National Park Service
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Natural Resource Stewardship and Science

Mount Rainier National Park Glacier Mass Balance Monitoring Annual Report, Water Year 2010

North Coast and Cascades Network

Natural Resource Data Series NPS/NCCN/NRDS—2012/355

ON THE COVER
Fall 2010 field work on Ingraham Glacier, Mount Rainier National Park. Previous summer glacier surfaces can be identified as dirty layers in crevasse stratigraphy.
Photograph by: Mount Rainier National Park

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Fort Collins, Colorado

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data. Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

This report is available from The North Coast and Cascades Network (http://science.nature.nps.gov/im/units/nccn/reportpubs.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm).

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Abstract

Glaciers are excellent indicators of climate change and important drivers of aquatic and terrestrial ecosystems. There are currently 27 major glaciers at Mount Rainier National Park, which cover about 90 km^2. Since 2003, we have monitored the seasonal mass balance changes of two of these glaciers, Emmons (11.6 km^2) and Nisqually (6.9 km^2), using six measurement points per glacier. The purpose of this report is to describe and summarize data collected during the 2010 water year.

Measurement of winter, summer, and net mass balance on Mount Rainier is complicated by steep (inaccessible) ice falls, debris cover, and a 2000 m range in elevation. With the large vertical extent, glacial melt begins at the terminus in early April and above 3000 m in July. Maximum accumulation occurs between about 2000 and 2500 m elevation, with significant redistribution of snow by wind from southwest to northeast at higher elevations.

Winter snow accumulation reached a maximum depth of 3.40 m w.e. on Nisqually Glacier and 3.44 m w.e. on Emmons Glacier in water year 2010. Water equivalent (w.e.) values averaged across the entire glacier were 129% of the 2003-2010 average on Nisqually Glacier [+3.06 (±0.36) m w.e.] and 110% of average on Emmons Glacier [+2.49 (±0.44) m w.e.].

Maximum summer melt reached -4.34 m w.e. at stake 4 on lower Nisqually Glacier in late September. Net summer balance averaged across the measurement sites on Nisqually Glacier was -2.55 (±0.48) m w.e., and -2.36 (±0.55) m w.e. on Emmons Glacier (73% of average for both glaciers). Significant debris cover on the lower portions of both glaciers slowed average ice melt to 54-82% of melt observed on adjacent stakes on clear glacier surfaces.

In 2010, annual net mass balance was positive for Nisqually Glacier [+0.50 (±0.65) m w.e.], the only positive year since monitoring began in 2003. Emmons Glacier also had a slight positive balance [+0.13 (±0.70) m w.e.]. Despite the modest increases in glacier balance in 2010, the overall trend in cumulative balance has been strongly negative for both glaciers. Since 2003, the cumulative balance for Nisqually Glacier is -9.05 m w.e. and for Emmons Glacier it is -7.69 m w.e. The cumulative net volume loss in the past eight years is 89.2 M m^3 and 61.2 M m^3 for Emmons and Nisqually glaciers, respectively.

Acknowledgments

Measurement of mass balance on four glaciers, adjustment of base maps, and administration of this project were only possible through the concerted effort of a large group of individuals. Field measurements were supported by Rebecca Lofgren, Benjamin Wright, Stefan Lofgren, Glenn Kessler and numerous Mount Rainer National Park climbing rangers.

Introduction

The National Park Service began long-term monitoring of Nisqually and Emmons glaciers in Mount Rainier National Park (MORA) in 2003 (Figures 1-3). Monitoring includes direct field measurements of snow accumulation and melt at a sequence of stations placed at different elevations to estimate the mass balance of each glacier. Methods used here are directly comparable with those taken at four glaciers in North Cascades National Park Complex (NOCA) by the US National Park Service (NPS), at South Cascade Glacier by US Geological Survey, and globally. The purpose of this report is to describe and summarize data collected during the 2010 water year.

Glaciers are a defining feature of Mount Rainier National Park; as of 1994 there were 27 major glaciers on Mount Rainier with a combined area of 90 km^2 (35 mi^2) and numerous unnamed permanent snow or ice patches (Nylen 2002). The Emmons Glacier has the largest area (11.6 km^2; 4.3 mi^2) and Carbon Glacier has the lowest terminus altitude (1100 m; 3,600 feet) of all glaciers in the conterminous 48 states.

Glaciers are integral components of the region's hydrologic, ecologic, and geologic systems. Glacial melt water buffers the region's aquatic ecosystems from seasonal and interannual droughts. Aquatic ecosystems, endangered species such as salmon, bull trout and western cutthroat trout, and the hydroelectric and agricultural industries benefit from the seasonal and interannual stability glaciers impart to the region's hydrologic systems.

Glaciers significantly change the distribution of aquatic and terrestrial habitat through their advance and retreat. They directly influence aquatic habitat by the amount of cold, turbid melt water and fine-grained sediment they release. Glaciers also indirectly influence habitat through their effect on nutrient cycling and microclimate. Many of the subalpine and alpine plant communities in the park flourish on landforms and soils created by glaciers in the last century. Further, glaciers are habitat to a number of species, and are the sole habitat for ice worms (*Mesenchytraeus solifugus*) and certain species of springtails (Collembola) (Hartzell, 2003).

Glaciers are also sensitive and dramatic indicators of regional and global climate change. The total volume of all ice and snow on Mount Rainier was estimated to be 4.42 B m^3 (Driedger and Kennard 1986). Nylen (2002) estimated the area of glaciers had declined 27% between 1927 and 1994.

The large volume of glaciers presents a significant geological hazard to park visitors and staff, and communities downstream of Mount Rainier. Glaciers are known to produce outburst floods, ice falls and other hazards regardless of volcanic activity, and can produce large volumes of water during larger eruptions (Scott et al. 1995). The most recent significant outburst flood occurred in 1947 on Kautz Creek, with smaller outburst floods on the Nisqually River in the 1940s and 1950s and Tahoma Creek in the 1990s. While monitoring for geologic hazards is not the focus of this program, incidental observations of changes in the mass, distribution, and surface condition of glaciers can provide important information to NPS personnel and the USGS Cascade Volcano Observatory.

The glaciers selected to monitor drain into two major watersheds (Nisqually and White rivers) from MORA and represent the entire altitude range of glaciers on the mountain. These glaciers allow us to monitor aspect-related extremes in climate and glacier change, with Emmons on the northeast side of the mountain and Nisqually on the southwest side. Established climbing routes allow for safe access without the need for helicopter support. Both Nisqually and Emmons have excellent records of historic and prehistoric change (e.g. Harrison 1956, Heliker et al. 1983, Nylen 2002).

Four broad goals frame our glacier monitoring:

1) Monitor change in area and mass of park index glaciers;
2) Relate glacier changes to status of aquatic and terrestrial ecosystems;
3) Link glacier observations to research on climate and ecosystem change; and
4) Share information on glaciers with the public and professionals.

Objectives identified for achieving the program goals are:

- Collect a network of point surface mass balance measurements sufficient to define elevation versus balance relationships to estimate glacier averaged winter, summer and net balance for Emmons and Nisqually glaciers.
- Map and quantify surface elevation changes of Emmons and Nisqually glaciers every 10 years.
- Identify trends in glacier mass balance.
- Inventory margin position, area, condition, and equilibrium line altitudes of all park glaciers every 20 years.
- Monitor changes in surface features of glaciers, including ponds and ice falls.
- Monitor glacier melt, water discharge, and glacier area/volume change.
- Share data and information gathered in this program with a variety of audiences from school children to colleagues and the professional community.

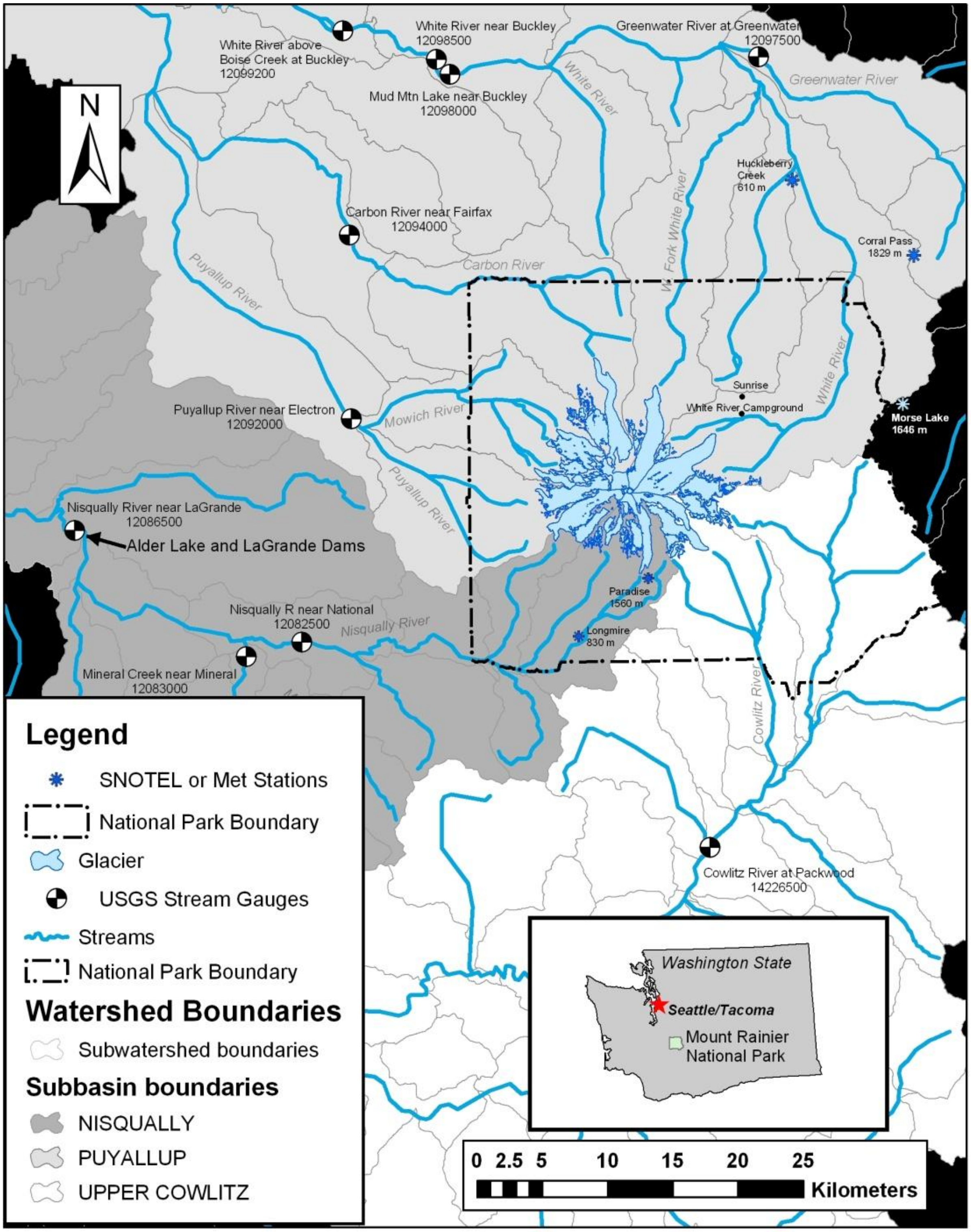

Figure 1. Locator map of Mount Rainier, major watersheds, streams, and USGS stream gauges. Weather stations are discussed in text.

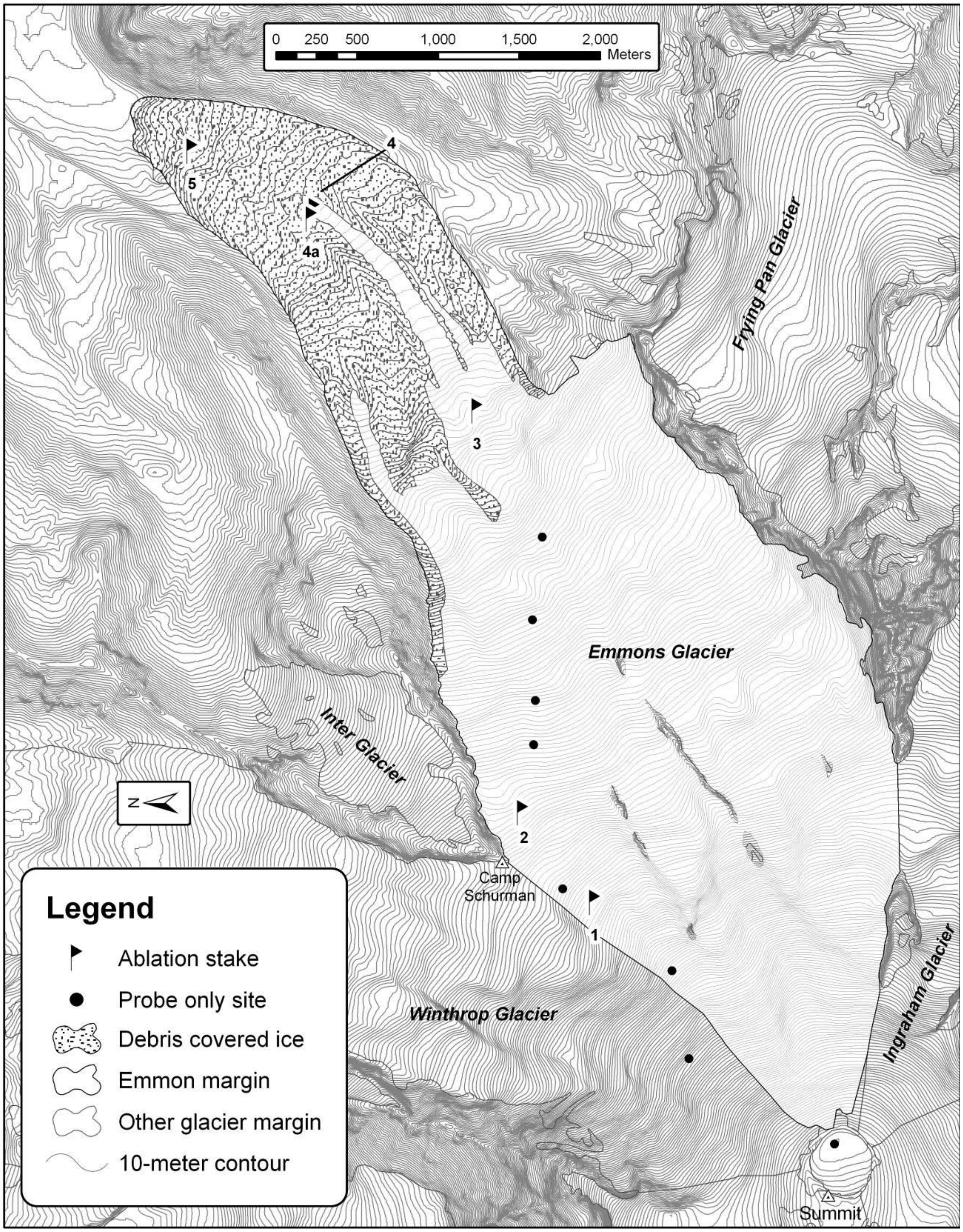

Figure 2. Emmons Glacier margin (1994), debris cover (2001), and measurement locations.

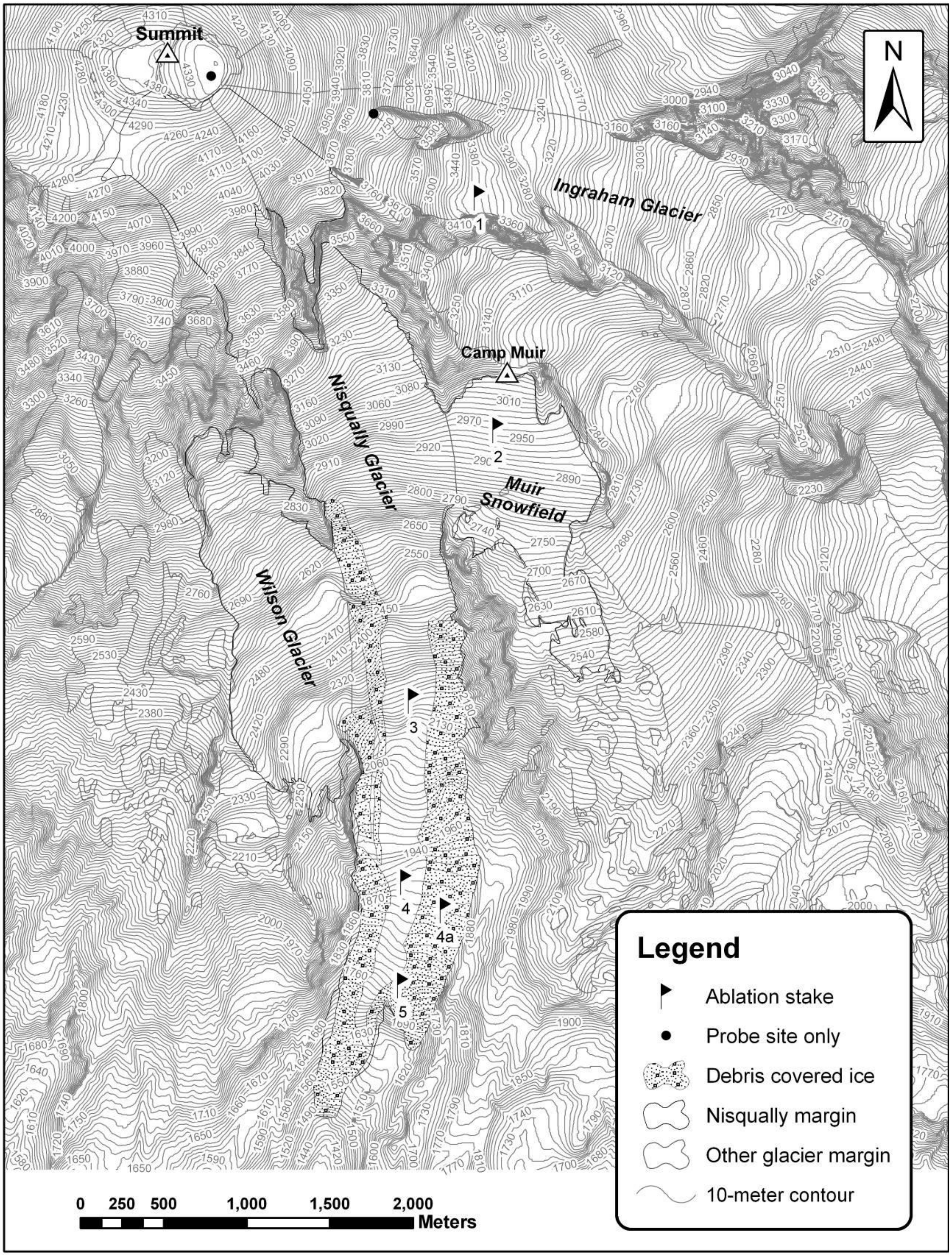

Figure 3. Nisqually Glacier margin (1994), debris cover (2001), and measurement locations.

Methods

Mass balance measurement methods used in this project follow the protocol developed by Riedel et al. (2010) which was modified from procedures used at NOCA since 1993 and published as a monitoring protocol by Riedel et al. (2008). Key studies that facilitated the development of these protocols were the 45 years of US Geological Survey (USGS) Water Resource Division research on the South Cascade Glacier in Mt. Baker-Snoqualmie National Forest by Meier (1961), Meier and Tangborn (1965), Meier et al. (1971), Tangborn et al. (1971), and Krimmel (1994-1996a, 1996b), and studies by Østrem and Stanley (1969), Paterson (1981), and Østrem and Brugman (1991). Data reduction methods in this report are modified from Østrem and Brugman (1991) and Krimmel (1994-1999a, 1999b, 2001), described in detail in Riedel et al. (2010), and incorporated into the measurement system summary provided below.

Measurement System

We use a two-season stratigraphic approach tailored to the conditions at Mount Rainier to calculate mass gained (winter balance) and mass lost (summer balance) on a seasonal basis (Riedel et al. 2010). Summation of these measurements allows for calculation of the net balance of a given glacier. The large altitude range of glaciers on Mount Rainier creates winter and summer seasons of dramatically different lengths at the terminus and the upper accumulation zone. Multiple spring, summer and fall visits are required to capture the maximum and minimum balances at different altitudes.

Winter balance is calculated from snow depth and bulk density measurements. Snow depth is measured at five to 10 points near six locations near the centerline of the glacier, resulting in 30-60 measurements per glacier. In years without reliable higher altitude data (above ~3400 meters), winter balance is assumed to follow the same pattern of decreasing winter accumulation above about 2200m observed during protocol development between 2002 and 2004. A minimum of two snow density measurements are taken in the spring on each glacier to determine the density versus altitude gradient.

Six ablation stakes are used to measure summer balance on each glacier, and are placed between late March and early June at locations from near the terminus to ~3400 meters altitude (Figures 2 and 3). For each glacier, two of the sites are located in areas with debris-covered ice, with the other stakes on debris-free ice. At a minimum, measurements of surface level change against the stakes are made in early summer through early October. The change in level against the stake indicates the mass lost at the surface during the summer season (summer balance). Summer melting above the highest stakes is determined by extrapolating the melt versus elevation curve. The extended curve is constrained by the local measured temperature lapse rate determined by Longmire, Paradise, and Camp Muir weather stations, and allows us to determine the elevation of the zero summer balance altitude.

Terrestrial-based photographs are taken of each index glacier as a record of annual change of the terminus, relative surface elevation against bedrock, equilibrium line altitude, and snow, firn and ice coverage. These color photographs are taken during fall field visits at the same locations and of the same views of the glacier.

Glacial Meltwater Discharge

Glacier contribution to summer streamflow is calculated annually for Nisqually and White River watersheds. The summer season is defined as the period between May 1 and September 30. These dates approximately coincide with winter and summer balance field measurements and the beginning and end of the ablation season. Glacier contributions to summer streamflow are estimated using summer balance data versus altitude from Nisqually and Emmons glaciers and the area-altitude distributions of all glaciers in each watershed.

2003 to 2010 Record

In this report, we present data measured in 2010 and compare it to data collected from 2003-2009, using the methods described in Riedel et al. (2008, 2010). We present eight-year comparisons of winter, summer, net, and cumulative glacial balance, and summer glacial meltwater contributions to the White and Nisqually River watersheds.

Results

Measurement Error

Sources of error in mass balance measurements include variability in snow depth probes, incorrect measurement of stake height, snow density, and stake/probe position and altitude, and non-synchronous measurements with actual maximum and minimum balances. Errors are calculated on an annual, stake-by-stake, and glacier-by-glacier basis. Errors associated with winter, summer, and net balance estimates in water year (WY) 2010 on Nisqually Glacier were below average (Table 1). At Emmons Glacier, error estimates were near average values, or about 10% of net balance

Table 1. Calculated error for Water Year 2010 mass balance on MORA glaciers (eight-year averages are in parenthesis).

	Average Error (m w.e.)		
Glacier	**Winter Balance**	**Summer Balance**	**Net Balance**
Emmons	±0.44 (0.45)	±0.55 (0.67)	±0.70 (0.81)
Nisqually	±0.36 (0.37)	±0.48 (0.80)	±0.65 (0.77)

Winter and Summer Balance

Maximum snow accumulation generally peaks near ~2160 m on the Nisqually Glacier and near ~3050 m on the Emmons Glacier, near our highest placed stake. However, in 2010 snow accumulation reached a maximum depth above the highest stake locations on both glaciers. A predicted maximum snow depth of 3.44 m w.e. occurred at 3215 m on Emmons Glacier and a peak depth of 3.40 m occurred at 3375 m on Nisqually Glacier (Figures 4 and 5). Net winter balance (averaged across the glacier) in WY2010 was 110% of average for Emmons Glacier at +2.49 (±0.44) m w.e.; and 129% of average for Nisqually Glacier at +3.06 (±0.36) m w.e. (Figures 6 and 7).

A cool and wet spring resulted in the summer melt season beginning several weeks later than in previous years. The melt season at the lower elevation stakes began in mid-to-late April and continued to early October. At upper stakes, summer melt season began in late May and continued to mid-September. Summer balance at the lowest stakes without debris cover on Emmons Glacier was -4.17 m w.e. and -4.34 m w.e. on Nisqually Glacier.

Net summer mass balance was 73% of average for Emmons Glacier [-2.36 (±0.55) m w.e.] and 73% of average for Nisqually Glacier [-2.55 (± 0.48) m w.e.]. Summer melt at debris covered stakes on the lower parts of both glaciers was below average, with values ranging from 54 to 82% of melt on adjacent debris-free parts of the glaciers (Figures 4-7). Based on extrapolated balance curves, there was a net gain of about 1.93 m w.e. on the summit of Mount Rainier.

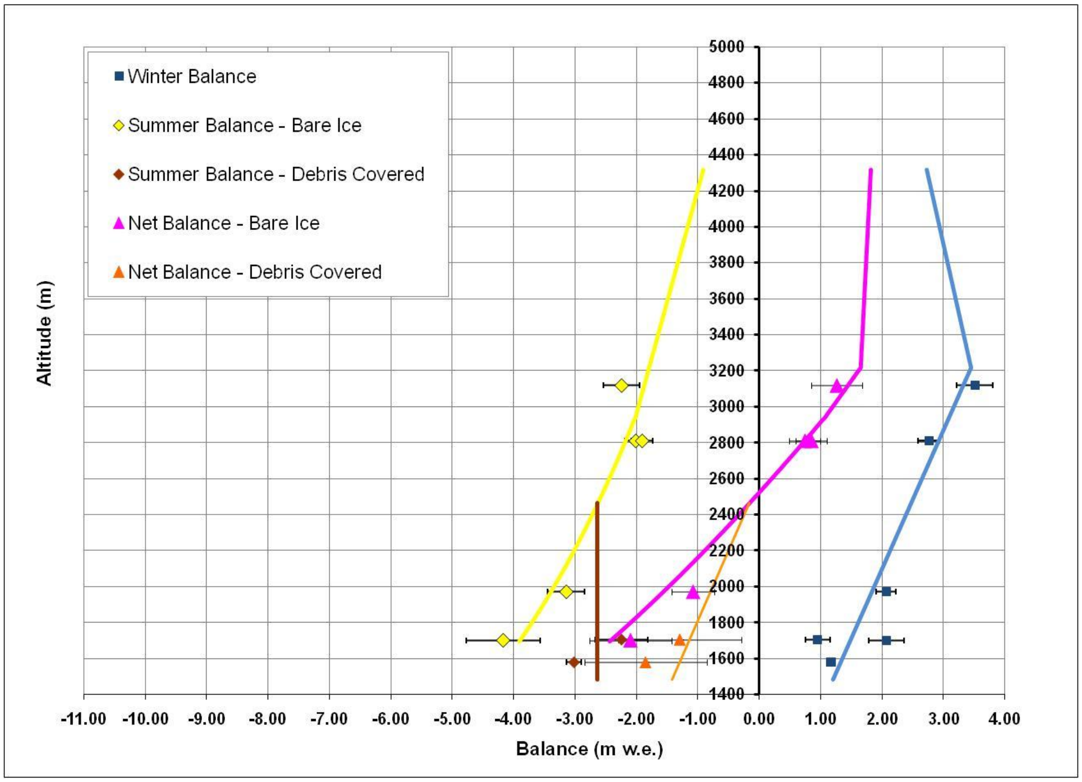

Figure 4. Emmons Glacier specific balance versus altitude, 2010.

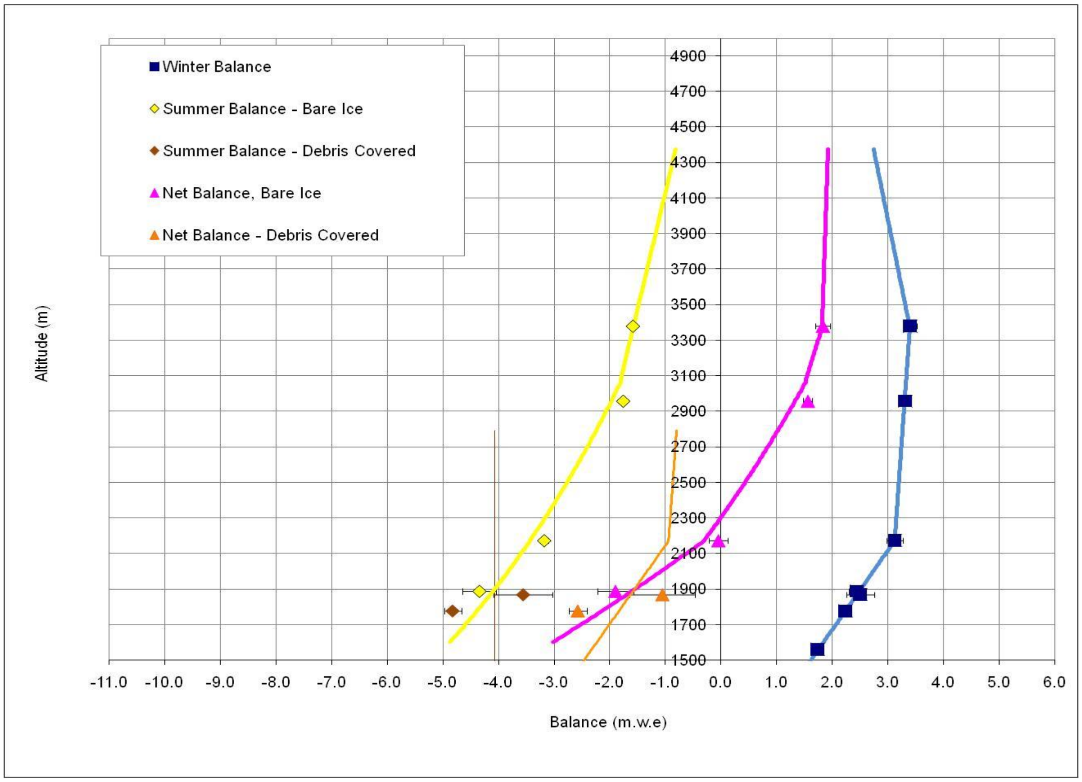

Figure 5. Nisqually Glacier specific balance versus altitude, 2010.

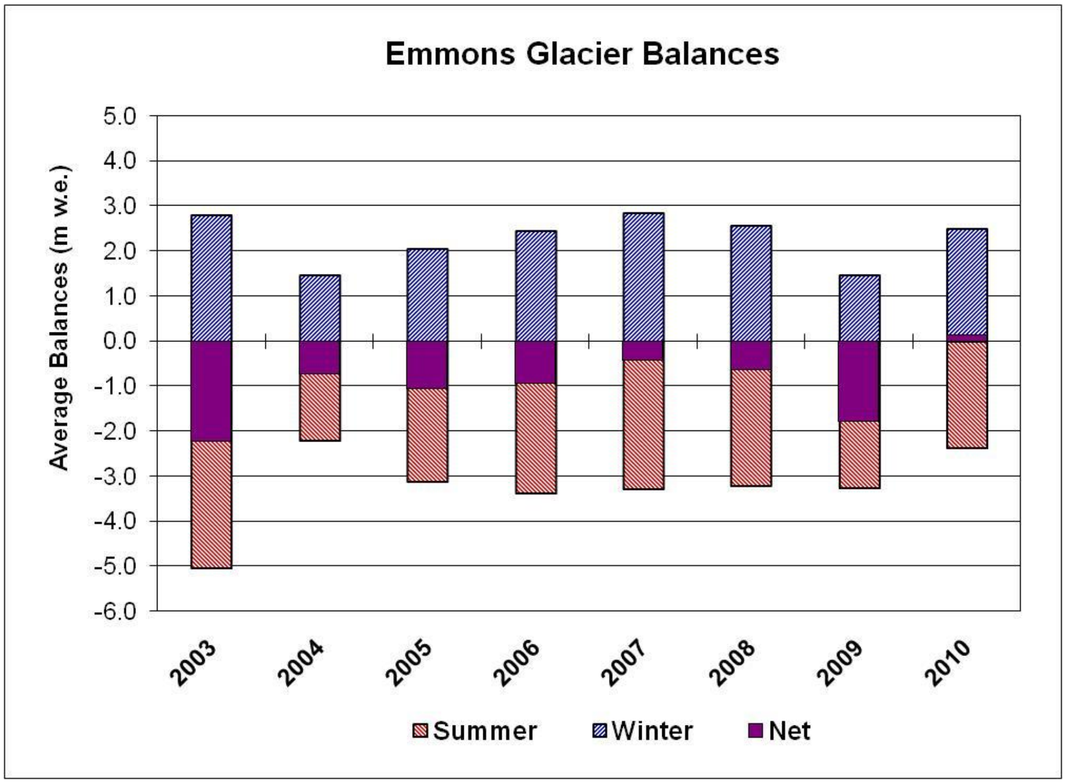

Figure 6. Winter, summer and net mass balances for Emmons Glacier by water year.

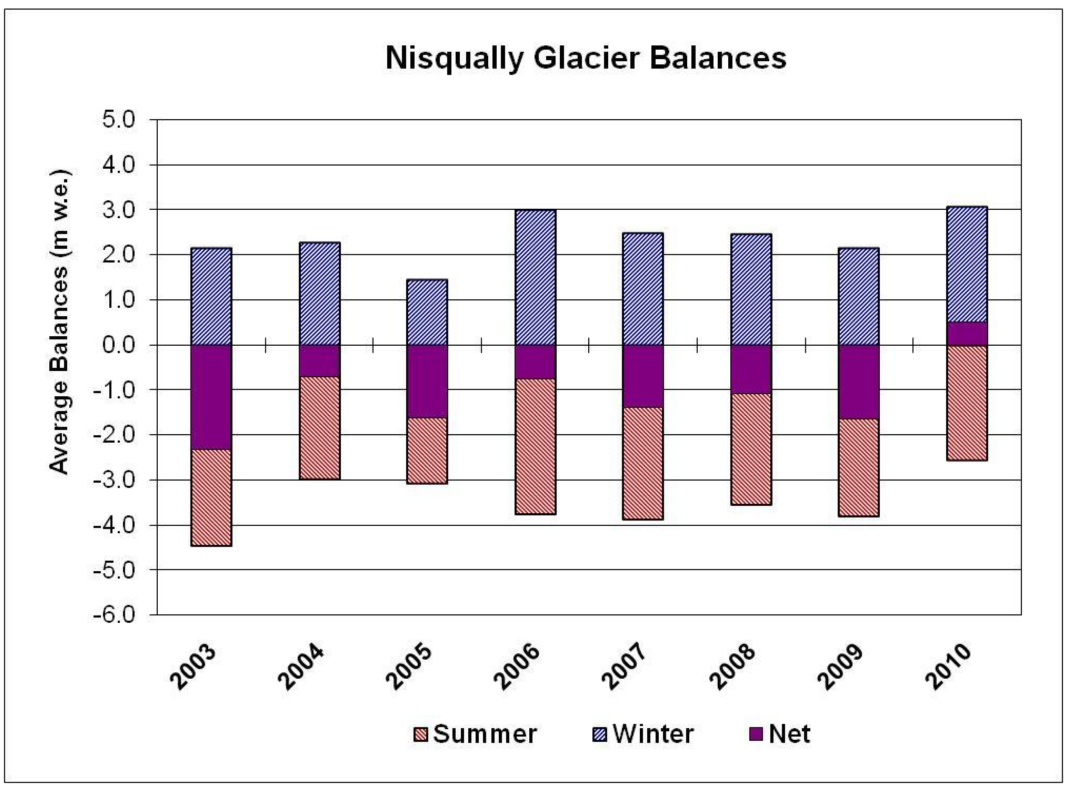

Figure 7. Winter, summer and net mass balances for Nisqually Glacier by water year.

Net Balance

Annual net mass balances for Nisqually and Emmons glaciers were positive for the first year since monitoring began in 2003 (Figure 8). Nisqually Glacier had a larger positive net mass balance [+0.50 (±0.65) m w.e.] compared to Emmons Glacier [+0.13 (±0.70) m w.e.]. The equilibrium line altitude (ELA) for Nisqually Glacier was lower and had a greater departure from average than the Emmons Glacier. The ELA for Nisqually Glacier was 2305 m, more than 800 m below the period of record average of 3138 m. The ELA for Emmons Glacier was 2525 m, approximately 250 m below the average of 2790 m. The volume gain from these two glaciers in WY 2010 is estimated at 3.4 M m^3 for Nisqually Glacier and 1.5 M m^3 for Emmons Glacier.

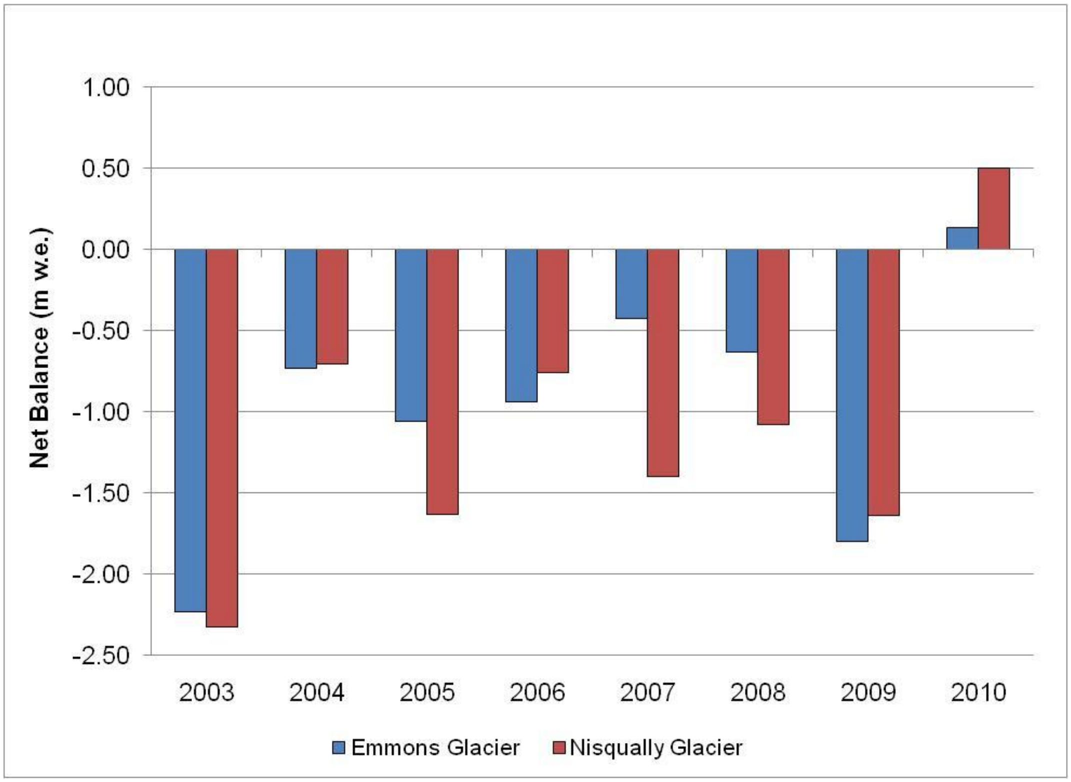

Figure 8. Net mass balance comparisons for each glacier by water year.

Cumulative Balance

Net mass balance for Emmons and Nisqually glaciers was positive in WY2010 for the first year since monitoring began in 2003. Despite the modest increases in glacier balance in WY2010, the overall trend in cumulative balance has been strongly negative for both glaciers. Since 2003, the cumulative balance for Nisqually Glacier is -9.05 m w.e. and for Emmons Glacier it is -7.69 m w.e. The cumulative net volume loss in the past eight years is 89.2 M m^3 and 61.2 M m^3 for Emmons and Nisqually glaciers, respectively.

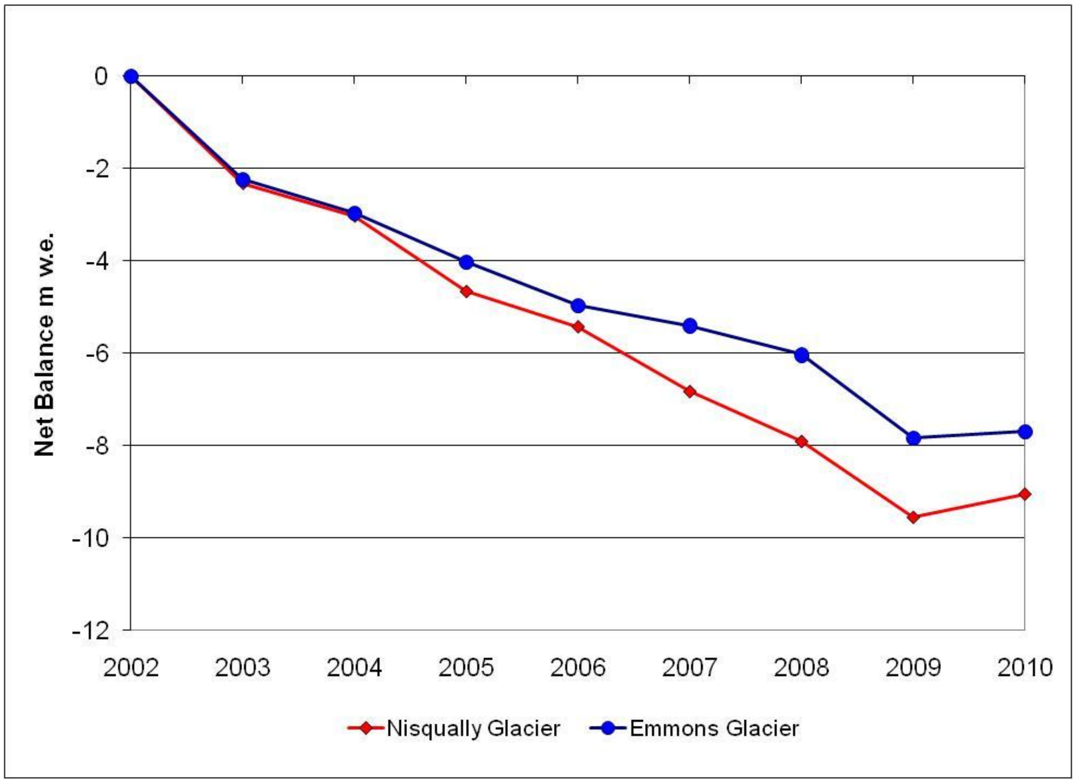

Figure 9. Cumulative balance for each glacier by water year.

Glacial Contribution to Streamflow

In White River basin at Buckley, glaciers contributed 62.7 M m^3 of water to streamflow between May 1 and September 30, representing about 11% of the total summer runoff (Table 2). Glaciers in the Nisqually basin above National contributed about 39.5 M m^3 to streamflow, or 12% of the total summer runoff. Glacial contribution to summer runoff was the lowest since monitoring began in 2003 at 71 and 72% of average for the White River and Nisqually River watersheds, respectively.

Since 2003, the range in total glacier melt-water contribution to Whiter River Basin is 62.7-138.6 M m^3 of water to summer streamflow, representing about 11-26% of the total. Glaciers in the Nisqually basin contribute between 39.5-68.6 M m^3 to summer streamflow, or about 12-33 of total runoff (Figure 10).

Table 2. Glacier contribution to summer streamflow for two MORA watersheds. Average, minimum and maximum values are for water years 2003-2010.

Site (% glacier area)	May-September Runoff (million cubic meters)				Percent Glacial Runoff to Total Summer Runoff			
	2010	average	min	max	2010	average	min	max
Nisqually Glacier	17.3	23.7	17.3	30.2				
Nisqually River Watershed (4.6)	39.5	55.0	39.5	68.6	12.4	21.1	12.4	33.1
Emmons Glacier	27.4	37.5	27.4	58.4				
White River Watershed (2.4)	62.7	81.5	62.7	138.6	10.6	16.5	10.6	25.8

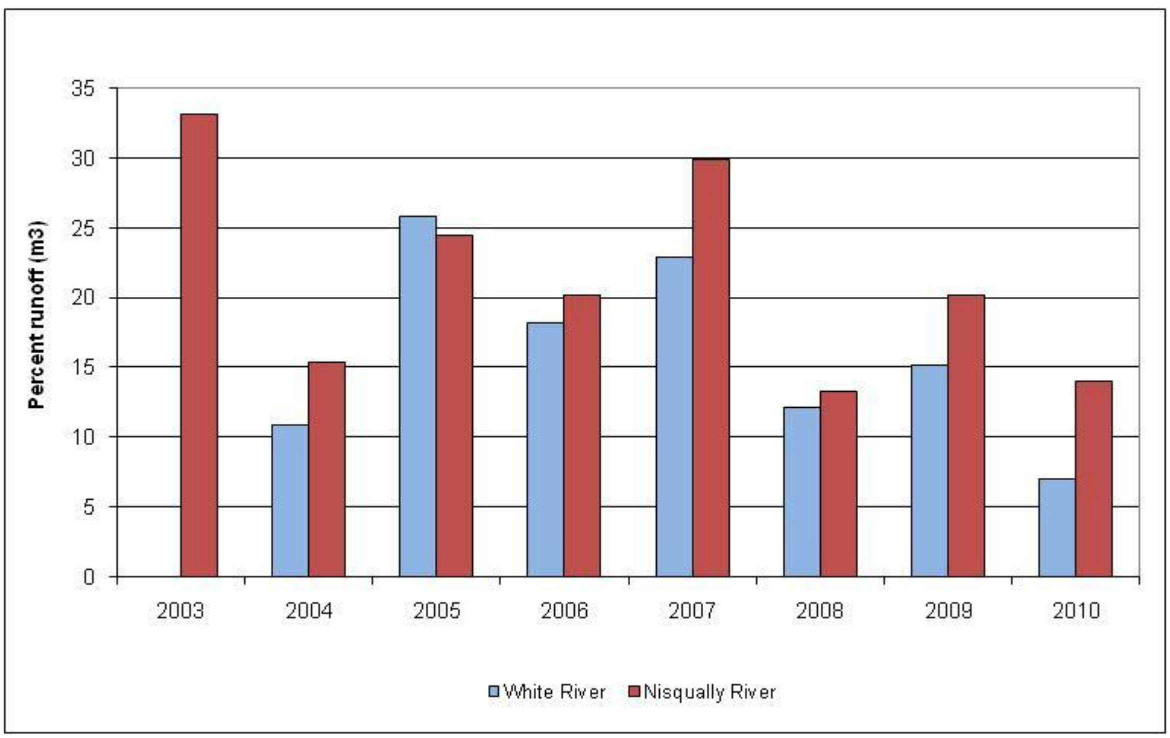

Figure 10. Total summer glacier meltwater contributions for two watersheds containing index glaciers.

Oblique Imagery

Oblique photographs are taken of each index glacier from permanent photo points as a record of change in area, surface elevation, equilibrium line altitude, and snow, firn and ice coverage. Photos from previous years are provided for comparison (Figures 11-14).

Figure 11. Emmons Glacier terminus, fall 2006. Photo was taken from moraine photo-point.

Figure 12. Emmons Glacier terminus, October 7, 2010. Photo was taken from moraine photo-point.

Figure 13. Nisqually Glacier, fall 2004. Photo was taken from Glacier Vista.

Figure 14. Nisqually Glacier, October 6, 2010. Photo was taken from Glacier Vista.

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