived by the Bahr et al. (1997) area / volume scaling technique. Cumulative balances were compiled by summing net balances. A comparison of estimated cumulative balance to cumulative balance for South Cascade (Fig 3.7b) showed Sandalee and Silver glaciers

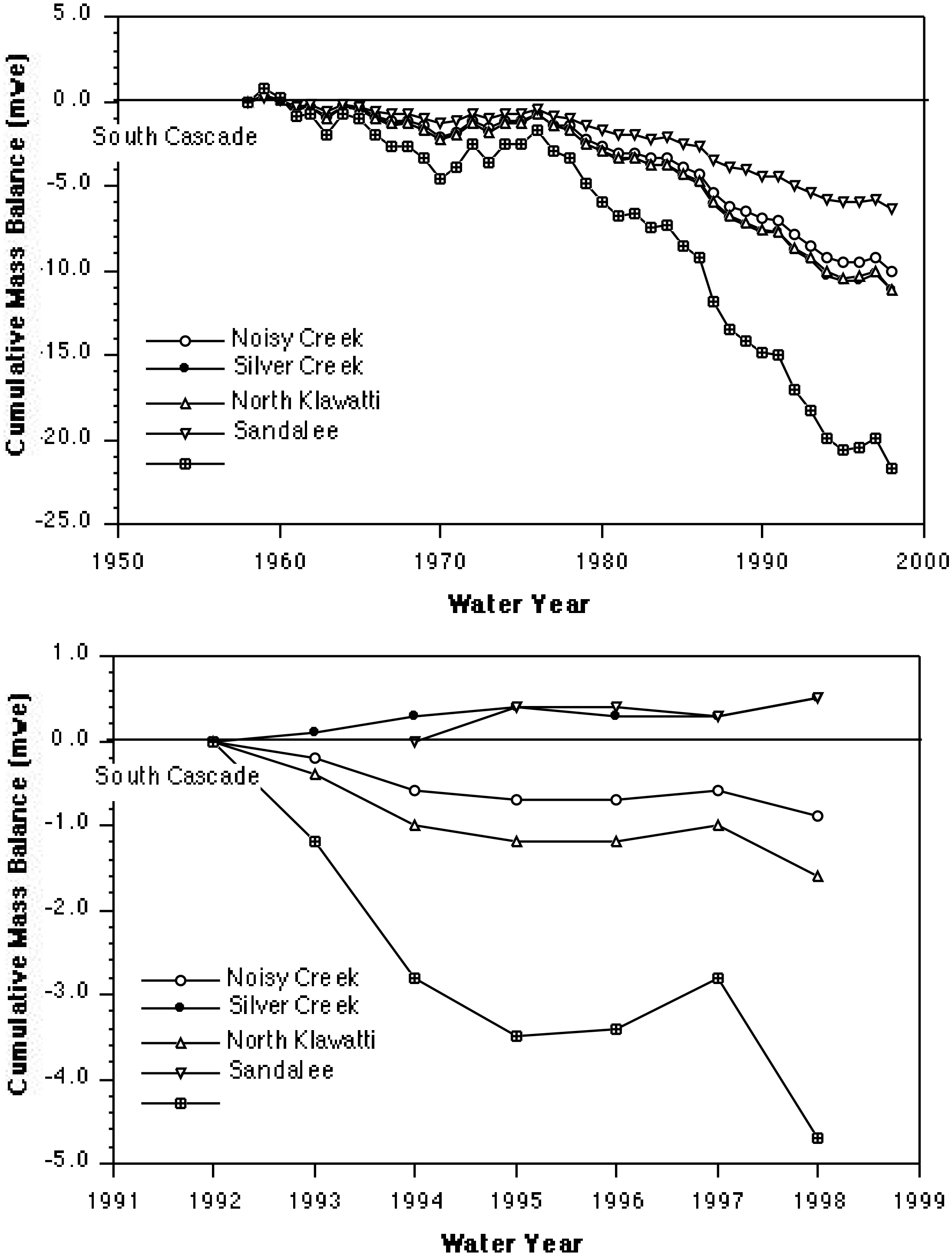

Figure 3.8 - Estimated mass balance histories for index glaciers for (a) 1958-1998 and (b) 1992-1998.

accumulating, and the remaining glaciers losing mass. So in a general way, the estimated balances were consistent with field derived balances. However, the magnitude of the estimated cumulative balances for Noisy and North Klawatti is less than half of their field derived values. One explanation for this problem involves the methods used to derive mass balance. When topographically derived mass balance is compared to stake derived balance, the stake derived balance has been shown to under represent mass loss on temperate glaciers (Krimmel 1996b). This problem is undoubtedly compounded by map errors. For instance, glacier areas derived from the 1998 regional layer were found to have an uncertainty of 10%. Errors in mass balance estimated using equation 3.1 ranged from 40 to 70%. Since errors of this magnitude would require area errors of 10 to 16%, the uncertainty in 1998 glacier area would be sufficient to produce the error in mass balance.

The estimated balance histories for Sandalee and Silver Creek glaciers present another problem. Glaciers having positive cumulative balance result in net and cumulative balance curves that are out of phase with South Cascade. In other words, net balance increases while the balance of South Cascade decreases. The principle explanation for this behavior involves the mathematics used to estimate net and cumulative balance. Since for any glacier having a positive cumulative balance ΔV must be positive, negative and cumulative balance for that glacier will decrease as South Cascade Glacier's balance increase since ΔV for South Cascade is negative. Consequently, for any period of time for which ΔV is either positive or zero equation 3.1 can not be applied. This means that South Cascade's balance record can not be used to estimate balance histories for the 27% of the population of the complex that were in equilibrium or grew between 1958 and 1998. However, since the complex as a whole saw a volume reduction it is possible to construct a balance history for the entire complex (Fig. 3.9). This complex balance history for the complex was calculated using the combined 1958 area and the combined volume change as estimated by the Bahr et al. (1997). Based on this method the cumulative balance for the entire region is -6.1 m (mwe).

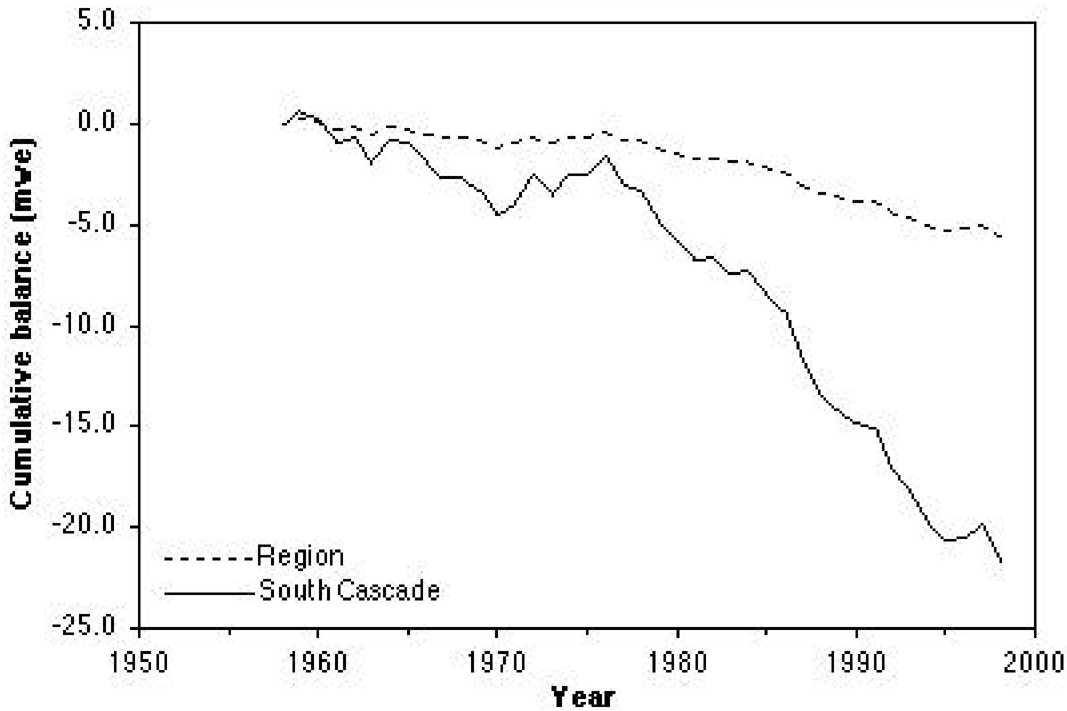

Figure 3.9 - Estimated mass balance histories for South Cascade Glacier and the entire glacier cover of the National Park Complex.

Summary

The five indicator glaciers represent a cross section of the glaciers of the National Park Complex. For instance, while Sandalee Glacier is typical of the smallest 60% of the glaciers, South Cascade represents the largest 3% of the population. All five glaciers are oriented between northwest and northeast, as are 67% of the glaciers in the complex. Average elevations ranges from 1865 m (Noisy Creek) to 2298 m (Silver Creek). South Cascade Glacier is closest to the regional average of 2011 m. All five glaciers have slopes less than 25°, while the regional average is 32°.

The question of which glacier is the most representative of the general population depends on the criteria used to define an index glacier. From a statistical point of view, Sandalee Glacier is representative of the typical glacier in the complex. It's area, orientation, and fractional area change are closest to the average. Consequently, it represents the largest group of glaciers in the complex. From this same perspective, South Cascade is an anomaly, since it is significantly larger, lower, and lost more of its 1958 area than most of the glaciers in the complex. However, from the perspective of volume and hydrology, South Cascade and North Klawatti glaciers are good indicators of glacier change, since they belong to that 10% of the population that makes up 60% of the combined glacier volume. In considering both arguments, it appears that the current approach of monitoring several glaciers of varying size provides the most accurate picture of glacier change in the complex.

In the case of the National Park Complex, the long mass balance record for South Cascade Glacier provides the only continuous record of glacier change for the region. Furthermore, the similarity of mass balance variations for 1994-1998 to balance changes for the four secondary glaciers for the same time period, indicates that the trends in mass balance for South Cascade Glacier appear throughout the complex. However, to use the record from South Cascade to estimate glacier change, the balance record from the glacier should be scaled on the basis of the records from the indicator glaciers.

Chapter 4 - Spatial and temporal climate

Changes in glacier volume result from temporal variations in climate. While mass input is largely from snowfall, mass output is controlled by the energy flowing to or from a glacier. Energy is generally gained or lost in the form of short-wave and long-wave radiation, sensible heat, and latent heat transferred by phase changes (Benn and Evans, 1998). Since temperature is an expression of energy exchange; annual and seasonal mass balance can be estimated using both air temperature and precipitation data from low elevation climatestations (Tangborn, 1980a). Snowfall at upper elevations is related to winter and annual temperature and precipitation at these stations, while ablation is related to their summer temperature and temperature range. For instance, while snowfall increases with decreased winter temperature or increased winter precipitation, ablation increases with increased summer temperature and temperature ranges. The significance of temperature range (difference between average maximum and minimum) is that it can be used to estimate cloud cover, which when combined with average temperature produces a measure of incoming short-wave radiation. Based on these concepts, glacier mass loss should take place during periods of increased annual and seasonal temperature, which may or may not be accompanied by decreased precipitation. The goal of the analysis described in this chapter is to test this hypothesis using station based climate data and climate indices to determine regional trends in both temperature and precipitation.

Background

Dyurgerov and Meier (2000) determined that glacier mass loss on a global scale started in the middle of the 19th century at the end of the Little Ice Age and has occurred in several stages. They argue that glacier loss in the Northern Hemisphere has occurred because of a shift toward a warmer and moister climate. In the Pacific Northwest, glacier and climate change during 1957-1997 is described by dividing the period into two intervals. The first interval, 1957-1976, is characterized by glacier advance, stagnation, or modest decrease. The second, 1977-1997, saw major glacier mass losses (McCabe and Fountain, 1995; Meier and Dyurgerov, 2000) and a shift toward warmer, wetter weather (JISAO, 2000).

To explore the relationship between regional climate and glacier change, three types of data were used: data from individual climate stations, division climate data, and climate indices. The principle advantage of the station data is that it contains detailed information on numerous weather variables (e.g. wind, air temperature, precipitation). The principle disadvantage is that station data are point values, and for the North Cascades stations are located at elevations lower than that of the glaciers (Daly et al., 1994). Divisional climate data are regional statistics produced by averaging the data from all the individual stations in that region. The advantage of divisional data is that it gives a simple, regional climate picture. A major problem is that the spatial representation depends on the distribution of stations. As previously mentioned, all permanent climate stations in the North Cascades are located in lower elevations. For both division and station data, differences in the data may be produced by changes in the operation of the stations rather than actual climatic events (Taylor, Oregon Climate Service, personal communication, 2000). Most of the National Park complex is located in the Cascade West Climate Division with small sections located in Cascade East and Cascade Foothills divisions (Fig. 4.1). However, none of the eight meteorologic stations in or adjacent to the complex are located in Cascade West, indicating that temperature and precipitation data for this division are based on climate stations in the Southern Washington Cascades and nearby stations in the Cascade Foothills and Cascade East.

A climate index is a single climatic factor that can be used to describe and predict other climatic factors in a region. Because of teleconnections, linkages over great distances of atmospheric and oceanic variables, a climate index from one hemisphere can be linked to climate variations in the other hemisphere. For instance, Southern Oscillation Index (SOI) is based on the difference in air pressure at Darwin, Australia, and the Tahiti Islands. Fluctuations in SOI correspond to El Niño and La Niña events

(Rasmussen 1985), hence, the name El Niño Southern Oscillation or ENSO. In general, years with negative SOI tend to be El Niño events, while years with positive SOI tend to be La Niña years. In the North Cascades, years of negative SOI tend to be warmer and drier than average, while positive SOI years tend to be cooler and wetter (Redmond and Koch, 1991). Therefore, it seems logical to presume that a period of glacier reduction in the North Cascades would be marked by a higher frequency of negative SOI years.

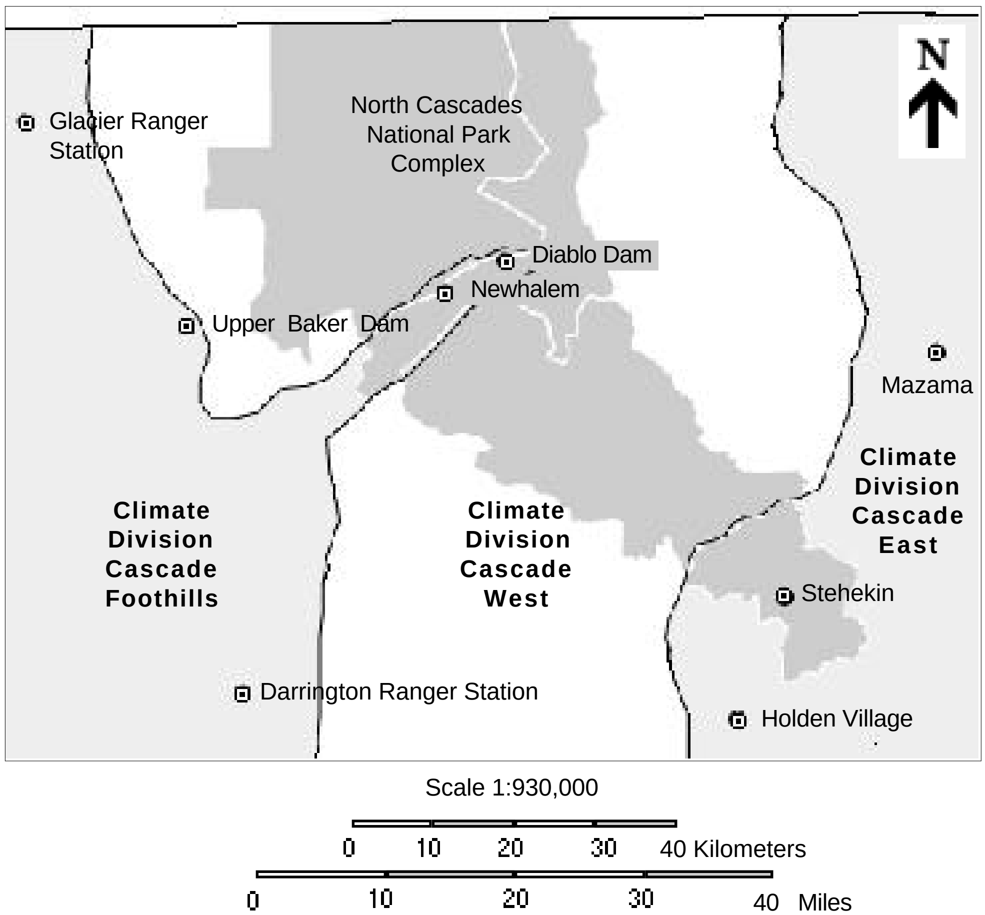

Figure 4.1 - Climate division boundaries and the location of climate stations in and around the national park complex.

Another index, called the Pacific Decadal Oscillation (PDO), is based on differences in sea level air pressure and sea surface temperature over the subtropical north Pacific Ocean and western North America (McCabe and Dettinger, 1998). Like SOI, PDO fluctuations correspond with tendencies in precipitation and temperature in the Pacific Northwest. Periods of positive PDO, referred to as “warm phase”, correspond in the Northwest to above average October through March air temperature, below average precipitation and below average spring time snow pack. “Cool phase” PDO is generally characterized by the opposite. The major difference between PDO and SOI, is that PDO is significantly more persistent. For instance, while El Niño /La Nina events last for a few months or years, PDO cycles last a decade or longer(Mantua, 2000). During the past century cool phase PDO has taken place twice, once from 1890-1928 and again in 1947-1976. Warm PDO phases occurred from 1925-1940 and 1977-1997(Mantua, 2000). Recent changes in Pacific climate suggest that 1998 began a new cool phase (Mantua, 2000).

Climate trends based on station data

Daily average temperature and total precipitation data for eight stations in and around the National Park Complex (Fig. 4.1) were obtained from the Western Regional Climate Center’s web site (http://www.wrcc.dri.edu/summary/climsmwa.html). These data were used to calculate average annual and seasonal temperature and precipitation, as well as average ablation season temperature range for 1957-1997, 1957-1976, and 1977-1997. The two periods, 1957-1976 and 1977-1997, were chosen on the basis of a switch from a largely cool phase PDO to largely warm phase PDO beginning in 1977 (Taylor and Hannan, 1999; JISAO, 2000). The seasons, October-May (winter) and June-September (summer), were selected to account for the accumulation and ablation seasons that control a glacier’s mass balance.

To calculate average annual and seasonal air temperature and total precipitation for each climate station, only years and seasons having complete records for all twelve months of the water year were included. A complete monthly record is one in which average air temperature and total precipitation exists for all days of the month. Of the eight climate stations examined, only three (Darrington Ranger Station, Diablo Dam, and

Stehekin) had records that are more that 96% complete for the entire 1957-1997 period, and are included in this discussion of climate trends. The other five had temperature and precipitation records which are between 44 and 94% complete.

Table 4.1 - Temperature and precipitation summaries for Diablo Dam, and Darrington and Stehekin ranger stations.

	Temperature (°C)				Precipitation (cm)		
Station	Annual	Accum	Ablation	Range'	Annual	Accum	Ablation
1957-1997 Averages							
Darrington	9.4	7.0	16.4	13.5	201.3	166.0	35.3
Diablo Dam	12.4	10.2	16.7	13.1	195.9	164.3	31.6
Stehkin	8.7	4.2	17.9	15.7	88.3	77.3	11.0
1957-1976 Averages							
Darrington	9.1	6.7	15.9	12.8	212.5	178.0	34.5
Diablo Dam	12.2	10.0	16.7	13.3	195.2	163.8	31.4
Stehkin	8.6	4.3	17.2	16.3	85.8	75.0	10.7
Deviation of 1957-1976 averages from 1957-1997 average							
Darrington	-3.2%	-4.3%	-3.0%	-5.2%	5.6%	7.2%	-2.3%
Diablo Dam	-1.6%	-2.0%	0.0%	1.5%	-0.4%	-0.3%	-0.6%
Stehkin	-1.1%	2.4%	-3.9%	3.8%	-2.8%	-3.0%	-2.7%
1977-1997 Averages							
Darrington	9.7	7.3	16.7	14	192.1	156.1	35.9
Diablo Dam	12.5	10.3	16.7	12.9	196.4	164.7	31.7
Stehkin	8.8	4.1	18.5	15.3	90.3	79.1	11.2
Deviation of 1977-1997 averages from 1957-1997 average							
Darrington	3.2%	4.3%	1.8%	3.7%	-4.6%	-6.0%	1.7%
Diablo Dam	0.8%	1.0%	0.0%	-1.5%	0.3%	0.2%	0.3%
Stehkin	1.1%	-2.4%	3.4%	-2.5%	2.3%	2.3%	1.8%

The general climate of the Pacific Northwest during 1977-1997 was warmer and wetter than in 1957-1976 (JISAO, 2000). Climate changes at the three stations were not always consistent with this trend. While changes in annual temperature for all three stations were in sync with regional variation, Darrington was drier during 1977-1997. Since 1977-1997 was a period of increased mass loss, it is likely that ablation season temperature range would be higher during that time period. Only Darrington behaved in this manner. Furthermore, deviations in precipitation for one of the stations, Diablo

Dam, had statistical significance's less than 0.05 for both 1957-1976 and 1977-1997. These results seriously challenge the use of data from the selected stations to explain regional glacier change. Not only is a portion of the data statistically insignificant, but the inconsistency in climate trends is contrary to index glacier mass balance data that points toward consistent climate change throughout the park complex.

Climatic trends based on divisional data

Of the three divisions, Cascade West had the lowest 1890-1997 average annual temperature and the highest total precipitation (Table 4.2). Cascade East had the lowest average annual precipitation, while Cascade Foothills had the highest annual temperature. Between 1890 and 1997 the average annual temperature increased for all three divisions at a rate of 2.1 to 2.3°C per 100 years, while total precipitation increased 0.2 to 0.9 cm per 100 years (Fig. 4.2 and 4.3). For all three divisions, average annual temperature was higher in 1977-1997, than in 1957-1976. Accumulation and ablation season average temperature also increased during this period, though deviations for ablation season temperatures were significantly lower than deviations in accumulation season temperatures. Annual and accumulation season precipitation was lowest in 1977-1997, while ablation season precipitation was highest during this same period, meaning that a higher fraction of this precipitation fell during the ablation season.

In general, divisional climate data shows that glaciers in the North Cascades lost mass despite increasing precipitation. This is possible because higher winter temperatures mean that less of the seasonal precipitation would fall as snow. Likewise, higher summer temperatures would cause increased ablation. Divisional data can also be used to explain accelerated mass loss during 1977-1997. During this period snowfall decreases because of increased winter temperature and decreased precipitation. Likewise, summer ablation increases primarily because of seasonal temperature increase.

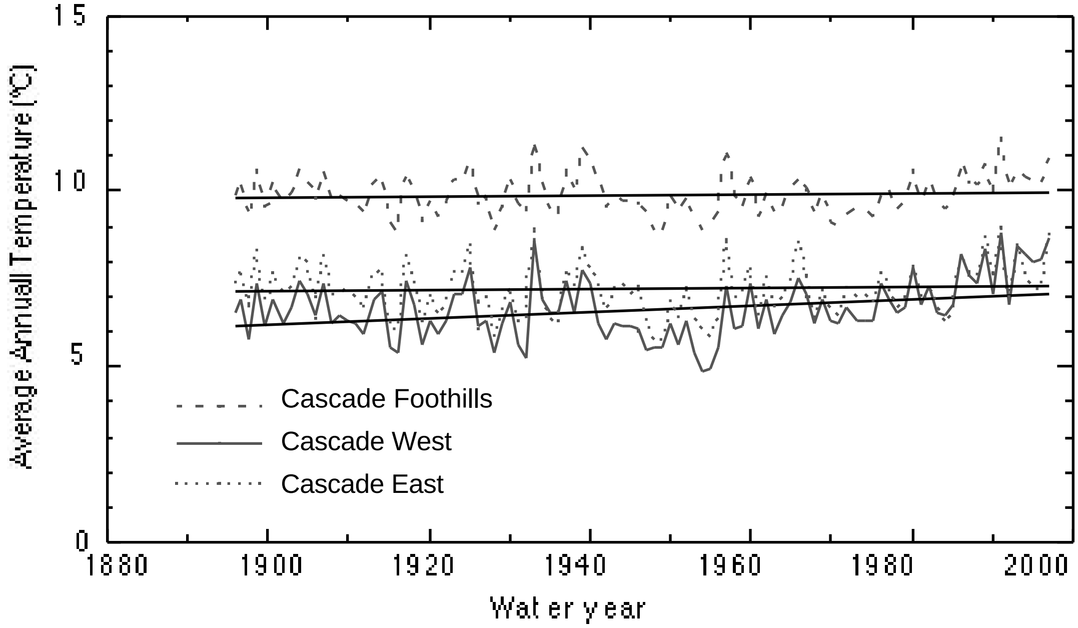

Figure 4.2 - Average annual temperature versus water year for Cascade Foothills, Cascade West, and Cascade East climate divisions. The dotted line shows average temperatures for individual years. The solid black line is a line regression of the data set.

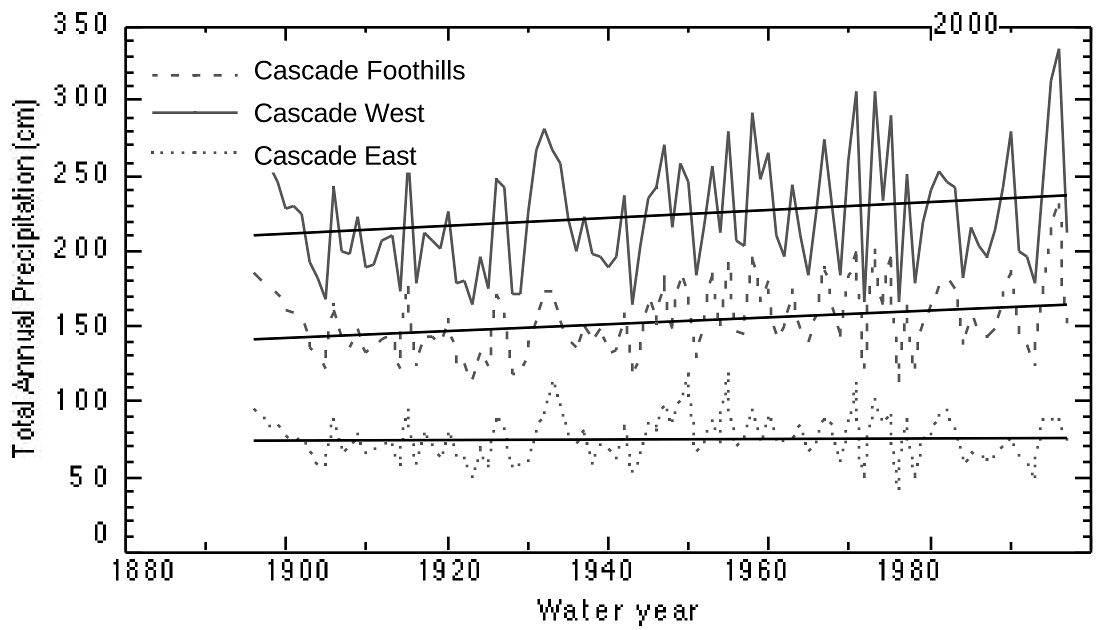

Figure 4.3 - Total annual precipitation versus water year for Cascade Foothills, Cascade West, and Cascade East climate divisions. The dotted line shows total precipitation for individual years. The solid black line is a line regression of the data set.

Table 4.2 - Temperature and Precipitation summary for Cascade Foothills, West, and East Climate Divisions.

	Temperature (°C)			Precipitation (cm)		
Division	Annual	Accum	Ablation	Annual	Accum	Ablation
1890-1997 Averages						
Cascade Foothills	9.8	7.1	15.4	154.3	132.1	22.2
Cascade West	6.6	3.5	12.7	223.9	195.7	28.2
Cascade East	7.2	3.1	15.3	74.8	66.7	8.0
1957-1997 Averages						
Cascade Foothills	9.9	7.2	15.5	163.0	139.6	23.4
Cascade West	7.0	3.9	13.2	233.1	204.8	28.3
Cascade East	7.4	3.3	15.6	74.8	66.7	8.1
1957-1976 Averages						
Cascade Foothills	9.7	6.9	15.2	166.5	143.7	22.8
Cascade West	6.5	3.4	12.8	234.2	212.0	26.7
Cascade East	7.2	3.2	15.3	79.9	72.8	7.2
Deviation of 1957-1976 averages from 1957-1997 average						
Cascade Foothills	-2.7%	-3.7%	-1.7%	2.2%	2.9%	-2.4%
Cascade West	-6.8%	-13.8%	-2.6%	2.4%	3.5%	-5.5%
Cascade East	-2.2%	-2.6%	-2.0%	6.9%	9.1%	-11.2%
1977-1997 Averages						
Cascade Foothills	10.2	7.4	15.7	159.9	136.1	23.9
Cascade West	7.4	4.4	13.5	228.2	198.5	29.6
Cascade East	7.5	3.4	15.8	70.3	61.5	8.8
Deviation of 1977-1997 averages from 1957-1997 average						
Cascade Foothills	2.3%	3.2%	1.5%	-1.9%	-2.5%	2.1%
Cascade West	5.9%	12.0%	2.3%	-2.1%	-3.0%	4.8%
Cascade East	1.9%	2.3%	1.7%	-6.0%	-7.8%	9.7%

Climatic Trends based on SOI and PDO

Average annual SOI and PDO data were obtained from the International Research Institute for Climate Prediction (Columbia University) and the Joint Institute for the Study of the Atmosphere and Ocean (University of Washington) via their web sites at <http://iri.ldeo.columbia.edu/ and http://tao.atmos.washington. edu/main.html>. SOI and PDO were obtained for both water and calendar years.

For the period 1957-1997, average SOI was -0.4 and years of negative SOI were significantly more frequent than positive SOI (Fig. 4.4). The average PDO for the period was 0.1, with positive PDO years occurring more often than negative PDO (Table 4.3). The SOI indicate that El Niño events were more frequent than La Niña events, while PDO trends pointed toward more frequent warm phase years. During 1957-1976, the average SOI was 0.2 and average PDO was -0.6, while during 1977-1997 SOI was -0.7 and PDO 0.6. Both indexes suggest that 1977-1997 was drier and warmer than the earlier period (Table 4.3).

Table 4.3 - Summary of SOI and PDO statistics. Frequency (%) is the percentage of each of the three periods where SOI and PDO was positive or negative.

	SOI			PDO		
		Frequency (%)			Frequency (%)	
Periods	Ave	SOI < 0	SOI > 0	Ave	PDO < 0	PDO > 0
1957-97	-0.4	63.6	36.4	0.1	47.5	52.5
1957-75	0.2	47.6	52.4	-0.6	88.9	11.1
1977-97	-0.7	78.3	21.7	0.6	17.4	82.6

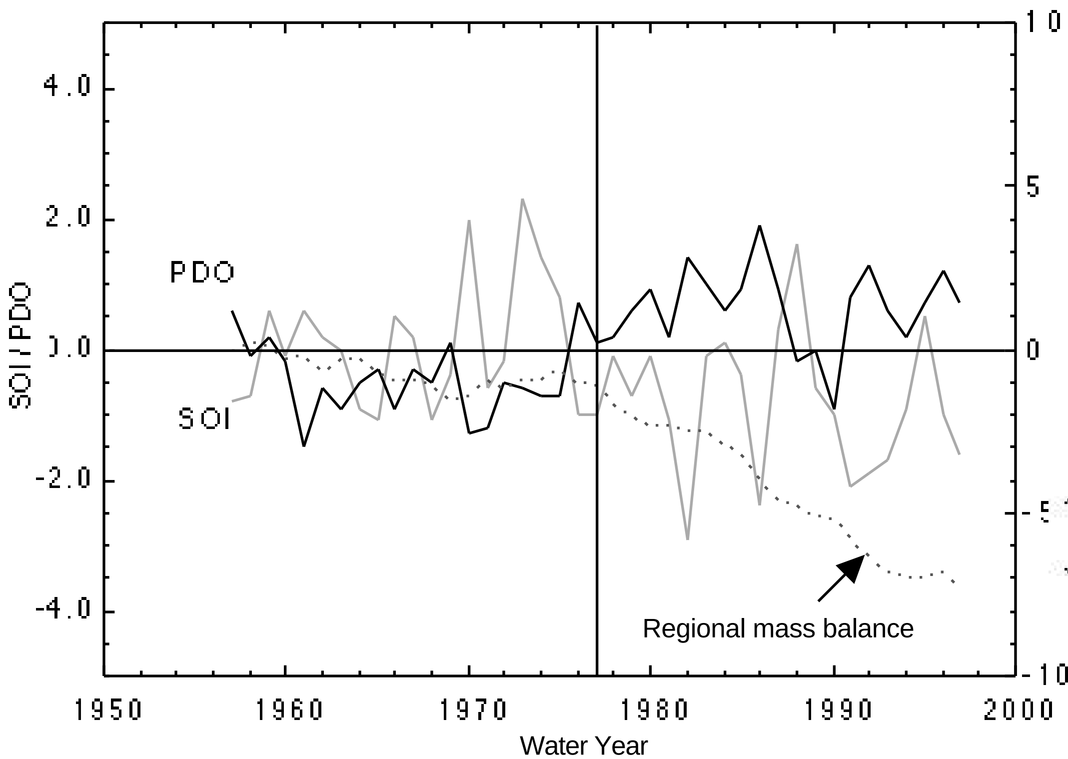

Figure 4.4 - Plot of SOI and PDO versus Water Year. Average SOI and PDO for 1957-1976 and 1977-1997 are shown by the indicated lines. The regional mass balance is estimated by techniques described in chapter 3.

Summary

Regional glacier data show that the water years 1957-1997 were characterized by glacier shrinkage. Changes in regional mass balance indicate that 92% of this loss took place between 1977 and 1997 (Fig. 4.4). Climate division data, PDO, and SOI provide the clearest explanation for this change. Based on SOI and PDO, during 1957-1997 water years that were warmer and drier than average were more frequent than cooler, wetter years. According to divisional climate data (Table 4.2), 1957-1976 was cooler and wetter than the 1957-1997 average, while 1977-1997 was warmer and drier. This trend was consistent for both annual and accumulation season temperature and precipitation. However, the average 1977-1997 ablation season was warmer and wetter than the 1957-1997 average, and the 1957-1976 ablation season was cooler and drier. Consequently, increased mass loss during 1977-1997 resulted not only from changes in temperature and precipitation, but also from changes in the timing of the precipitation.

Abrupt changes in climate during 1977-1997 are consistent with the climatic shifts noted by McCabe and Fountain (1995) and Dyurgerov and Meier (2000). However, the change toward warmer, drier conditions in the North Cascades during 1977-1997 seems to be contrary to Dyurgerov and Meiers's (2000) conclusion that glacier mass loss in the Northern Hemisphere is taking place in a warmer and wetter environment. This is explained by noting that divisional data shows increases in annual temperature and precipitation for 1890-1997 that are consistent with the hemispheric trend. Furthermore, the average precipitation for the entire 1957-1997 period was higher than the 1890-1997 for all three divisions. Consequently, the shift toward warmer, drier conditions is relative to 1957-1976, not to the entire century. What is more problematic is that the change to warmer, drier conditions concluded from divisional data is inconsistent with the shift toward warmer, wetter climate for the entire Pacific Northwest.

The use of data from individual climate stations to explain regional glacier change could not be done because of inconsistencies in climate variations for individual stations and the incompleteness of the records from many of these stations. Of the eight stations located in or around the park complex, only three had records that were more than 95% complete for the water years 1957-1997. Though all three showed annual temperature variations consistent with divisional climate data and climate indices, there was little agreement in terms of variations in seasonal temperature, and annual and seasonal precipitation. Furthermore, a bulk of the variations calculated for one of the stations failed tests of statistical significance.

Chapter 5

The response of streamflow to climatic variations

Post and others estimated that glacier mass loss for the entire North Cascades Range contributes about 0.8 km^3 per year to stream flow (Post et al, 1971). Nearly two thirds of this water is released during the warmest part of the year and that the greatest ice melt occurs during years that are abnormally dry. In this chapter, I examine how runoff from glacier-carved watersheds changes in response to climatic variation. To determine the impact of climate variations, stream volumes were correlated with climate data. Variations in discharge, annual and seasonal stream volume, and timing of peak discharge were looked at for the water years 1957-1997.

Hydrology and stream monitoring of the Park Complex

There are four major drainage's in the park complex, the Chilliwack, Nooks, Skagit, and Stehekin rivers (Fig. 5.1). The Chilliwack, Nooksak and the Skagit Rivers are located west of the Cascade divide. Two of these basins (the Nooksak and Skagit) drain into the Puget Sound, while the third (the Chilliwack) is a tributary of the Fraser River. The Stehekin River /Lake Chelan basin is located east of the divide and drains into the Columbia River. Between 58% and 74% of the average annual runoff from these rivers occurs during May through September when less than 20% of the precipitation is received, indicating that a significant portion of the runoff from all three basins is produced by snow and ice melt (Rasmussen and Tangborn, 1976a). The northernmost of the four basins, the Chilliwack, drains the northwest corner of the park complex and flows to the northwest before joining the Fraser River in southern British Columbia. South of the Chilliwack basin, the Nooksak River begins on the slopes of Mt. Baker, Mt. Shuksan, and the Skagit Range and flows west emptying into the Puget Sound north of the Bellingham, Washington. This basin is 146 km^2 and less than 2% of this basin is in the complex.

The Skagit River is the largest of the four basins, with an area of 5766 km^2. Approximately 84% of the basin is located inside the United States, with 33% of its area located inside the National Park Complex. With headwaters in British Columbia, the Skagit river flows south becoming Ross Lake at the U.S. Canadian border. Below Ross Dam the river turns west becoming Diablo Lake, after which it flows unobstructed into the Puget Sound.

The Stehekin River basin empties into Lake Chelan on the east side of the North Cascades. The basin covers an area of 92 km^2. Stehekin River begins in the glacier covered highlands south of Boston Peak and Mount Logan and ends south of Stehekin Washington where it joins with Lake Chelan. Nearly 50 km^2 or 54% of the watershed is located inside the park complex.

Stream flow in the complex is monitored by the U.S. Geological Survey using a network of gauging stations located on all three rivers and several of their major tributaries. There are currently four stations inside the park complex, and another three stations in watersheds partly contained within the complex. Daily discharge values derived from six gauging stations located in or near the complex (Fig. 5.1) were used to determine total stream volume for entire water years as well for the periods October through July and August through September. Only those gauging stations with operational periods longer than 10 years were used in this analysis. Historical data was acquired from the U.S. Geological Survey's Washington District "Washington NWIS-W Data Retrieval web" site (http://waterdata.usgs.gov/nwis-w/WA/). The original values, average daily stream discharge in ft^3-s^{-1}, were converted into total daily, seasonal, and annual stream volumes in km^3.

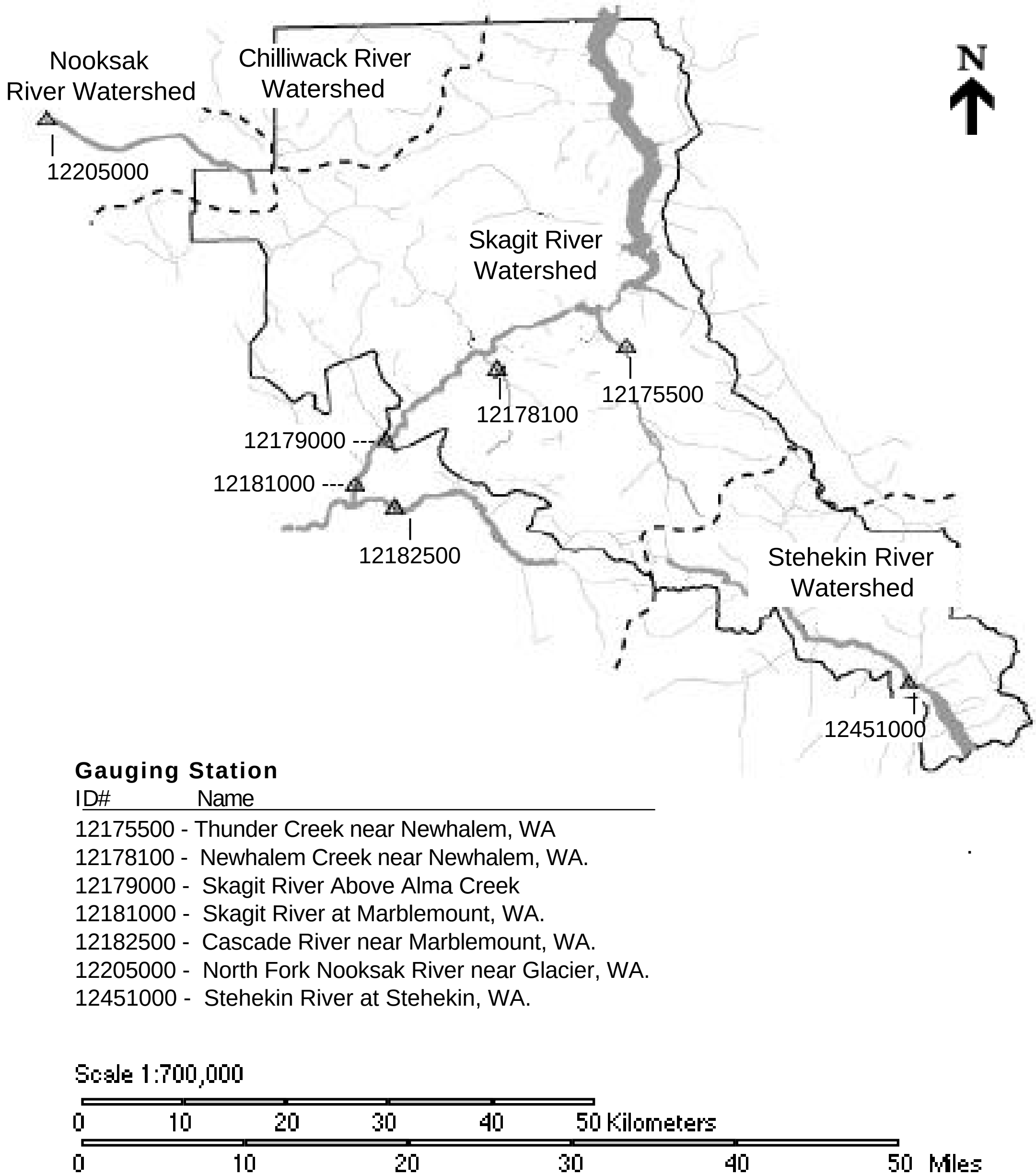

Figure 5.1 - Map of Gauging Stations and Major Watersheds

Hydroclimatology of watersheds with glaciers

Glaciers in watersheds have significant impact on the variability and timing of stream flow (Fountain and Tangborn, 1985; Krimmel and Tangborn, 1974; Meier and Roots, 1982; Briathwaite 1990). Precipitation received by low lying river basins in the Cascades falls largely as rain. Since rainfall in the Pacific Northwest is highest during the winter, monthly streamflows in lower basins tend to be greatest from December through January (Fig. 5.2). Intermediate elevation basins generally have two streamflow peaks, one in winter (November through January) from rain and a second in late spring (April through May) from snowmelt. High altitude basins, those most likely to have glaciers and a thick snow pack, receive most of their annual precipitation as snow which melts in late spring. This last type of basin is characteristic of all of the major watersheds in the National Park Complex.

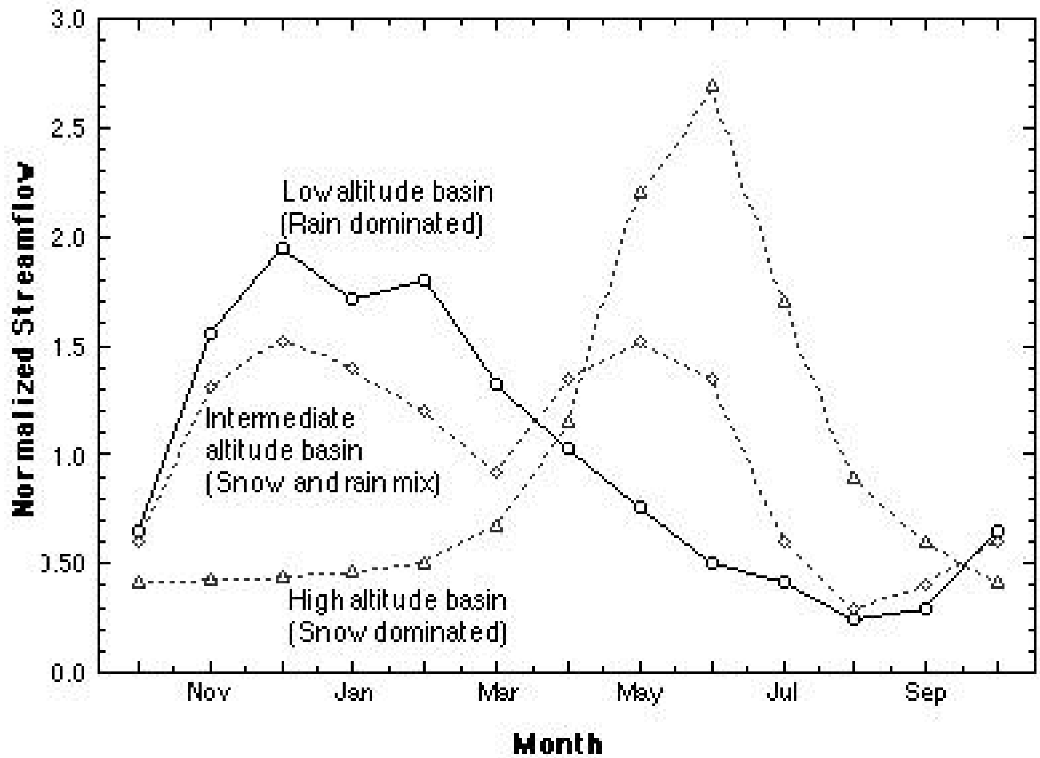

Figure 5.2 - Average monthly stream flow for three types of river basins (JISAO, 1997).

Runoff in mountainous regions is dependent on both the timing and magnitude of precipitation and temperature. Obviously, annual precipitation determines the amount of water entering a watershed. Air temperature tends to control amount of water that leaves it. While an increase in precipitation should increase runoff, a decrease in temperature could dampen this change by increasing the fraction of annual precipitation that falls as snow. Likewise, while decreased precipitation should diminish runoff, increased air temperature increases melting of stored snow and ice (Østrem and Brugman, 1991). Consequently, warm, dry years would have a larger than expected runoff due to glacier mass loss.

Trends in streamflow

Average annual runoff, specific runoff (Table 5.1), and annual deviations from average were calculated for the period of record. Average volume, specific volume (stream volume /watershed area), deviations from average, and seasonal fractions were also calculated for October-July and August-September runoff. Months having two or more missing days and seasons and years having one or more missing months were not used.

Table 5.1 - Summary statistics for individual gauging stations. % Glacier cover is the percentage of each basin that is covered with glaciers.

Station	Operational Period	Annual runoff		Runoff fractions		% Glacier Cover
		Average	Std Dev	Oct.-Jul.	Aug-Sept.	
Thunder Creek	1957-97	0.0693	0.0018	59.1%	40.9%	13.1±0.2%
Newhalem Creek	1960-97	0.1572	0.0022	74.4%	25.6%	0.6±0.1%
Cascade River	1957-79	0.9220	0.0020	71.1%	28.9%	3.5±0.1%
Nooksak River	1957-97	0.7129	0.0021	84.9%	15.1%	5.6±0.1%
Skagit River	1957-97	4.6960	0.0013	74.6%	25.4%	1.9±0.1%
Stehekin River	1957-97	1.2943	0.0016	72.7%	27.3%	3.3±0.1%

Significant differences in annual volume exist between stations because of differences in basin area. For the period 1957 to 1997, average annual stream volumes varied from 4.65 km^3 for Skagit to 0.71 km^3 for the Newhalem Creek station. When normalized by basin area (Fig. 5.3), average specific runoff from these basins ranged from 2 m yr^{-1} for Newhalem Creek to 1.3 m yr^{-1} for the Skagit. With the exception of Skagit River, differences in the specific runoff of these stations can be readily explained by differences in precipitation.

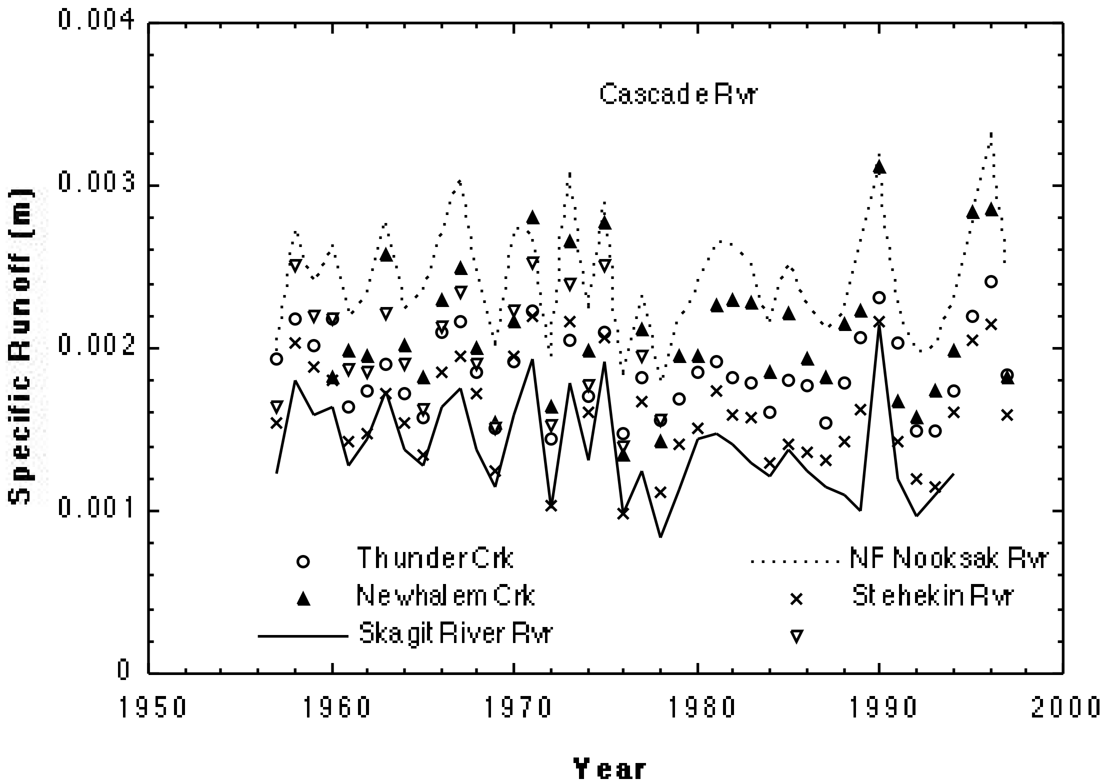

Figure 5.3 - Annual specific discharge for the six gauging stations in and around the National Park Complex.

All six stations showed a close similarity in deviation from average stream flow (Fig. 5.4) indicating that these variations were tied to regional rather than basin specific climate variations. Because of this similarity, deviations for all the stations were averaged to produce a regional indicator of stream flow variation. Based on a plot of regional variation (Fig. 5.5), lower than average years were found to be more frequent than higher than average years during 1957-1997. Furthermore, lower than normal flow years were most frequent during the period 1976-1997.

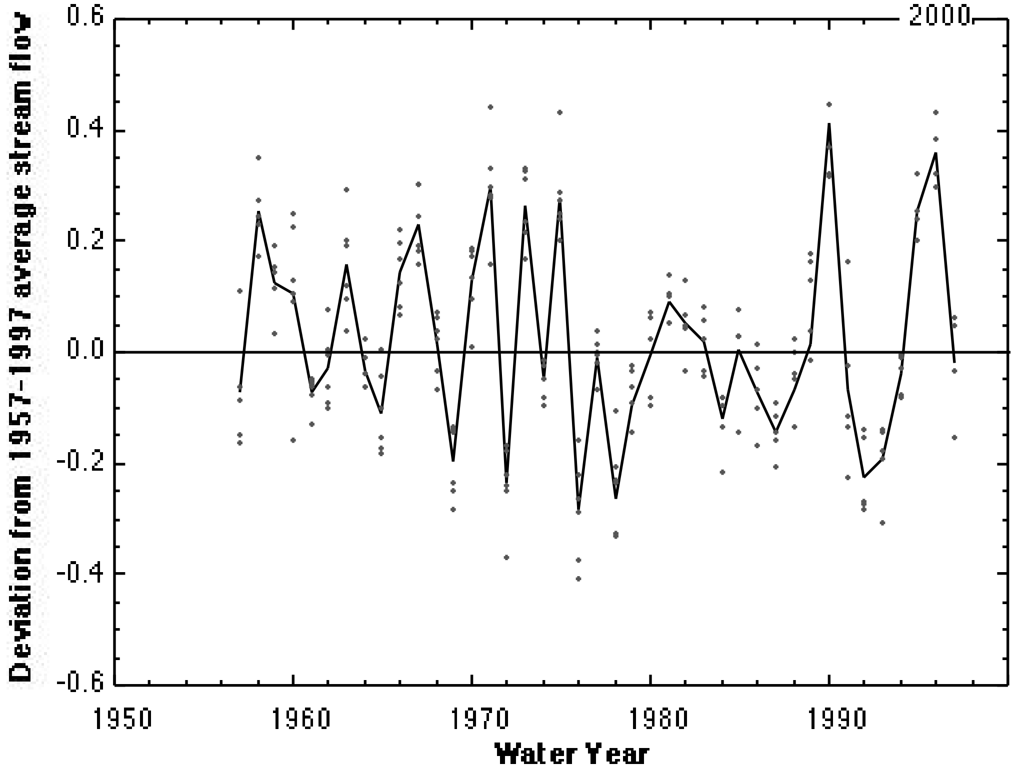

Figure 5.4 - Average deviation from 1957-1997 average of six gauging stations. The individual points show the deviations for individual stations relative to the average deviation.

Timing and annual variability of stream flow

The influence of glacier ice melt on the timing and variability of runoff from a basin depends on its glacier cover (Fountain and Tangborn, 1985; Krimmel and Tangborn, 1974; Meier and Roots, 1982; JISAO, 1997). The impact of glacier cover on timing is shown by figure 5.2. Based on this figure, as the glacier area of a basin decreases, the date of peak runoff should shift to earlier in the year and a second peak runoff should emerge that would correspond to the winter time precipitation high. The reason for this shift is that any increase in annual temperature should result in an earlier major snow melt (the cause of peak runoff from high altitude basins). Furthermore, increased annual temperature means that a greater fraction of the winter precipitation falls as rain that runoffs immediately, rather than being locked up as snow until the spring /summer melt.

Figure 5.5 shows the impact of glacier cover on the variability of runoff terms of the coefficient of variation in runoff for eleven watersheds in the North Cascades. The coefficient of variation is the standard deviation of annual runoff divided by mean runoff. For basins that have less 25% of their area covered by glaciers, variation decreases significantly as the fraction of the basin covered by glaciers increases. For basins with more than 30% coverage, variation increases as the coverage fraction increases. Since all watersheds in the North Cascades have less than 25%, annual runoff should become more variable as glacier area decreases.

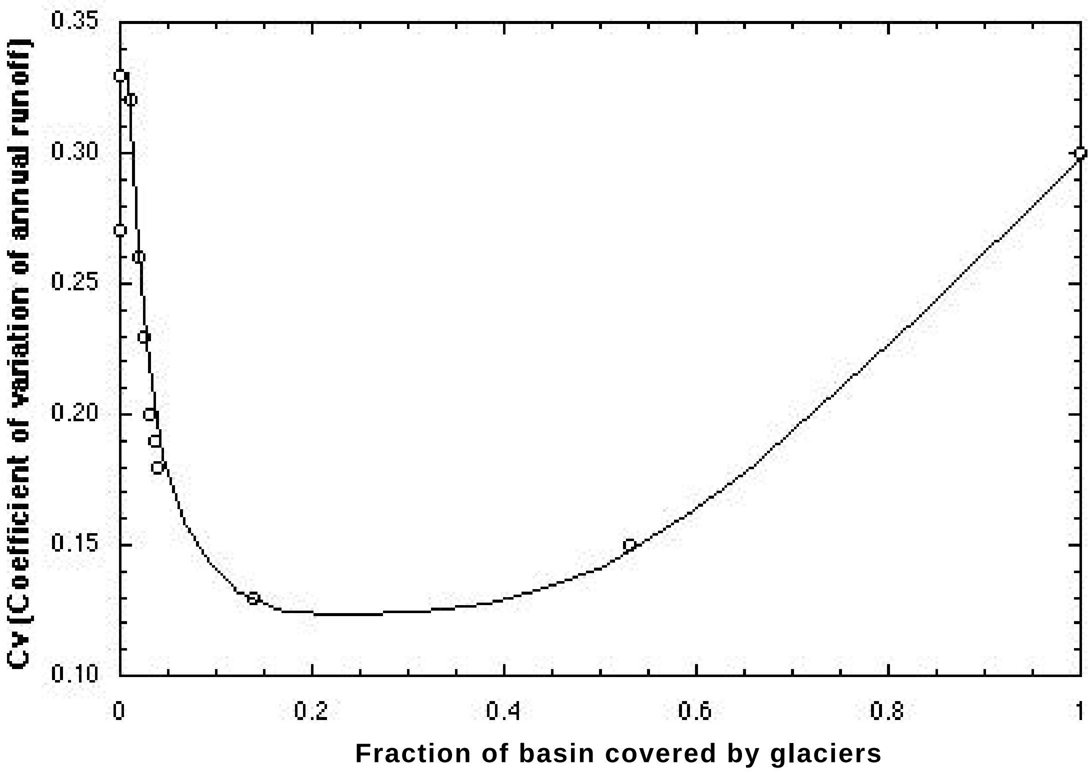

Figure 5.5 - Variability of annual runoff for eleven basins in the North Cascades, Washington as a function of glacier cover. (Fountain and Tangborn, 1985).

To determine changes in the date of annual peak discharge, daily stream volumes were averaged for each stream gage for each of the five decades between 1950 and 1998. The daily decadal averages were fitted with a fifth order polynomial because it provided the best visual fit to the data. The date corresponding to the peak of the curve was designated the date of peak discharge. The result was that no significant shift in the date of annual peak discharge was found, indicating that glacier loss taking placing in the basins had no detectable impact on timing of flow at these gauging stations (table 5.2).

Table 5.2 - Timing of peak discharge by decade

	Decade				
Gage Station	1950	1960	1970	1980	1990
Thunder Creek	7/02	6/30	7/14	7/05	7/03
Newhalem Creek	n/a	6/18	6/20	6/16	6/13
Cascade River	6/19	6/21	6/26	n/a	n/a
Nooksak River	6/23	6/25	6/28	6/23	6/22
Skagit River	6/17	6/20	6/28	6/27	n/a
Stehekin River	6/11	6/13	6/18	6/11	6/10

Changes in annual stream flow variability were determined by calculating the coefficient of variation for each decade between 1957 and 1997 using equation 5.1.

$$C_v = \frac{\sigma_d}{\bar{d}} \quad \textbf{5.1}$$

where C_v is the coefficient of variation, σ_d is the standard deviation of annual runoff, and $\bar{d}$ is the mean discharge. σ_d and $\bar{d}$ were calculated for each decade. Based on the plot of C_v versus fraction of basin covered by glacier (Fig. 5.5), C_v for each of the selected watersheds should have increased as glacier volume decreased. The results (Table 5.3) show no such trend. For nearly all of the stations, C_v is lowest during the 1980s and 1990s, a time of what should be decreased glacier cover. The most likely explanation for this contradiction is that variations in streamflow resulting from annual fluctuations in precipitation are significantly larger than changes in Cv produced by the minor changes in percent glacier cover that took place between water years 1957 and 1997.

Table 5.3 - Coefficient of variation in runoff by decade

	Decade				
Gage Station	1950	1960	1970	1980	1990
Thunder Creek	0.169	0.173	0.184	0.166	0.150
Newhalem Creek		0.145	0.141	0.139	0.119
Cascade River	0.127	0.131	0.138		
Nooksak River	0.128	0.122	0.126	0.119	0.101
Skagit River	0.055	0.076	0.083	0.058	0.076
Stehekin River	0.232	0.251	0.238	0.215	0.212

Comparison of streamflow to climate

The relationship between stream flow and climate was investigated by correlating deviations from average 1957-1997 flow with deviations from average air temperature and precipitation. Deviations from average temperature and precipitation were calculated using climate division data (Fig. 5.6). Correlation coefficients were calculated between temperature, precipitation, and runoff for the periods 1957-1975 and 1976-1997, and for the entire 1957-1997 period. The correlation between annual precipitation and runoff is 0.82 for 1957-1997, 0.70 for 1957-1975, and 0.87 for 1976-1997. Not surprisingly, precipitation and runoff are highly correlated. Correlation between temperature and runoff, however, is weak and negative for all three periods (-0.15 for 1957-1997, -0.17 for 1957-1975, and -0.06 for 1976-1997). Correlations calculated for ablation season runoff, temperature, and precipitation yielded extremely similar results. Given that warm years tend to be dry years (see previous chapter) it is logical that temperature and runoff should be inversely correlated. The weakness of this correlation indicates that that in the North Cascades variations in stream flow are explained by precipitation variations and glaciers are not a significant influence.

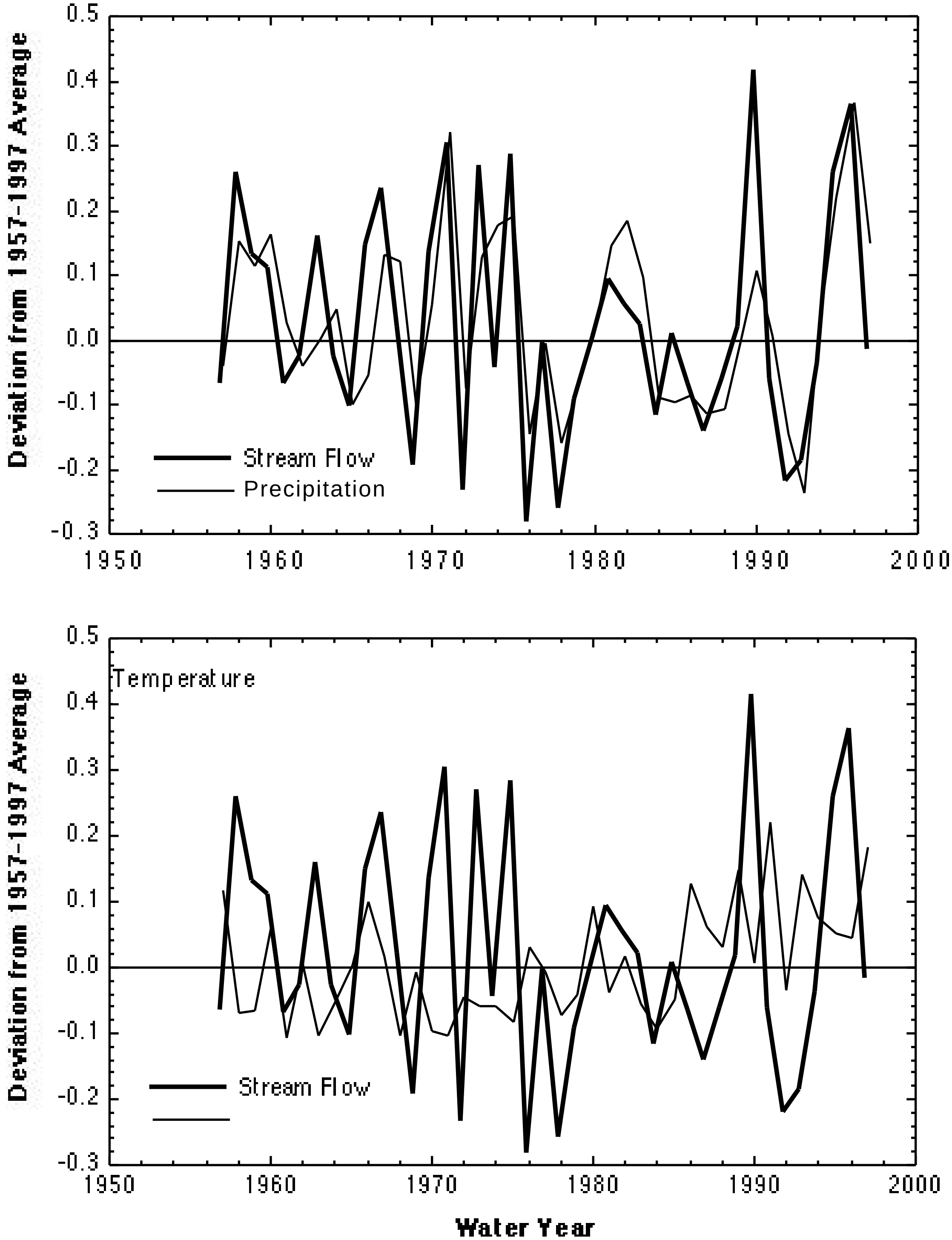

Figure 5.6 - Deviations of runoff, temperature, and temperature from 1957-97 averages

Summary

Average annual runoff recorded at six gage stations in and around the National Park Complex ranged from 0.7 to 4.7 km^3, with 15 to 41% of that runoff occurring during the two driest months of the year, August and September. Annual deviations from the 1957-1997 average runoff varied from -40 to +42%. During this time the ratio of low flow to high flow years was higher than it was during the previous 18 years. A correlation of changes in climate with variations in streamflow revealed a particularly strong connection between precipitation and streamflow (0.70 to 0.87). However, the connection be between temperature and streamflow was uncertain due to very weak, negative correlations (-0.06 to -0.15). These correlations suggest that variations in precipitation have a strong influence on variations in runoff. This idea is reinforced by examining two climatic trends, SOI and divisional precipitation data. Koch et al. (1991) and Redmond and Koch (1991) argue that in the Pacific Northwest there is a positive correlation between SOI and runoff. In other words, runoff during El Niño years will be lower than average. Since negative SOI (El Niño years) tend to be warmer and drier than positive SOI years (Redmond and Koch, 1991) there appears to be a strong connection between precipitation and runoff. The higher ratio of negative to positive SOI years during 1976-1997 indicates diminished precipitation resulted in diminished runoff. The divisional data confirms this hypothesis by the high correlation between precipitation and streamflow and the higher frequency of years having lower than average precipitation during 1976-1997.

The impact of glacier change on stream flow was more difficult to determine. The strong correlation between precipitation and streamflow implies that precipitation tends to overwhelm any contribution that glacier mass loss makes to regional stream flow. This is a reasonable conclusion given that the combined volume loss (less than 1 km^3) of all the glaciers in the entire complex for 40 years is less than the average annual runoff (1.3 km^3) of the Stehekin River basin alone. Furthermore, attempts to determine changes in the timing of peak annual discharge or annual variability in runoff produced no consistent results. The implication here is that changes in precipitation tend to overwhelm the contribution of glacier wastage to streamflow (an idea that will be explored to a limited degree in the next chapter). An issue that was not explored in this chapter was the contribution of glacier mass loss to runoff during the two driest months of the year, August and September. This will also be explored in the following chapter.

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 1958	Glacier Population 1998	Area (km^2) 1958	Area (km^2) 1998	% coverage 1958	% coverage 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%

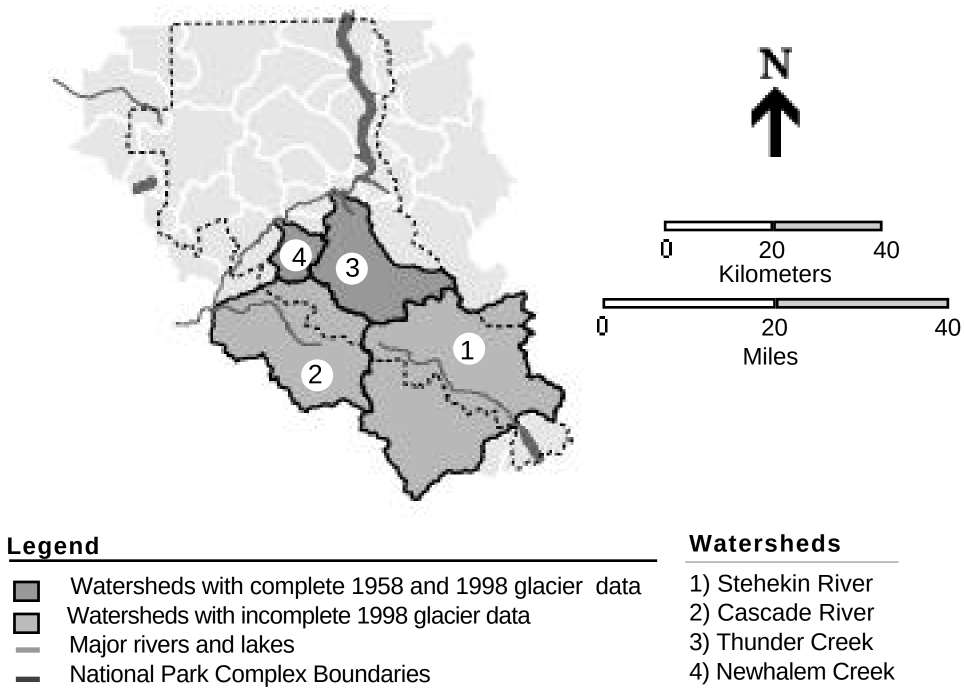

Figure 6.1 - Map of selected watersheds

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

$$\%C = \frac{V_g}{V_{ro}} \quad \textbf{(6.2)}$$

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.

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

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.

Chapter 7 - Discussion and Conclusions

This study is a contribution to a global effort to determine rates of change of small glaciers. By doing so it looks at both the impact of climate change on glaciers, as well as the impact of glacier change on water resources. My work is similar to glacier inventories for Washington, Oregon, and Western Canada (Nylen, in process; Mennis, 1997; Champoux and Ommanny, 1985*)* in that it uses both remote sensing data and geographic information system technology (GIS) to construct a geospatial portrait of a glacier covered region. It is unique because it provides a detailed baseline for estimating and assessing the impact of glacier change in Western Washington by reinventorying a major portion (25%) of the glaciers of the continental United States. Also, it tests the validity of using detailed data from a single regularly monitored (benchmark) glacier to estimate glacier change for an entire glacial region.

Based on the comparisons made in this study, during 1958 the North Cascades National Park Complex had 321 glaciers having a combined area of 117.3±1.0 km^2, and an estimated total volume of 10.1±0.2 km^3. By 1998 this population had decreased to 316, with the area dropping to 109.1±1.1 km^2 and a volume of 9.3±0.2 km^2. Currently most (93%) the glaciers in the complex have areas less than 1 km^2, 84% have average elevations above 1800 meters, 67% are oriented from northwest to northeast, 86% have average slopes less than 40°, all but nine terminate on bedrock, and 84% have no discernible debris cover.

Between 1957 and 1997, combined glacier area decreased by 7.0% (8.2±0.1 km^2) and combined volume by 7.9% (0.8±0.1 km^3). With fractional area change for individual glaciers ranging from 10% to -100%, mass loss is a nearly universal theme for the entire population. Investigations of climate division data, SOI and PDO show that this change is the result of both increased temperature and decreased precipitation, as evidenced by a high frequency of warmer, drier years (particularly in 1977-1997) during the study period. Comparisons of glacier spatial characteristics to fractional area change indicate that rates of glacier change are primarily influenced by glacier size, orientation, and average elevation. Generally, glaciers with the largest fractional area loss had areas less than 1 km^2, were oriented toward the south, or had low average elevations. Slope, terminus condition, and debris cover had no discernible impact on fractional area change.

Studies of stream flow and glacier change in selected watersheds reveal that streams in the Complex have their peak discharge in early summer. Furthermore, in basins with a large fraction of glacier cover, glacier mass loss has contributed up to 6% to August-September runoff and augmented August-September precipitation by nearly 16%. Given that these two months are the driest of the year and precipitation accounts for only 25 to 35% of the runoff for that period, it can be argued that glacier mass loss is important to water resource management. Tests of the impact of glacier change on the timing and variability of annual runoff failed to produce consistent results, indicating that changes in annual and seasonal precipitation overshadow contributions from glacier mass loss.

A comparison of spatial changes of South Cascade Glacier (the benchmark glacier for the North Cascades) to changes in the glaciers of the National Park Complex portray South Cascade as anomalous. Because this glacier is larger, has a lower average elevation, and a larger fractional area change during 1957-1997, it is tempting to say that data from it cannot be used to estimate glacier change in the region. However, the length of its mass balance record, plus the similarity of its net balance to mass balance records from the four glaciers within the complex show that data from the glacier is valuable for estimating glacier change for most of the glaciers of the complex. Based on this, a method was developed for constructing mass balance histories for glaciers having mass loss that involved scaling the mass balance for South Cascade Glacier by specific volume change for the glacier in question. Tests revealed that this method could not be applied to glaciers that were in equilibrium or grew in size. This method when applied to entire glacier cover of the complex showed a cumulative mass balance of -8.0 m between 1958 and 1998, with 92% of that loss taking place between 1977 and 1998.

The glacier change observed in this study is consistent with changes observed in other inventories and glacier monitoring programs. Like numerous well-studied glaciers in North America, Europe, and Asia, the area of most glaciers in the North Cascades has decreased dramatically during the past century. Estimates of volume change for all small glaciers in the world (Dyurgerov and Meier, 2000) show a net mass balance of -5.5 m (mwe) between 1961 and 1997. This is similar in magnitude and trend to a regional net balance of -5.6 m for the National Park Complex. If glacier change continues at the current rate, it is estimated that it would take between two and six centuries for the North Cascades to become glacier free. If estimates of a 4°C increase in average global temperature over the next century (Ruddiman, 2001) become reality, total deglaciation would probably take less than a century.

Chapter 8 - Recommendations for Future Work

Recommendations to refine this study:

One of the more difficult tasks in this study was accurately determining the 1998 extent of the glaciers. Glacier outlines for this year were drawn using uncorrected aerialphotography. Boundaries were drawn by determining their position relative to topographic features appearing in both GIS relief layers and the photos. Because of time and budget limitations, no photometric work was done to determine boundary positions with greater precision. Furthermore, very few ground observations were available to test the accuracy of the outlines.

Though I have confidence in the methods used to produce the 1998 glacier outlines, I recommend acquiring additional aerial photography and digital orthoquad (DOQs) to further test their accuracy. Additional aerial photography, both vertical and oblique, could be used to check the classification of snow and ice and confirm the disappearance of several small glaciers. Additional DOQs could be used to confirm the location of glacier outlines drawn from the currently available aerial photography. At the time this thesis is being written DOQs based on 1998 aerial photography exist for only one quadrangle in the complex.

Recommendations for expanding this study:

The glacier coverage of the basins inside the park complex is incomplete, making it impossible to accurately determine the impact of glacier change on runoff for several watersheds. Since both the Skagit and Stehekin basins contain several hydroelectric facilities and provide water for agriculture and several cities, extending this study to include all of the basins in the park complex is an important contribution to managing the water resources of the region. In addition, I recommend extending this study to include all of the North Cascades as well as the Nooksak and Skagit watersheds north of the Canadian Border.

A major limitation with the collection of glacier inventories for the North Cascades is that they are a very sparse temporal record. Currently, only two regional inventories of the North Cascade glaciers exist. Post et al. (1971) defines the 1958 glacier extent for the entire North Cascades Range and this study which describes glaciers in the National Park Complex for 1998. This temporal sparseness makes it difficult to correlate regional glacier change with mass balance variations on benchmark and secondary glaciers. Furthermore, because of a lack of information about annual glacier spatial changes, the impact of glacier change on runoff is done using extremely coarse annual averages of glacier volume change. Since complete vertical aerial photography of the park complex exists for 1967 and 1974, additional GIS glacier data for these two years could be produced to create a more detailed temporal portrait of glacier change in the complex. Additional GIS coverage could also be produced using DOQs and aerial photography available from the U.S. Forest Service and Washington State Department of Natural Resources.

During the time that this thesis was being written, an event took place that could impact glacier change in the North Cascades. During the winter of 1998, a record snowfall was recorded at Mt. Baker. Climate data from the Cascade West division showed that winter to be wetter and colder than average. This climate change is reflected in a positive net balance for South Cascade Glacier during the 1998 water year. The previous year, which had been drier and warmer than average, was accompanied by a negative net balance at South Cascade. If this climate change were to continue, it would seem reasonable to expect an expansion of the region's glaciers. While this may be a brief reversal of past trends, the questions are how significant of a reversal it is and long will it continue? One approach to answering these questions is to compare 1998-2001 area /volume changes for South Cascade and the four USNPS monitored glaciers to pre 1998 area /volume changes. In this analysis trends in pre-1998 to post-1998 variations in area and mass balance could be used as a proxy for the entire study area. Regional area variations could be determined by incorporating satellite imagery into the current GIS database. A trial analysis involving a SPOT image of the North Cascades taken in July 1992 showed that it is possible to quickly extract snow and glacier cover from such an image. The primary advantage to this approach is a savings in time. Furthermore, because many satellite images have such a low view angle, spatial distortion is at a minimum, making orthorectification largely unnecessary.   Currently the expense and resolution of this imagery limits its use for glacier monitoring. However, as higher resolution imagery becomes available at lower cost, using satellite images could greatly streamline glacier map production.

One additional question raised by this study is how glacier change in the National Park Complex compares to glacier change on a regional level (the Pacific Northwest). Glacier inventories currently exist for Mt. Rainier (Nylen, in process), Mt. Baker (Harper, 1992), and the Olympic Mountains (Spicer, 1986). With the completion of an inventory for glaciers in the Oregon and Southern Washington Cascades (Pinotti, *in process*) it will be possible to create a digital inventory of all glaciers in the Pacific Northwest for several time periods. What is problematic about this task is that the current collection of inventories have little temporal consistency. This study and the Post et al. (1971) inventory show regional glacier cover for only two time points, 1958 and 1998. While the other inventories show more years, these years are often not synchronous with each other. Consequently, a major task in assembling a regional glacier inventory would be to use the existing digital data and available remote sensing imagery to construct regional maps for at least two years. Once assembled, these digital maps could be used to assess glacier change in the same way as was done in this study.

One final question is how glaciers will change during the next two centuries given projected changes in global climate. A simple model of glacier change in four selected watersheds (chapter 6) indicates that given current rates of glacier change, the last of the glaciers in the complex would disappear in 209 to 610 years. However, these forecasts are based on determining rates of area change for entire basins and using these rates to forecast annual areas. A major problem with this approach is that it ignores increases in rates of change as glaciers become smaller. Furthermore, the model constructed in this study does not take into account projected changes in regional and global temperature. Therefore, a more robust model would determine regional glacier change by determining changes for individual glaciers. Rates of change would be scaled to glacier size and adjusted on the basis of projected temperature change. Once completed, such a model would provide a useful tool for assessing the impact of projected climate change on the water resources of western Washington.

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Appendix A - Glacier Inventory

Table A1 - Summary statistics for glacier area / area change

Population 1958	Population 1998	Change		Area (km^2) 1958	Area (km^2) 1998	Area change (km^2)	%1958
321	316	-5	Total	117.3 ± 1.0	109.1 ± 1.1	-8.2 ± 0.1	-7.0%

	Area (km^2) 1958	Area (km^2) 1998		Fractional Area change %1958
Average	0.4	0.3	Average	-11.4%
Minimum	0.1	0.1	Minimum	-57.0%
Maximum	6.8	6.5	Maximum	10.3%

Table A2

Glacier area and area change by area class (Area classes are in 0.1 km^2 intervals)

Class	Population 1958	Population 1998	Change		Area (km^2) 1958	Area (km^2) 1998	Area Change km^2	Area Change %1958
0.1	100	97	-3	-3.0%	5.85 ± 2.00	5.11 ± 1.64	-0.73 ± 2.00	-12.6%
0.2	95	94	-1	-1.1%	13.20 ± 3.25	11.54 ± 2.64	-1.66 ± 3.17	-12.5%
0.3	45	44	-1	-2.2%	11.16 ± 2.34	9.75 ± 1.97	-1.42 ± 2.42	-12.7%
0.4	16	16	0	0.0%	5.44 ± 0.99	4.89 ± 0.82	-0.55 ± 0.99	-10.0%
0.5	10	10	0	0.0%	4.35 ± 0.67	4.06 ± 0.57	-0.28 ± 0.67	-6.6%
0.6	11	11	0	0.0%	6.07 ± 0.90	5.56 ± 0.73	-0.50 ± 0.90	-8.3%
0.7	4	4	0	0.0%	2.65 ± 0.37	2.39 ± 0.31	-0.26 ± 0.16	-9.9%
0.8	7	7	0	0.0%	5.33 ± 0.73	5.07 ± 0.58	-0.27 ± 0.73	-5.0%
0.9	8	8	0	0.0%	6.80 ± 0.78	6.27 ± 0.66	-0.53 ± 0.78	-7.8%
1.0	3	3	0	0.0%	2.86 ± 0.43	2.69 ± 0.37	-0.17 ± 0.43	-5.9%
1.1	2	2	0	0.0%	2.11 ± 0.16	2.04 ± 0.14	-0.07 ± 0.16	-3.2%
1.2	4	4	0	0.0%	4.56 ± 0.39	4.36 ± 0.32	-0.20 ± 0.39	-4.4%
1.3	1	1	0	0.0%	1.23 ± 0.09	1.10 ± 0.07	-0.12 ± 0.09	-10.1%
1.7	1	1	0	0.0%	1.62 ± 0.12	1.59 ± 0.10	-0.03 ± 0.12	-2.0%
1.8	3	3	0	0.0%	5.32 ± 0.60	4.98 ± 0.47	-0.34 ± 0.60	-6.4%
2.0	1	1	0	0.0%	1.97 ± 0.17	1.89 ± 0.11	-0.08 ± 0.17	-4.2%
2.1	1	1	0	0.0%	2.04 ± 0.15	1.98 ± 0.12	-0.06 ± 0.15	-3.1%
2.3	1	1	0	0.0%	2.22 ± 0.12	2.11 ± 0.11	-0.11 ± 0.12	-4.9%
2.5	1	1	0	0.0%	2.47 ± 0.26	2.38 ± 0.22	-0.09 ± 0.26	-3.6%
2.8	1	1	0	0.0%	2.74 ± 0.21	2.65 ± 0.16	-0.09 ± 0.21	-3.2%
3.4	1	1	0	0.0%	3.36 ± 0.20	3.31 ± 0.19	-0.05 ± 0.20	-1.5%
3.6	1	1	0	0.0%	3.54 ± 0.20	3.42 ± 0.14	-0.12 ± 0.20	-3.5%
4.0	1	1	0	0.0%	3.99 ± 0.17	3.81 ± 0.20	-0.17 ± 0.17	-4.3%
4.6	1	1	0	0.0%	4.55 ± 0.22	4.56 ± 0.19	0.01 ± 0.22	0.2%
5.1	1	1	0	0.0%	5.04 ± 0.31	5.00 ± 0.25	-0.05 ± 0.31	-0.9%
6.9	1	1	0	0.0%	6.83 ± 0.24	6.53 ± 0.21	-0.29 ± 0.24	-4.3%

Table A3 - Glacier population and area by average elevation (1958)

Elevation	Population		Area		Class Statistics		
1958	Number	% total	km^2	% total	Ave	Min	Max
1300	2	0.6%	0.5	0.4%	0.24	0.12	0.35
1400	2	0.6%	0.2	0.2%	0.11	0.09	0.13
1500	9	2.8%	1.1	0.9%	0.12	0.03	0.38
1600	13	4.0%	1.8	1.5%	0.14	0.05	0.23
1700	26	8.1%	7.2	6.1%	0.28	0.02	1.78
1800	36	11.2%	13.2	11.2%	0.37	0.02	2.47
1900	61	19.0%	15.0	12.8%	0.25	0.02	1.14
2000	51	15.9%	21.9	18.7%	0.43	0.01	5.04
2100	59	18.4%	35.1	30.0%	0.60	0.02	6.83
2200	45	14.0%	16.9	14.4%	0.38	0.03	2.22
2300	15	4.7%	3.3	2.8%	0.22	0.03	0.76
2400	2	0.6%	1.1	0.9%	0.53	0.12	0.95

Table A4 - Glacier population and area by slope (1958)

Slope	Population		Area		Class Statistics		
1958	Number	% total	km^2	% total	Ave	Min	Max
20° -> 29°	142	44.2%	78.1	66.6%	0.55	0.01	6.83
30° -> 39°	133	41.4%	32.9	28.1%	0.25	0.03	2.47
40° -> 49°	39	12.1%	5.8	4.9%	0.15	0.02	0.95
50°-> 59°	6	1.9%	0.4	0.4%	0.07	0.02	0.14
60°-> 69°	1	0.3%	< 0.1	< 0.1%	0.03	0.03	0.03

Table A5 - Glacier population and area by orientation (1958)

Orientation	Population		Area		Class statistics		
Class	Number	% total	km^2	% total	Ave	Min	Max
000° -> 030°	106	33.0%	26.4	22.6%	0.31	0.03	0.44
030° -> 060°	51	15.9%	23.2	19.8%	0.32	0.02	0.58
060° -> 090°	16	5.0%	10.7	9.1%	0.56	0.02	1.06
090° -> 120°	24	7.5%	3.7	3.2%	0.27	0.04	0.25
120° -> 150°	7	2.2%	9.9	8.5%	0.43	0.04	0.73
150° -> 180°	7	2.2%	5.6	4.8%	0.63	0.01	1.00
180° -> 210°	16	5.0%	0.5	0.4%	0.08	0.02	0.04
210° -> 240°	8	2.5%	2.8	2.4%	0.18	0.02	0.21
240° -> 270°	16	5.0%	3.4	2.9%	0.31	0.04	0.36
270° -> 300°	12	3.7%	3.4	2.9%	0.24	0.05	0.22
200° -> 330°	29	9.0%	9.4	8.0%	0.52	0.04	1.15
330° -> 000°	29	9.0%	18.1	15.5%	0.40	0.04	0.61

Table A6 - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	WGMS	Area (km²) 1958	1998	Area Change (km²)	%1958
	211301	USM0011301	0.02 ± 0.01	0.01 ±0.01	-0.01 ±0.00	-50.0%
	211401	USM0011401	0.10 ± 0.04	0.09 ±0.04	-0.01 ±0.01	-12.4%
	211402	USM0011402	0.12 ± 0.04	0.09 ±0.03	-0.03 ±0.01	-24.2%
	211403	USM0011403	0.04 ± 0.02	0.04 ±0.02	0.00 ±0.00	0.0%
	211404	USM0011404	0.02 ± 0.01	0.02 ±0.01	0.00 ±0.00	0.0%
	211405	USM0011405	0.06 ± 0.03	0.05 ±0.02	-0.01 ±0.00	-17.7%
	211406	USM0011406	0.05 ± 0.01	0.04 ±0.01	-0.00 ±0.00	-4.3%
	211407	USM0011407	0.03 ± 0.01	0.03 ±0.01	0.00 ±0.00	0.0%
	211408	USM0011408	0.14 ± 0.03	0.10 ±0.02	-0.04 ±0.01	-28.0%
	211409	USM0011409	0.08 ± 0.02	0.08 ±0.02	0.00 ±0.00	0.0%
	211410	USM0011410	0.04 ± 0.02	0.04 ±0.02	0.00 ±0.00	0.0%
	211411	USM0011411	0.01 ± 0.01	± 0.00	-0.01 ±0.00	-100.0%
	211412	USM0011412	0.09 ± 0.03	0.09 ±0.03	0.00 ±0.00	0.0%
	211413	USM0011413	0.06 ± 0.02	0.06 ±0.02	0.00 ±0.00	0.0%
	211414	USM0011414	0.03 ± 0.01	± 0.00	-0.03 ±0.01	-100.0%
	211415	USM0011415	0.06 ± 0.03	0.06 ±0.03	-0.00 ±0.00	-1.7%
	211416	USM0011416	0.05 ± 0.01	0.05 ±0.01	0.00 ±0.00	0.0%
	211501	USM0011501	0.11 ± 0.02	0.10 ±0.02	-0.01 ±0.00	-4.6%
	211502	USM0011502	0.07 ± 0.02	0.07 ±0.02	0.00 ±0.00	1.4%
	211503	USM0011503	0.05 ± 0.01	0.04 ±0.01	-0.01 ±0.00	-10.2%
	211504	USM0011504	0.11 ± 0.03	0.11 ±0.03	-0.00 ±0.00	-3.5%
	211505	USM0011505	0.12 ± 0.04	0.07 ±0.03	-0.05 ±0.01	-38.7%
Redoubt	211506	USM0011506	2.04 ± 0.13	1.98 ±0.14	-0.06 ±0.01	-3.1%
	211507	USM0011507	1.18 ± 0.08	1.09 ±0.08	-0.09 ±0.02	-7.9%
	211508	USM0011508	0.43 ± 0.06	0.41 ±0.07	-0.02 ±0.01	-4.7%
	211509	USM0011509	0.18 ± 0.04	0.18 ±0.04	0.00 ±0.00	0.0%
	211510	USM0011510	0.18 ± 0.04	0.17 ±0.04	-0.01 ±0.00	-4.5%
	211601	USM0011601	0.04 ± 0.01	0.04 ±0.01	0.00 ±0.00	0.0%
	211602	USM0011602	0.06 ± 0.03	0.06 ±0.03	0.00 ±0.00	0.0%
	211603	USM0011603	0.18 ± 0.03	0.16 ±0.04	-0.03 ±0.01	-14.8%
	211604	USM0011604	0.03 ± 0.01	0.03 ±0.01	0.00 ±0.00	0.0%
	211701	USM0011701	0.05 ± 0.01	0.05 ±0.01	0.00 ±0.00	0.0%
	211702	USM0011702	0.04 ± 0.01	0.04 ±0.01	0.00 ±0.00	0.0%
	211801	USM0011801	0.26 ± 0.03	0.21 ±0.04	-0.04 ±0.01	-17.3%
	211802	USM0011802	0.18 ± 0.03	0.11 ±0.02	-0.07 ±0.01	-38.5%
	211803	USM0011803	0.08 ± 0.02	0.08 ±0.02	0.00 ±0.00	0.0%
	211804	USM0011804	0.51 ± 0.09	0.49 ±0.09	-0.03 ±0.01	-4.9%
	211901	USM0011901	0.14 ± 0.03	0.12 ±0.03	-0.02 ±0.01	-12.6%
	211902	USM0011902	0.10 ± 0.04	0.07 ±0.04	-0.03 ±0.01	-26.0%
	211905	USM0011905	0.32 ± 0.04	0.29 ±0.04	-0.03 ±0.01	-10.6%
	212301	USM0012301	0.04 ± 0.01	0.04 ±0.01	0.00 ±0.00	0.0%
	212302	USM0012302	0.58 ± 0.06	0.54 ±0.05	-0.04 ±0.01	-7.4%
Icy Peak	212303	USM0012303	0.58 ± 0.07	0.49 ±0.08	-0.09 ±0.02	-15.3%

Table A6 continued - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	WGMS	Area (km²) 1958	1998	Area Change (km²)	%1958
Nooksak	212304	USM0012304	2.47 ± 0.21	2.38 ±0.23	-0.09 ±0.02	-3.6%
West Nooksak	212305	USM0012305	0.17 ± 0.04	0.12 ±0.02	-0.05 ±0.01	-29.0%
Price	212306	USM0012306	1.62 ± 0.16	1.59 ±0.17	-0.03 ±0.01	-2.1%
Hanging	212307	USM0012307	0.11 ± 0.02	0.11 ±0.02	-0.00 ±0.00	-0.9%
	212401	USM0012401	0.58 ± 0.09	0.55 ±0.09	-0.03 ±0.01	-4.8%
	212402	USM0012402	0.81 ± 0.10	0.75 ±0.11	-0.06 ±0.01	-7.9%
White Salmon	212403	USM0012403	0.16 ± 0.04	0.15 ±0.04	-0.01 ±0.01	-6.9%
Curtis	221204	USM0021204	0.89 ± 0.09	0.85 ±0.10	-0.04 ±0.01	-4.5%
	221205	USM0021205	0.28 ± 0.04	0.22 ±0.04	-0.06 ±0.01	-20.9%
	221206	USM0021206	0.12 ± 0.02	0.12 ±0.03	-0.00 ±0.00	-3.3%
Sulfide	221301	USM0021301	3.54 ± 0.16	3.42 ±0.17	-0.12 ±0.02	-3.5%
Crystal	221302	USM0021302	2.74 ± 0.17	2.65 ±0.18	-0.09 ±0.02	-3.3%
	221303	USM0021303	0.26 ± 0.09	0.23 ±0.08	-0.03 ±0.01	-9.6%
	221304	USM0021304	0.29 ± 0.05	0.28 ±0.05	-0.00 ±0.00	-1.0%
	221401	USM0021401	0.29 ± 0.07	0.25 ±0.06	-0.04 ±0.01	-14.0%
	221402	USM0021402	0.12 ± 0.03	0.09 ±0.02	-0.03 ±0.01	-24.3%
Spillway	221403	USM0021403	0.27 ± 0.07	0.24 ±0.07	-0.03 ±0.01	-11.7%
	221404	USM0021404	0.02 ± 0.02	0.02 ±0.02	0.00 ±0.00	0.0%
	221405	USM0021405	0.22 ± 0.05	0.19 ±0.05	-0.04 ±0.01	-15.7%
	221406	USM0021406	0.05 ± 0.02	0.05 ±0.02	0.00 ±0.00	0.0%
	221501	USM0021501	0.38 ± 0.07	0.34 ±0.08	-0.03 ±0.01	-9.1%
	221502	USM0021502	0.04 ± 0.01	0.03 ±0.01	-0.02 ±0.01	-40.9%
	221503	USM0021503	0.18 ± 0.04	0.14 ±0.04	-0.03 ±0.01	-18.6%
	221504	USM0021504	0.12 ± 0.02	0.12 ±0.02	0.00 ±0.00	0.0%
	221601	USM0021601	0.09 ± 0.02	0.08 ±0.02	-0.01 ±0.00	-8.7%
	221602	USM0021602	0.11 ± 0.02	0.10 ±0.03	-0.01 ±0.00	-7.1%
	221603	USM0021603	0.79 ± 0.09	0.76 ±0.10	-0.03 ±0.01	-3.7%
	221604	USM0021604	0.16 ± 0.04	0.11 ±0.03	-0.05 ±0.01	-32.5%
	221605	USM0021605	0.20 ± 0.03	0.17 ±0.03	-0.04 ±0.01	-17.5%
	221606	USM0021606	0.69 ± 0.11	0.57 ±0.11	-0.12 ±0.02	-17.4%
	221701	USM0021701	0.29 ± 0.04	0.22 ±0.03	-0.08 ±0.01	-25.9%
	221702	USM0021702	0.10 ± 0.02	0.08 ±0.03	-0.01 ±0.01	-15.8%
	221703	USM0021703	0.11 ± 0.02	0.09 ±0.02	-0.03 ±0.01	-22.8%
	221704	USM0021704	0.44 ± 0.06	0.36 ±0.06	-0.08 ±0.01	-17.9%
	221705	USM0021705	0.10 ± 0.03	0.10 ±0.03	-0.01 ±0.00	-8.7%
	221706	USM0021706	0.20 ± 0.03	0.18 ±0.03	-0.02 ±0.01	-10.3%
	221707	USM0021707	0.09 ± 0.01	0.08 ±0.01	-0.01 ±0.00	-5.9%
	221708	USM0021708	0.10 ± 0.02	0.09 ±0.02	-0.01 ±0.00	-9.7%
	221709	USM0021709	0.14 ± 0.02	0.14 ±0.02	-0.01 ±0.00	-4.9%
	221710	USM0021710	0.07 ± 0.01	0.07 ±0.02	-0.00 ±0.00	-4.2%
	221711	USM0021711	0.13 ± 0.02	0.12 ±0.02	-0.01 ±0.00	-7.6%
	221712	USM0021712	0.04 ± 0.01	0.04 ±0.01	0.00 ±0.00	0.0%
	221713	USM0021713	0.07 ± 0.01	0.06 ±0.01	-0.01 ±0.00	-7.6%

Table A6 continued - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	WGMS	Area (km²) 1958	1998	Area Change (km²)	%1958
	221714	USM0021714	0.47 ± 0.07	0.39 ± 0.08	-0.08 ± 0.01	-16.8%
	221801	USM0021801	0.25 ± 0.04	0.23 ± 0.04	-0.02 ± 0.01	-8.0%
	221802	USM0021802	0.08 ± 0.02	0.06 ± 0.02	-0.02 ± 0.01	-23.8%
	221803	USM0021803	0.09 ± 0.03	0.08 ± 0.03	-0.01 ± 0.01	-13.8%
	221804	USM0021804	0.28 ± 0.04	0.24 ± 0.04	-0.04 ± 0.01	-13.6%
	221805	USM0021805	0.24 ± 0.04	0.19 ± 0.04	-0.05 ± 0.01	-22.5%
	221806	USM0021806	0.14 ± 0.02	0.00 ± 0.00	-0.14 ± 0.02	-100.0%
	221807	USM0021807	0.09 ± 0.02	0.07 ± 0.02	-0.02 ± 0.01	-26.1%
	221808	USM0021808	0.13 ± 0.02	0.13 ± 0.02	0.00 ± 0.00	0.0%
	221809	USM0021809	1.10 ± 0.07	1.06 ± 0.08	-0.04 ± 0.01	-3.4%
Noisy Creek	221901	USM0021901	0.78 ± 0.08	0.72 ± 0.07	-0.06 ± 0.01	-8.1%
	221902	USM0021902	0.11 ± 0.02	0.11 ± 0.02	0.00 ± 0.00	0.0%
	221903	USM0021903	0.14 ± 0.03	0.11 ± 0.04	-0.03 ± 0.01	-22.9%
	222101	USM0022101	1.14 ± 0.08	1.08 ± 0.08	-0.06 ± 0.01	-4.8%
	222102	USM0022102	0.23 ± 0.02	0.00 ± 0.00	-0.23 ± 0.03	-100.0%
	222103	USM0022103	0.10 ± 0.02	0.07 ± 0.02	-0.03 ± 0.01	-28.9%
	222201	USM0022201	0.04 ± 0.01	0.04 ± 0.01	-0.01 ± 0.00	-11.4%
	222202	USM0022202	0.18 ± 0.03	0.16 ± 0.04	-0.03 ± 0.01	-15.1%
	222203	USM0022203	0.11 ± 0.03	0.09 ± 0.03	-0.02 ± 0.01	-22.0%
	222204	USM0022204	0.07 ± 0.01	0.07 ± 0.01	0.00 ± 0.00	0.0%
	222205	USM0022205	0.88 ± 0.05	0.80 ± 0.07	-0.08 ± 0.01	-9.2%
	222206	USM0022206	1.14 ± 0.07	1.12 ± 0.08	-0.02 ± 0.01	-1.7%
	222207	USM0022207	0.11 ± 0.02	0.11 ± 0.02	-0.01 ± 0.00	-5.4%
	222208	USM0022208	0.44 ± 0.05	0.39 ± 0.05	-0.05 ± 0.01	-10.7%
	222209	USM0022209	0.04 ± 0.01	0.03 ± 0.01	-0.01 ± 0.00	-20.5%
	222210	USM0022210	0.08 ± 0.02	0.04 ± 0.01	-0.04 ± 0.01	-52.4%
	222301	USM0022301	0.54 ± 0.06	0.46 ± 0.07	-0.08 ± 0.01	-14.5%
	222302	USM0022302	0.21 ± 0.05	0.13 ± 0.05	-0.08 ± 0.01	-37.7%
	222303	USM0022303	0.13 ± 0.02	0.13 ± 0.02	0.00 ± 0.00	0.0%
	222304	USM0022304	0.03 ± 0.01	0.02 ± 0.01	-0.01 ± 0.00	-17.9%
	222305	USM0022305	0.21 ± 0.02	0.19 ± 0.03	-0.02 ± 0.01	-11.0%
	222306	USM0022306	0.22 ± 0.03	0.20 ± 0.04	-0.02 ± 0.01	-10.3%
	222307	USM0022307	0.09 ± 0.02	0.04 ± 0.01	-0.05 ± 0.01	-57.0%
	222308	USM0022308	0.16 ± 0.04	0.14 ± 0.04	-0.02 ± 0.01	-13.3%
	222309	USM0022309	0.29 ± 0.03	0.26 ± 0.05	-0.03 ± 0.01	-10.8%
	222310	USM0022310	0.05 ± 0.01	0.04 ± 0.01	-0.01 ± 0.00	-13.5%
	222311	USM0022311	0.15 ± 0.04	0.10 ± 0.03	-0.05 ± 0.01	-33.3%
	222312	USM0022312	0.10 ± 0.02	0.10 ± 0.03	0.00 ± 0.00	0.0%
	222313	USM0022313	0.23 ± 0.05	0.18 ± 0.03	-0.06 ± 0.01	-23.4%
	222314	USM0022314	0.73 ± 0.06	0.71 ± 0.07	-0.01 ± 0.01	-1.8%
	222315	USM0022315	0.19 ± 0.03	0.19 ± 0.03	0.00 ± 0.00	0.0%
	222316	USM0022316	0.21 ± 0.03	0.16 ± 0.02	-0.06 ± 0.01	-27.0%
	222401	USM0022401	0.35 ± 0.04	0.24 ± 0.04	-0.12 ± 0.02	-33.0%

Table A6 continued - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	WGMS	Area (km²) 1958	1998	Area Change (km²)	%1958
	222402	USM0022402	0.19 ±0.03	0.18 ±0.03	-0.00 ±0.00	-2.2%
	222403	USM0022403	0.17 ±0.05	0.17 ±0.05	0.00 ±0.00	0.0%
	222404	USM0022404	0.17 ±0.03	0.09 ±0.02	-0.08 ±0.01	-47.4%
	222405	USM0022405	0.13 ±0.03	0.08 ±0.03	-0.05 ±0.01	-36.5%
	222406	USM0022406	0.10 ±0.03	0.07 ±0.02	-0.03 ±0.01	-30.9%
	222407	USM0022407	0.09 ±0.02	0.07 ±0.02	-0.02 ±0.01	-24.4%
	222408	USM0022408	0.28 ±0.04	0.25 ±0.05	-0.04 ±0.01	-12.6%
Ladder Creek	222501	USM0022501	0.47 ±0.05	0.47 ±0.06	-0.00 ±0.00	-0.8%
	222502	USM0022502	0.24 ±0.04	0.22 ±0.04	-0.02 ±0.01	-8.8%
	222601	USM0022601	0.09 ±0.02	0.08 ±0.02	-0.01 ±0.01	-14.3%
	222602	USM0022602	0.10 ±0.02	0.09 ±0.03	-0.01 ±0.01	-15.0%
	222603	USM0022603	0.27 ±0.06	0.26 ±0.05	-0.02 ±0.01	-5.9%
	222701	USM0022701	0.17 ±0.02	0.16 ±0.02	-0.01 ±0.01	-7.1%
	223101	USM0023101	0.53 ±0.07	0.52 ±0.08	-0.02 ±0.01	-3.2%
	223102	USM0023102	0.95 ±0.15	0.87 ±0.18	-0.08 ±0.01	-8.4%
	223103	USM0023103	0.14 ±0.03	0.11 ±0.03	-0.03 ±0.01	-20.1%
	223104	USM0023104	0.10 ±0.03	0.08 ±0.03	-0.03 ±0.01	-25.7%
	223105	USM0023105	0.63 ±0.06	0.60 ±0.07	-0.03 ±0.01	-4.9%
	223201	USM0023201	0.12 ±0.03	0.13 ±0.04	0.01 ±0.01	9.8%
	223202	USM0023202	0.36 ±0.06	0.31 ±0.07	-0.05 ±0.01	-12.8%
	223203	USM0023203	0.39 ±0.03	0.37 ±0.04	-0.02 ±0.01	-4.6%
	223204	USM0023204	0.37 ±0.07	0.30 ±0.07	-0.07 ±0.01	-18.9%
	223205	USM0023205	1.78 ±0.19	1.64 ±0.19	-0.14 ±0.02	-7.9%
	223206	USM0023206	0.30 ±0.03	0.28 ±0.04	-0.02 ±0.01	-7.9%
	223207	USM0023207	1.02 ±0.05	0.98 ±0.06	-0.04 ±0.01	-4.2%
	223301	USM0023301	0.77 ±0.05	0.71 ±0.05	-0.06 ±0.01	-7.7%
Challenger	223302	USM0023302	3.36 ±0.17	3.31 ±0.22	-0.05 ±0.01	-1.5%
	223303	USM0023303	0.35 ±0.05	0.33 ±0.06	-0.02 ±0.01	-6.9%
	223304	USM0023304	0.37 ±0.05	0.27 ±0.04	-0.10 ±0.02	-27.5%
	223305	USM0023305	0.05 ±0.02	0.03 ±0.01	-0.01 ±0.01	-30.6%
	223401	USM0023401	0.12 ±0.03	0.11 ±0.03	-0.01 ±0.01	-12.3%
	223402	USM0023402	0.06 ±0.02	0.05 ±0.02	-0.01 ±0.00	-13.8%
	223403	USM0023403	0.06 ±0.01	0.06 ±0.01	-0.00 ±0.00	-3.5%
	223404	USM0023404	0.06 ±0.02	0.06 ±0.02	-0.01 ±0.00	-12.7%
	223405	USM0023405	0.15 ±0.03	0.13 ±0.03	-0.01 ±0.01	-8.8%
	223406	USM0023406	0.14 ±0.04	0.13 ±0.05	-0.00 ±0.00	-2.9%
	223407	USM0023407	0.55 ±0.04	0.49 ±0.05	-0.06 ±0.01	-11.1%
	223408	USM0023408	0.10 ±0.02	0.09 ±0.03	-0.01 ±0.01	-15.0%
	223501	USM0023501	0.05 ±0.01	0.05 ±0.01	-0.00 ±0.00	-3.8%
	223502	USM0023502	0.52 ±0.06	0.43 ±0.06	-0.09 ±0.02	-17.8%
	223503	USM0023503	0.23 ±0.03	0.20 ±0.03	-0.03 ±0.01	-13.7%
	223504	USM0023504	0.35 ±0.06	0.30 ±0.06	-0.05 ±0.01	-14.4%
	223601	USM0023601	0.07 ±0.02	0.06 ±0.02	-0.00 ±0.00	-4.6%

Table A6 continued - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	WGMS	Area (km²) 1958	1998	Area Change (km²)	%1958
	223602	USM0023602	0.11 ± 0.03	0.10 ± 0.04	-0.01 ±0.00	-5.5%
	223603	USM0023603	0.30 ± 0.05	0.24 ± 0.05	-0.05 ±0.01	-17.6%
	223604	USM0023604	0.15 ± 0.04	0.12 ± 0.04	-0.03 ±0.01	-22.8%
	223605	USM0023605	0.07 ± 0.02	0.06 ± 0.02	-0.00 ±0.00	-5.9%
Silver Creek	223606	USM0023606	0.84 ± 0.08	0.67 ± 0.08	-0.17 ±0.02	-20.3%
	223607	USM0023607	0.20 ± 0.04	0.17 ± 0.04	-0.03 ±0.01	-12.7%
	223608	USM0023608	0.41 ± 0.06	0.41 ± 0.07	0.00 ±0.00	0.0%
	223609	USM0023609	0.12 ± 0.02	0.12 ± 0.02	-0.00 ±0.00	-1.6%
	223610	USM0023610	0.81 ± 0.06	0.80 ± 0.06	-0.00 ±0.00	-0.1%
	223611	USM0023611	0.31 ± 0.05	0.30 ± 0.05	-0.01 ±0.00	-2.3%
	223612	USM0023612	0.20 ± 0.04	0.17 ± 0.03	-0.03 ±0.01	-16.0%
	223701	USM0023701	0.15 ± 0.03	0.14 ± 0.04	-0.00 ±0.00	-2.7%
	223702	USM0023702	0.56 ± 0.07	0.51 ± 0.07	-0.05 ±0.01	-8.6%
	223703	USM0023703	0.11 ± 0.02	0.10 ± 0.02	-0.01 ±0.01	-11.9%
Masachie	224701	USM0024701	0.57 ± 0.06	0.56 ± 0.07	-0.01 ±0.00	-1.9%
	224702	USM0024702	0.22 ± 0.03	0.22 ± 0.03	-0.01 ±0.00	-2.2%
Katsuk	224703	USM0024703	0.78 ± 0.06	0.78 ± 0.07	-0.00 ±0.00	-0.5%
	224704	USM0024704	0.16 ± 0.03	0.13 ± 0.03	-0.03 ±0.01	-17.6%
	224705	USM0024705	0.09 ± 0.02	0.09 ± 0.02	-0.01 ±0.00	-6.5%
Kimtah	224706	USM0024706	0.84 ± 0.09	0.71 ± 0.09	-0.13 ±0.02	-15.2%
	224707	USM0024707	0.07 ± 0.02	0.07 ± 0.02	0.00 ±0.00	0.0%
	224708	USM0024708	0.14 ± 0.04	0.12 ± 0.04	-0.01 ±0.01	-10.9%
	224709	USM0024709	0.04 ± 0.01	0.03 ± 0.01	-0.00 ±0.00	-10.5%
	224710	USM0024710	0.06 ± 0.01	0.05 ± 0.02	-0.01 ±0.00	-12.5%
	224711	USM0024711	0.08 ± 0.02	0.05 ± 0.02	-0.03 ±0.01	-41.0%
	224712	USM0024712	0.13 ± 0.03	0.08 ± 0.03	-0.05 ±0.01	-36.2%
	224713	USM0024713	0.05 ± 0.02	0.04 ± 0.02	-0.01 ±0.00	-12.8%
	224714	USM0024714	0.11 ± 0.03	0.10 ± 0.03	-0.00 ±0.00	-3.7%
	224801	USM0024801	0.16 ± 0.05	0.16 ± 0.05	0.00 ±0.00	0.0%
	225101	USM0025101	0.08 ± 0.02	0.07 ± 0.02	-0.01 ±0.00	-8.8%
	225102	USM0025102	0.05 ± 0.01	0.05 ± 0.01	0.00 ±0.00	0.0%
	225103	USM0025103	0.03 ± 0.01	0.03 ± 0.01	0.00 ±0.00	0.0%
	225104	USM0025104	0.03 ± 0.01	0.02 ± 0.01	-0.00 ±0.00	-11.5%
	225105	USM0025105	0.17 ± 0.02	0.17 ± 0.03	-0.01 ±0.00	-2.9%
	225106	USM0025106	0.10 ± 0.03	0.10 ± 0.03	-0.01 ±0.00	-8.6%
	225107	USM0025107	0.18 ± 0.03	0.17 ± 0.03	-0.01 ±0.01	-7.1%
Douglas	225108	USM0025108	0.46 ± 0.05	0.45 ± 0.06	-0.01 ±0.01	-3.0%
Douglas	225109	USM0025109	0.96 ± 0.08	0.91 ± 0.09	-0.05 ±0.01	-5.2%
	225110	USM0025110	0.20 ± 0.03	0.18 ± 0.04	-0.02 ±0.01	-10.9%
	225111	USM0025111	0.19 ± 0.04	0.18 ± 0.05	-0.01 ±0.00	-5.7%
	225112	USM0025112	0.07 ± 0.02	0.06 ± 0.02	-0.00 ±0.00	-4.6%
	225113	USM0025113	0.21 ± 0.04	0.19 ± 0.04	-0.02 ±0.01	-9.6%
Banded	225114	USM0025114	0.76 ± 0.06	0.67 ± 0.07	-0.09 ±0.02	-12.2%

Table A6 continued - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	WGMS	Area (km²) 1958	1998	Area Change (km²)	%1958
Fremont	225115	USM0025115	0.95 ± 0.11	0.91 ± 0.11	-0.04 ±0.01	-4.0%
	225201	USM0025201	0.10 ± 0.02	0.08 ± 0.02	-0.02 ±0.01	-19.0%
	225202	USM0025202	0.07 ± 0.02	0.07 ± 0.02	0.00 ±0.00	0.0%
	225203	USM0025203	0.24 ± 0.04	0.23 ± 0.05	-0.01 ±0.00	-2.5%
Thunder	225204	USM0025204	0.16 ± 0.02	0.16 ± 0.02	0.00 ±0.00	0.0%
Boston	225205	USM0025205	6.83 ± 0.20	6.53 ± 0.29	-0.29 ±0.03	-4.3%
	225301	USM0025301	0.11 ± 0.02	0.08 ± 0.01	-0.04 ±0.01	-31.9%
	225302	USM0025302	0.14 ± 0.02	0.14 ± 0.02	0.00 ±0.00	0.0%
Forbidden	225303	USM0025303	1.78 ± 0.21	1.66 ± 0.20	-0.12 ±0.02	-6.8%
	225304	USM0025304	0.15 ± 0.02	0.16 ± 0.02	0.00 ±0.00	2.6%
	225305	USM0025305	0.10 ± 0.02	0.11 ± 0.02	0.00 ±0.00	3.9%
Inspiration	225306	USM0025306	4.55 ± 0.18	4.56 ± 0.24	0.01 ±0.00	0.2%
	225307	USM0025307	0.55 ± 0.06	0.54 ± 0.06	-0.01 ±0.01	-2.4%
	225308	USM0025308	0.13 ± 0.03	0.12 ± 0.04	-0.01 ±0.00	-8.5%
Klawatti	225309	USM0025309	2.22 ± 0.10	2.11 ± 0.13	-0.11 ±0.02	-4.9%
North Klawatti	225310	USM0025310	1.76 ± 0.12	1.69 ± 0.13	-0.08 ±0.01	-4.3%
	225401	USM0025401	0.23 ± 0.05	0.22 ± 0.05	-0.01 ±0.00	-2.7%
	225402	USM0025402	0.29 ± 0.07	0.29 ± 0.07	0.00 ±0.00	0.0%
	225403	USM0025403	0.15 ± 0.03	0.15 ± 0.03	0.00 ±0.00	0.0%
Borealis	225501	USM0025501	1.23 ± 0.10	1.10 ± 0.11	-0.12 ±0.02	-10.2%
	225502	USM0025502	0.07 ± 0.02	0.07 ± 0.02	0.00 ±0.00	0.0%
	225503	USM0025503	0.05 ± 0.01	0.05 ± 0.01	0.00 ±0.00	0.0%
	225504	USM0025504	0.40 ± 0.06	0.40 ± 0.06	-0.01 ±0.00	-1.5%
	225505	USM0025505	0.20 ± 0.03	0.19 ± 0.03	-0.01 ±0.00	-3.6%
	225506	USM0025506	0.20 ± 0.04	0.12 ± 0.03	-0.08 ±0.01	-38.4%
	225507	USM0025507	0.07 ± 0.01	0.05 ± 0.02	-0.01 ±0.01	-18.5%
	225508	USM0025508	0.14 ± 0.03	0.10 ± 0.04	-0.04 ±0.01	-30.0%
McAllistar	225509	USM0025509	5.04 ± 0.25	5.00 ± 0.29	-0.05 ±0.01	-0.9%
	225510	USM0025510	0.30 ± 0.04	0.30 ± 0.04	0.00 ±0.00	0.0%
	225511	USM0025511	0.10 ± 0.03	0.10 ± 0.03	0.00 ±0.00	0.0%
	225512	USM0025512	0.88 ± 0.08	0.85 ± 0.09	-0.03 ±0.01	-3.3%
	225513	USM0025513	0.12 ± 0.02	0.12 ± 0.02	-0.01 ±0.00	-7.3%
	225514	USM0025514	0.22 ± 0.06	0.21 ± 0.06	-0.01 ±0.00	-3.2%
	225601	USM0025601	0.21 ± 0.04	0.21 ± 0.04	0.00 ±0.00	0.0%
Neve	225602	USM0025602	3.99 ± 0.14	3.81 ± 0.23	-0.17 ±0.02	-4.3%
Colonial	225701	USM0025701	1.09 ± 0.10	1.06 ± 0.11	-0.02 ±0.01	-2.2%
	225702	USM0025702	0.21 ± 0.04	0.20 ± 0.04	-0.01 ±0.01	-6.7%
	226101	USM0026101	0.02 ± 0.01	0.02 ± 0.01	0.00 ±0.00	0.0%
	226102	USM0026102	0.13 ± 0.03	0.13 ± 0.03	0.00 ±0.00	0.0%
	226103	USM0026103	0.73 ± 0.09	0.72 ± 0.10	-0.01 ±0.00	-1.1%
	226104	USM0026104	0.12 ± 0.02	0.12 ± 0.02	-0.00 ±0.00	-1.7%
	226105	USM0026105	0.42 ± 0.04	0.40 ± 0.06	-0.03 ±0.01	-6.0%
	226106	USM0026106	0.20 ± 0.05	0.16 ± 0.06	-0.04 ±0.01	-18.9%

Table A6 continued - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	ID Code WGMS	Area (km²) 1958	Area (km²) 1998	Area Change (km²)	Area Change %1958
	226107	USM0026107	0.10 ± 0.03	0.10 ± 0.03	-0.01 ±0.00	-4.8%
	226108	USM0026108	0.30 ± 0.04	0.30 ± 0.05	-0.00 ±0.00	-1.0%
	226109	USM0026109	0.27 ± 0.05	0.25 ± 0.07	-0.02 ±0.01	-7.7%
	226110	USM0026110	0.41 ± 0.04	0.40 ± 0.04	-0.01 ±0.00	-2.7%
	226201	USM0026201	0.09 ± 0.03	0.09 ± 0.03	0.00 ±0.00	0.0%
	226202	USM0026202	0.08 ± 0.03	0.08 ± 0.03	0.00 ±0.00	0.0%
	226203	USM0026203	1.97 ± 0.14	1.89 ± 0.13	-0.08 ±0.01	-4.2%
	226204	USM0026204	0.03 0.01	0.00 ± 0.00	-0.03 ±0.01	-100.0%
	226205	USM0026205	0.06 ± 0.01	0.04 ± 0.01	-0.03 ±0.01	-42.6%
	226206	USM0026206	0.07 ± 0.01	0.04 ± 0.01	-0.03 ±0.01	-40.0%
	226207	USM0026207	0.32 ± 0.05	0.32 ± 0.05	0.00 ±0.00	0.0%
	226208	USM0026208	0.15 ± 0.03	0.14 ± 0.03	-0.00 ±0.00	-2.0%
Quien Sabe	226209	USM0026209	0.68 ± 0.07	0.66 ± 0.07	-0.03 ±0.01	-4.2%
	226210	USM0026210	0.06 ± 0.02	0.05 ± 0.02	-0.01 ±0.00	-9.1%
	226211	USM0026211	0.06 ± 0.02	0.05 ± 0.02	-0.01 ±0.00	-11.7%
	226212	USM0026212	0.14 ± 0.05	0.12 ± 0.05	-0.02 ±0.01	-11.3%
	226213	USM0026213	0.27 ± 0.06	0.24 ± 0.07	-0.02 ±0.01	-8.9%
	244601	USM0044601	0.03 ± 0.01	0.03 ± 0.01	0.00 ±0.00	0.0%
	244602	USM0044602	0.09 ± 0.03	0.09 ± 0.03	0.00 ±0.00	0.0%
	244603	USM0044603	0.28 ± 0.05	0.27 ± 0.06	-0.01 ±0.00	-3.3%
	244604	USM0044604	0.13 ± 0.02	0.13 ± 0.02	0.00 ±0.00	0.0%
	244605	USM0044605	0.08 ± 0.02	0.07 ± 0.02	-0.01 ±0.00	-11.0%
	244606	USM0044606	0.06 ± 0.02	0.06 ± 0.02	0.00 ±0.00	0.0%
	244607	USM0044607	0.18 ± 0.04	0.16 ± 0.03	-0.02 ±0.01	-11.9%
	244608	USM0044608	0.07 ± 0.02	0.07 ± 0.02	0.00 ±0.00	0.0%
	244609	USM0044609	0.29 ± 0.04	0.28 ± 0.04	-0.02 ±0.01	-5.8%
Sahale	244610	USM0044610	0.16 ± 0.02	0.15 ± 0.03	-0.00 ±0.00	-0.6%
Davenport	244611	USM0044611	0.26 ± 0.04	0.26 ± 0.04	0.00 ±0.00	0.0%
	244612	USM0044612	0.04 ± 0.01	0.03 ± 0.01	-0.01 ±0.00	-21.1%
	244613	USM0044613	0.14 ± 0.02	0.13 ± 0.03	-0.00 ±0.00	-0.7%
	244614	USM0044614	0.11 ± 0.02	0.07 ± 0.02	-0.03 ±0.01	-31.5%
	244615	USM0044615	0.05 ± 0.01	0.05 ± 0.01	0.00 ±0.00	0.0%
	244616	USM0044616	0.06 ± 0.01	0.06 ± 0.01	0.00 ±0.00	0.0%
	244617	USM0044617	0.07 ± 0.01	0.07 ± 0.01	0.00 ±0.00	0.0%
	244618	USM0044618	0.02 ± 0.01	0.02 ± 0.01	0.00 ±0.00	0.0%
	244619	USM0044619	0.04 ± 0.01	0.04 ± 0.01	0.00 ±0.00	0.0%
Buckner	244620	USM0044620	0.32 ± 0.06	0.31 ± 0.06	-0.01 ±0.00	-2.2%
Buckner	244621	USM0044621	0.33 ± 0.04	0.32 ± 0.05	-0.01 ±0.00	-2.5%
Buckner	244622	USM0044622	0.28 ± 0.04	0.27 ± 0.05	-0.00 ±0.00	-0.4%
	244623	USM0044623	0.10 ± 0.02	0.10 ± 0.02	0.00 ±0.00	0.0%
	244624	USM0044624	0.02 ± 0.01	0.02 ± 0.01	-0.01 ±0.00	-29.2%
	244625	USM0044625	0.04 ± 0.01	0.02 ± 0.01	-0.01 ±0.01	-40.5%
	244701	USM0044701	0.03 ± 0.01	0.03 ± 0.01	-0.00 ±0.00	-5.9%

Table A6 continued - Glacier catalog (Area and area change)

Glacier Name	ID Code Post	ID Code WGMS	Area (km²) 1958	Area (km²) 1998	Area Change (km²)	Area Change %1958
	244702	USM0044702	0.07 ± 0.02	0.08 ± 0.02	0.00 ±0.00	5.4%
Goode	244703	USM0044703	0.65 ± 0.07	0.56 ± 0.07	-0.08 ±0.01	-12.7%
	244704	USM0044704	0.21 ± 0.03	0.20 ± 0.03	-0.02 ±0.01	-7.5%
	244705	USM0044705	0.05 ± 0.01	0.04 ± 0.01	-0.01 ±0.00	-13.0%
	244706	USM0044706	0.02 ± 0.01	0.02 ± 0.01	0.00 ±0.00	0.0%
	244707	USM0044707	0.07 ± 0.02	0.07 ± 0.02	0.00 ±0.00	0.0%
Wyeth	244708	USM0044708	0.86 ± 0.10	0.84 ± 0.12	-0.02 ±0.01	-2.4%
	244709	USM0044709	0.14 ± 0.02	0.11 ± 0.02	-0.03 ±0.01	-20.0%
	244710	USM0044710	0.32 ± 0.06	0.32 ± 0.06	-0.00 ±0.00	-0.6%
	244711	USM0044711	0.05 ± 0.02	0.05 ± 0.02	-0.01 ±0.00	-14.8%
	244712	USM0044712	0.26 ± 0.04	0.26 ± 0.05	-0.01 ±0.00	-2.3%
	244713	USM0044713	0.09 ± 0.03	0.07 ± 0.02	-0.01 ±0.01	-13.8%
	244714	USM0044714	0.12 ± 0.02	0.12 ± 0.02	0.00 ±0.00	0.0%
	244805	USM0044805	0.16 ± 0.03	0.13 ± 0.03	-0.03 ±0.01	-18.1%
Sandalee	244806	USM0044806	0.06 ± 0.02	0.04 ± 0.02	-0.02 ±0.01	-33.9%
Sandalee	244807	USM0044807	0.12 ± 0.02	0.10 ± 0.02	-0.01 ±0.01	-9.5%
Sandalee	244808	USM0044808	0.24 ± 0.03	0.22 ± 0.03	-0.02 ±0.01	-9.2%
Sandalee	244809	USM0044809	0.11 ± 0.02	0.10 ± 0.03	-0.01 ±0.00	-6.3%
Sandalee	244810	USM0044810	0.17 ± 0.02	0.13 ± 0.02	-0.04 ±0.01	-22.4%
	244811	USM0044811	0.10 ± 0.02	0.07 ± 0.03	-0.03 ±0.01	-26.0%

Table A7 - Glacier catalog (1958 characteristics) - Location is in UTM zone 10.

Glacier Name	ID Code Post	WGMS	Location UTME	UTMN	Elevation (m)	Slope (degrees)	Orientation (degrees)
	211301	USM0011301	608943	5423924	1986	26	45
	211401	USM0011401	613146	5420924	1964	29	0
	211402	USM0011402	612845	5421299	1944	33	45
	211403	USM0011403	612470	5422124	1999	38	45
	211404	USM0011404	612320	5422349	1977	30	60
	211405	USM0011405	612470	5422949	1931	33	30
	211406	USM0011406	611945	5423099	1994	32	45
	211407	USM0011407	612545	5427450	1992	30	15
	211408	USM0011408	612095	5427751	2051	38	30
	211409	USM0011409	611720	5428051	2174	25	45
	211410	USM0011410	611419	5428051	2129	39	330
	211411	USM0011411	611644	5427601	2064	23	150
	211412	USM0011412	610894	5427601	2014	29	15
	211413	USM0011413	610519	5427751	2012	34	45
	211414	USM0011414	610294	5424900	1857	30	60
	211415	USM0011415	609468	5425425	1903	47	15
	211416	USM0011416	608192	5425725	2032	28	330
	211501	USM0011501	627781	5427150	2360	21	285
	211502	USM0011502	627480	5426325	2202	22	90
	211503	USM0011503	627856	5426025	2383	31	45
	211504	USM0011504	628306	5425125	2284	32	300
	211505	USM0011505	627931	5424600	2085	31	270
Redoubt	211506	USM0011506	626580	5423849	2190	19	345
	211507	USM0011507	625304	5424450	2106	29	15
	211508	USM0011508	624328	5424825	2137	33	45
	211509	USM0011509	623503	5424900	2170	35	0
	211510	USM0011510	622602	5425350	1979	34	0
	211601	USM0011601	624103	5423549	2311	28	255
	211602	USM0011602	624628	5423249	2229	23	225
	211603	USM0011603	622902	5420999	1880	37	345
	211604	USM0011604	621851	5421074	1958	62	0
	211701	USM0011701	620125	5416347	1992	31	15
	211702	USM0011702	619900	5416572	1994	46	0
	211801	USM0011801	618924	5413046	1900	35	330
	211802	USM0011802	618249	5412971	1762	27	0
	211803	USM0011803	617724	5412971	1754	32	0
	211804	USM0011804	616673	5413121	1736	29	345
	211901	USM0011901	613146	5412671	1968	26	45
	211902	USM0011902	612995	5413121	1882	30	45
	211905	USM0011905	608192	5413346	1872	21	45
	212301	USM0012301	607442	5412521	1977	34	225
	212302	USM0012302	607592	5410570	1857	24	285
Icy Peak	212303	USM0012303	607291	5409295	1754	31	285

Table A7 continued - Glacier catalog (1958 characteristics)

Glacier	ID Code		Location		Elevation	Slope	Orientation
Name	Post	WGMS	UTME	UTMN	(m)	(degrees)	(degrees)
Nooksak	212304	USM0012304	605115	5409445	1847	33	0
West Nooksak	212305	USM0012305	604665	5410795	1854	32	60
Price	212306	USM0012306	603464	5410795	1846	34	0
Hanging	212307	USM0012307	602788	5410720	2140	40	0
	212401	USM0012401	602638	5410120	2156	38	300
	212402	USM0012402	601137	5409895	1738	27	345
White Salmon	212403	USM0012403	600462	5409970	1773	30	0
Curtis	221204	USM0021204	601062	5408845	1877	30	255
	221205	USM0021205	601362	5407945	1967	30	285
	221206	USM0021206	601663	5407570	2148	35	255
Sulfide	221301	USM0021301	602788	5407494	2083	20	120
Crystal	221302	USM0021302	603689	5408245	2126	22	165
	221303	USM0021303	605190	5407720	1781	31	120
	221304	USM0021304	605941	5408095	1917	32	165
	221401	USM0021401	607141	5408395	1800	45	60
	221402	USM0021402	608117	5409820	1873	28	210
Spillway	221403	USM0021403	608117	5410946	1863	31	30
	221404	USM0021404	607742	5411546	1749	20	210
	221405	USM0021405	607892	5412821	1998	31	90
	221406	USM0021406	609393	5412671	1720	30	210
	221501	USM0021501	613146	5411246	1599	38	60
	221502	USM0021502	613296	5412446	1893	31	90
	221503	USM0021503	619975	5410495	1777	46	315
	221504	USM0021504	619150	5410420	1375	29	345
	221601	USM0021601	620426	5410195	2146	27	225
	221602	USM0021602	620651	5410120	2184	25	225
	221603	USM0021603	621176	5409820	2102	26	210
	221604	USM0021604	621401	5408620	1957	33	255
	221605	USM0021605	620876	5406594	1766	41	345
	221606	USM0021606	618924	5405394	1916	27	60
	221701	USM0021701	617874	5405619	1975	27	315
	221702	USM0021702	618549	5400817	1696	27	0
	221703	USM0021703	617874	5400968	1549	21	15
	221704	USM0021704	616298	5400667	1759	29	345
	221705	USM0021705	615247	5399392	1857	27	345
	221706	USM0021706	615097	5399767	1585	28	45
	221707	USM0021707	614271	5398792	1416	20	0
	221708	USM0021708	612995	5399092	1835	36	45
	221709	USM0021709	612620	5399317	1648	27	0
	221710	USM0021710	611720	5399317	2026	23	45
	221711	USM0021711	612545	5399917	1478	24	60
	221712	USM0021712	611870	5400142	1971	28	120
	221713	USM0021713	612320	5400592	1721	30	120

Table A7 continued - Glacier catalog (1958 characteristics)

Glacier Name	ID Code Post	WGMS	Location UTME	UTMN	Elevation (m)	Slope (degrees)	Orientation (degrees)
	221714	USM0021714	612245	5401418	2001	23	90
	221801	USM0021801	613521	5402918	1862	21	345
	221802	USM0021802	612545	5402093	1955	31	330
	221803	USM0021803	612095	5401943	1818	40	300
	221804	USM0021804	611720	5401643	1975	37	345
	221805	USM0021805	611119	5401643	1944	27	0
	221806	USM0021806	611269	5399992	1847	30	0
	221807	USM0021807	611419	5399692	2009	25	240
	221808	USM0021808	611344	5399167	1961	16	315
	221809	USM0021809	610444	5398042	1922	24	330
Noisy Creek	221901	USM0021901	608492	5391965	1865	18	345
	221902	USM0021902	609018	5391140	2016	38	255
	221903	USM0021903	605866	5389864	1691	38	0
	222101	USM0022101	610068	5390914	1942	17	135
	222102	USM0022102	610669	5390539	1621	12	255
	222103	USM0022103	611194	5389114	1706	23	330
	222201	USM0022201	611870	5389189	1839	36	90
	222202	USM0022202	611644	5389714	1823	31	45
	222203	USM0022203	611194	5390689	1737	23	45
	222204	USM0022204	611119	5391140	1824	18	210
	222205	USM0022205	610744	5392040	1838	15	0
	222206	USM0022206	609768	5391890	1922	18	30
	222207	USM0022207	609168	5392490	1912	21	285
	222208	USM0022208	611720	5398567	1870	24	30
	222209	USM0022209	615847	5399767	1872	20	120
	222210	USM0022210	618849	5399767	1683	43	270
	222301	USM0022301	621476	5395566	1739	33	75
	222302	USM0022302	621176	5396541	1605	37	345
	222303	USM0022303	620125	5396541	1648	37	30
	222304	USM0022304	620501	5399392	1533	53	15
	222305	USM0022305	619675	5399617	1926	41	90
	222306	USM0022306	619675	5400292	1874	31	30
	222307	USM0022307	620125	5400367	1579	45	30
	222308	USM0022308	619075	5400817	1614	32	0
	222309	USM0022309	619525	5404719	1961	27	30
	222310	USM0022310	620726	5405544	1592	24	195
	222311	USM0022311	621551	5406069	1795	42	75
	222312	USM0022312	623202	5407044	1779	37	120
	222313	USM0022313	624929	5403293	2049	28	225
	222314	USM0022314	625829	5402618	2044	25	120
	222315	USM0022315	626805	5403218	2030	28	150
	222316	USM0022316	626880	5402543	1733	21	120
	222401	USM0022401	632809	5399167	1396	34	45

Table A7 continued - Glacier catalog (1958 characteristics)

Glacier Name	ID Code Post	WGMS	Location UTME	UTMN	Elevation (m)	Slope (degrees)	Orientation (degrees)
	222402	USM0022402	631758	5399092	1911	32	0
	222403	USM0022403	628531	5399017	1656	48	15
	222404	USM0022404	628606	5401193	1961	26	120
	222405	USM0022405	628831	5402018	1599	38	30
	222406	USM0022406	628456	5402243	1693	45	45
	222407	USM0022407	627705	5402318	1924	39	45
	222408	USM0022408	627480	5403293	1862	39	105
Ladder Creek	222501	USM0022501	636261	5390389	1922	27	345
	222502	USM0022502	635136	5389639	2026	30	0
	222601	USM0022601	633710	5381987	2051	26	315
	222602	USM0022602	631158	5380786	1752	41	0
	222603	USM0022603	627856	5382362	1995	30	90
	222701	USM0022701	627405	5381612	1951	27	330
	223101	USM0023101	626129	5403818	1867	47	0
	223102	USM0023102	624178	5404419	1866	41	45
	223103	USM0023103	624553	5406369	2125	32	120
	223104	USM0023104	625154	5406819	1965	45	15
	223105	USM0023105	624628	5407344	2214	32	120
	223201	USM0023201	626805	5410270	2024	56	0
	223202	USM0023202	625679	5408470	1906	39	315
	223203	USM0023203	624778	5408320	2006	33	0
	223204	USM0023204	624103	5408170	2179	46	0
	223205	USM0023205	622302	5409295	1796	36	45
	223206	USM0023206	622377	5410720	2161	30	105
	223207	USM0023207	622827	5411621	2049	16	105
	223301	USM0023301	623353	5412821	2105	20	0
Challenger	223302	USM0023302	620951	5411396	2065	22	345
	223303	USM0023303	619600	5412371	2080	27	135
	223304	USM0023304	619900	5413346	1863	38	45
	223305	USM0023305	624553	5420098	2028	14	75
	223401	USM0023401	626129	5419273	2073	41	30
	223402	USM0023402	625829	5419423	2111	41	45
	223403	USM0023403	625604	5419798	2005	42	30
	223404	USM0023404	625229	5420098	2083	48	60
	223405	USM0023405	625004	5420623	2054	38	45
	223406	USM0023406	624553	5420999	2113	34	45
	223407	USM0023407	625154	5423399	2306	22	120
	223408	USM0023408	627180	5422724	2222	28	285
	223501	USM0023501	628981	5422274	1735	40	45
	223502	USM0023502	628006	5422349	2155	34	0
	223503	USM0023503	627856	5423249	2132	36	45
	223504	USM0023504	628981	5424900	2358	30	120
	223601	USM0023601	630482	5424825	1770	53	30

Table A7 continued - Glacier catalog (1958 characteristics)

Glacier Name	ID Code Post	WGMS	Location UTME	UTMN	Elevation (m)	Slope (degrees)	Orientation (degrees)
	223602	USM0023602	629957	5424900	1919	36	30
	223603	USM0023603	629282	5425200	2278	36	75
	223604	USM0023604	629657	5426100	2145	38	75
	223605	USM0023605	629432	5426625	2382	33	315
Silver Creek	223606	USM0023606	628756	5426175	2298	25	315
	223607	USM0023607	628531	5427450	2346	25	105
	223608	USM0023608	630332	5428726	1967	38	0
	223609	USM0023609	629657	5429026	2457	38	15
	223610	USM0023610	628756	5428726	2257	27	345
	223611	USM0023611	628156	5427901	2295	34	330
	223612	USM0023612	627630	5427901	2208	39	345
	223701	USM0023701	636637	5412371	1661	32	45
	223702	USM0023702	635361	5412296	2074	31	30
	223703	USM0023703	634610	5412746	1765	33	0
Masachie	224701	USM0024701	657351	5383037	2189	31	345
	224702	USM0024702	656225	5383037	2167	33	345
Katsuk	224703	USM0024703	655249	5383037	2221	26	0
	224704	USM0024704	655024	5383487	2087	35	45
	224705	USM0024705	654499	5383787	2136	38	0
Kimtah	224706	USM0024706	653673	5383862	2271	31	45
	224707	USM0024707	652097	5383937	1947	31	345
	224708	USM0024708	649170	5384313	2131	32	45
	224709	USM0024709	648795	5384688	2176	30	45
	224710	USM0024710	648420	5385213	2148	26	30
	224711	USM0024711	648270	5385513	2130	29	45
	224712	USM0024712	647519	5386263	2134	38	0
	224713	USM0024713	650221	5390689	2053	44	345
	224714	USM0024714	650821	5390314	2113	44	30
	224801	USM0024801	644517	5394966	2138	29	30
	225101	USM0025101	660578	5379286	2233	39	345
	225102	USM0025102	660278	5379736	1920	24	330
	225103	USM0025103	659677	5379961	1935	49	15
	225104	USM0025104	659377	5379661	2226	35	15
	225105	USM0025105	658852	5379586	2259	37	330
	225106	USM0025106	657351	5377711	2096	40	0
	225107	USM0025107	654349	5376585	2243	27	0
Douglas	225108	USM0025108	653148	5376885	2121	24	0
Douglas	225109	USM0025109	652022	5377635	2236	25	60
	225110	USM0025110	652247	5378686	2159	33	75
	225111	USM0025111	651947	5379436	2007	27	345
	225112	USM0025112	651497	5379136	2242	39	15
	225113	USM0025113	650971	5379511	2196	31	15
Banded	225114	USM0025114	651272	5378386	2322	22	315

Table A7 continued - Glacier catalog (1958 characteristics)

Glacier Name	ID Code Post	WGMS	Location UTME	UTMN	Elevation (m)	Slope (degrees)	Orientation (degrees)
Fremont	225115	USM0025115	650821	5377260	2444	19	255
	225201	USM0025201	651197	5375535	2284	18	270
	225202	USM0025202	651122	5374109	2051	29	300
	225203	USM0025203	648795	5374034	1903	37	30
Thunder	225204	USM0025204	648195	5374335	2095	32	30
Boston	225205	USM0025205	646018	5374560	2166	23	15
	225301	USM0025301	644517	5376735	2258	35	330
	225302	USM0025302	644067	5376360	2293	29	330
Forbidden	225303	USM0025303	642791	5375460	2131	31	345
	225304	USM0025304	641140	5375460	2033	26	330
	225305	USM0025305	640614	5375685	2031	38	15
Inspiration	225306	USM0025306	639113	5377485	2190	21	75
	225307	USM0025307	640389	5378686	2227	24	210
	225308	USM0025308	640840	5378386	2091	24	120
Klawatti	225309	USM0025309	640614	5379811	2227	24	45
North Klawatti	225310	USM0025310	640764	5381462	2121	19	75
	225401	USM0025401	643241	5381012	2081	22	30
	225402	USM0025402	642491	5381612	2183	25	45
	225403	USM0025403	642190	5382587	2111	44	60
Borealis	225501	USM0025501	641215	5383112	2096	25	15
	225502	USM0025502	640915	5383937	2020	35	0
	225503	USM0025503	640314	5383412	2265	27	285
	225504	USM0025504	640089	5382812	2271	33	315
	225505	USM0025505	639113	5382437	2139	42	345
	225506	USM0025506	638213	5382737	1772	39	15
	225507	USM0025507	638738	5381987	2154	19	195
	225508	USM0025508	638813	5381837	2193	27	210
McAllistar	225509	USM0025509	639188	5380336	2092	24	315
	225510	USM0025510	636336	5380561	1939	31	0
	225511	USM0025511	636261	5380861	1856	37	0
	225512	USM0025512	635436	5381087	1950	29	30
	225513	USM0025513	634760	5381612	1847	25	15
	225514	USM0025514	634235	5381837	1914	32	30
	225601	USM0025601	639414	5388964	1911	44	30
Neve	225602	USM0025602	637387	5389414	2120	19	45
Colonial	225701	USM0025701	637237	5391365	1993	21	30
	225702	USM0025702	636487	5392190	2095	29	90
	226101	USM0026101	634985	5380711	2075	21	195
	226102	USM0026102	635736	5380411	2105	23	195
	226103	USM0026103	636712	5379586	2224	24	255
	226104	USM0026104	637087	5378836	2207	25	195
	226105	USM0026105	637537	5378236	2247	33	270
	226106	USM0026106	636937	5376585	1971	45	315

Table A7 continued - Glacier catalog (1958 characteristics)

Glacier Name	ID Code Post	WGMS	Location UTME	UTMN	Elevation (m)	Slope (degrees)	Orientation (degrees)
	226107	USM0026107	636937	5377410	1855	36	270
	226108	USM0026108	636186	5375910	1926	35	330
	226109	USM0026109	634685	5375385	1969	25	330
	226110	USM0026110	627630	5381012	1916	17	135
	226201	USM0026201	635736	5375235	2092	24	195
	226202	USM0026202	636411	5375535	2012	29	135
	226203	USM0026203	637912	5376435	2215	18	165
	226204	USM0026204	640840	5375160	2008	28	165
	226205	USM0026205	641515	5374935	2048	31	255
	226206	USM0026206	641815	5374635	2123	24	240
	226207	USM0026207	642491	5374410	2128	22	210
	226208	USM0026208	643241	5374485	2237	28	210
Quien Sabe	226209	USM0026209	644667	5372909	2334	28	270
	226210	USM0026210	642941	5369383	1882	50	0
	226211	USM0026211	642341	5369533	1964	56	15
	226212	USM0026212	641665	5369833	1763	53	30
	226213	USM0026213	640990	5369983	2213	41	0
	244601	USM0044601	647819	5372534	2436	44	225
	244602	USM0044602	649470	5366382	2013	40	330
	244603	USM0044603	645643	5366307	2132	31	15
	244604	USM0044604	645943	5366907	1634	23	45
	244605	USM0044605	646243	5367808	1575	40	105
	244606	USM0044606	645568	5367657	1984	37	120
	244607	USM0044607	645117	5367808	1880	37	0
	244608	USM0044608	644367	5368033	2049	37	0
	244609	USM0044609	643842	5368333	1998	31	0
Sahale	244610	USM0044610	644892	5372159	2359	22	165
Davenport	244611	USM0044611	645493	5372609	2246	26	120
	244612	USM0044612	647894	5371709	2251	39	315
	244613	USM0044613	648495	5371259	2297	19	165
	244614	USM0044614	648570	5370808	2159	18	165
	244615	USM0044615	649771	5370508	2285	30	210
	244616	USM0044616	650371	5370358	2170	42	30
	244617	USM0044617	650296	5370808	1938	46	15
	244618	USM0044618	649771	5371409	1833	51	15
	244619	USM0044619	649470	5371934	1597	38	30
Buckner	244620	USM0044620	648720	5371859	2035	33	15
Buckner	244621	USM0044621	648270	5372459	2283	32	120
Buckner	244622	USM0044622	648570	5373134	2207	37	120
	244623	USM0044623	653823	5372009	2305	35	270
	244624	USM0044624	654874	5370883	2132	23	45
	244625	USM0044625	654874	5370733	2233	40	15
	244701	USM0044701	656150	5371559	2123	41	30

Table A7 continued - Glacier catalog (1958 characteristics)

Glacier Name	ID Code Post	WGMS	Location UTME	UTMN	Elevation (m)	Slope (degrees)	Orientation (degrees)
	244702	USM0044702	655925	5371859	2191	29	60
Goode	244703	USM0044703	655174	5372384	2038	38	15
	244704	USM0044704	654049	5372609	2236	39	0
	244705	USM0044705	654049	5373359	1695	38	30
	244706	USM0044706	653298	5373434	1983	43	15
	244707	USM0044707	653223	5372684	2385	34	135
Wyeth	244708	USM0044708	652322	5373284	2284	27	45
	244709	USM0044709	651872	5374935	2063	35	45
	244710	USM0044710	651572	5376360	2231	32	105
	244711	USM0044711	661629	5377335	2380	35	315
	244712	USM0044712	661254	5377110	2230	39	345
	244713	USM0044713	663130	5374485	2254	28	300
	244714	USM0044714	661254	5373284	2127	37	345
	244805	USM0044805	664856	5363756	2136	34	15
Sandalee	244806	USM0044806	664406	5363981	2182	37	345
Sandalee	244807	USM0044807	664105	5363906	2234	31	345
Sandalee	244808	USM0044808	663655	5364056	2192	27	345
Sandalee	244809	USM0044809	663280	5363981	2310	31	30
Sandalee	244810	USM0044810	663055	5364206	2288	27	30
	244811	USM0044811	662604	5364507	2143	30	30

Appendix B - Climate data

Table B1 - Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), and divisional climate data. All data is for water years. SOI data derived from < http://iri.ldeo.columbia.edu >. PDO data derived from < http://tao.atmos.washington.edu/ main.html >. Climate division data from < http://www/wrcc.dri.edu/spi/divplot1map.html >. Climate divisions are Cascade Foothills (CFH), Cascade Mountains West (CMW), and Cascade Mountains East (CME).

			Average Temperature (°C)			Total Precipitation (cm)		
Year	SOI	PDO	CFH	CMW	CME	CFH	CMW	CME
1957	0.6	-0.8	11.2	7.2	8.7	146	204	76
1958	-0.1	-0.7	9.8	6.0	7.0	199	292	94
1959	0.2	0.6	9.5	6.1	7.1	166	248	72
1960	-0.2	-0.1	10.5	7.3	7.9	182	266	90
1961	-1.5	0.6	9.2	6.0	6.5	142	209	72
1962	-0.6	0.2	9.9	6.9	7.6	150	198	73
1963	-0.9	0.0	9.3	5.9	6.7	175	246	74
1964	-0.5	-0.9	9.5	6.4	7.0	144	210	83
1965	-0.3	-1.1	10.0	6.8	7.5	140	185	65
1966	-0.9	0.5	10.4	7.5	8.6	161	226	72
1967	-0.3	0.2	10.0	7.0	7.6	189	274	87
1968	-0.5	-1.1	9.3	6.2	6.3	162	229	82
1969	0.1	-0.4	9.9	6.9	7.2	140	184	58
1970	-1.3	2.0	9.1	6.3	6.6	184	261	86
1971	-1.2	-0.6	9.0	6.2	6.5	202	307	112
1972	-0.5	-0.2	9.3	6.6	7.3	121	166	46
1973	-0.6	2.3	9.5	6.3	7.0	202	307	100
1974	-0.7	1.4	9.4	6.3	7.1	160	233	84
1975	-0.7	0.8	9.2	6.3	6.8	200	292	93
1976	0.7	-1.0	9.9	7.3	7.7	112	166	40
1977	0.1	-1.0	10.0	6.9	7.3	164	252	89
1978	0.2	-0.1	9.4	6.5	6.7	120	178	47
1979	0.6	-0.7	9.7	6.6	7.0	153	220	74
1980	0.9	-0.1	10.6	7.8	8.0	166	240	75
1981	0.2	-1.1	9.7	6.7	6.9	178	253	91
1982	1.4	-2.9	10.2	7.2	7.2	181	247	94
1983	1.0	-0.1	9.7	6.5	6.7	175	244	79
1984	0.6	0.1	9.4	6.4	6.3	137	184	57
1985	0.9	-0.4	9.8	6.7	6.7	156	216	66
1986	1.9	-2.4	10.8	8.1	8.2	147	204	62
1987	0.9	0.3	10.2	7.6	7.7	143	196	62
1988	-0.2	1.6	10.1	7.3	7.6	148	214	63
1989	0.0	-0.6	10.7	8.3	8.7	171	242	70

Table B1 - Continued - Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), and divisional climate data.

			Average Temperature (°C)			Total Precipitation (cm)		
Year	SOI	PDO	CFH	CMW	CME	CFH	CMW	CME
1990	-0.9	-1.0	10.7	8.3	8.7	171	242	70
1991	0.8	-2.1	9.8	7.0	7.5	191	280	75
1992	1.3	-1.9	11.5	8.8	9.1	143	200	62
1993	0.6	-1.7	10.0	6.7	6.8	139	196	58
1994	0.2	-0.9	10.6	8.4	8.5	122	178	47
1995	0.7	0.5	10.4	8.1	7.5	175	247	88
1996	1.2	-1.0	10.2	7.9	7.2	214	314	87
1997	0.7	-1.6	10.1	8.0	7.2	234	336	89
1998	1.9	-0.6	10.9	8.6	8.8	150	213	73

Table B2 Climate station identification, location, elevation, and operational period. Data from < http://www.wrcc.dri.edu/summary/climsmwa.html >. Operational period in year / month / day. For instance 19310101 is January 1, 1931.

Station		Location		Elev	Operational Period	
ID#	Name	Lat	Long	m	Start	End
451992	Darrington RS.	48°15'	121°36'	110	19310101	19980930
452157	Diablo Dam	48°43'	121°09'	271	19310101	19980930
453730	Holden Village	48°12'	120°47'	189	19620601	19980930
455133	Mazama	48°36'	120°26'	665	19500405	19980930
455840	Newhalem	48°41'	121°15'	162	19590101	19980930
458059	Stehekin	48°20'	120°42'		19310101	19980930
458715	Upper Baker Dam	48°39'	121°41'	210	19651001	19980930

Tables B3 - Climate station average annual temperature (°C).
Data from < http://www.wrcc.dri.edu/summary/climsmwa.html >.

	Station ID - - - >							
Year	451992	452157	453160	453730	455133	455840	458059	458715
1958	10.7	13.7	10.4	…	…	…	10.2	…
1959	9.1	12.8	8.6	…	…	…	8.6	…
1960	8.6	12.1	8.2	…	…	9.8	8.6	…
1961	9.5	12.8	10.2	…	…	10.8	9.4	…
1962	8.6	12.5	8.1	…	…	9.4	8.2	…
1963	9.5	12.2	8.6	6.0	…	10.3	8.5	…
1964	8.8	11.5	…	5.1	…	9.2	8.3	…
1965	8.6	11.4	…	5.9	…	9.7	7.8	…
1966	9.5	12.8	11.5	9.0	…	9.9	8.8	8.8
1967	9.9	12.7	9.8	6.9	…	10.5	9.4	9.4
1968	8.7	12.7	9.2	5.2	…	9.9	8.5	8.8
1969	8.5	11.8	10.3	4.6	…	9.1	7.2	7.8
1970	9.5	12.5	8.9	5.6	6.0	10.2	8.5	8.9
1971	8.4	12.0	8.5	4.5	4.1	9.0	8.4	7.7
1972	8.1	11.5	8.5	4.3	5.3	8.8	8.2	7.5
1973	9.2	12.1	8.0	5.3	6.6	9.7	9.3	8.3
1974	8.6	12.0	7.7	5.2	4.9	10.0	9.1	8.3
1975	9.3	11.3	8.5	5.2	6.1	9.7	8.2	8.4
1976	8.6	11.4	7.4	5.0	5.6	9.0	8.6	8.0
1977	9.6	12.0	8.5	6.0	7.1	10.2	9.4	9.2
1978	9.4	12.6	7.9	5.1	6.4	9.6	8.6	8.9
1979	9.4	12.4	…	3.9	6.0	9.2	8.1	8.4
1980	9.4	12.2	6.4	4.5	6.5	9.5	8.6	8.9
1981	10.3	12.5	9.1	5.2	7.3	10.2	9.3	9.6
1982	9.3	11.7	8.2	4.5	6.1	9.0	8.4	8.7
1983	10.1	12.5	7.7	4.6	6.6	9.8	9.5	9.0
1984	9.2	11.8	…	4.8	6.1	9.1	8.1	8.7
1985	9.1	13.7	…	4.1	5.6	9.0	8.3	8.3
1986	9.6	12.7	…	4.8	6.1	9.3	8.4	8.4
1987	10.9	12.9	…	5.6	8.0	11.2	9.7	9.7
1988	10.8	12.0	…	5.4	7.4	12.1	9.3	9.0
1989	9.5	12.1	…	5.0	6.9	9.7	9.0	8.7
1990	10.8	12.8	…	5.8	7.9	10.3	9.9	9.2
1991	9.6	12.5	…	4.8	7.4	9.2	8.7	8.2
1992	12.1	13.5	…	6.1	8.3	11.2	10.3	10.2
1993	8.8	12.2	…	4.1	6.1	9.4	8.4	8.4
1994	10.2	12.8	…	5.7	7.9	10.4	10.0	9.6
1995	…	12.9	…	3.6	6.7	9.8	8.9	8.4
1996	9.1	11.9	…	4.9	6.2	9.3	8.3	8.6
1997	9.1	12.8	…	4.2	6.0	8.9	5.7	8.5
1998	9.3	13.2	…	6.3	8.2	10.7	10.3	9.7

Tables B4 - Climate station average August-September temperature (°C).
Data from < http://www.wrcc.dri.edu/summary/climsmwa.html >.

Year	Station ID 451992	452157	453160	453730	455133	455840	458059	458715
1958	16.6	17.5	15.7	…	…	…	18.0	…
1959	14.6	15.1	13.9	…	…	…	15.2	…
1960	14.2	16.0	14.9	…	…	16.4	15.9	…
1961	15.3	17.4	16.2	…	…	17.9	17.1	…
1962	15.4	16.1	14.8	…	…	16.6	15.8	…
1963	16.9	18.1	17.4	15.0	…	18.3	16.8	…
1964	14.2	14.9	14.0	13.0	…	15.2	14.4	…
1965	15.1	16.6	12.9	15.0	…	16.8	15.7	…
1966	16.0	17.3	16.1	15.2	…	17.3	17.4	15.8
1967	18.3	19.4	18.7	16.9	…	19.6	18.9	17.9
1968	15.0	16.2	15.2	12.8	…	16.2	15.8	14.8
1969	14.7	15.7	15.2	13.6	…	15.6	15.7	14.5
1970	15.0	15.7	15.1	12.8	14.0	15.8	15.9	14.2
1971	15.8	16.5	15.8	13.2	14.4	16.9	17.8	15.2
1972	14.6	15.7	15.3	12.8	14.8	16.1	16.3	14.5
1973	15.1	16.4	14.3	13.9	17.0	16.9	18.3	15.0
1974	18.1	18.4	17.9	15.0	17.4	18.8	13.0	16.6
1975	15.8	16.3	14.7	13.9	15.5	16.9	12.2	15.2
1976	15.4	16.2	14.2	13.4	15.0	16.5	17.2	15.3
1977	16.1	17.4	15.4	13.8	17.0	17.0	18.3	15.9
1978	15.1	15.6	14.1	12.5	15.0	15.1	16.6	14.6
1979	17.4	17.6	15.6	14.5	17.4	17.4	18.5	16.8
1980	15.6	15.8	…	12.6	15.6	15.5	16.9	14.8
1981	17.8	17.8	…	12.9	17.6	17.6	18.8	16.6
1982	16.5	16.3	…	13.4	15.9	15.9	17.6	15.7
1983	15.2	15.7	…	12.2	15.4	15.6	16.8	17.4
1984	15.9	15.6	…	12.9	15.3	15.7	16.7	15.4
1985	15.9	15.3	…	12.5	15.1	16.0	16.6	14.9
1986	17.4	17.6	…	14.2	17.1	17.6	18.5	16.2
1987	17.5	17.8	…	14.8	18.0	17.7	19.0	16.3
1988	16.1	16.7	…	13.3	16.8	16.4	17.7	15.4
1989	16.9	17.1	…	13.3	16.6	17.2	17.8	15.8
1990	18.3	18.5	…	14.7	18.5	18.7	19.4	17.1
1991	17.5	17.8	…	14.5	18.1	17.7	19.1	16.5
1992	16.5	16.2	…	12.8	16.2	16.3	17.7	15.1
1993	15.9	17.1	…	12.9	16.5	17.1	18.0	16.0
1994	18.2	17.7	…	14.5	18.3	17.8	19.3	16.8
1995	18.4	16.8	…	13.5	16.0	16.6	17.5	16.7
1996	17.0	16.2	…	13.6	16.2	15.8	17.4	14.9
1997	17.7	19.6	…	14.4	17.1	17.6	21.0	17.0
1998	16.6	18.7	…	16.5	19.4	18.5	21.1	17.3

Table B5 - Climate station total annual precipitation (cm).
Data from < http://www.wrcc.dri.edu/summary/climsmwa.html >.

	Station ID							
Year	451992	452157	453160	453730	455133	455840	458059	458715
1958	174	148	140	…	…	…	78	…
1959	253	263	199	…	…	…	100	…
1960	217	192	176	…	…	216	83	…
1961	226	222	178	…	…	238	84	…
1962	184	163	130	…	…	182	67	…
1963	174	179	139	71	…	192	84	…
1964	246	229	…	99	…	239	82	…
1965	186	162	…	82	…	186	87	…
1966	170	152	…	41	…	175	73	223
1967	232	208	174	109	…	234	88	278
1968	238	248	221	132	…	274	105	319
1969	215	185	90	90	…	189	99	236
1970	169	157	131	78	46	159	68	199
1971	255	201	170	120	39	219	94	258
1972	273	250	217	131	67	280	115	319
1973	137	116	95	32	86	142	50	207
1974	277	256	183	134	35	242	92	355
1975	198	182	56	115	54	194	94	240
1976	272	294	214	146	53	280	113	333
1977	133	156	114	51	59	144	49	176
1978	198	195	129	120	25	197	114	242
1979	140	156	…	62	72	163	62	178
1980	210	197	135	84	36	194	96	251
1981	201	220	178	90	68	216	94	258
1982	226	208	203	106	50	218	124	241
1983	233	200	180	104	73	193	98	239
1984	220	204	…	97	75	199	96	273
1985	165	123	…	65	52	163	72	190
1986	191	201	…	82	46	196	87	242
1987	180	172	…	82	45	159	88	228
1988	154	181	…	83	48	…	80	196
1989	174	175	…	85	46	156	86	221
1990	196	215	…	101	48	206	94	268
1991	224	284	…	127	52	256	126	334
1992	179	176	…	92	68	181	82	228
1993	144	141	…	78	56	155	69	200
1994	151	159	…	67	46	161	64	202
1995	146	196	…	100	42	184	103	263
1996	192	257	…	132	77	250	101	328
1997	297	211	…	128	75	277	90	348
1998	187	150	…	125	80	162	81	217

Tables B6 - Climate station total precipitation (cm) for August and September. Data from < http://www.wrcc.dri.edu/summary/climsmwa.html >.

	Station ID - - - >							
Year	451992	452157	453160	453730	455133	455840	458059	458715
1958	15	17	17	…	…	…	6	…
1959	32	34	34	…	…	…	14	…
1960	15	10	20	…	…	15	7	…
1961	17	13	27	…	…	17	11	…
1962	24	21	25	…	…	23	11	…
1963	9	13	4	9	…	16	15	…
1964	23	22	…	7	…	24	10	…
1965	10	12	…	8	…	15	12	…
1966	8	6	…	3	…	6	12	7
1967	9	8	10	3	…	8	4	9
1968	20	21	22	10	…	25	14	29
1969	26	24	26	10	…	22	13	29
1970	16	17	13	5	5	18	6	23
1971	16	14	6	5	3	15	8	15
1972	28	27	15	13	4	27	24	25
1973	9	9	5	4	8	8	7	13
1974	2	4	0	3	4	5	7	6
1975	14	9	12	8	0	9	11	15
1976	14	14	16	5	4	15	9	18
1977	26	14	14	12	8	15	13	23
1978	26	26	26	18	5	25	20	34
1979	13	12	…	7	9	14	8	14
1980	21	22	17	9	10	19	12	23
1981	14	11	18	4	4	11	13	16
1982	12	18	…	8	4	17	13	18
1983	19	16	…	10	6	14	20	4
1984	15	17	…	12	8	16	8	17
1985	14	11	…	9	3	12	10	12
1986	9	9	…	6	6	10	8	13
1987	5	5	…	1	2	4	7	8
1988	10	16	…	7	0	16	12	22
1989	10	5	…	2	3	6	9	10
1990	8	11	…	6	2	12	15	12
1991	11	10	…	4	4	10	8	18
1992	14	16	…	8	2	17	15	22
1993	7	7	…	6	2	6	16	3
1994	11	8	…	4	3	8	6	14
1995	33	11	…	5	4	12	10	8
1996	13	10	…	3	3	11	8	18
1997	25	3	…	14	4	21	4	31
1998	2	2	…	1	5	2	9	3

Appendix C - Hydrologic data

Metadata in Table C1 and daily discharge data used to compile stream volumes in tables C2 and C3 downloaded from Data downloaded from U.S. Geological Survey - Surface-Water Data for Washington - Daily Streamflow for Washington at...
< http://water.usgs.gov/wa/nwis/discharge >

Table C1 - USGS Gage station identification, location, elevation, area drained, and operational period. Operational period in year / month / day format.

Station ID#	Name	Period of Record Start	Last
12175500	Thunder Creek Nr. Newhalem	1930.10.02	1998.09.30
12178100	Newhalem Creek Nr. Newhalem	1961.02.01	1998.09.30
12179000	Skagit River Abv Alma Cr	1950.10.01	1995.09.30
12181000	Skagit River At Marblemount	1943.09.01	1998.09.30
12182500	Cascade River near Marblemount	1928.10.01	1979.09.30
12205000	N.F. Nooksack R Blw Casc. Cr Nr Glacier	1937.10.01	1998.09.30
12451000	Stehekin River At Stehekin	1910.12.01	1998.09.30

Station ID#	Name	Location Lat	Long	Drainage (km^2)	Datum (m)
12175500	Thunder Creek Nr. Newhalem	48°40'	121°04"	272	372
12178100	Newhalem Creek Nr. Newhalem	48°39'	121°14'	72	329
12179000	Skagit River Abv Alma Cr	48°36'	121°21'	3300	109
12181000	Skagit River At Marblemount	48°32'	121°25'	3577	93
12182500	Cascade River near Marblemount	48°31'	121°24'	480	101
12205000	N.F. Nooksack R Blw Casc. Cr Nr Glacier	48°54'	121°50'	272	380
12451000	Stehekin River At Stehekin	48°19'	120°41'	831	335

Table C2 - Total annual stream volume by water year. Volume in km^3

	Station ID - - - - ->						
Year	12175500	12178100	12179000	12181000	12182500	12205000	12451000
1958	0.65	...	5.98	...	1.20	0.80	1.62
1959	0.60	...	5.28	...	1.05	0.70	1.50
1960	0.65	0.14	5.43	...	1.04	0.77	1.44
1961	0.49	0.15	4.22	...	0.89	0.64	1.14
1962	0.52	0.14	4.77	...	0.89	0.68	1.18
1963	0.57	0.19	5.73	...	1.06	0.81	1.37
1964	0.52	0.15	4.53	...	0.91	0.66	1.23
1965	0.47	0.14	4.25	...	0.78	0.69	1.07
1966	0.62	0.17	5.42	...	1.02	0.79	1.48
1967	0.65	0.18	5.77	...	1.12	0.89	1.56
1968	0.56	0.15	4.53	...	0.91	0.73	1.37
1969	0.45	0.12	3.81	...	0.72	0.58	0.99
1970	0.57	0.16	5.27	...	1.07	0.80	1.56
1971	0.67	0.21	6.38	...	1.21	0.79	1.75
1972	0.43	0.12	3.33	...	0.73	0.57	0.83
1973	0.61	0.20	5.89	...	1.15	0.90	1.72
1974	0.51	0.15	4.36	...	0.85	0.65	1.28
1975	0.63	0.21	6.33	...	1.20	0.84	1.65
1976	0.44	0.10	3.26	3.93	0.67	0.53	0.78
1977	0.54	0.16	4.12	5.09	0.94	0.68	1.33
1978	0.47	0.11	3.41	4.05	0.75	0.52	0.89
1979	0.51	0.15	4.32	5.32	...	0.64	1.13
1980	0.56	0.16	4.75	6.01	...	0.70	1.21
1981	0.57	0.21	4.89	6.23	...	0.78	1.39
1982	0.55	0.12	4.63	5.68	...	0.77	1.27
1983	0.53	0.20	4.29	5.42	...	0.74	1.26
1984	0.48	0.15	4.00	4.86	...	0.62	1.03
1985	0.54	0.21	4.55	5.36	...	0.73	1.13
1986	0.53	0.10	4.14	4.84	...	0.66	1.09
1987	0.46	0.16	3.79	4.49	...	0.62	1.04
1988	0.53	0.11	4.22	5.07	...	0.65	1.14
1989	0.61	0.15	5.16	5.81	...	0.77	1.29
1990	0.69	0.23	7.13	8.71	...	0.93	1.73
1991	0.61	0.12	3.93	4.87	...	0.66	1.14
1992	0.45	0.12	3.19	3.88	...	0.58	0.96
1993	0.45	0.13	3.65	4.27	...	0.59	0.91
1994	0.52	0.15	4.07	5.02	...	0.67	1.28
1995	0.66	0.21	...	6.85	...	0.82	1.63
1996	0.72	0.21	...	7.08	...	0.97	1.71
1997	0.55	0.14	...	4.83	...	0.72	1.27

Table C3 - Total August / September stream volume by water year. Volume in km3

Year	Station ID 12175500	12178100	12179000	12181000	12182500	12205000	12451000
1958	0.14	...	0.69	...	0.18	0.12	0.21
1959	0.11	...	0.55	...	0.12	0.09	0.14
1960	0.13	0.01	0.54	...	0.11	0.09	0.12
1961	0.11	0.02	0.51	...	0.14	0.12	0.14
1962	0.12	0.02	0.57	...	0.11	0.11	0.15
1963	0.11	0.03	0.66	...	0.17	0.13	0.17
1964	0.12	0.01	0.49	...	0.11	0.10	0.15
1965	1.45	0.42	0.48	...	0.10	0.10	0.14
1966	0.15	0.01	0.60	...	0.13	0.13	0.17
1967	0.12	0.02	0.57	...	0.14	0.13	0.16
1968	0.11	0.02	0.53	...	0.11	0.12	0.13
1969	0.10	0.01	0.55	...	0.09	0.09	0.11
1970	0.14	0.02	0.56	...	0.15	0.14	0.20
1971	0.14	0.03	0.69	...	0.19	0.11	0.24
1972	0.11	0.01	0.40	...	0.10	0.09	0.12
1973	0.14	0.02	0.59	...	0.17	0.16	0.28
1974	0.11	0.01	0.45	...	0.11	0.11	0.16
1975	1.77	0.27	0.77	...	0.19	0.16	0.28
1976	0.14	0.01	0.29	0.38	0.12	0.10	0.14
1977	0.14	0.02	0.60	0.77	0.17	0.15	0.17
1978	0.13	0.01	0.47	0.53	0.10	0.10	0.11
1979	0.10	0.01	0.49	0.60	...	0.09	0.12
1980	0.14	0.01	0.58	0.71	...	0.10	0.15
1981	0.14	0.02	0.60	0.78	...	0.11	0.17
1982	0.12	0.02	0.61	0.76	...	0.10	0.16
1983	0.12	0.02	0.50	0.64	...	0.11	0.16
1984	0.09	0.01	0.47	0.58	...	0.08	0.12
1985	1.39	0.28	0.48	9.59	...	0.10	0.11
1986	0.11	0.01	0.45	0.53	...	0.08	0.10
1987	0.10	0.01	0.57	0.64	...	0.09	0.15
1988	0.09	0.01	0.49	0.59	...	0.08	0.12
1989	0.13	0.01	0.61	0.65	...	0.09	0.14
1990	0.14	0.02	0.68	0.80	...	0.14	0.23
1991	0.12	0.01	0.44	0.57	...	0.10	0.10
1992	0.09	0.01	0.42	0.50	...	0.08	0.10
1993	0.10	0.01	0.49	0.56	...	0.07	0.10
1994	0.10	0.01	0.40	0.55	...	0.07	0.12
1995	...	0.18	...	...	...	0.09	0.13
1996	0.16	0.02	...	0.69	...	0.14	0.22
1997	0.12	0.01	...	0.53	...	0.09	0.12

Appendix D - Data directory and sources

Glacier Outlines

- Snow and ice for North Cascades National Park - Digitized from USGS 1:24K quadrangles by US National Park Staff - Ann Bratten - North Cascades National Park (Sedro Wolley, Washington).
- Snow and ice for Mt. Baker-Snoqualmie National Forest - Digitized from USGS 1:24,000 topographic maps by US Forest Service.
- Snow and ice for Wenatchee National Forest - Digitized from USGS1:24,000 topographic maps by US Forest Service.
- Ice cover of the Cascade range - Digitized from 1:100,000 scale USGS topographic maps by US Geological Survey.
- Glaciers of the North Cascades Range - Digitized from 1:31,680 topographic maps used by Post et al. to construct the 1971 inventory. Maps archived at North Cascades Glacier Climate Project (Nichols College, Dudley, MA.)

Aerial Photography

- Uncorrected aerial photography of North Cascades National Park taken by WAC corp. (Eugene OR.) during July and August 1998. Photos archived at North Cascades National Park, Marblemount, Washington.
- Digital orthoquads (DOQs) of selected sections of the Mt. Baker Snoqualmie, Wenatchee, and Okanagan National Forest as well as portions of the North Cascades National Park Complex. DOQs available from University of Washington Library, Seattle, Washington.

Digitial Elevation Models

- 30 m SDTS DEMs compiled by the US Geological Survey - Downloaded from USGS Geographic Data Download web site at, <http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html >

- 10 m DEMs compiled by Washington DNR for - Downloaded from Washington State Geospatial data archive at < http://wagda.lib.washington.edu/data/ >

Gaging Station Data

- Stream discharge data for gaging stations in and around the North Cascades National Park Complex. Data downloaded from U.S. Geological Survey - Surface-Water Data for Washington - Daily Streamflow for Washington at < http://water.usgs.gov/wa/nwis/discharge >
- Stream discharge data for Cascade River gaging station. Data provided by US Geological Survey water resources division, Tacoma Washington.

Climate Data

- Southern Oscillation Index data for 1958 to 1998. Data downloaded from International Research Institute for Climate Prediction Climate Data Library (Lamont-Doherty Earth Observatory, Pallisades, N.Y.) Indices Southern Oscillation Index web site at, < http://ingrid.ldgo.columbia.edu/SOURCES/.Indices/.soi/ >
- Pacific Decadal Oscillation data for 1958 to 1998. Data downloaded from Joint Institute for the Study of Atmosphere and Ocean (University of Washington, Seattle, Washington) Pacific Decadal Oscillation web site at, < http://tao.atmos.washington.edu/pdo/ >
- Precipitation and temperature data for the Cascade foothills, Western Cascade, and Eastern Cascade climate divisions. Data downloaded from Western Regional Climate Center (Desert Research Institute, Las Vegas, NV.) U.S.A. Divisional Climate Data web site at < http://www.wrcc.dri.edu/spi/divplot1map.html >
- Precipitation and temperature data for climate stations in and around the National Park Complex. Data downloaded from Western Regional Climate Center (Desert Research Institute, Las Vegas, NV.) Washington Climate Summaries web site at, < http://www.wrcc.dri.edu/summary/climsmwa.html >.

Appendix E - Contents of the Companion CD

The CD accompanying this thesis is in a ISO 9660 format which readable by computers having Windows 9.x and above, MacOS 8.6 and above, or UNIX operating systems.

1) *nccd_readme.html* - A web page that describes the contents of the CD in detail and gives instructions for viewing the files contained in it. This file is located in the "thesis" folder.
2) gis_data - Principle GIS data used in this project.
   a) *data_av* - GIS data created using ArcView 3.1 by Environmental Research Systems Institute Inc. (ESRI).
      - *noca_av* - Glacier, hydrology, watershed, and administrative coverages for the entire complex.
      - *indicator_av* - Glacier, glacial features, elevation, and hydrologic coverages for Sandalee, North Klawatti, Noisy, and Silver Creek glaciers.

   b) *data_mfw* - GIS data created using MFworks 2.6 by Kiegan Systems (formerly Thinkspace Inc.).
      - noca_mfw - Glacier,, 30m DEM, hydrology, and administrative coverage for the entire complex.
3) *tabular_data* - Folder containing principle spreadsheets used for analysis. All data produced using Microsoft Excel 2001.

   NOCA_Glacier.xls - Glacier inventory and data summary for the entire complex.

   NOCA_Stream.xls - Metadata for stream gauging stations located in and around the park complex and stream flow statistics for each station.

   NOCA_Climate.xls - Metadata and climate characteristics for climate stations in and around the park complex, annual and seasonal temperature and precipitation by climate division, and annual and seasonal SOI and PDO.
4) *thesis* - Folder containing the entire thesis in pdf format. To read these documents your browser must be equipped with Acrobat Reader 4.0 or higher.