National Park Service
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Natural Resource Stewardship and Science

North Cascades National Park Complex Glacier Mass Balance Monitoring Annual Report, Water Year 2012

North Coast and Cascades Network

Natural Resource Data Series NPS/NCCN/NRDS—2017/1128

ON THIS PAGE
Silver Glacier, North Cascades National Park
Photograph by: North Cascades National Park Complex

ON THE COVER
Summer 2012 field work on Silver Glacier, North Cascades National Park
Photograph by: North Cascades National Park Complex

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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.

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Abstract

Glaciers cover approximately 93.6 km^2 in North Cascades National Park Service Complex (NOCA), and are a high-priority Vital Sign in the North Coast and Cascades Network (NCCN) monitoring plan because they are sensitive, dramatic indicators of climate change and drivers of aquatic and terrestrial ecosystems (Riedel et al. 2008). Since 1993, seasonal volume changes at four NOCA glaciers have been monitored using methods developed as part of the NCCN Glacier Monitoring Protocol (Riedel et al, 2008). In this report, glacier monitoring data for water year (WY) 2012 are presented as point mass balance, provisional glacier-wide mass balances and provisional glacier contribution to summer streamflow.

Point mass balances were measured at 18 sites on four glaciers for WY2012. Winter accumulation was above average (120-137 percent of average from 1993-2011), with the greatest accumulations measured on the west slopes. Summer balances were near average (92-109 percent of average). Point annual balances were below average ranging from -2.06 to +1.58 meters water equivalent.

Glacier-wide mass balances, which are the integration of point mass balance values across the entire glacier surface were calculated. Winter accumulation was above average (122-144 percent of average), and summer melt was near or below average (91-103 percent of average). Glacier-wide annual balances were positive for all glaciers for the second consecutive years and for the 7th year since 1993.

Glacier contribution to May-September runoff was estimated for four watersheds. In WY2012, meltwater originating from glaciers contributed 345 million m^3. The percent of glacial contribution to streamflow was below average for the year.

Acknowledgments

Measurement of mass balance on four glaciers and administration of this project were only possible through the concerted effort of a large group of individuals. Field measurements were supported by B. Wright, S. Brady, S. Dorsch, P. Roberts, and I. Delaney. We want to thank S. Welch, M. Huff, H. Anthony, and J. Oelfke for their administrative support.

Glossary

Ablation: All processes that remove mass from a glacier such as melting, runoff, evaporation, sublimation, calving and wind erosion.

Accumulation: All processes that add mass to the glacier such as snowfall, wind drifting, avalanching, rime ice buildup, rainfall, superimposed ice and internal accumulation

Annual mass balance: The sum of winter balance (which is positive) and summer balance (which is negative), or two successive minima. Annual mass balance is positive if the glacier has gained mass and negative if it has lost mass.

Equilibrium line altitude (ELA): The altitude where annual accumulation and ablation are equal and annual balance is zero. The ELA is determined by the either the altitude of the snow or firn line in the fall or from fitting a curve to point mass balance data, termed balanced-budget ELA.

Firn: A metamorphosed material between snow and ice. Snow becomes higher density firn after existing through one summer melt season but having not yet metamorphosed into glacier ice.

Glacier-wide mass balance: The mass balance averaged across glacier area. Typically determined from point mass balance measurements integrated across glacier surface.

Mass balance: The change in mass of a glacier measured between two points in time.

Point mass balance: The balance (winter, summer or annual) at an individual site (e.g. ablation stake).

Snow bulk density: The density of snow determined by dividing the volume of a sample by its weight.

Snow Telemetry (SNOTEL): Meteorological stations that provide real-time snow and climate data in the mountainous regions of the Western United States using automated remote sensing. They are operated by the Natural Resources Conservation Service.

Summer mass balance: The loss of snow, firn, and ice from ablation (mostly melting).

Water equivalent (w.e.): A measure of the amount of water contained in snow, firn and ice. Balance values are expressed in water equivalent due to the varying densities of water, snow, firn and ice, thus allowing for a single normalized value to be used.

Winter mass balance: The gain of a winter season snowfall, wind drifting, avalanching, rime ice buildup, rainfall, superimposed ice and internal accumulation.

Water year (WY): The water year (or hydrologic year) is most often defined as the period from October 1st to September 30 of the following year. It is called by the calendar year in which it ends. Thus, Water Year 2012 is the 12-month period beginning October 1, 2011 and ending September 30, 2012. The period is chosen so as to encompass a full cycle of winter accumulation and melt.

Introduction

The National Park Service began long-term monitoring of glacier mass balance within North Cascades National Park Complex (NOCA) in 1993. Monitoring includes direct field measurements of accumulation and melt to estimate the volume gained and lost on a seasonal and water-year basis. Noisy Creek, Silver Creek, and North Klawatti Glaciers have been monitored at NOCA since 1993 and a fourth glacier, Sandalee, since 1995 (Figure 1). This report describes field work and summarizes data collected for water year (WY) 2012, beginning on October 1, 2011 and ending on September 30, 2012.

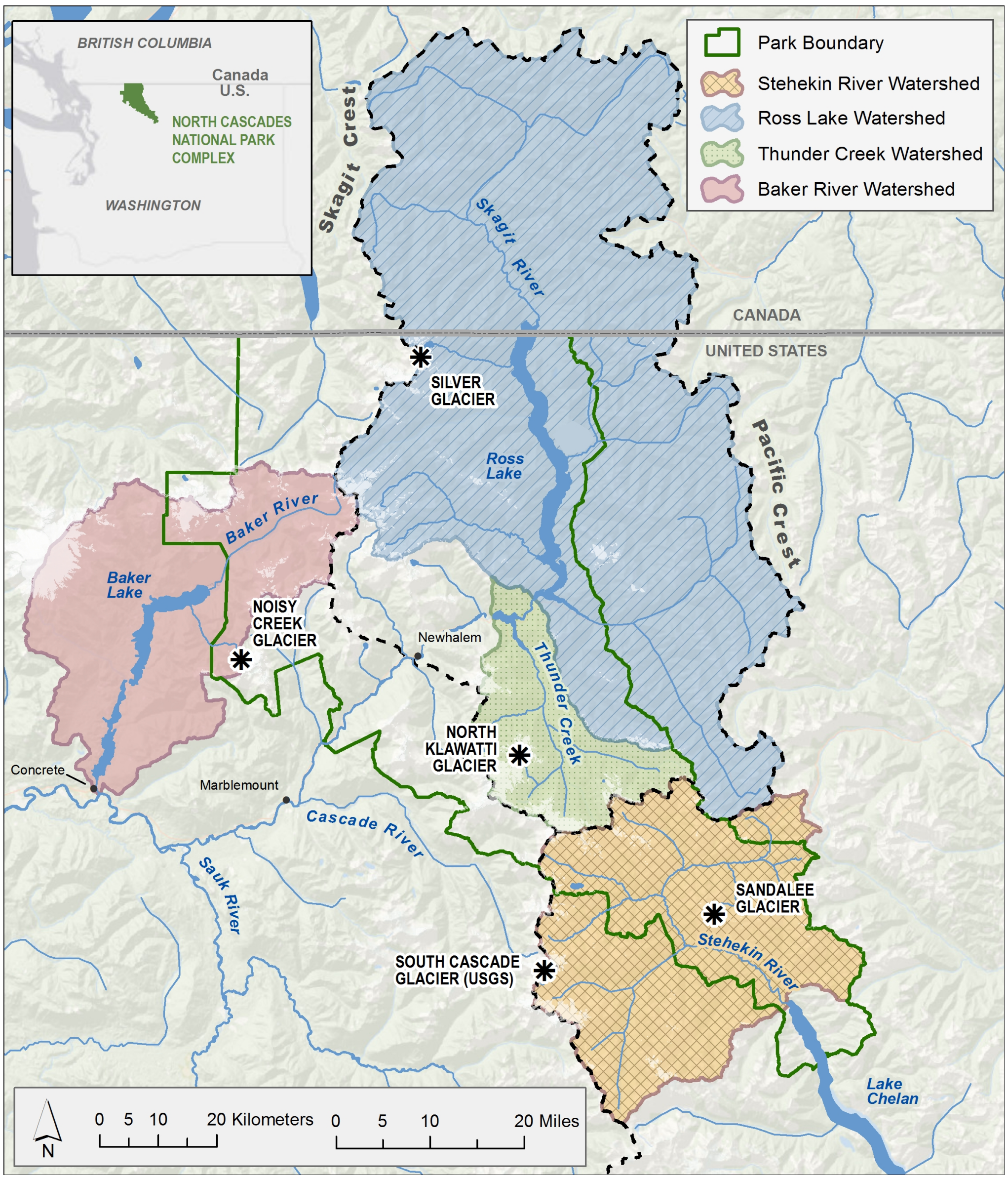

Figure 1. Locations of four glaciers monitored in this study and of the glacier monitored by US Geologic Survey (USGS) within the major hydrologic divides in the North Cascades National Park Complex (Riedel et al. 2008).

Glaciers are a significant resource of the Cascade Range in Washington State. North Cascades National Park contained 312 glaciers that covered 93.56 km^2 in a 2009 inventory (Dick 2013). Glaciers are integral components of the region's hydrologic, ecologic and geologic systems. Delivery of glacial melt water peaks during the hot, dry summers in the Pacific Northwest, buffering 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 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 through 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 that were created by glaciers within the last century. Further, glaciers provide habitat for a number of species, and are the sole habitat for ice worms (*Mesenchytraeus solifugus*) and certain species of springtail anthropods (*Collembola;* Hartzell 2003).

Glaciers are also important indicators of regional and global climate change. At NOCA, glacial extent determined from neoglacial moraines, unpublished maps made by from USGS geologist Austin Post in the 1950's, and a 2009 inventory (Dick 2013) indicate that glacier area has declined ~56% in the last 100 years.

The four NOCA index glaciers monitored by the North Coast and Cascades Network (NCCN) represent varying characteristics of glaciers found in the North Cascades range, including altitude, aspect, and geographic location in relation to the main hydrologic crests (Figure 1). The glaciers selected drain into four major park watersheds and represent a 1000 meter range in altitude from the terminus of Noisy Glacier (1685 m) to the top of Silver Glacier (2705 m).

Glacier monitoring at NOCA has four broad goals:

1. Monitor the range of variation and trends in volume of NOCA glaciers;
2. Relate glacier changes to the 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 to reach the program goals include:

- Collect a network of surface mass balance measurements sufficient to estimate glacier averaged winter, summer and annual balance for all index glaciers.
- Map and quantify surface elevation changes of all index 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 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.

Methods

Mass balance measurement methods used in this project are based on procedures established during 55 years of research on the South Cascade Glacier by the USGS-Water Resources Division (Meier 1961, Meier and Tangborn 1965, Meier et al. 1971, Tangborn et al. 1971, Krimmel 1994, 1995, 1996, 1996a). They are very similar to those used around the world, as described by Ostrem and Stanley (1969), Paterson (1981), and Ostrem and Brugman (1991). Detailed procedures are outlined in Riedel et al. (2008).

Measurement System

We use a two-season stratigraphic approach to calculate glacial mass gained (winter balance) and glacial mass lost (summer balance) on a seasonal basis. Summation of these measurements allows for calculation of the annual mass balance of a given glacier during the course of one water year (October 1-September 30). Measurements of accumulation and ablation are made at around the same time every year in early spring and fall at approximately the same locations. Sampling dates coincide roughly with the actual maximum and minimum mass balances, but may vary due to weather and logistical limitations.

Winter balance is calculated from snow depth and bulk density measurements. Snow depth is measured at five to 10 points at 4-5 fixed stations along the centerline of each glacier resulting in 20-50 measurements per glacier. Snow bulk density is routinely measured at the station that is closest to the mid-point altitude of the glacier. When not directly measured, the average measured density of the spring snowpack since 1993 is used. This value is also compared to values measured independently at snow telemetry (SNOTEL) sites by the Natural Resource Conservation Service and at South Cascade Glacier by the U.S. Geological Survey.

Ablation stakes are used to measure summer balance. Stakes are placed in late April/early May when snow depth is probed to measure the depth of winter accumulation. Measurements of surface level change against the stakes are made in early to mid-summer and in late September to early October on each glacier. The change in ice, snow and firn elevation against the stake, while accounting for changes in the densities of firn and glacier ice, indicates the mass lost at the surface during the summer season (summer balance).

Occasionally, snowpack conditions result in fewer than 5 measurements per station. Commonly this is due to the depth of the snowpack exceeding the length of the snow probes, difficult probing conditions, or the previous summer surface was uncertain. When this occurs, reconstructions of snow depth are determined by summing measurements of snow depths collected during a subsequent site visit with melt observed at stakes since the original spring visit.

Seasonal balances from 2012 were compared to the period record average, 1993-2011 for Noisy, North Klawatti, and Silver glaciers, and 1995-2011 for Sandalee Glacier. Previous period of records are found in Riedel and Larrabee (2013).

Oblique aerial photographs are taken of each index glacier as a record of change in area, surface elevation, equilibrium line altitude, and snow, firn and ice coverage. These color photographs are taken during field visits in early spring and late summer.

Point mass balances are direct field measurements of winter accumulation and summer melt at one location. For both winter and summer balances, the measurement points are typically located at ablation stakes sites. For a single glacier there are 4-5 sites corresponding with the number of ablation stakes (Figures 2-5).

Glacier-wide mass balances are the integration of point mass balance values across the entire glacier surface using area and altitude data taken from base maps. These estimates are necessary to understand glacial meltwater production. Accurate glacier maps are integral to glacier-wide mass balance calculations. The four index glaciers are remapped on a 10-year cycle. The updated reference maps are used for mass balance calculations until the next reference maps are created; they are also used to back-adjust mass balance calculation for five previous years, or the mid-point between the current map and the map from previous cycle (Table 1). As a result, mass balance data remains provisional until the next mapping cycle is completed and all pertinent mass balance calculations have been back-adjusted. New base maps will be completed in 2017.

Table 1. Map years of glacier margin and contour data used for glacier-wide mass balances calculations in this report.

Monitoring years (WY)	Noisy Creek		N. Klawatti		Silver		Sandalee	
	Margin	**Contour**	**Margin**	**Contour**	**Margin**	**Contour**	**Margin**	**Contour**
1993-1999	1993	1993	1993	1993	1993	1993	1996	1996
2000-2012	2009	2010	2006	2006	2004	2004/2005	2004	2006

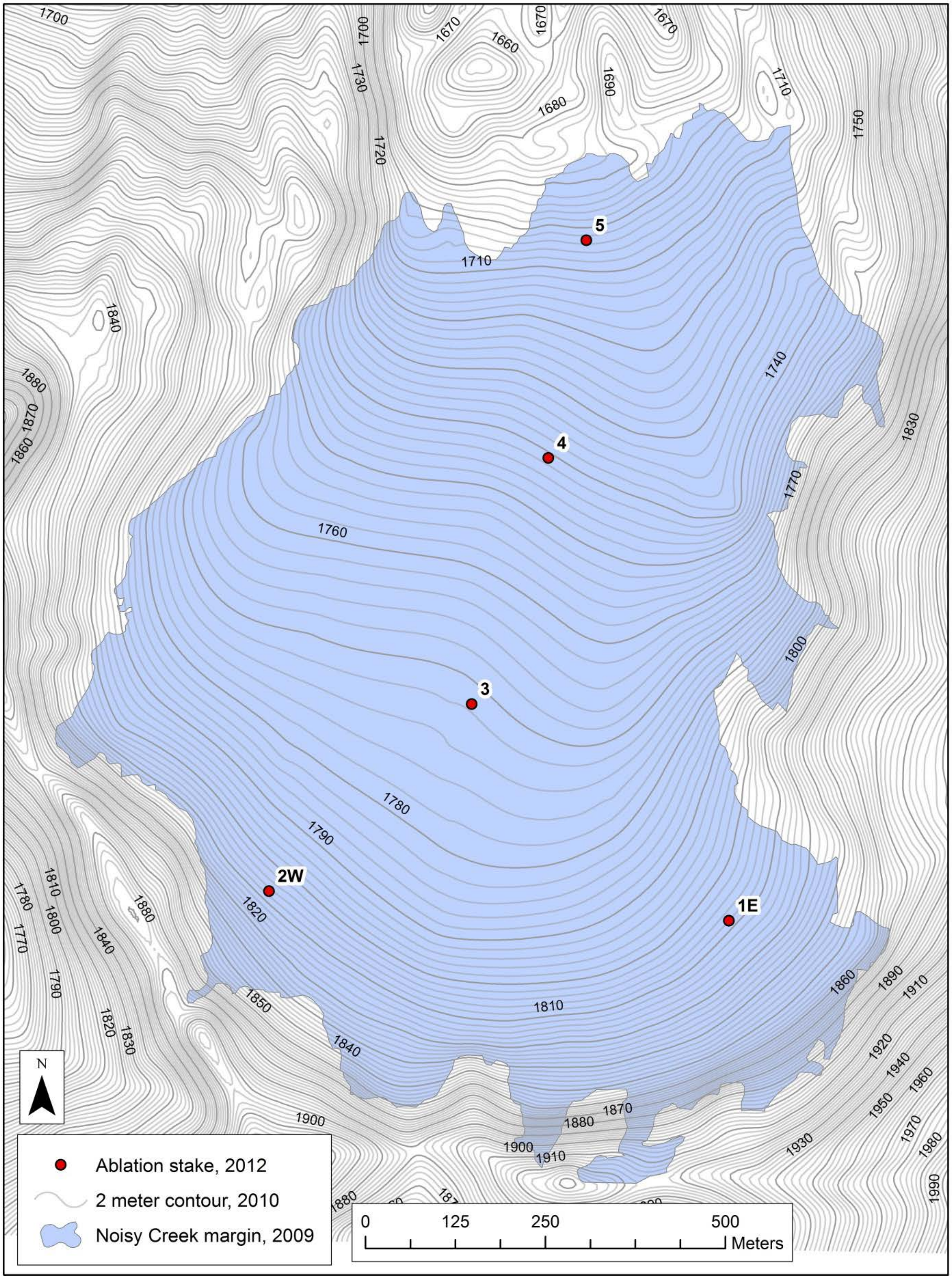

Figure 2. Noisy Creek Glacier with locations of 2012 ablation stakes.

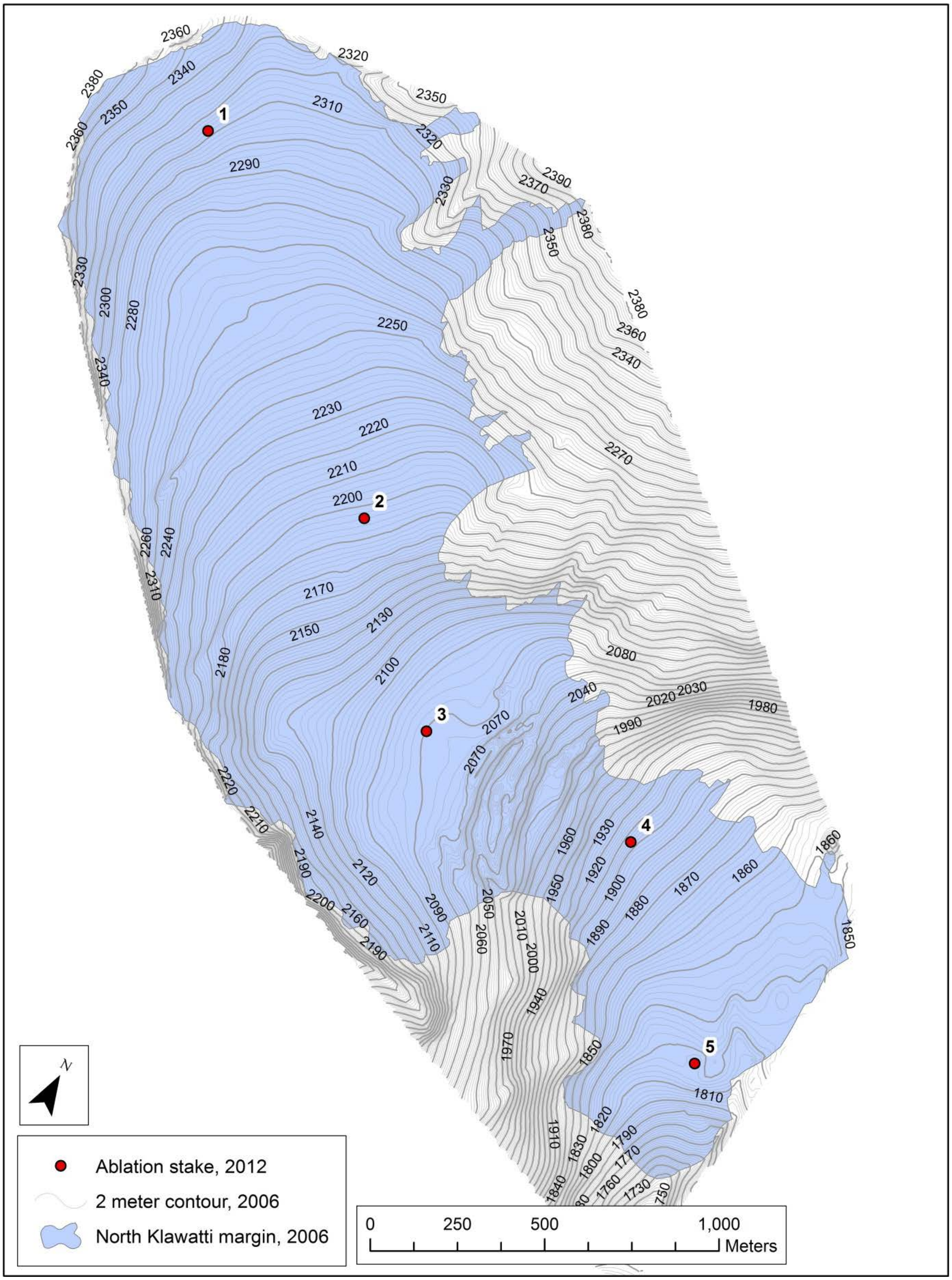

Figure 3. North Klawatti Glacier with locations of 2012 ablation stakes.

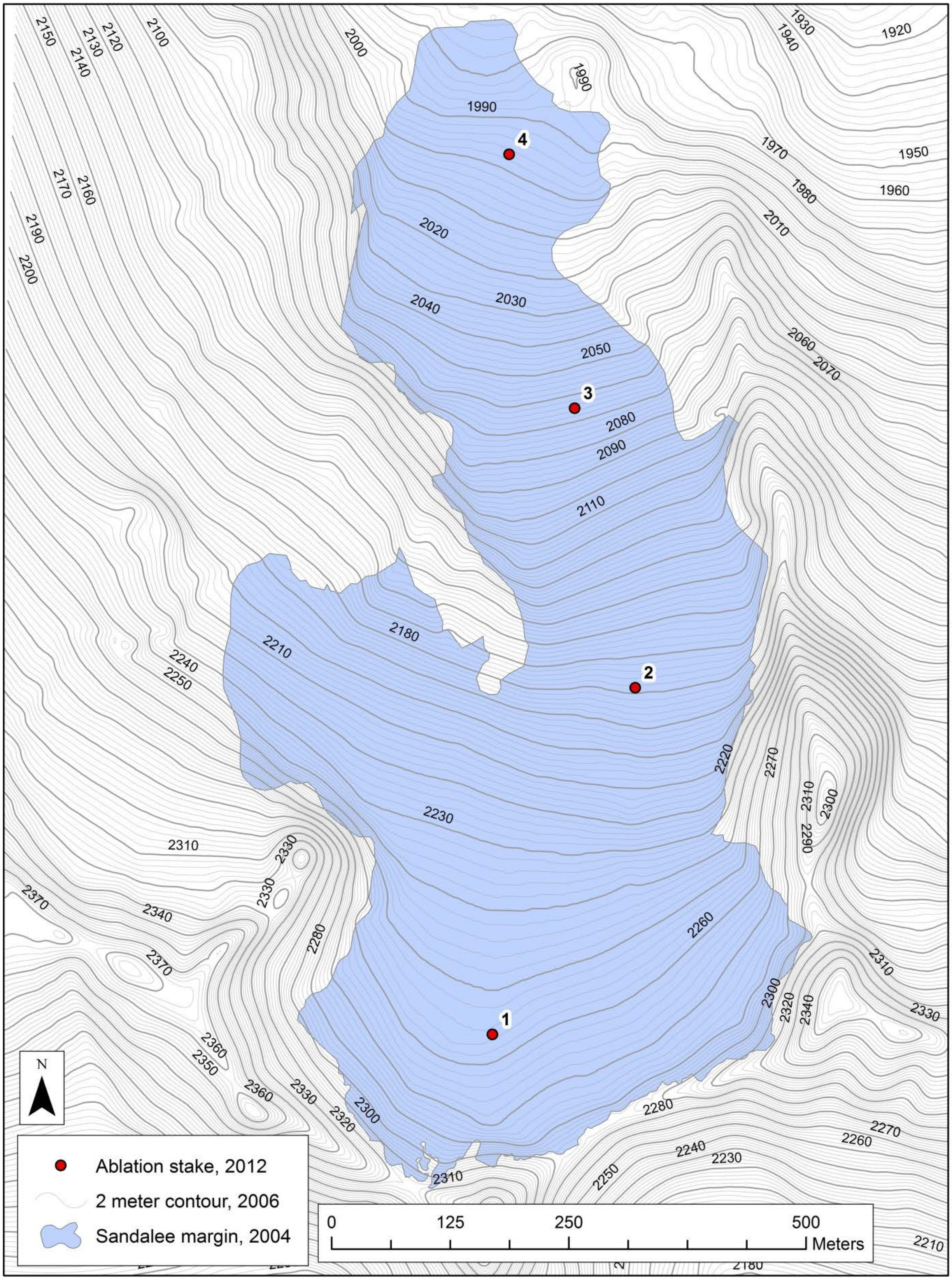

Figure 4. Sandalee Glacier with locations of 2012 ablation stakes.

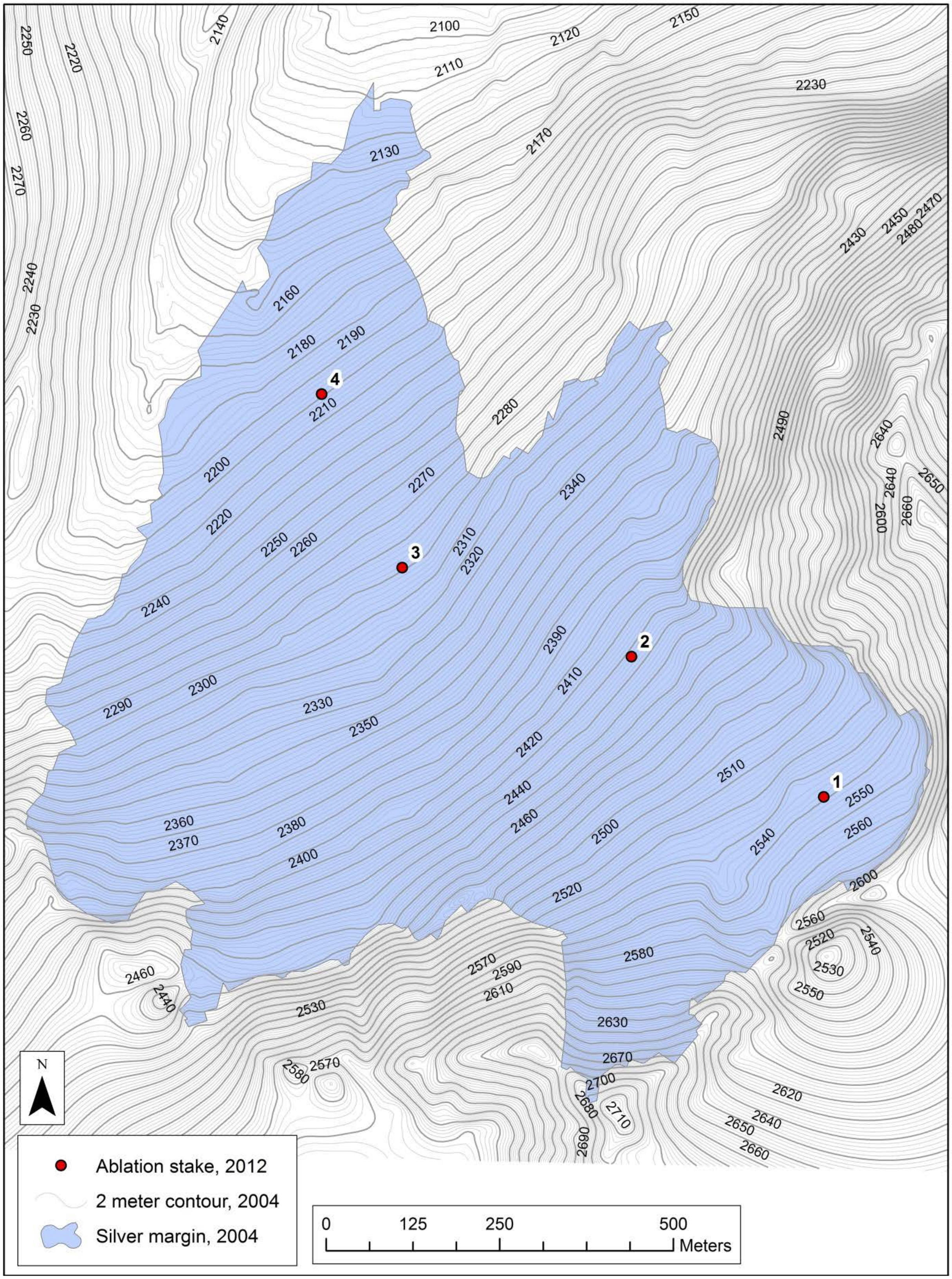

Figure 5. Silver Glacier with locations of 2012 ablation stakes.

Glacier Meltwater Discharge

Glacier contribution to summer streamflow is calculated annually in four park watersheds: Baker River, Thunder Creek, Ross Lake, and Stehekin River (Figure 1). The summer melt season is defined as the period between May 1 and September 30 (Riedel and Larrabee 2016). These dates approximately coincide with winter and summer balance field measurements and the beginning and end of the ablation season. Selection of these dates means that runoff estimates from glaciers include snow as well as firn and ice.

A simple model, based on the strong relationship between summer ablation and altitude, is used to estimate glacier contributions to summer stream flow. Ablation and elevation data are collected from 18 ablation stakes on four glaciers. Data taken at these stakes are used to generate a melt balance curve inferring vertical ablation values along elevation gradient. For 1993 and 1994, prior to monitoring at Sandalee Glacier, the melt balance curve is calculated from the remaining three glaciers. For each glacier, surface area for each 50 meter elevation band is calculated using GIS. The band area is multiplied by the corresponding vertical ablation value, which is derived from the melt balance curve by using the mean elevation of the corresponding band. The resulting values are summed for each watershed. The proportion of glacial meltwater is then determined by comparing it to total summer runoff measured at USGS gage sites on each river.

Results

Measurement Error

Sources of error in glacial 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. Error in mass balance estimates are calculated on an annual, stake-by-stake, and glacier-by-glacier basis. Errors associated with winter, summer, and annual balance estimates in WY 2012 were above the period of record average (POR; Table 2). Annual balance error on Sandalee Glacier was the highest of all four glaciers at ±0.52 m water equivalent (w.e.). This was due to highly variable snow depth caused by avalanche deposits on the glacier surface.

Table 2. Calculated error in meters water equivalent (m w.e.) for water year 2012 mass balance estimates of NOCA index glaciers, with period of record averages in parentheses.

	Average Stake Error (m w.e.)		
Glacier	**Winter Balance**	**Summer Balance**	**Annual Balance**
Noisy Creek	±0.27 (0.20)	±0.27 (0.26)	±0.38 (0.33)
North Klawatti	±0.27 (0.19)	±0.38 (0.31)	±0.47 (0.36)
Sandalee	±0.33 (0.21)	±0.39 (0.27)	±0.52 (0.35)
Silver	±0.29 (0.21)	±0.37 (0.28)	±0.47 (0.35)

Data Quality and Completeness

Winter snow accumulation (henceforth accumulation) was measured on April 23rd at Noisy Creek and North Klawatti glaciers and May 7th for Sandalee and Silver glaciers. The gap in timing was due to poor weather conditions not suitable for safe access to field sites. Snow bulk densities were estimated from period of record averages at 0.50 for Noisy Creek and North Klawatti glaciers, 0.45 for Silver Glacier and 0.44 for Sandalee Glacier.

Reconstructions of winter accumulation had to be made for several stations (Table 2). They included: stakes 1 and 2 at Noisy Creek, stake 3 at Silver, and stake 4 at Sandalee glaciers where snow depth exceeded the length of the snow probe; and, stakes 1-3 at North Klawatti and stakes 1 and 2 at Silver glaciers. The probing conditions were difficult and previous summer surfaces were uncertain, resulting in fewer than 5 measurements per station.

Mid-season field visits as a check on winter accumulation and early summer melt occurred between June 27th and August 30th. Final summer ablation measurements were collected on September 24th and 26th.

Point Mass Balances

Winter accumulation was above the POR average, ranging from 120-137 percent of average (Tables 3 and 4, Figures 6 and 7). Winter balances were generally greatest on index glaciers on the west slope of the North Cascades, with lower values to the east. The summer balances were near the POR average, ranging between 92-109 percent of average. Point annual balances were above the POR average at all stakes, with balances at 18 melt stakes ranging from -2.66 to +1.58 m w.e. Only 4 of 18 stakes had negative annual balances and this was generally elevation dependent, with the lowest stakes on each glacier having negative balances. All stakes on Noisy Creek Glacier had positive annual balances.

Table 3. WY2012 spring snow depth measurements for four index glaciers monitored at North Cascades National Park Complex. Stake elevations based on 2004, 2006, and 2010 reference maps. Average, minimum and maximum values calculated from a series of measurements at each stake. Units are in meters (m).

Glacier	Stake ID	Stake Elevation[1] (m)	Date	WY2012 Average (m)	Min. (m)	Max. (m)	Difference (m)	Std. Dev. (m)
Noisy	1E	1808	4/23	9.22[a]	9.05[a]	9.36[a]	0.31	0.13
	2W	1806	4/23	8.98[a]	8.87[a]	9.08[a]	0.21	0.10
	3	1772	4/23	8.03	7.80	8.25	0.45	0.32
	4	1740	4/23	7.87	7.84	7.90	0.06	0.04
	5	1704	4/23	7.77	7.67	7.86	0.19	0.13
N. Klawatti	1	2312	4/23	8.23[a]	7.52[a]	8.97[a]	1.45	0.54
	2	2196	4/23	8.17[a]	7.75[a]	8.79[a]	1.04	0.35
	3	2080	4/23	8.81[a]	8.48[a]	9.18[a]	0.70	0.35
	4	1916	4/23	6.62	6.33	7.03	0.70	0.36
	5	1828	4/23	6.18	5.50	6.66	1.16	0.48
Sandalee	1	2538	5/7	7.11	6.90	7.19	0.29	0.12
	2	2422	5/7	6.95	6.41	7.69	1.28	0.42
	3	2288	5/7	6.36	5.98	6.98	1.00	0.35
	4	2198	5/7	9.77[a]	8.05[a]	10.71[a]	2.66	0.85
Silver	1	2254	5/7	7.00[a]	6.61[a]	7.55[a]	0.94	0.32
	2	2178	5/7	6.04[a]	5.76[a]	6.35[a]	0.59	0.20
	3	2066	5/7	8.85[a]	7.97[a]	9.75[a]	1.78	0.66
	4	1996	5/7	4.14	3.50	4.47	0.97	0.37

[1] Elevations determined from XY locations on geodetic maps. Map years used: Noisy Creek Glacier = 2010; N. Klawatti = 2006; Sandalee = 2006; Silver = 2004.

[a] Reconstructed from summer or fall snow depth values and stake melt.

Table 4. WY2012 point mass balances for four index glaciers monitored at North Cascades National Park Complex. Units are in meters (m) and meters water equivalent (m w.e.). Period of record (POR) average is calculated from 1993-2011 data (Sandalee 1995-2011). Stake elevations based on 2004/ 2006/ 2010 reference maps.

			Winter Balances (m w.e.)		Summer Balances (m w.e.)		Annual Balances (m w.e.)	
Glacier	**Stake ID**	**Stake Elevation[1] (m)**	**2012**	**POR Average**	**2012**	**POR Average**	**2012**	**POR Average**
Noisy Creek	1E	1808	4.61	3.34	-3.68	-3.54	0.93	-0.19
	2W	1806	4.49	3.41	-3.48	-3.48	1.01	-0.08
	3	1772	4.01	3.02	-3.22	-3.11	0.80	-0.09
	4	1740	3.94	2.83	-3.41	-3.62	0.53	-0.80
	5	1704	3.88	2.89	-3.59	-3.85	0.29	-0.97
North Klawatti	1	2312	4.12	2.89	-2.74	-2.44	1.38	0.45
	2	2196	4.09	3.03	-3.03	-2.73	1.06	0.30
	3	2080	4.40	3.03	-3.08	-3.24	1.32	-0.21
	4	1916	3.31	2.59	-5.37	-4.76	-2.06	-2.17
	5	1828	3.09	2.32	-5.75	-5.12	-2.66	-2.80
Silver	1	2538	3.15	2.55	-1.87	-1.61	1.28	0.94
	2	2422	2.72	2.18	-2.30	-2.27	0.42	-0.08
	3	2288	3.98	2.60	-2.40	-2.33	1.58	0.28
	4	2198	1.86	1.50	-3.22	-3.21	-1.36	-1.71
Sandalee	1	2254	3.13	2.55	-2.36	-2.53	0.77	0.02
	2	2178	3.06	2.79	-2.42	-2.64	0.64	0.15
	3	2066	2.80	2.58	-3.13	-3.33	-0.33	-0.75
	4	1996	4.30	3.11	-3.10	-3.51	1.20	-0.39

[1]Elevations determined from XY locations on geodetic maps. Map years used: Noisy Creek Glacier = 2010; N. Klawatti = 2006; Sandalee = 2006; Silver = 2004.

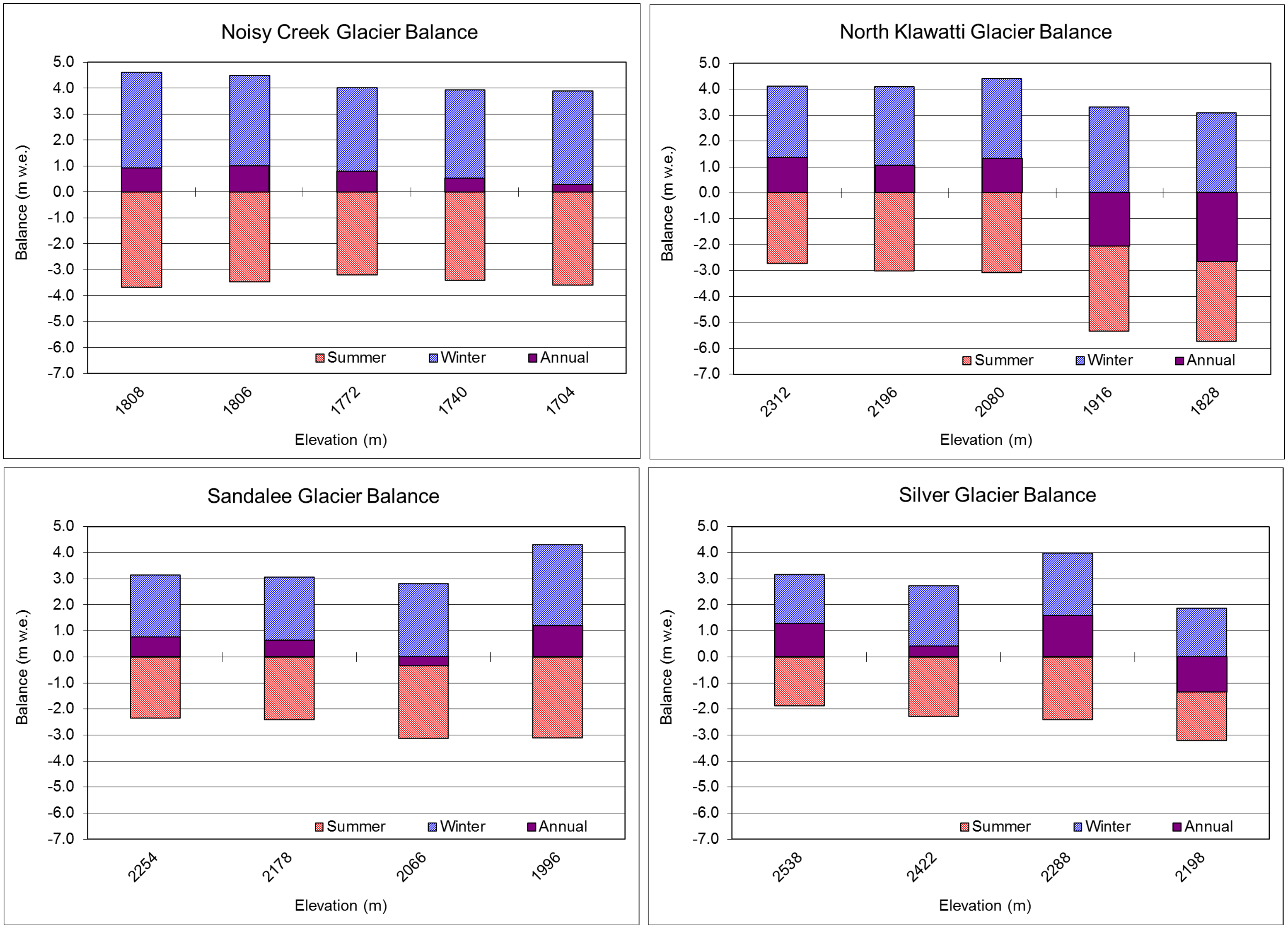

Figure 6. Seasonal and annual point mass balances of four North Cascades National Park Complex index glaciers for water year 2012. Units are in meters water equivalent (m w.e.).

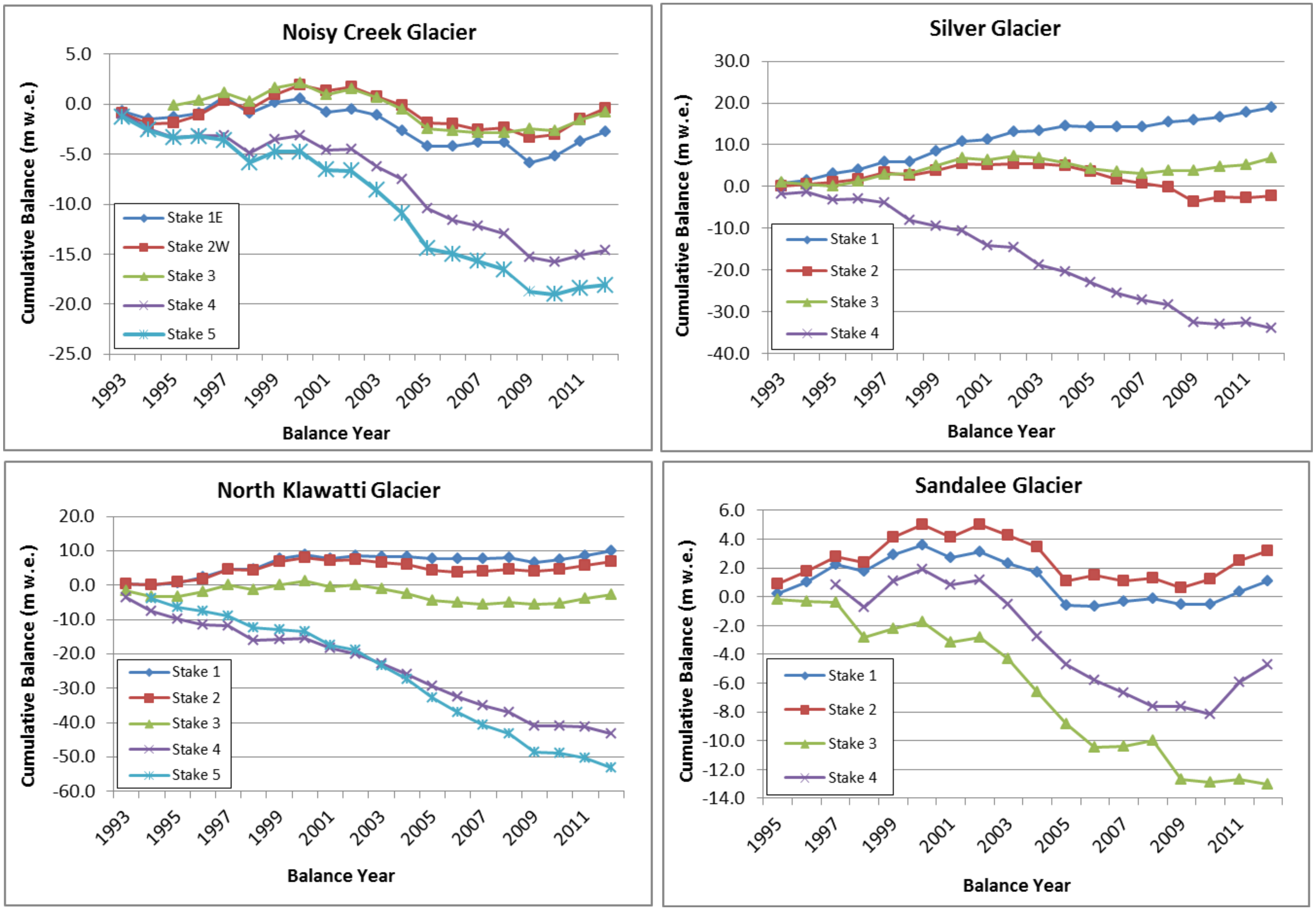

Figure 7. Cumulative point annual (net) mass balances for each of four index glaciers at North Cascades National Park Complex for water years 1993-2012. Units are in meters water equivalent (m w.e.).

Glacier-wide Mass Balances

Glacier-wide winter accumulation was above the POR average, ranging from 122 to 141 percent of average. Winter balances were the second greatest since 1993 for Noisy Glacier and fifth greatest for Sandalee Glacier. Summer melt in WY2012 was near the POR average (99-103% of average) for the three index glaciers located west of the Pacific Crest and below the POR average for Sandalee Glacier (91% of average). Glacier-wide annual mass balances in WY2012 were positive for all four glaciers. This was the second consecutive year with positive annual balances for all four glaciers and the seventh year since 1993. Glacier-wide balances are presented in Table 5 and Figures 8-10.

Table 5. Provisional WY2012 glacier-wide mass balances and equilibrium line altitudes (ELA) for four index glaciers monitored at North Cascades National Park Complex. Units are in meters water equivalent (m w.e.) and meters (m). Period of record average is calculated from 1993-2011 data (Sandalee 1995-2011). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

	Winter Balance (m w.e.)		Summer Balance (m w.e.)		Annual Balance (m w.e.)		ELA (m)	
Glacier	**2012**	**POR Average**	**2012**	**POR Average**	**2012**	**POR Average**	**2012**	**POR Average**
Noisy Cr.	4.22	3.03	-3.42	-3.46	0.80	-0.42	1650	1843
N. Klawatti	3.98	2.83	-3.34	-3.35	0.64	-0.52	2085	2171
Silver	2.93	2.17	-2.44	-2.38	0.49	-0.21	2340	2368
Sandalee	3.30	2.71	-2.60	-2.87	0.70	-0.18	2090	2167

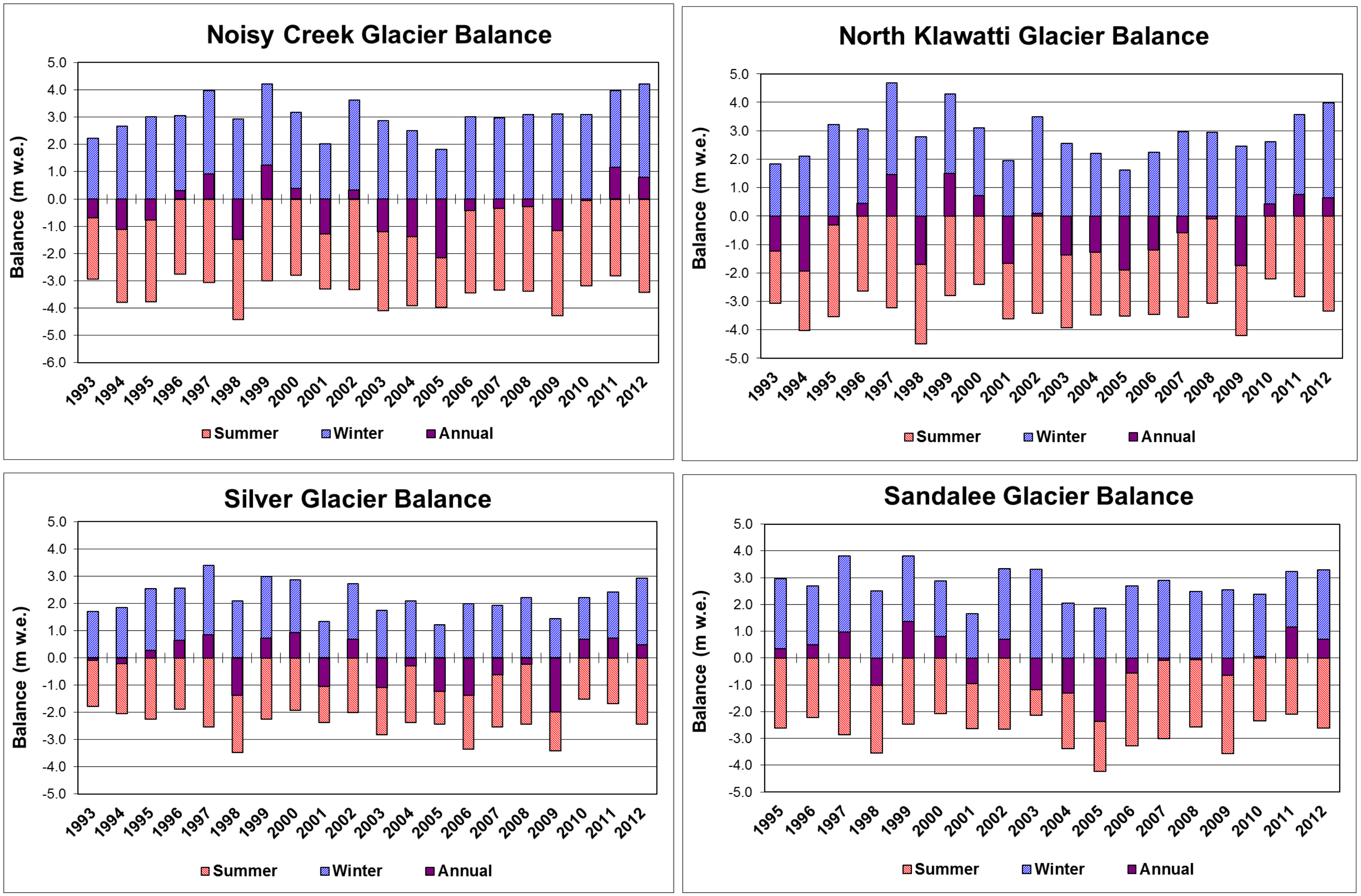

Figure 8. Provisional winter, summer and annual mass balances of four North Cascades National Park Complex index glaciers for water years 1993 to 2012. Units are in meters water equivalent (m w.e.). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

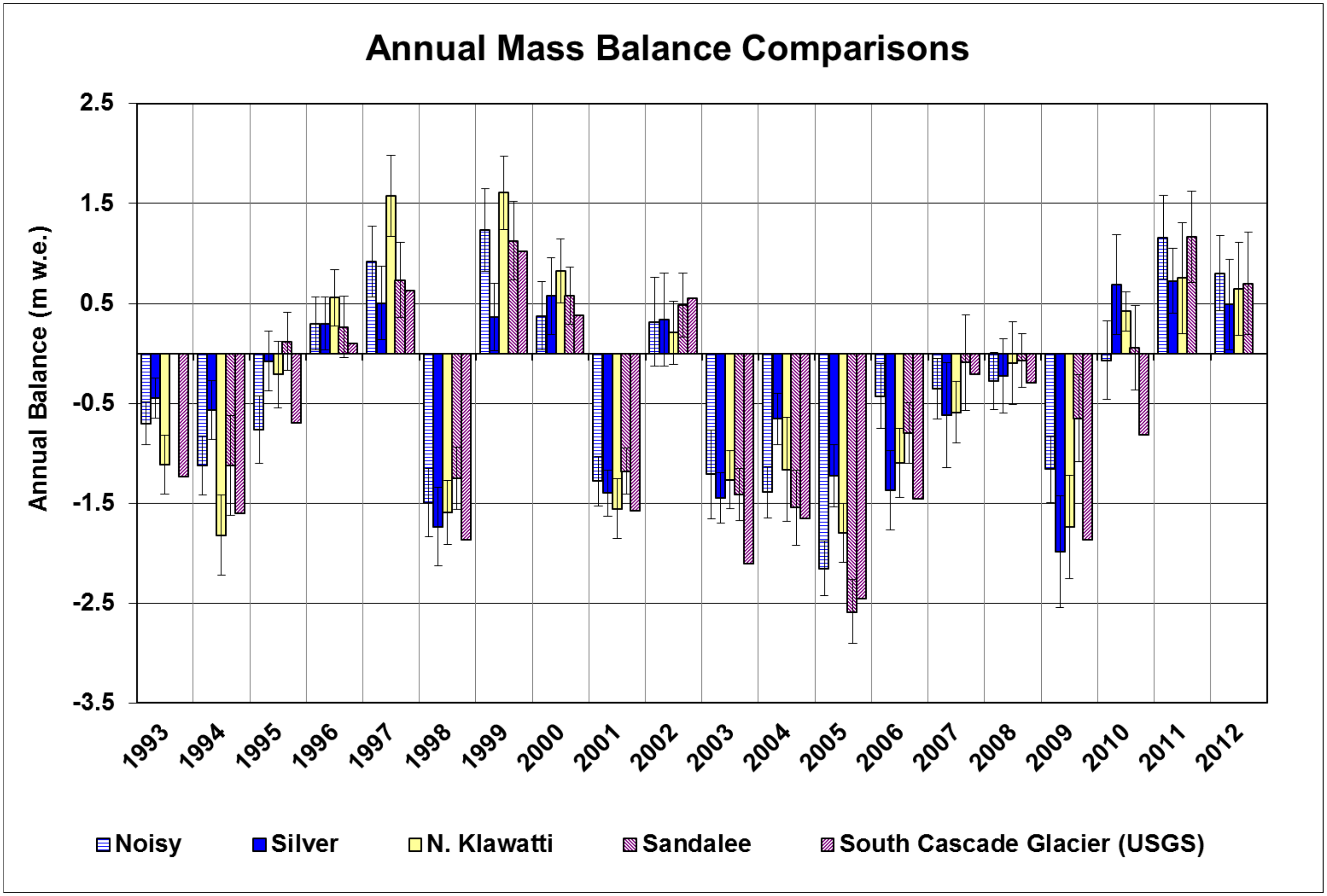

Figure 9. Provisional glacier-wide annual mass balances for each glacier of four index glaciers at North Cascades National Park Complex for water years 1993-2012, compared to South Cascade Glacier (USGS) for 1993-2010. Units are in meters water equivalent (m w.e.). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

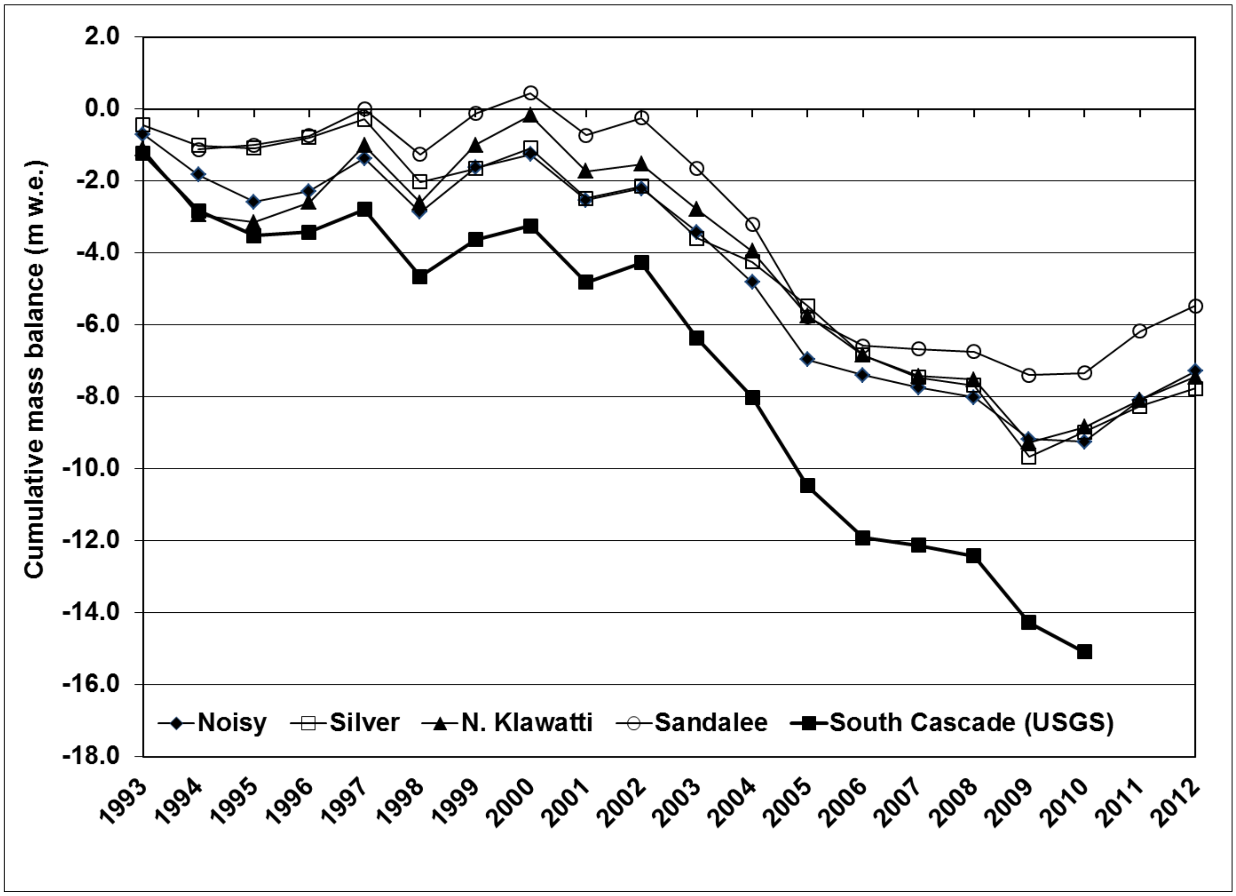

Figure 10. Provisional cumulative balances of four index glaciers at North Cascades National Park Complex for water years 1993-2012, compared to South Cascade Glacier (USGS) for the 1993-2010. Units are in meters water equivalent (m w.e.). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

Glacier Contribution to Streamflow

Glacial contribution to runoff was near the POR average in four NOCA watersheds in summer 2012, contributing an estimated 345 million m^3 of meltwater to streamflow (Table 6 and Figure 11). However, the percent of glacial meltwater to summer streamflow was below the POR average, ranging from 2.4-19.5 percent, due in part to the above the POR average winter snowpack. There is no apparent trend in the total volume of glacial meltwater or percent contribution; this may be masked by inter-annual variability of spring snowpack and summer melt.

Table 6. Provisional glacial contribution to summer streamflow for four North Cascades National Park Complex watersheds. Meltwater contributions are provided for each index glacier and from all glaciers within the watershed. In parentheses is the percent of total watershed area that is glaciated. Period of record (POR) average, minimum and maximum values are calculated from 1993-2011 data (Sandalee 1995-2011). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

		May-September Runoff (million cubic meters)				Percent Glacial of Total Summer Runoff			
Watershed	**Site (% area glaciated)**	**2012**	**POR average**	**POR min.**	**POR max.**	**2012**	**POR average**	**POR min.**	**POR max.**
Baker River	Noisy Creek Glacier	1.6	1.7	1.3	2.4	–	–	–	–
	All glaciers (4.1%)	107.5	104.6	72.0	132.2	8.0	11.3	6.7	17.2
Thunder Creek	North Klawatti Glacier	4.9	4.8	3.1	6.7	–	–	–	–
	All glaciers (12.2%)	102.4	99.8	70.4	127.2	23.6	26.7	17.4	40.6
Stehekin River	Sandalee Glacier	0.5	0.5	0.4	0.8	–	–	–	–
	All glaciers (2.4%)	61.6	60.1	42.3	76.6	5.5	7.2	4.1	15.8
Ross Lake	Silver Glacier	1.0	1.0	0.6	1.7	–	–	–	–
	All glaciers (0.8%)	73.4	71.9	49.7	91.4	3.2	5.0	2.3	12.3

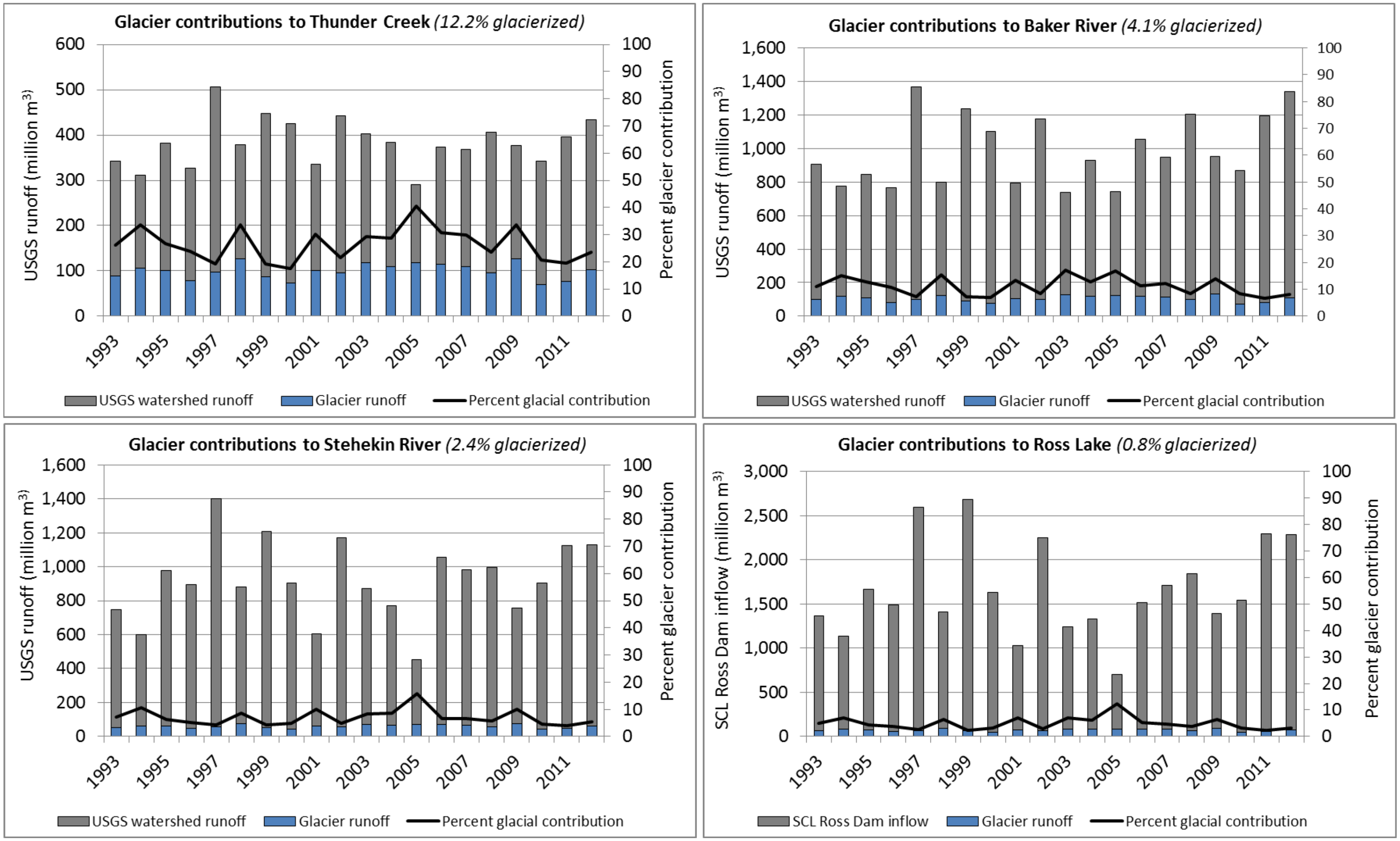

Figure 11. Provisional total May-September glacier meltwater contributions for the four watersheds containing glaciers monitored by the North Cascades National Park Complex. Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

Aerial Imagery

Oblique photographs of three index glaciers are shown in Figures 12-14 as records of change in area, surface elevation, equilibrium line altitude, and snow, firn and ice coverage.

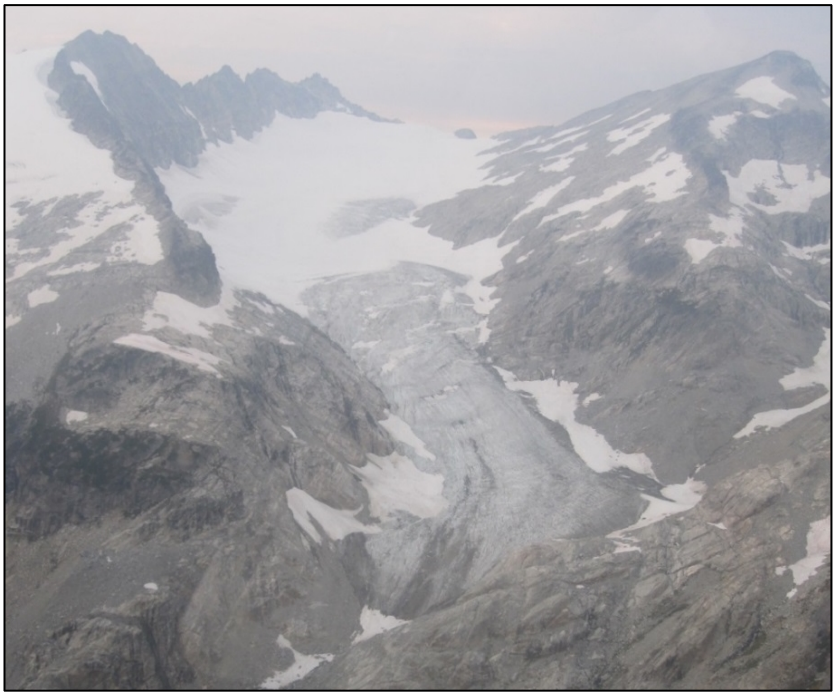

Figure 12. North Klawatti Glacier from east, September 26, 2012.

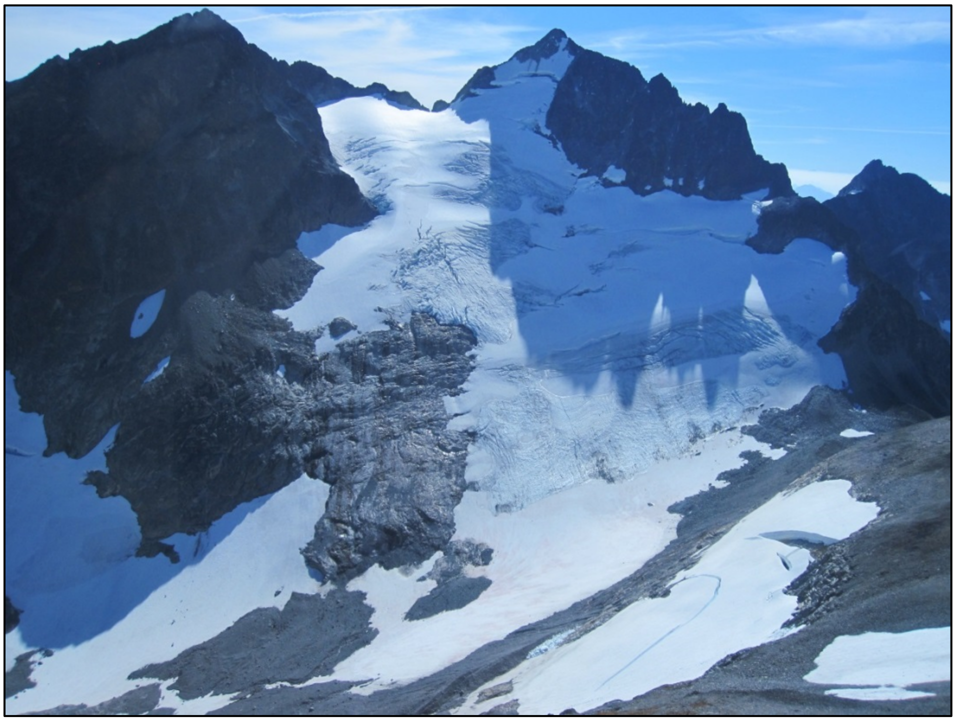

Figure 13. Silver Glacier from north, September 26, 2012.

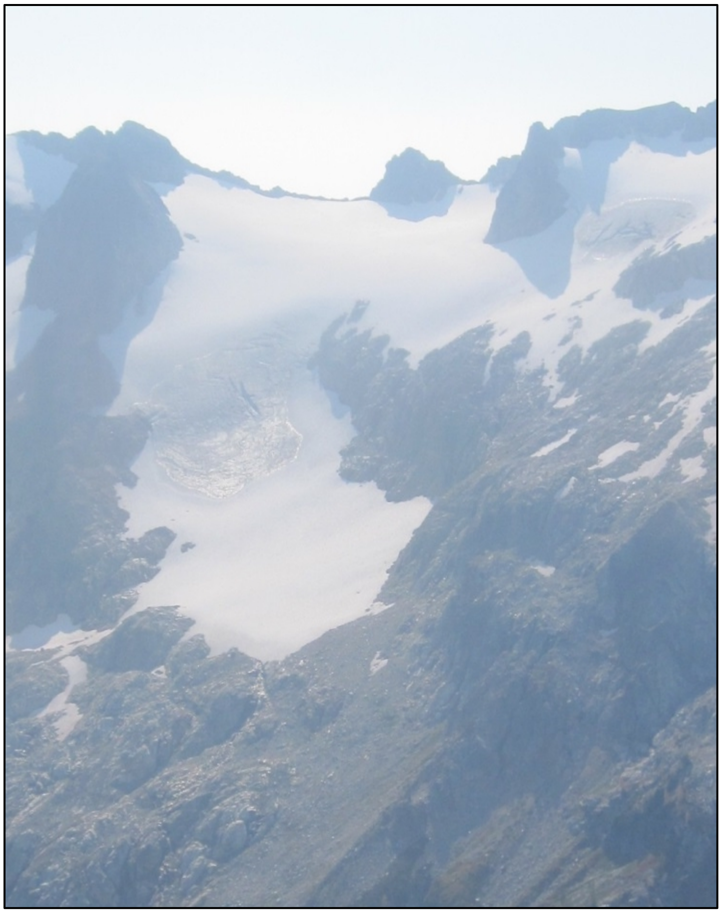

Figure 14. Sandalee Glacier from north, September 24, 2012

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