NOOKSACK RIVER WATERSHED
GLACIER MONITORING SUMMARY REPORT
2015

Prepared For:

Nooksack Indian Tribe

Contributors:

Jezra Beaulieu	Water Resources Specialist
Oliver Grah	Water Resources Program Manager

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Contents

1. INTRODUCTION

Trends in climate change since the 1900's suggest that a warmer climate will occur with wetter falls, winters, and springs, but drier summers. Rainfall with greater intensity will likely become more dominant in the mountainous areas. More intense rainfall on areas usually covered and protected by snow and glaciers will be more prone to erosion, entrainment, and transport to streams thereby increasing sediment loads. Further, as glaciers recede unstable over-steepened hillslopes will be more vulnerable to mass failure, also due to increased rainfall intensities on such areas. Glaciers and summer melt in the Nooksack River watershed that support summer flows that are critical to salmonids have been shown to be receding and losing volume. Recent studies suggest glaciers have diminished in size today to their smallest extent in the last 4000 years (Pelto 2015). According to Pelto (2015), the mass balance loss in 2015 is the largest of the last 32 years in the North Cascades with losses average over 3 meters water equivalent. There is evidence that the valley glaciers on the north side of Mount Baker have receded approximately 1,000 feet just in the last 20 years. In addition, substantial thinning and loss of volume have also occurred due to climate change. These trends transform into changes in the hydrology, thermal regime and sediment dynamics of the Nooksack River. Decreased snow accumulation on the glaciers and loss of glacier melt translates to decreased summer flows and higher water temperatures that may be adverse to reproduction and approach lethal levels to salmonids. Grah and Beaulieu (2015) discuss the jmplications of climate change and fish survival to members of the Nooksack Indian Tribe. Changed sediment dynamics will likely involve an increased sediment loading of the river from increased exposure and entrainment of sediment from the surface and interior of melting/receding glaciers, and removal of mass loading at the base of steep colluvial slopes covered by a thin veneer of glacial ground moraine that becomes unstable and prone to slides as the glacier retreats. Based on these trends and modeling of climate, more pronounced changes in climate are anticipated in the future. Such climate changes will further adversely impact the Nooksack River in regard to available water, altered hydrographs and sediment dynamics, as well as suitable fish habitat and fish survival. As such, there is a real need to more accurately evaluate the hydrology, water temperature and sediment dynamics of the upper Nooksack River basin under today's conditions and more importantly in the future under various accepted climate change scenarios. Thus, establishing an adequate baseline of conditions today is fundamental to detecting change in conditions in the future with continued and projected climate change.

Understanding how the river's hydrology and sediment dynamics may change with future climate change is vital to management and protection of these fish that the Nooksack Indian Tribe and Lummi Nation rely on. As indigenous Tribal groups are place-based and cannot migrate to new areas where salmon will survive, understanding the likely impacts of climate change, and ensuring that actions are implemented now to perpetuate these species in the Nooksack River basin, will be particularly important for the cultural survival of these groups. The hydrology and sediment dynamics of the Nooksack River basin is of great interest to many users and interest groups including members of the Nooksack Indian Tribe, Lummi Nation, agricultural, residential, and industrial users, and those agencies responsible for managing water resources within the Nooksack River basin including Whatcom County, the City of Bellingham, Washington Department of Ecology, City of Lynden, City of Ferndale, and Public Utility District No. 1. Recent climate change trends and future climate change scenarios suggest that altered streamflow and sediment dynamics will adversely impact all of these users. Not only will changed sediment dynamics impact fish habitat and survival, increased sediment loads will adversely impact water withdrawal for irrigation, industrial, and municipal uses. These impacts will exacerbate existing and future legacy impacts caused by land management. Of particular interest to the Nooksack Indian Tribe and Lummi Nation is how changes in flow and sediment dynamics will effect survival of salmonids in the Nooksack River that both groups rely on for subsistence, cultural, ceremonial, and commercial uses. Thus, there is a need to address the impacts of climate change on glacier ablation, the hydrology and sediment dynamics of the Nooksack River basin, and associated impacts on fish habitat (vulnerability assessment), and inform managers and those involved with habitat restoration on how to effectively address the needs of salmon in the face of climate change.

This project focuses on evaluating existing or baseline conditions against which changes in climate and glacier behavior can be detected. Further, it is fundamental to project the effects of climate change on glacier melt contribution to streamflow, stream temperature and sediment dynamics of the Nooksack River, and subsequent effects on salmonid habitat. The results of this project will have direct management application in regard to addressing hydrologic change in the face of climate change (salmon vulnerability assessment) and how to develop and/or prioritize restoration tools (adaptation plans) that facilitate survival of salmonids in the Nooksack River. This project will eventually perform a salmon and habitat vulnerability assessment and develop an adaptation plan that includes restoration actions that address the impacts of continued climate change. This work will be integrated with the work funded by our existing BIA FY2015 Climate Change grant, EPA-NEP Capacity Building Grant, Northwest Indian Fisheries Commission grant, North Pacific Landscape Conservation Cooperative grant, and EPA Performance Partnership Grant programs. The vulnerability assessment process and the adaptation plan will have direct use by the Lummi Nation and will serve as a template for other Puget Sound Tribes to use in addressing the impacts of climate change on glacier ablation, river hydrology, sediment dynamics, and fish support. We recently completed work with the EPA Research and Development office (Steve Klein, Research Scientist) in Corvallis, OR, to develop the qualitative methodology to identify existing stressors, interpret likely climate change impacts, evaluate existing salmon habitat restoration plans, and develop new restoration priorities that will provide the base information for the vulnerability assessment and adaptation planning in response to climate change (US-EPA 2015). An adaptation plan included in the qualitative assessment will support restoration planning in the face of climate change. This salmon vulnerability assessment, adaptation plan, and fish habitat restoration planning project will serve as a pilot that can be applied in similar watersheds with similar limiting factors by other Tribes such as Lummi Nation, Stillaguamish, Sauk-Suiattle, Upper Skagit, Snoqualmie, Nisqually, Quinault, Hoh, and Lower Elwha Tribes.

The purpose of the original pilot project was to become familiar with methodology for assessing the glacier melt contribution to the Nooksack River, its effect on the physical habitat of salmonids (i.e., discharge and stream temperature), and its projection with continued climate change. We accomplished this on a small scale by establishing baseline characteristics of summertime flow and temperature in the Sholes Glacier outlet stream, collecting snow depth measurements and calculating ablation rates on the Sholes Glacier, and collecting stream samples from glaciated streams and springs in the Nooksack River watershed for isotopic analysis. The project was a success although more work than initially planned. Originally the project identified multiple glaciers to be monitored during the study period, however that proved to be difficult due to access, transportation, staffing, and funding and scheduling conflicts. Subsequently, the main focus in 2013 and 2014 was the Sholes Glacier and Bagley Creek as paired watersheds that would be used for comparison. In 2014, three glaciers were monitored for the purpose of this project: Hadley Glacier, Heliotrope Glacier and Sholes Glacier. In addition to monitoring glacier ablation, snow depth, streamflow, stream temperature, and isotopic composition of glacier melt, the project in 2014 monitored turbidity of stream water and collected samples for suspended sediment concentration analysis to show the relative difference of turbidity and sediment discharge in glacier fed streams and snowmelt fed streams. In 2015, only Sholes Glacier and Hadley Glacier were monitored, with paired non-glacial tributaries Bagley Creek (for Sholes Glacier) and Dobbs Creek (for Hadley Glacier). Glacier ablation, snow depth, streamflow, turbidity, suspended sediment, stream temperature and isotopic composition were studied in 2015. In addition to field visits, a weather station was installed at Sholes Glacier to continuously monitor air temperature, precipitation, solar radiance, humidity, and turbidity. A continuous turbidimeter was also installed at Hadley Glacier. In addition to these field studies, we contracted University of Washington and Western Washington University to jointly model glacier ablation and altered hydrology of the Nooksack River and tributary streams with projected future climate change (Murphy 2015). Further, we conducted an inventory of mountainous areas prone to mass failure and an assessment of recent glacier retreat from a series of aerial photos (Nielsen 2015, See Appendix C).

2. STUDY AREA

2.1 Nooksack River Watersheds

The Nooksack River originates on the western slopes of the Cascades Mountains in northwestern Washington State and drains about 832 square miles (Figure 2.1). Most of the watershed is located within Whatcom County, although portions of the watershed extend northward and into British Columbia and southward into Skagit County. The watershed is the largest drainage (62 percent by area) within Water Resource Inventory Area (WRIA) 1 and supports the greatest abundance of salmonids within the WRIA1 geographic area (WRIA 1 SRB 2005). Three major forks form the Nooksack River: the North Fork, Middle Fork, and South Fork Nooksack rivers. There are approximately 148 glaciers and glacierets in the Nooksack River watershed and cover approximately 15.8 square miles.

The North Fork Nooksack River (NFN) is the largest tributary to the mainstem Nooksack River, originating from the East Nooksack Glacier on the north side of Mt. Shuksan and draining about 281 square miles. The North Fork ranges in elevation from approximately 10,781 feet on Mt. Baker to approximately 236 feet at the confluence with the South Fork Nooksack River (SFN). The watershed ranges from rainfall driven hydrology at the lower elevations, rainfall-snowmelt transition at the mid-elevations, and snowmelt dominated at the higher elevations above 5,000 feet. However, most of the watershed falls within the rainfall-snowmelt transition, and snowmelt driven hydrologies. The river length is approximately 38 miles to the confluence with the South Fork Nooksack River, transporting snow melt and glacial meltwater, and rainfall to the Nooksack River and eventually to Bellingham Bay and the Salish Sea. Average annual precipitation is 100 inches in the higher reaches of the watershed, with average annual discharge 796 cubic feet per second at the USGS Stream Gage on the NFN below Cascade Creek, near Glacier, WA which is upstream of several large tributaries (Baldwin et. al 2002). The watershed is predominantly forested, with glaciers, ice fields, permanent snowfields, alpine tundra, and talus covering elevations above 5,000 feet; while most areas below 5,000 ft in the NFN watershed are forested. There are approximately 12.0 square miles of glaciers and glacierets in the NFN river watershed. The numerous glaciers in the upper watershed augment late season stream flows from melt water. Lowland areas on the valley bottom lands are used for small communities, plantations, hobby farms and recreational facilities. A relatively small number of lakes are present in the NFN watershed. Silver Lake (in the Maple Creek Valley) and Sprague and Kendall Lakes (in the Columbia Valley) are located in glacial outwash valleys trending south from the Canadian Border and draining south to the NFN. There are numerous alpine lakes that occupy glacial cirques in the higher elevation areas. Both valleys have extensive wetlands and hydraulically connected shallow aquifer systems. Outside these systems, wetlands in the NFN watershed are hydraulically linked to the main channel of the NFN. Bagley and Chain Lakes and numerous alpine lakes, located higher in the watershed, are not accessible to anadromous fish due to Nooksack Falls and other fish migration impediments. Because these lakes and wetlands are not providing habitat for priority fish species targeted for recovery actions, they are not the focus of Nooksack Natural Resources Department water temperature monitoring and assessment activities.

The Middle Fork Nooksack River (MFN) watershed is 101 square miles in area, ranging in elevation from approximately 10,781 feet on Mt. Baker to approximately 280 feet at the confluence with the NFN. The total river length is about 20 miles. The watershed ranges from rainfall driven hydrology at the lower elevations, rainfall-snowmelt transition at the mid-elevations, and snowmelt dominated at the higher elevations above 5,000 feet. However, most of the watershed falls within the snowmelt driven hydrology area. The average annual flow measured at USGS Stream Gage on the MFN near Deming is 525 cubic feet per second (Baldwin et. al 2002). There are approximately 3.3 square miles of glaciers and glacierets in the NFN river watershed. Glacial melt from the Deming Glacier and Thunder Glacier on Mt. Baker supports MFN late summer seasonal flows, while flows during the late fall, winter, and spring are supported by snowmelt and rainfall at lower elevations. A water diversion dam operated by the City of Bellingham is located at river mile eight, where water is diverted through a pipeline to Lake Whatcom. Water drawn from the Lake Whatcom provides municipal supply for the City of Bellingham. The diversion dam is currently being considered for redesign and refurbishment to allow fish passage to unoccupied effective fish habitat. Diversion from the river is the subject of ongoing negotiations to establish and maintain adequate instream flows to support recovery of Endangered Species Act (ESA) listed salmon in the Nooksack River watershed and to provide fish passage to upstream sections of the river above the diversion dam. The lower MFN watershed includes Mosquito Lake, Jorgenson lakes, and an extensive wetland system. These drain to the MFN near river mile five. Other wetlands are associated with the river channel and associated flood plains and side channels of the main MFN along the lower five river miles.

The South Fork Nooksack River (SFN) originates on the south east side of the snow-dominated Twin Sisters Mountain Range, Loomis Mountain, and Park Butte on the east side of the upper watershed. The watersheddrains about 164 square miles before joining the NFN at river mile 36.6. The total river length is about 50 miles. Elevation ranges from approximately 7,000 ft on the Twin Sisters Range to approximately 236 feet at the confluence of the NFN and SFN rivers. There are no longer active glaciers on the Sisters Range; however, vestigial ice, or glacierets remain covering only 0.4 square miles. The watershed ranges from rainfall driven hydrology at the lower elevations to rainfall-snowmelt transition at the mid-elevations, with a small area of snowmelt dominated at the higher elevations above 5,000 feet. However, most of the watershed falls within the rainfall and rainfall-snowmelt transition driven hydrology area. The river has an average annual flow of 1104 cubic feet per second measured USGS South Fork Nooksack River at Saxon Road Bridge (Baldwin et. al 2002). Base flow during the summer is supported by a small amount of melting ice but predominantly groundwater inflow. Late fall, winter, and spring flows are provided by rainfall and snowmelt. The lower valley (below river mile 13) is a wide, glacially carved, flat glacial outwash valley with steep walls. The valley floor has an extensive wetland system, and houses a number of dairy farming operations, berry fields, and Christmas tree plantations.

Downstream of the SFN confluence, the Nooksack River flows approximately 37 miles to Bellingham Bay in the Salish Sea. The Lummi River is a largely disconnected distributary of the Nooksack River that flows to Lummi Bay. The mainstem Nooksack River average annual discharge at North Cedarville Road USGS gage is 3,839 cubic feet per second and the discharge for the Nooksack River at Ferndale USGS gage is 3,863 cubic feet per second. The Lummi River only receives surface water from the Nooksack River when the Nooksack River flows exceed approximately 9,600 cubic feet per second. The Sumas River is also a distributary channel of the mainstem Nooksack River that flows north to the Fraser River in Canada. Land use in the lower Nooksack River, Sumas River, and Lummi River subbasins is predominantly agriculture (55-58 percent), with some forested uplands (25-28 percent) and development (8-12 percent) (Coe and Cline 2009)

The Nooksack River watershed supports nine Pacific salmonid species, including populations of Chinook (spring and fall), sockeye, chum, pink, and Coho salmon, steelhead/rainbow, cutthroat, and bull trout, and Dolly Varden. Nooksack early (or “spring”) Chinook Salmon hold great cultural, subsistence, and economic importance to the Tribe. The abundance of both early Chinook Salmon populations (North Fork/Middle Fork early Chinook Salmon, South Fork Nooksack early chinook salmon) is critically low, on the order of 100-300 natural-origin spawners for each population. The populations comprise two of 22 independent populations in the Puget Sound Chinook Salmon Evolutionarily Significant Units (ESU), which are listed as threatened under the Endangered Species Act (ESA); both populations are considered essential for recovery of the ESU (WDFW 2002). Nooksack bull trout and steelhead are components of the Coastal/Puget Sound Bull Trout Distinct Population Segment (DPS) and Puget Sound Steelhead DPS, respectively, both of which are also listed as threatened under the ESA. It is clear that abundances of several local salmonids populations have diminished substantially from historic levels, as only two of 16 salmonid stocks identified by Washington State Salmonid Stock Inventories are currently considered healthy (WDFW 2002). Fish stocks today are less than 10 percent of the historical capacity and for the two Nooksack River populations of spring Chinook, the current populations are 0.8 percent and 1.8 percent of the estimated historical levels in the late 1800’s (Nooksack Indian Tribe, et. al. 2005; Lackey 2000).

2.2 The Glaciers of Mount Baker

As indicated previously, there are approximately 148 glaciers and glacierets in the Nooksack River watershed covering an area of 15.8 square miles. Approximately 12.o square miles occurs in the NFN, 3.3 square miles in the MFN, and only about 0.4 square miles in the SFN watersheds. The Sholes, Hadley and Heliotrope Glaciers were originally selected for this project due to their relatively easy and safe access, simple hypsometry, and well-defined outlet streams (Figure 2.2). However, in 2015, we dropped the Heliotrope Glacier from our field studies because it did not have a well-defined watershed and had several outlet streams making meaningful stream measurements difficult. Also, the Heliotrope Glacier was

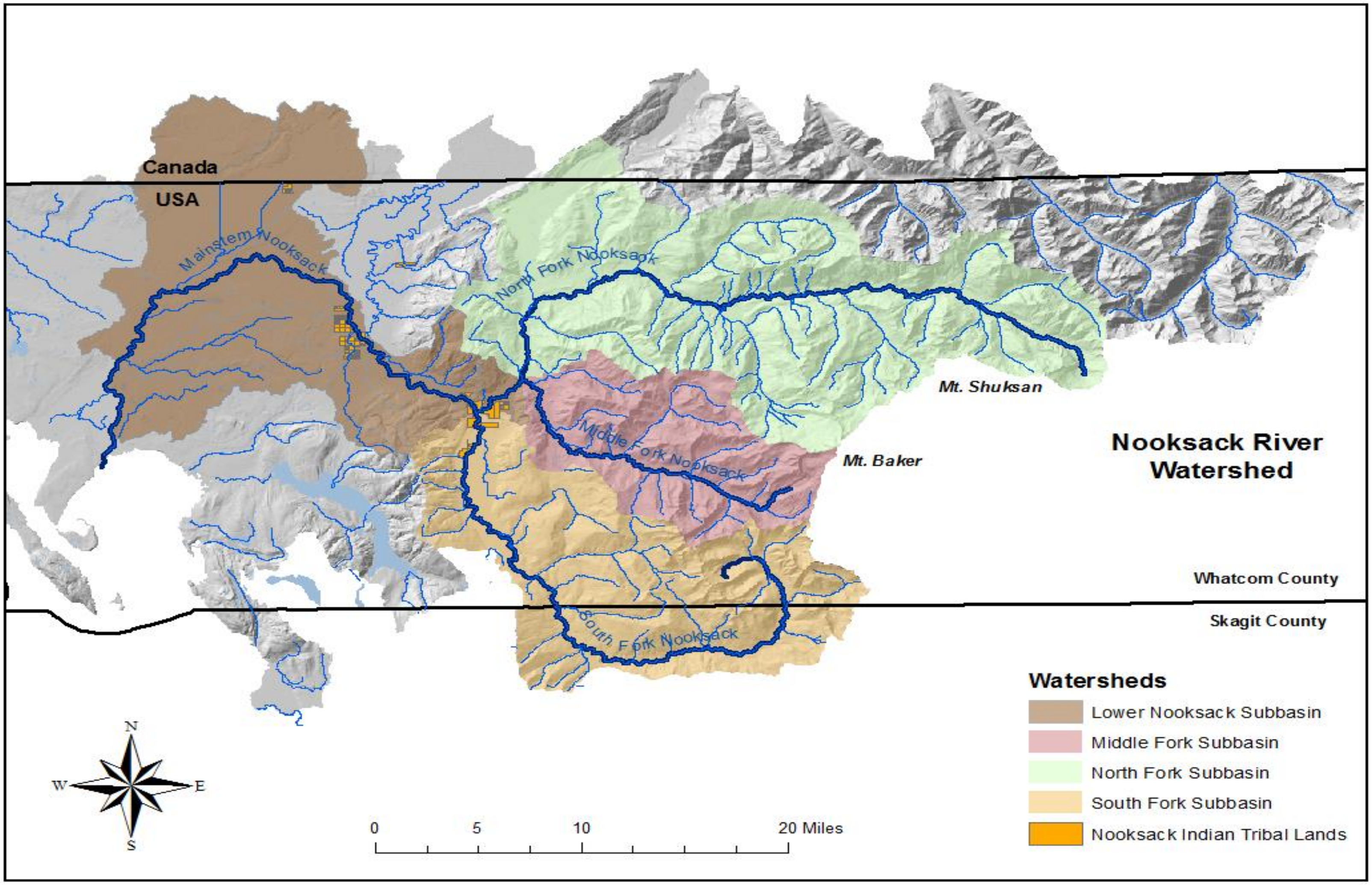

Figure 2.1 Regional location of the Nooksack River watershed and Nooksack Indian tribal lands.

somewhat of a duplication of the Sholes Glacier and thus to conserve time and budget, dropped the glacier from our filed studies. The PHOTO LOG presents photos of the two glaciers studied for this report. The Sholes Glacier has mass balance and stream runoff records dating back to 1990, when the North Cascade Glacier Climate Project (NCGCP) began monitoring the glacier annually. The Hadley Glacier was monitored in 2014 and again in 2015. Dobbs Creek was also monitored for this study as it is a predominantly snow-fed drainage that is adjacent to Hadley Creek and serves as a valuable comparison site (paired watersheds in close proximity). Similarly Bagley Creek serves as a comparison creek to Sholes Glacier, although it is a few drainages to the northeast of Sholes Creek.

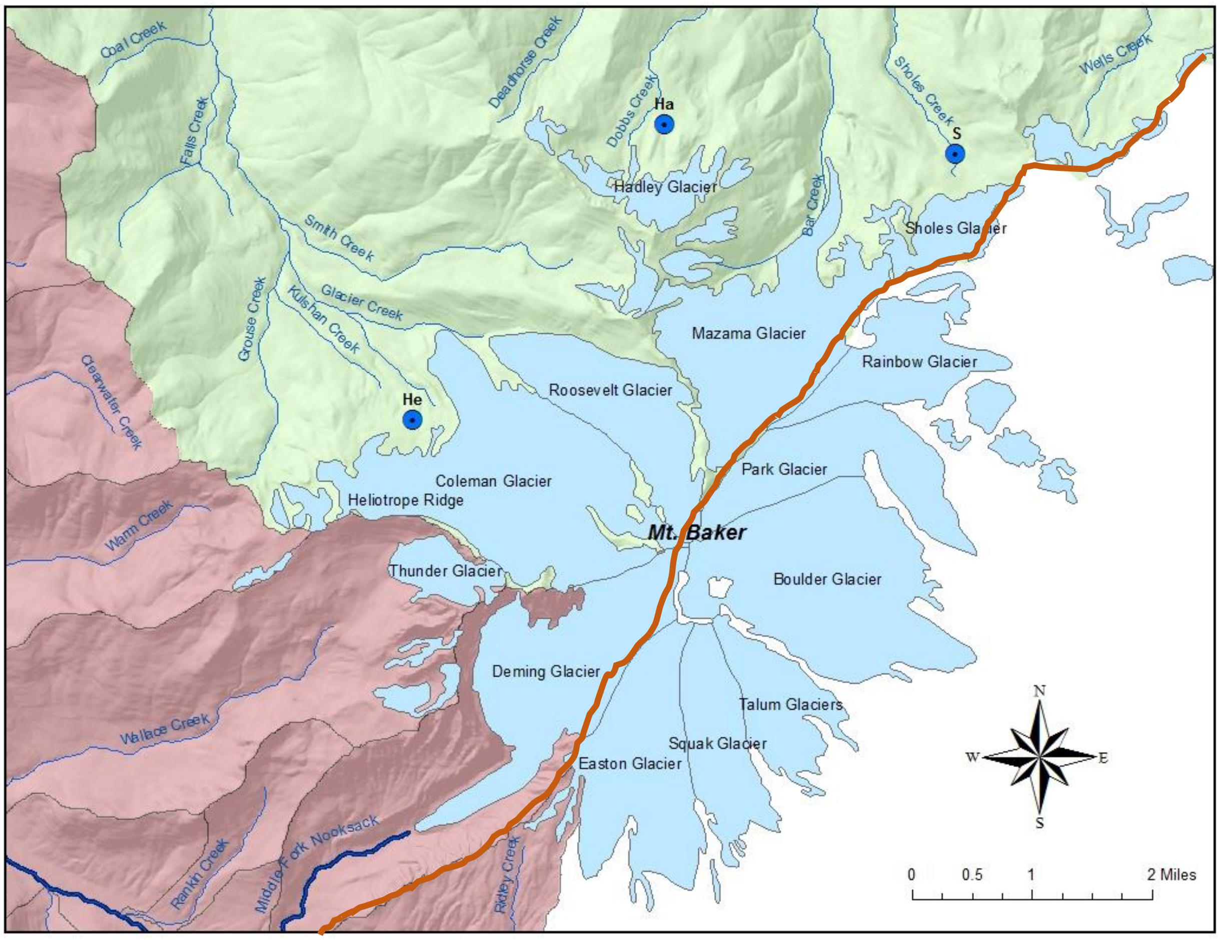

Figure 2.2 The glaciers of Mount Baker and field site locations (blue dots). Sholes Glacier = S, Heliotrope Glacier = He, Hadley Glacier = Ha. The orange line indicates the watershed divide between Nooksack River watershed to the Northwest and the Skagit River watershed to the Southeast.

2.3 Glacier Recession

Glaciers in the Nooksack River watershed have advanced and receded since the end of the ice age approximately 12,000 years ago. The glaciers have undergone a rapid recession since the end of the Little Ice age, about 125 years ago. By applying aerial photo interpretation using images presented on Google

Earth, estimates of glacier recession since 1890 can be made. Although the images do not go back as far as 1890, the trim line of the glaciers are noticeable and the abrupt edge of mature trees and shrub-covered areas are evident providing an indication of glacier extent at the end of the Little Ice Age. Table __ summarizes the cumulative length of glacier recession for many of the glaciers on the Nooksack River watershed side of Mount Baker. As can be discerned in Table ___, the Rainbow Glacier on the east side of Mount Baker has undergone the largest recession, 10515 feet since 1890, 11,830 feet by 1993, and 11,865 feet by 2013. Average recession of the valley glaciers has been approximately 8,200 feet since 1890 and 1,270 feet for the hanging glaciers.

3. METHODS

This project involves complex linkages between several independent yet connected watershed processes and needs to establish baseline conditions and address the impact of climate change on Nooksack River hydrology, sediment dynamics, fish and fish habitat, and restoration planning. The Tribe has contracted with Dr. Mauri Pelto, Nichols College, MA, to serve as senior scientist on our glacier field studies by proving guidance on field methods. However, we collect our own full complement of data independently of Dr. Pelto. Out sampling scheme is more comprehensive and occurs frequently over the melt season as compared to Dr. Pelto's single visit in early August. Dr. Pelto has been studying glaciers of the North Cascades in the field for over 30 years. He provides guidance to the Tribe in gathering field data. We have contracted with Dr. Christina Bandaragoda of the University of Washington to calibrate and validate the glacier model to the Distributed Hydrology Soil Vegetation Model (DHSVM). We have contracted with Dr. Robert Mitchell of Western Washington University to update, calibrate, validate, and model Nooksack River hydrology using the DHSVM for historical, current, and future climate change conditions. The results

Table 3.1. Glaciers on Mount Baker and Glacier Recession since the end of the Little Ice Age, 1993, and 2013 (feet).

Glacier	**1890-1993**	**2013**	**1993-2013**	**TOTAL**
Roosevelt	**7830**	**8220**	**390**	**8220**
Coleman	**5220**	**6140**	**920**	**6140**
Deming	**6050**	**7495**	**1445**	**7495**
Mazama	**4980**	**7220**	**2240**	**7220**
Rainbow	**10515**	**11830**	**1350**	**11865**
Thunder	**7190**	**7860**	**670**	**7860**
Sholes	**4060**	**4710**	**650**	**4710**
Heliotrope	**2460**	**3410**	**950**	**3410**
Hadley	**3380**	**3890**	**510**	**3890**
Bastille	**5580**	**6020**	**440**	**6020**

of this work will be used to evaluate likely shifts in exceedance probabilities of flows important to minimum instream flows for fish into the future with climate change. Oliver Grah, Water Resources Program Manager and Principal Investigator and Jezra Beaulieu, Water Resources Specialist and Co-Principal Investigator are the staff primarily responsible for this work. Kari Nielsen was contracted to map glacier area change over time based on aerial photo interpretation and map areas prone to mass failure due to glacier recession (See Appendix C).

3.1 Ablation Measurements

Glacier mass balance is defined as the difference between the total annual snow and ice accumulation and the total annual snow and ice loss from a glacier during a given year. Since 1990, the North Cascades Glacier Climate Project (NCGCP), led by Dr. Mauri Pelto, has collected snow depth and daily ablation rates on the Sholes Glacier in order to estimate the *annual mass balance* of the Mt. Baker. Over this period, daily ablation measurements are related to air temperature at nearby Snotel stations to develop a degree day function for ablation (see Appendix B). The resulting model incorporates 109 days of observations from 1990-2015, where daily ablation and air temperature have a correlation of 0.91 (Appendix B). Once daily ablation is modeled over a given period, it can be extrapolated over the area of a given glacier to determine the amount of runoff over that period. This project adopts the methodology developed by the NCGCP and compares the Nooksack Indian Tribe's results to their results for the 2015 melt season. The daily ablation and total seasonal ablation will be calculated using the model developed by Dr. Pelto and the continuous air temperature record at the glacier streams. Some overarching questions of the NCGCP program that the Nooksack Tribe is interested in answering are:

1) How variable is annual mass balance from glacier to glacier?

2) What factors determine the variability from glacier to glacier?

3) What is the recent mass balance record of the North Cascade glaciers?

4) What trends in glacier ablation, mass balance, stream discharge, and sediment dynamics might be discerned over time?

5) Were snow accumulation, snowmelt, and glacier melt conditions in water year 2015 indicative of projected climate change in the future?

Four ablation stakes were inserted into the snow and ice of the Sholes and Hadley glaciers in order to determine snow depth at the beginning and end of the summer (Figure 3.1). Snow completely melted from the Sholes glacier by July 2015, whereby the ablation stakes were then drilled into the ice to directly measure ice ablation on a weekly basis from July 1 through September 18, 2015. Many of the ablation stakes melted out before we could revisit the site, so we acquired an extension drill bit to drill deeper into the ice. By the second half of the summer, field visits were regularly once per week which enabled us to measure ice ablation with confidence and accuracy. Four ablation stakes were originally installed at Hadley Glacier, however this site was more difficult to access this year due to the Wells Creek Road closure, so ablation measurements were abandoned for this project in 2015. However, Hadley Creek and Dobbs Creek continued to be monitored until September 2015. If the Wells Creek Road opens in 2016, it would be ideal to gather ablation measurements at Hadley in the future to supplement the data at Sholes Glacier.

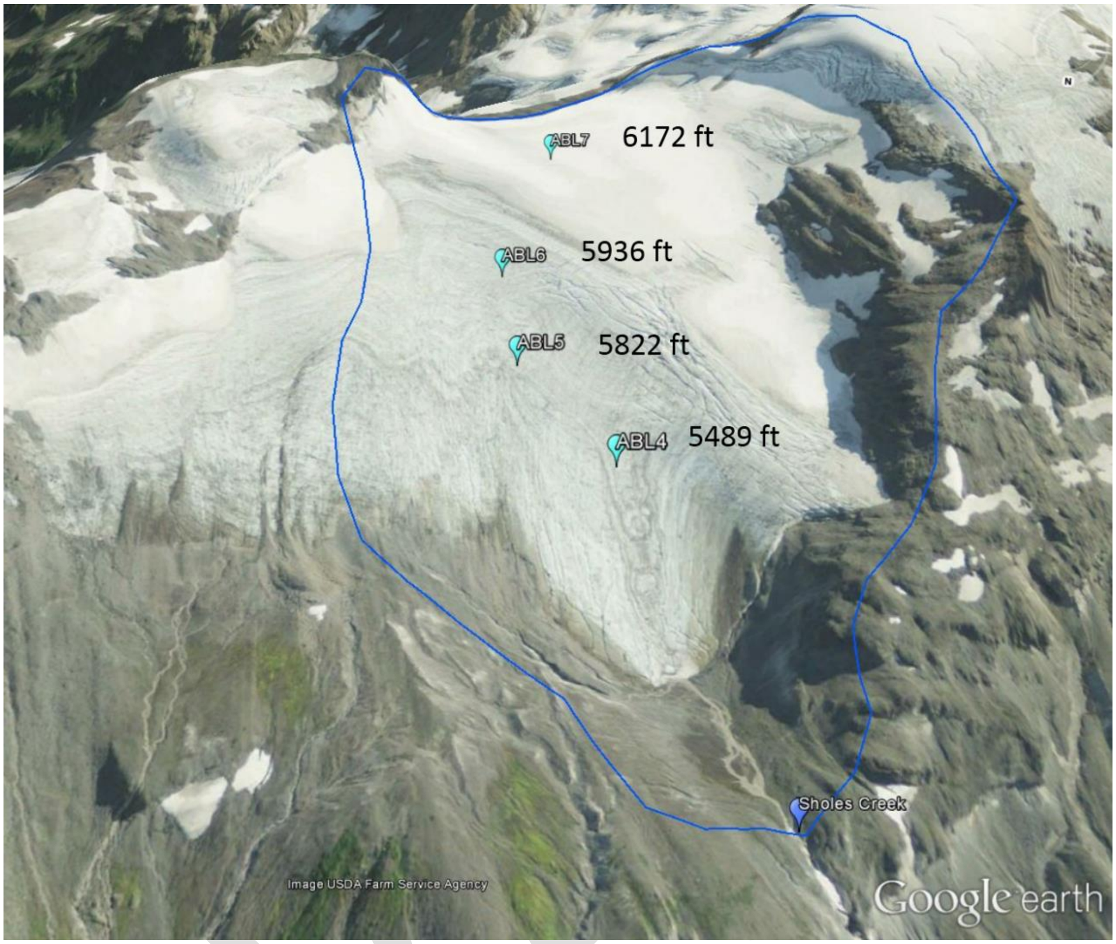

Figure 3.1. Ablation stake network and watershed area of the Sholes Glacier outlet stream.

3.2 Hydrological Conditions

To estimate streamflow and develop a rating curve, we placed stilling wells in the glacier streams that contain dataloggers to record water level, water temperature, air temperature, and barometric pressure at outlet streams form the Sholes and Hadley glaciers as well as Bagley and Dobbs Creeks, which are snow-dominated watersheds. Each sensor was set to 20-minute intervals and recorded in sync with each other so that direct correlations and relationships could be interpreted between the glaciers. We then measured discharge at each location multiple times throughout the summer to capture flow at various stage heights. Stream flow velocity was measured with a Xylem Flowprobe©. Discharge was estimated by integrating flow velocity with cross-sectional channel area at various stream stages during each visit. A discharge rating curve was then developed for each creek in order to model continuous discharge over the field season from late June through mid-September.

As with most field investigations and projections of future climate change, there are many assumptions and uncertainties in our field and continuous measurements which we will strive to better constrain in following years of this project. The slope of the channel, stream roughness (function of slope and bedload material), and aggradation or degradation of the channel are examples of parameters and processes that were not measured for this project that all have some effect on discharge and subsequent rating curve modelling. The stage-discharge relationship is greatly affected by channel degradation and/or aggradation with changes in flow or sediment output, and sediment output is ample in glaciated streams. In 2013, the site of the stilling well and discharge measurements at Sholes Creek was moved downstream 50 feet due to an unstable channel cross-section due to high suspended-bedload loads. In 2014 the measurement site was moved downstream where the gradient was slightly steeper and the channel more stable and dominated by cobbles and gravel to avoid temporal changes associated with the sand bed channel. The stream gage was installed in the same location in 2015 and left over the winter to attempt to capture the spring snowmelt peak and early summer streamflow and to determine the durability of the equipment over the 2016 winter and spring period.

It is useful, when possible, to have a datum of the stage-discharge relationship where discharge is zero at a given particular low stage. This value essentially sets the y-intercept for the rating curve, yet this value is nearly always difficult to measure. Many of the stage and discharge observations for this study were similar and most likely on the moderate spectrum of flow for a given site; it is best to get a range of these observations, especially at high and low values. For the purpose of developing the rating curves, a datum of 0 cfs of discharge and 0 ft of stage was used to anchor the modelled curve, so as not to yield negative discharge values for any given stage value. This also prevents the model from yielding unrealistic positive values of discharge at very low stages.

In addition to the remote glacier streams, stream gages were installed at Canyon Creek, a large snow-fed tributary to the North Fork Nooksack River, and at Sisters Creek--a glacier fed tributary to the Middle Fork Nooksack River. Discharge measurements were made throughout the summer to develop rating curves for the streams. Suspended sediment and oxygen isotope samples were also collected as a comparison to the other glacier streams. The Canyon Creek stilling well was damaged in late summer 2015 and was not reinstalled due to the turbulent winter flows and unstable nature of the channel in the fall with higher than normal flows. The Sisters Creek gage will remain in place indefinitely.

3.3 Meteorological Conditions

Air temperature was measured continuously at each stilling well with the baralogger, and a weather station was installed at Sholes Glacier to record humidity, precipitation, and solar radiance. Other meteorological data will be obtained from the nearby Wells Creek or Middle Fork SNOTEL stations in order to assess relationships with snow depth and snow water equivalent (NRCS, 2015: *www.wcc.nrcs.usda.gov*). ***Have we done this yet? The Wells Creek Snotel station is located in the Wells Creek Drainage downstream of the Sholes Glacier outlet at an elevation of 4039 feet. The Middle Fork Snotel is in the Middle Fork drainage to the South of Heliotrope Ridge Glacier at an elevation of 4934 feet. The challenge of using data at these sites relates to their lower elevations relative to the study glaciers at elevations ranging from 6,000 to 7,000 feet. Descriptive statistics will be calculated and compared to measurements made at the glaciers. Climate normals from 1981-2010 for air temperature and precipitation will be obtained from the Parameter Regression of Independent Slopes Model (PRISM) in order to compare the 2015 melt season to the historical conditions (Daly et al., 1994). Meteorological conditions and climate normals will be discussed in a more comprehensive report in 2016.

3.4 Turbidity and Suspended Sediment Concentration

Turbidity was measured and suspended samples were collected at each glacier stream at every site visit throughout the summer to develop a sediment yield estimate for each stream—results for these samples are available in the sediment summary report and will be further analyzed in early 2016 due to the large number of sample collected during 2015 and submitted to the USGS Cascade Volcanic Observatory (CVO) and the lag time in receiving results in December 2015. At times it was possible to measure two or more turbidity levels at each site visit to assess the diurnal range of turbidity and suspended sediment concentration. To measure the suspended sediment concentration (SSC) of the streams, we collected 1L samples of water concurrently with turbidity measurements, which were analyzed at the USGS Cascade Volcanic Observatory (CVO). Fifteen suspended sediment samples were collected at Sholes Creek, 10 samples were collected at Hadley Creek, seven samples were collected at Dobbs Creek and six samples were collected at Bagley Creek. The turbidity, SSC and discharge relationship will be modeled for each glacier stream. These results will be analyzed in more detail in the *2016 Sediment Monitoring Report.* Grab samples were also collected along a longitudinal profile in the Nooksack River and tributaries to estimate relative sediment contribution of glaciated tributaries to the mainstem (Figure 3.2). These results will be also analyzed in more detail in the *2016 Sediment Monitoring Report.*

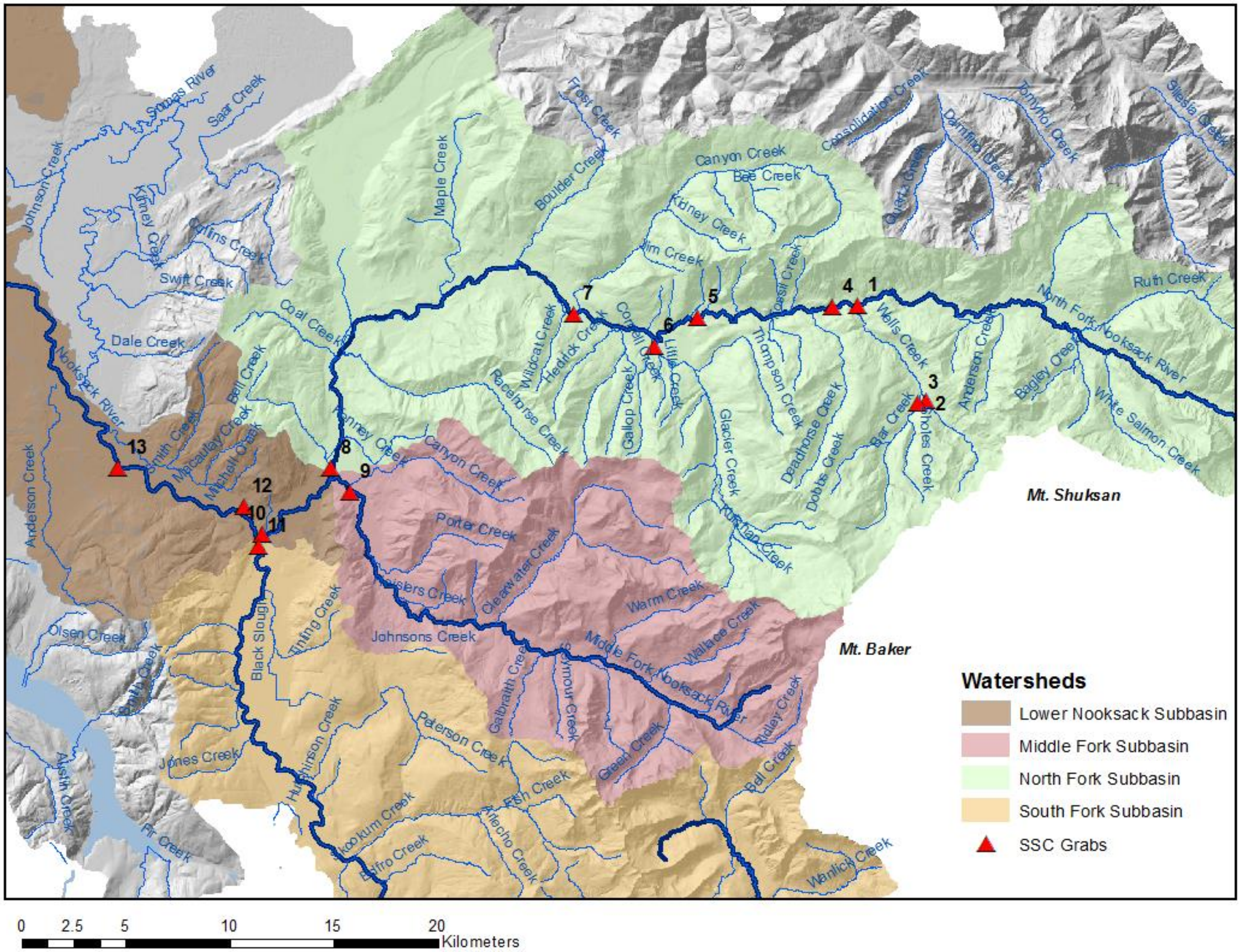

Figure 3.2. Locations of suspended sediment grab sample sites along the longitudinal transect of the watershed.

3.5 Oxygen Isotopes

Water samples were collected at each glacier stream in order to distinguish the percent glacier melt contribution to streamflow and variability from site to site and over the melt season. In order to relate the glacier contribution to runoff, we collected samples in the morning and the afternoon when possible to assess the diurnal variance of such contribution. We tried to collect samples at each field visit to assess the seasonal variance of glacial contribution over the course of the summer, although lack of supplies and time sometimes prevented sample collection. Stream water was collected in 7 ml bottles and sent to the University of Washington's IsoLab for analysis. The lab uses a Picarro liquid water laser analyzer dedicated to measuring δD and $\delta^{18}O$ isotopes that includes cavity ring-down spectroscopy (*http://isolab.ess.washington.edu*). Glacial periods are marked by cooler temperatures that cause greater amounts of ^{16}O to be trapped in glacial ice and greater amounts of ^{18}O to be trapped in the oceans. Interglacial periods, such as modern day, are marked by greater amounts of ^{18}O in the water molecules of surface water, therefore, more negative results indicate a greater component of glacier melt.

In addition to the Sholes, Hadley, Bagley and Dobbs Creeks, we collected water samples along a longitudinal transect within the Nooksack River watershed, following the same procedures as the summers of 2013 and 2014. We followed guidelines of synoptic sampling, which is a method of sampling many locations within a short time period to take a snapshot of isotopic relationships within the watershed (Mark and McKenzie, 2007; Nolin et al., 2010). Samples were collected off of State Route 542 (Mount Baker Highway), where each glaciated stream enters the Nooksack River (Figure 3.3). Oxygen Isotope results will be discussed in a more comprehensive report in 2016.

3.6 Lapse Rates

Throughout the DHSVM glacier-hydrology model development that was contracted to University of Washington and Western Washington University, one parameter that was poorly constrained is temperature lapse rate in the Nooksack River Watershed. Lapse rates at high elevation (>5000 ft) are poorly understood, yet play a critical role in precipitation type and glacier melt dynamics. Previous studies by Susan Dickerson-Lange and Jessica Lundquist of UW have performed lapse rate studies in the Sierra Nevada and the North Cascades that investigated microclimatic patterns in temperature across a transect of the respective mountain crests in order to better inform climate change forecast models. These studies have served as models for a lapse rate study in the Nooksack watershed that will ultimately better inform future runs with the DHSVM glacier model and stream temperature model.

In October 2015, University of Washington PhD student Claire Beveridge and Post Doc Christina Bandaragoda joined the water resources staff to install temperature sensors in an elevational transect in the North Fork Nooksack River watershed. The field work resulted in the installation of seven sites that are accessible by Mt. Baker Highway, forest roads and hiking trails. Sites were chosen based on bands of elevation, accessibility, and tree cover. Because the temperature probes must remain out of the snowpack, they were attached to tree limbs that were at least 30 feet in the air. The highest elevation we could install air temperature probes was limited to locations with trees tall enough that the top of the tree remains above snow line in the winter. Probes were deployed at least 100 feet from any major road so as to reduce long wave radiation influences. The probes were also encased in plastic funnels to reduce direct solar radiation. The temperature and humidity data will be collected in 15 minute intervals until June 2016 when we can return to the sites, download the data, recharge the batteries, and reinstall for continued data collection. The data collected will be useful for improving our understanding of how temperature and precipitation are correlated and change with elevation (lapse rate), which is a critical component to adjusting climate forcing data in watershed modeling for studying future climate change impacts on the Nooksack River system and salmonid species. Data will be collected through 2016 and no analysis has yet been accomplished to present as of the date of this report.

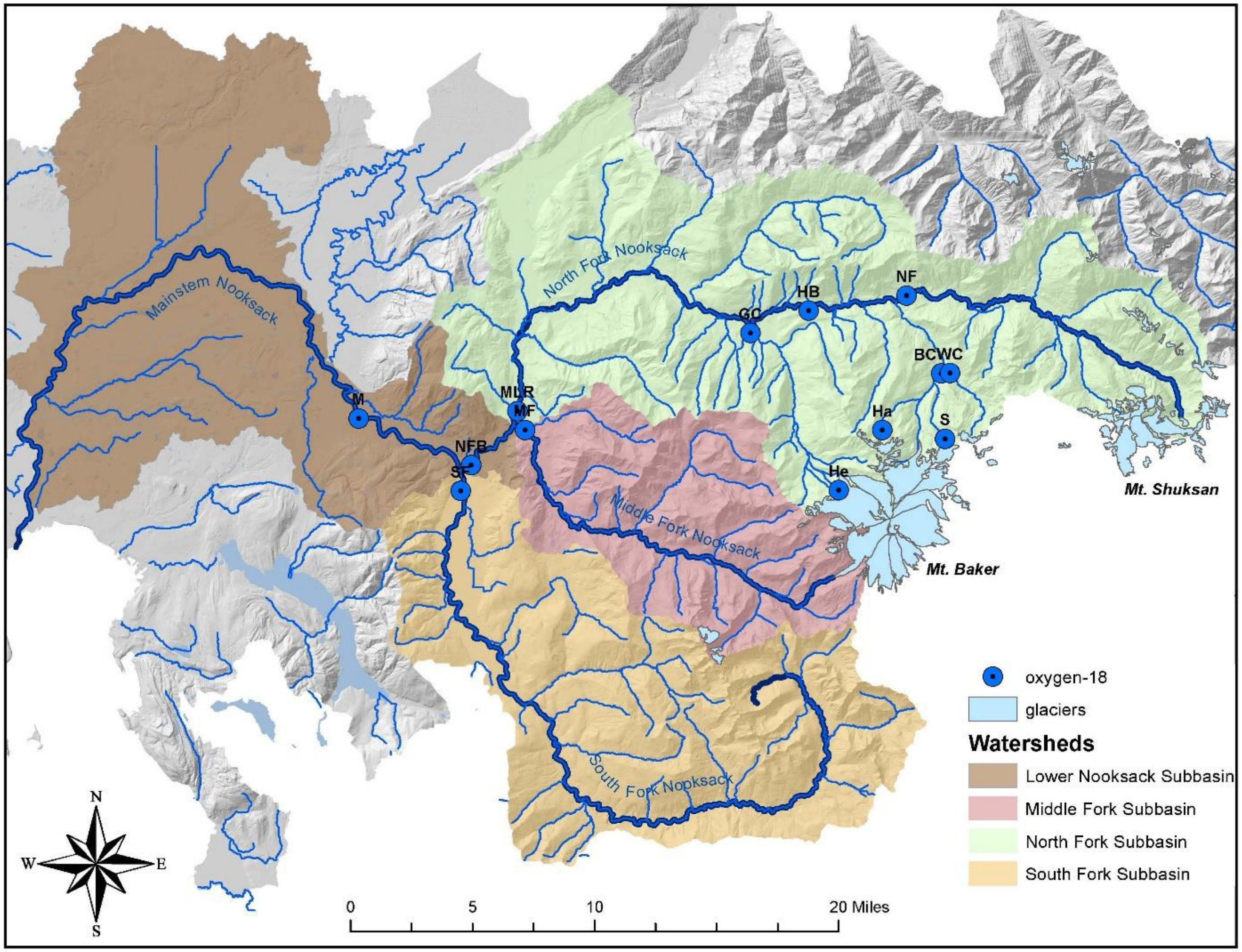

Figure 3.3. Locations of 18-O samples in tributaries of the Nooksack River.

3.7 Distributed Hydrology, Soils and Vegetation Model

Climate change forecasts suggest a warming rate over the next century of 0.1-0.6°C/decade and variable changes in precipitation for the Pacific Northwest (PNW), which is driving planning strategies by stakeholders for regional rivers (e.g., Mote and Salathé, 2010; Vano et al., 2010). In general, climate modeling in the PNW has projected higher winter and spring streamflow, a decrease in summer flows, and an earlier melt season in snowmelt dominated basins (Elsner et al., 2010; Vano et al., 2010). In addition, the area and depth of snow accumulation are projected to decreases with climate change and thus cause reduced flows in the summer and early fall. Similar trends were observed for the upper mountainous region in the Nooksack drainage (Dickerson and Mitchell, 2013). In this project, we will expand upon and update the work of Dickerson and Mitchell (2013) and examine the impact of climate change forecasts on snowpack and glacier size and streamflow in the upper reaches of Nooksack River watershed. In this work wemodeled the hydrology using upgraded climate change scenarios and refined gridded downscaled data from the Washington State Climate Change Impacts Assessment (Hamlet et al., 2010a); and spatially distributed historical climate data developed for the upper Nooksack basin by Bandaragoda et al. (2012). We contracted the University of Washington and Western Washington University to conduct the modeling (See Murphy 2015 for comprehensive results).

Hydrology modeling in the Nooksack River basin will employ the distributed-hydrology-soil-vegetation model (DHSVM) version 3.1.1. The DHSVM is a physically based, spatially distributed hydrology model that was developed at the University of Washington and the Pacific Northwest National Lab for mountainous watersheds. The model was originally tested and validated in the Middle Fork Flathead River basin in Montana (Wigmosta et al., 1994). The model has been used extensively in the PNW to examine the impact of land use and climate change on streamflow (e.g., Stork et al., 1998; Leung and Wigmosta, 1999; Bowling et al., 2000; Whitaker et al., 2002; Elsner et al., 2010; Battin et al., 2007; Cuo et al., 2011; Dickerson and Mitchell, 2013). The DHSVM requires digital grids of spatially variable watershed characteristics, including a digital elevation model (DEM), soil type, soil thickness, vegetation, and stream networks. The DHSVM utilizes physical relationships and a time series of meteorological input data including temperature, precipitation, wind speed, humidity, and short-wave and long-wave radiation to model the flux of water and energy at the pixel scale of the DEM; excess water is routed through a stream network. The University of Washington has been contracted to calibrate and validate the glacier module of the DHSVM. Western Washington University has been contracted to model the Nooksack River hydrology with contemporary downscaled climate data and to model the impacts of climate change on river flows. The setup, calibration, and validation of the DHSVM to modern and historical data in the upland portion of the Nooksack River basin (east of Deming, WA) will follow the methods outlined in Carrasco and Hamlet (2010; 2011). Required spatial digital data inputs will be compiled and processed at a 150 m grid resolution. Meteorological inputs will employ gridded data developed for the Nooksack basin as part of the hydrologic assessment of the Nooksack River basin (Bandaragoda et al., 2012). The DHSVM will be calibrated and validated against historical records of measured streamflow from USGS gauging stations including the gauge at the base of the mountainous region at the North Cedarville, the Saxton Bridge gauge on the South Fork, the Middle Fork near Deming gauge and the Cascade Creek gauge on the North Fork. Snow depth and snow-water equivalent will be calibrated to historical data from the Elbow Lake SNOTEL, the MF Nooksack SNOTEL and the Wells Creek SNOTEL stations.

Hydrology forecast modeling will require statistically downscaling output from General Circulation Models (GCMs) to the Nooksack River basin. Downscaled data sets at a resolution of $1/16^{o}$ are available from the Columbia Basin Climate Change Scenarios project (Hamlet et al., 2010a). Data downscaled using the hybrid delta approach (Hamlet et. al., 2010b) will be used for the modeling. We will use quantile mapping to map the GCM forecasted climate onto long regional historic records, which imparts the underlying GMC future climate trend while preserving the full range of temporal variability of weather at a local level. Multiple forecast scenarios based upon combinations of different GMCs and different emissions scenarios will be used to bracket the range of potential impacts on the basin surroundings the years 2025, 2050 and 2080. These data will be processed to obtain the remaining meteorological inputs for DHSVM and disaggregated into 3-hr time steps. Simulations were performed using these meteorological data sets and the calibrated DHSVM model and analyzed to examine the impact of the climate scenarios on hydrologic responses in the basin including the impact of snow accumulation and melt and glacial size on streamflow as evaluated in the glacier ablation portion of this proposal. Preliminary results were made available In November 2015. A comprehensive presentation on the modeling results is provided by Murphy (2015).

3.8 Changes in physical fish habitat as a result of climate change

The proposed work is necessary to evaluate the effects of climate change on glacier ablation and streamflow hydrology of the Nooksack River watershed, particularly for the better resolution of instream flows pertinent to recovery of spring Chinook salmon. The Minimum Water Flows and Levels Act (1969; RCW 90.22.010) and Water Resources Act (1971; RCW 90.54.020) provide for the enhancement of base flows for the purposes of protecting fish and other uses (Caldwell, 2002). Spring Chinook salmon is a vital resource to the Nooksack Indian Tribe and the Lummi Nation as these groups rely on these fish for cultural, subsistence, and commercial uses. . Glacier ablation and altered streamflows as a result of climate change could have significant implications for salmon habitat during all life stages of each of the nine salmonid species in the river system. As part of the WRIA 1 Watershed Management Project, technical information has been developed to evaluate the quantity of water required to maintain and/restore salmon populations and improve fish habitat (Hardy, 2002; Kennard, 2000). Estimates of the relationship between stream flow and fish habitat quantity and quality for several of nine salmonid species and life stages have been accomplished throughout WRIA 1 (Hardy, 2000; Bandaragoda, 2013). High resolution data for intensive sites and moderate resolution at rapid assessment sites provide the analytic components of channel hydraulics and fish habitat required to evaluate instream flows, but of all the components of watershed management and processes, the uncertainty of climate change and quality of climate data have the most impact on estimates of instream flows. The outputs of the proposed hydrologic modeling using the results of the DHSVM modeling described above were used to calculate changes to exceedance probabilities that relate to the quantity of fish habitat at the various flow levels. This projectprovides the linkage from glacier ablation, to changed hydrology, to altered fish habitat, to the effects on spring Chinook salmon habitat, biology, and ecology in the face of climate change. Altered instream flows and fish habitat as a result of climate change will inform restoration efforts in regard to implementing the results of EPA's South Fork Nooksack River temperature TMDL-climate change pilot research project (Klein 2013) and in the effective implementation of Beechie et al.'s (2012) approach toward evaluating and modifying restoration tools and priorities in the face of climate change. Threats to fish biology and habitat restoration tools to address such threats in the face of hydrology will be identified in the recently completed Climate Change Pilot Research Project Qualitative Assessment co-produced by the Nooksack Indian Tribe (US-EPA 2015).

4. RESULTS

The 2015 glacier monitoring field season was exceptional due to the lack of snowpack in the winter of 2014-2015 and early melt out of snow thus providing an earlier entry and extended field season. Little snowpack and early peak snowmelt enabled us to access the glacier sites in late June. The above-normal air temperatures and reduced snowpack and early melt out resulted in earlier access to glacial ice, above-normal ablation rates, discharge, and sediment output compared to previous years. A PowerPoint presentation for the Pacific Northwest Climate Science Conference is provided to supplement this summary report, which includes graphs, location maps, and summary tables of the data collected in 2015 (See Appendix A). This section describes the preliminary results for ablation rates, hydrological conditions and turbidity and suspended sediment. A more comprehensive analysis of these parameters along with meteorological conditions and oxygen isotope composition will be discussed in a more comprehensive report in 2016 when all suspended sediment samples have been analyzed and we have the data.

4.1 Ablation Measurements

The PHOTO LOG shows conditions on the glaciers through time from early July through late September 2015. See the Photo Log at the end of this report for photos that exhibit conditions and features of the glaciers and monitoring during the 2015 field season.

Our findings indicate that average ablation rate over the course of the summer was 2.0 inches per day (Table 4.1). This equates to approximately 11 feet of glacial ice melt from mid-July through mid-September. The high ablation rate was 3.6 inches per day, while the low was 1.1 inches per day. Average air temperature and discharge at Sholes Glacier over the same period were also calculated. Four ablation stakes were originally installed at Hadley Creek, however this site is more difficult to access so was abandoned for this project. Ablation rates have a strong correlation to air temperature over the summer, especially when there is lack of precipitation (Figure 4.1). Interestingly, the highest and lowest ablation stakes consistently experienced the most ablation, ABL7 and ABL 4, respectively. ABL7 reflects more snowmelt than ice melt because it was covered in snow until August, at which point, firn and young ice was being melted. The melt at ABL4 is indicative of direct ice melt, as there was no snowcover at this site in early July. The ice at this location consisted of large ice crystals that are indicative of old ice. A more robust analysis of the relationships of ablation, air temperature, water temperature, turbidity, sediment, isotopes, and discharge will be completed in early 2016.

Dr. Mauri Pelto was contracted in 2015 to evaluate ablation on the Sholes Glacier independently of our field studies. He found that the winter accumulation in 2015 was 52% of normal, which was the second lowest of the last 32 years. The winter was also warmest on record in the state of Washington. The summer melt season was the warmest since 1989. According to Landsat imagery, there was no retained snowpack retained by September on the Sholes Glacier. Ablation measured during August 6-11 at a series of stakes on the Sholes Glacier measured 4.2 cm/day water equivalent (w.e.) of snowpack and 6.1 cm/day w.e. of ice. The same area of loss for ice and snowpack may be equivalent, yet given the greater density of ice the water equivalent is 30% higher. The mass balance loss is the largest of the last 32 years with losses averaging over 3.36 m w.e at the Sholes Glacier. The total glacier covered area declined from 13 km2 to 12.3 km2 in 2015, a 5.4% reduction in area. The glacier terminus retreated 21 m from August 7th, 2014 to August 7th, 2015.

Table 4.1. Average ablation rates, air temperature, degree days, and discharge at the Sholes Glacier for the 2015 monitoring period.

Date Range	# days	ABL 4	ABL5	ABL6	ABL7		Air temp	Degree Days	Q
		Ablation (in/day)				average	°C	°C/day	cfs
7/14/15-7/29/15	15	1.5	1.8	1.8	2.7	**1.9**	8.5	0.6	10.0
7/29/15-8/7/15	8	NA	2.3	NA	NA	**2.3**	9.9	1.2	9.2
8/7/15-8/13/15	6	3.0	2.7	2.8	3.6	**3.0**	10.5	1.8	10.1
8/13/15-8/18/15	5	2.8	2.1	2.3	3.0	**2.6**	9.7	1.9	11.4
8/18/15-8/25/15	7	2.6	1.8	1.6	2.4	**2.1**	10.5	1.5	10.8
8/25/15-9/7/15	13	1.3	1.2	1.2	1.3	**1.3**	5.9	0.5	12.9
9/7/15-9/18/15	11	1.5	0.9	1.1	1.6	**1.3**	6.7	0.6	8.0
average:	**9.3**	**2.1**	**1.8**	**1.8**	**2.4**	**2.0**	**8.8**	**1.2**	**10.3**

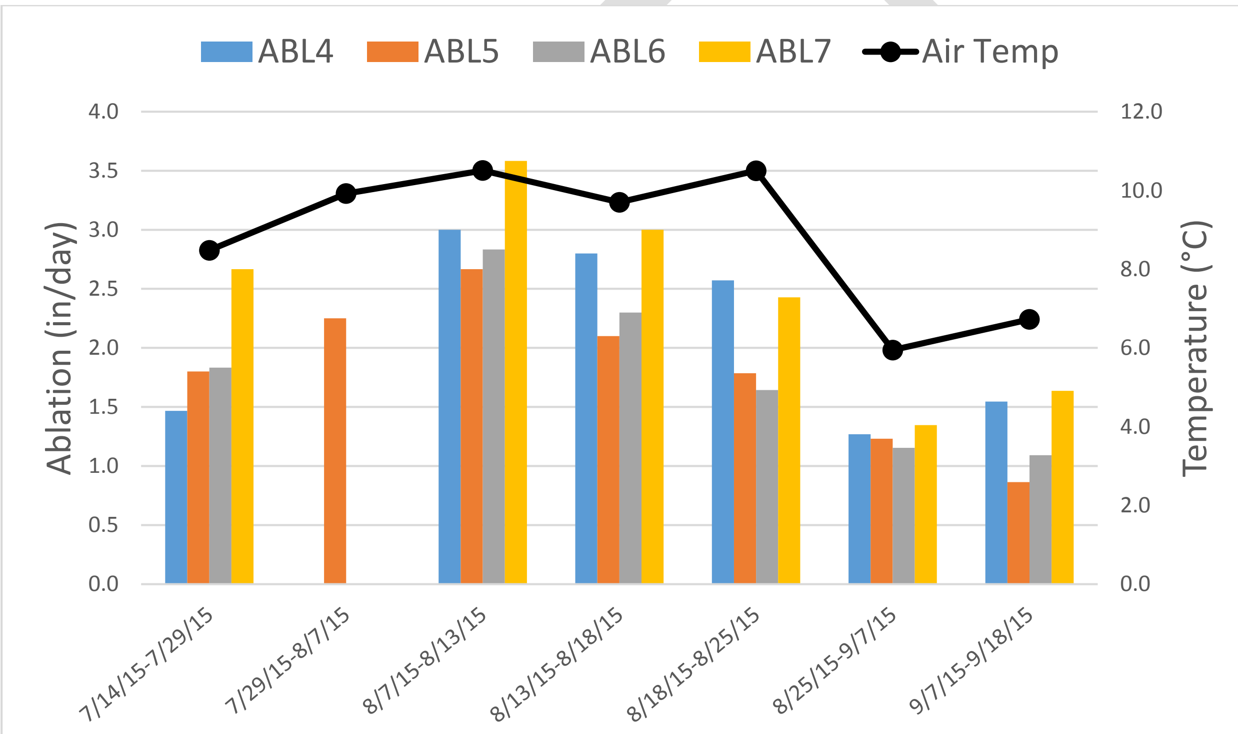

Figure 4.1. Comparison of ablation rates and air temperature during summer 2015.

4.2 Hydrological Conditions

The hydrology, turbidity, temperature, and isotopic components of the Hadley, Sholes and Heliotrope glacier streams were monitored from June through the end of September of 2015. Rating curves were developed for each stream with continuous stage measurements and field observations of discharge (Figures 4.2-4.4). The amount of field measurements at each site differed making each rating curve have a slightly different accuracy and confidence. Overall, each rating curve generally had a good fit with the field observations with a goodness of fit over 0.7, except Hadley Glacier, which had an R^2 of 0.43. We suspect there could have been measurement error or malfunctioning equipment that added to the data scatter. The rating curves were then used to model the corresponding discharge for each stage measurement collected by the datalogger at 20 minute intervals (Figures 4.2-4.4). Continuous air temperature (AT) and stream temperature (ST) were then compared to stream discharge (Q) to assess their relationships. The continuous record of stream stage at Bagley has not been assessed because of a malfunction with the datalogger downloading device. The stilling well is currently under snow so may not be accessible until summer 2016. Daily lagtimes and diurnal ranges of all creeks will be analyzed and reported in more detail in our comprehensive *2016 Glacier Monitoring Report.* Sholes Glacier

Sholes Creek

The discharge at Sholes glacier is responsive to both air temperature and precipitation (Figures 4.5-4.6). A peak flow event occurred on August 29th that coincides with a significant rainfall event (Figure 4.6). Similarly, peaks in discharge correspond with peaks in air temperature (Figure 4.5). According to modeled discharge, which is most likely an overestimate, the peak flow reached 33 cfs in 2015, which is very similar to the peak flow in 2014, which was 32 cfs. The air temperature during this high flow event was lower than the days preceding it, corresponding with a heavy rainfall event. The same trend occurred on 8/29/15 at Hadley Glacier, suggesting this storm was a regional event. Stream temperature variation is small and never exceeds 3°C or goes below 1°C, typical of glacier fed streams. (Figure 4.5). Dr. Mauri Pelto was contracted in 2015 to evaluate discharge of Sholes Creek independently of our field studies. He combined stage and discharge measurements from 2014 and 2015 to develop a fairly robust rating curve for the outlet stream, with an R2 of 0.78. The average runoff recorded at the Sholes Glacier outlet stream was 11.77 cfs. In 2015, the drought conditions of the melt season increased the importance of glacier runoff, indicated by 42 days of the season having more than 40% of total streamflow being generated by glacier melt. In the unglaciated South Fork Nooksack River, discharge was 0.5 cfs/square mile and 4.3 cfs/square mile in the heavily glaciated North Fork Nooksack River. In the North Fork, average modeled glacier runoff was estimated to be 340 cfs compared to total flow of 460 cfs, which is 74 percent of the total flow even though only 6.1 % of the basin is glacier covered. Stream temperature was also affected by increased glacier melt in 2015. Temperatures in the North Fork did not exceed 14°C, whereas temperatures in the South Fork peaked to 25°C.

Hadley Glacier and Dobbs Creek

Discharge at Hadley and Dobbs Creeks were normalized for their watershed areas to allow a direct comparison of their flow output (Figure 4.7). Flow at Dobbs was higher than Hadley in early summer during the snowmelt period; however, flow at Hadley was greater than Dobbs Creek during the baseline summer period that had high temperatures and no precipitation. This seasonal trend in flow at both creeks is indicative of the glacier melt contribution to Hadley Creek and the lack of ice melt in Dobbs Creek. Although their seasonal trends differ, the diurnal variation in both creeks is similar; however, Hadley Creek is slightly muted as compared to Dobbs Creek, which has higher peaks. Both Hadley and Dobbs Creek discharge increases during rainfall events, whereas stream temperature generally decreases (Figure 4.8). The decrease in stream temperature during rainfall events could indicate facilitated melting of rain on snow or ice events, thereby increasing Q and decreasing ST. Also, stream temperature is a function of air temperature, the cooler stream temperatures are likely associated with rainfall events that also are accompanied by cooler air temperatures. During the precipitation event on 8/29/15, the peak discharge was 42 cfs at Dobbs Creek and 15 cfs at Hadley Creek. This large difference in peak Q could either be a reflection of the storage capacity of the glacier ice at Hadley to hold rainfall, thereby detaining discharge, or it could be the difference in significance of the rating curves. Hadley rating curve had a relatively low R^2 value meaning the modeled peak discharge in particular could be an underestimate. The large peak in discharge at Dobbs on 9/20/15 is likely an error, as no precipitation occurred, which will be investigated for quality in future reports.

Stream temperature at Hadley Creek has much more daily variability than Sholes Glacier with relatively warmer mean, maximum and minimum temperatures. Daily average stream temperature was up to 6°C at times at Hadley Creek and up to 10°Cat Dobbs Creek. The greater variability in stream temperature, air temperature and discharge at Hadley Creek is likely due to the fact that the stream gage at Hadley is much further from the glacier than that of Sholes Creek. The greater area upstream of the gage at Hadley Creek allows stream water to warm as it travels downstream. Figure 4.7 compares discharge and stream temperature between Hadley Creek and Dobbs Creek. Dobbs Creek generally is 1-2 °C higher than Hadley Creek likely due to ice melt as compared to runoff from later season snow melt and a larger area of exposed watershed.

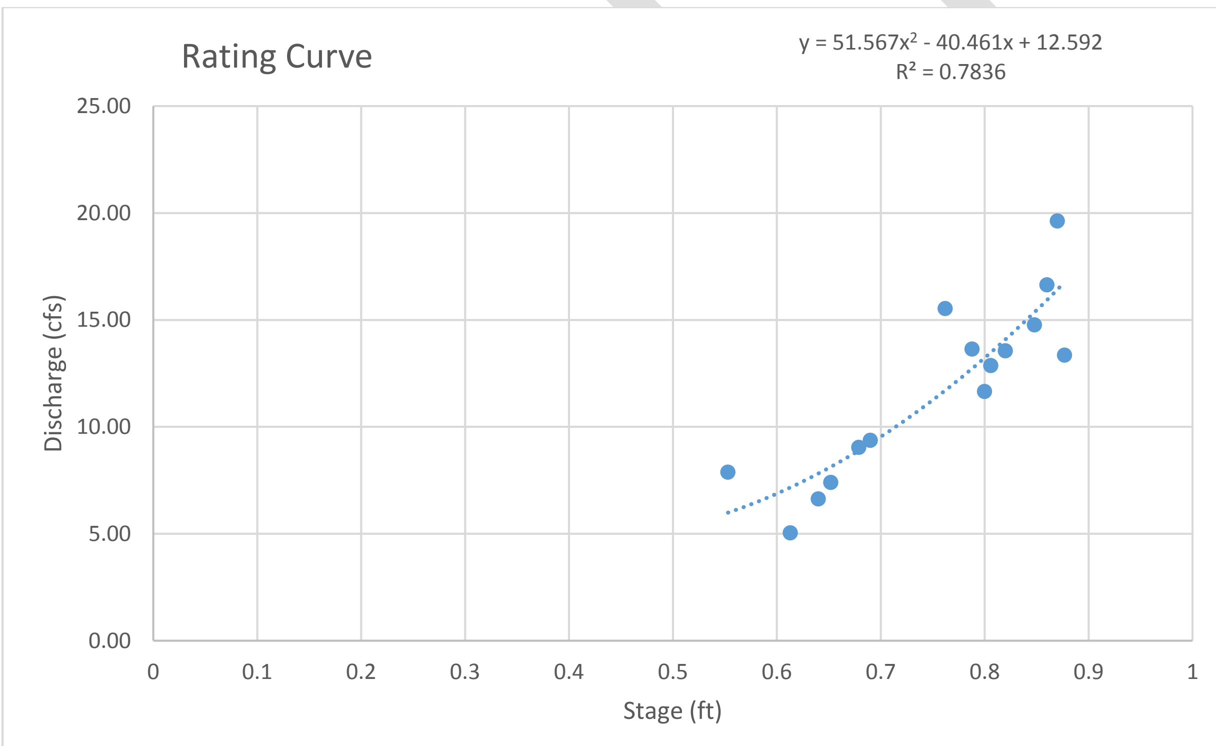

Figure 4.2. Stage-Discharge rating curve for the Sholes Glacier

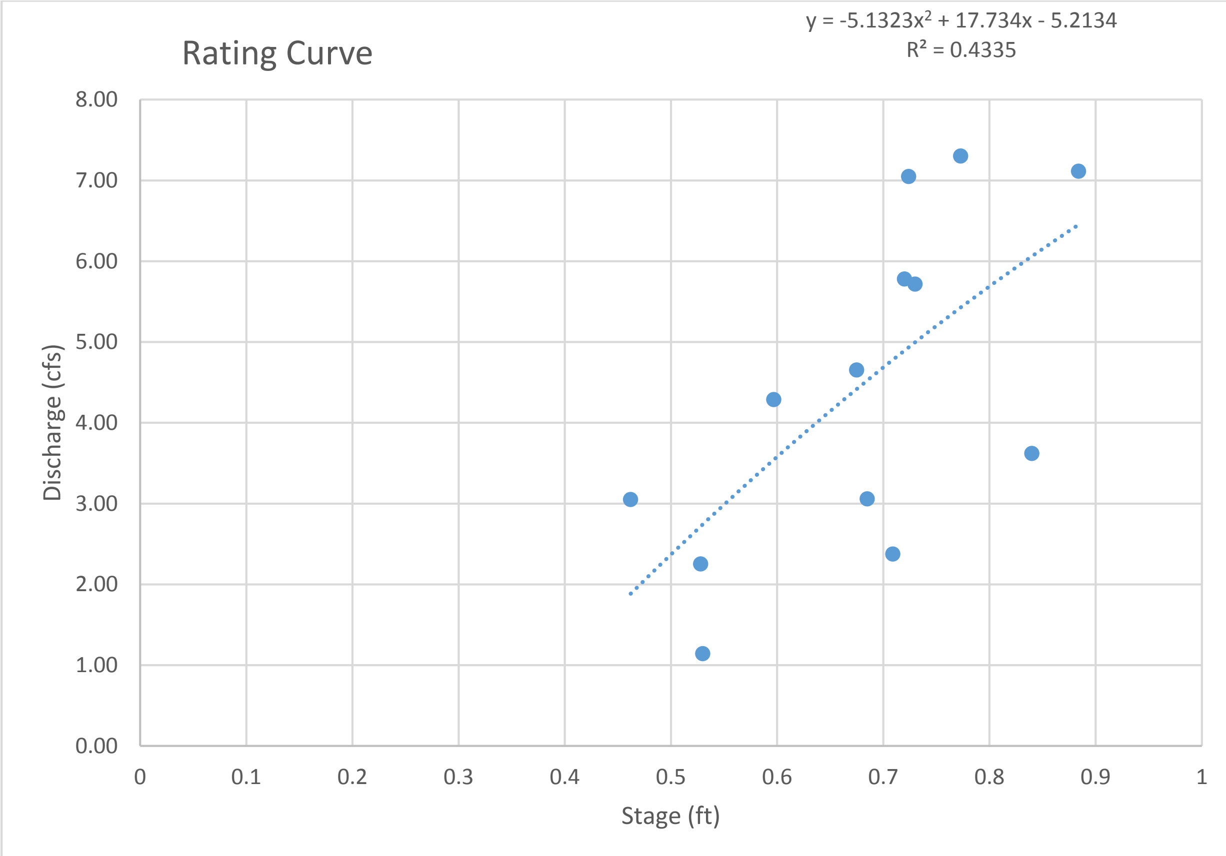

Figure 4.3. Stage-Discharge rating curve for the Hadley Glacier.

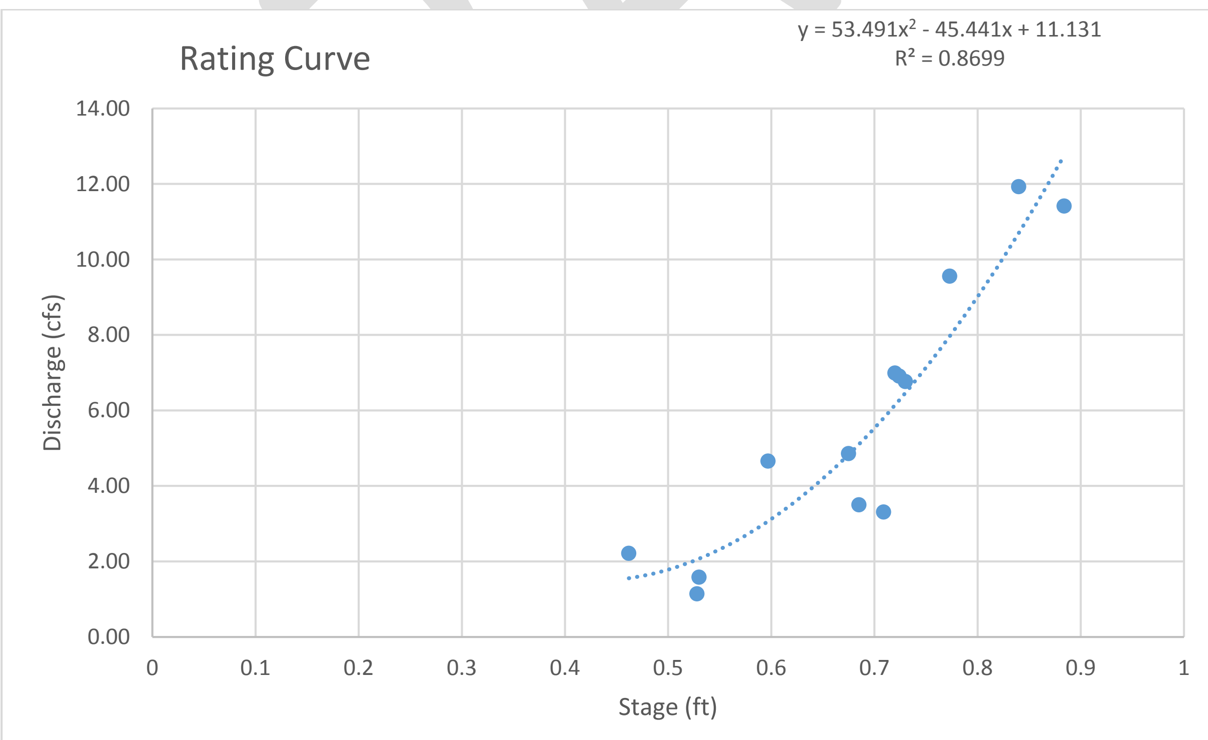

Figure 4.4. Stage-Discharge rating curve for the Dobbs Creek.

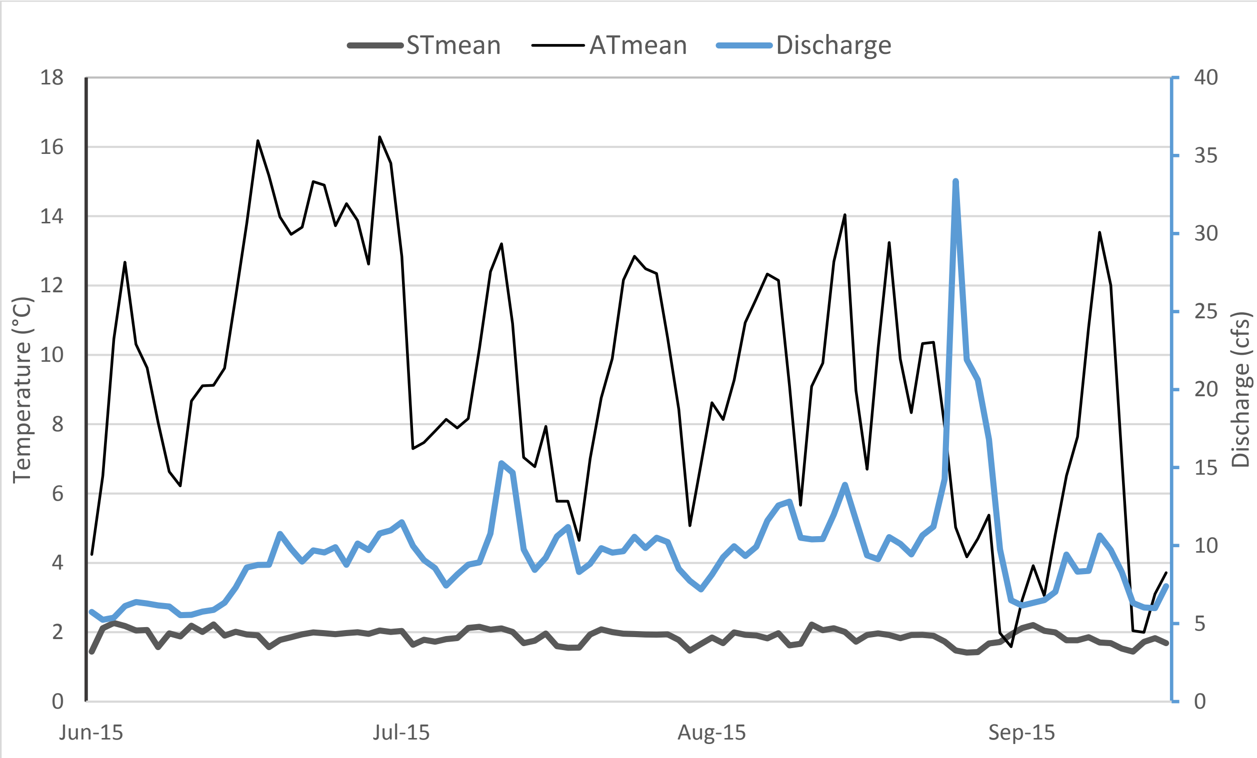

Figure 4.5. Daily modelled discharge and measured air temperature and stream temperature at the Sholes Glacier.

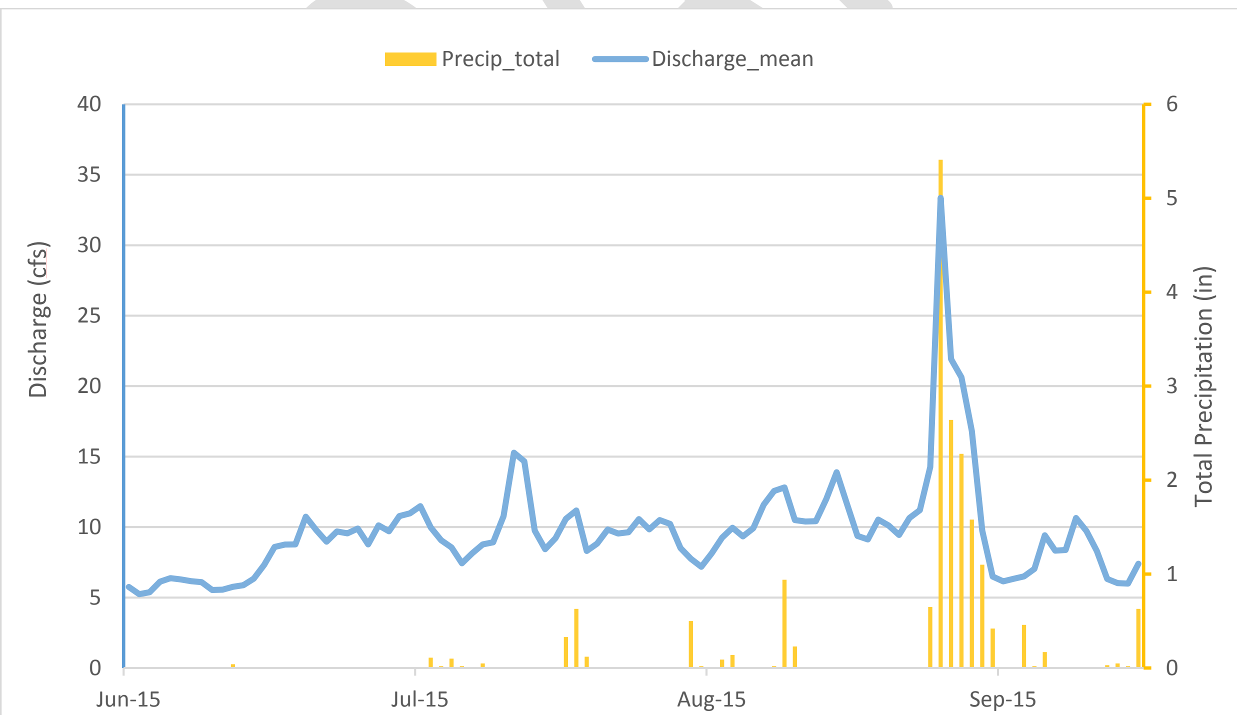

Figure 4.6. Modeled discharge and precipitation recorded at the Sholes Glacier weather station.

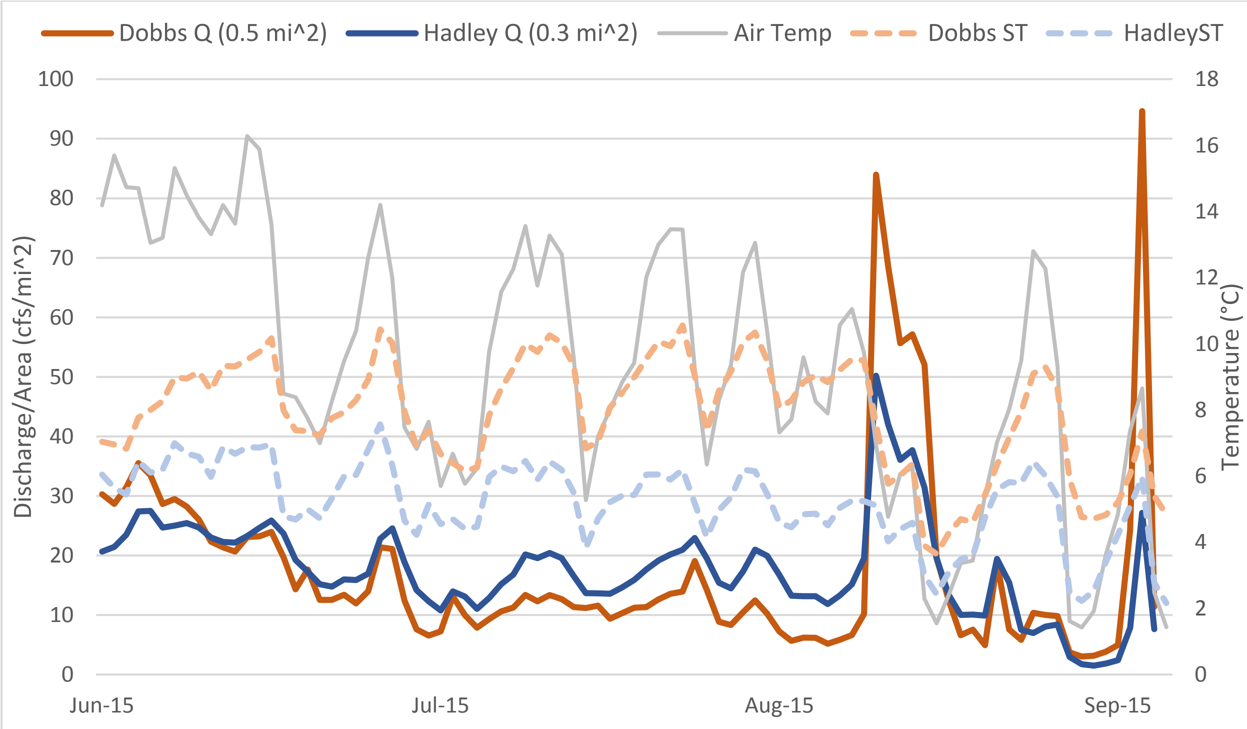

Figure 4.7. Modeled discharge and measured air temperature and stream temperature at Hadley Glacier and Dobbs Creek.

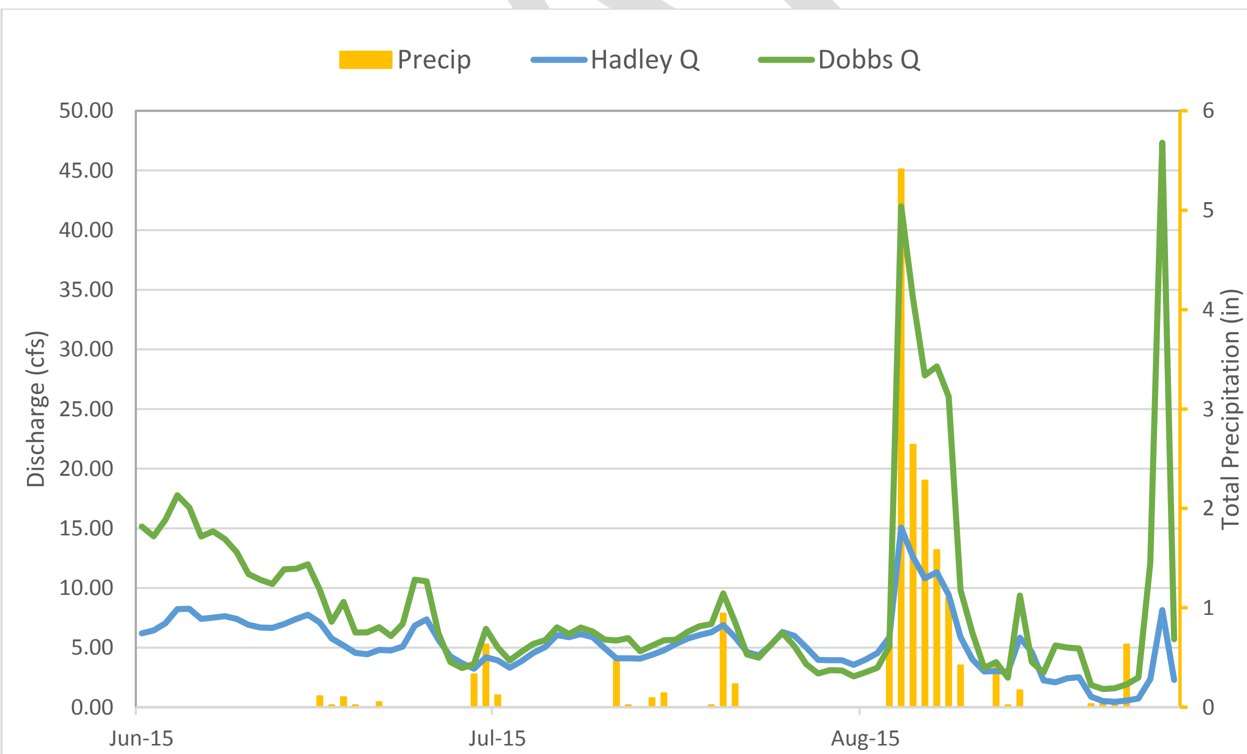

Figure 4.8. Modeled discharge at Hadley and Dobbs Creek compared with precipitation at Sholes Glacier.

4.3 Turbidity and Suspended Sediment Concentration

Turbidity was measured during field visits at the same time as suspended sediment samples were collected in order to establish a statistical relationship. In this manner, turbidity that is more easily and readily measured than suspend sediment, can be used as a surrogate or predictor of suspended sediment. Water samples were collected and sent to the USGS Cascade Volcanic Observatory (CVO) for analysis in September 2015 and results were received in December 2015, too late to conduct a comprehensive analysis for this summary report. Therefore a thorough analysis has not been completed, but will be completed in the *2015 Nooksack River Watershed Sediment Monitoring Report*. Relationships between turbidity, discharge, air temperature, and stream temperature will be assessed for the purpose of this project in a more robust analysis that will be provided in 2016. Table 4.4 gives a summary of the samples collected and the corresponding turbidity and suspended sediment concentration (SSC).

Hadley Creek and Dobbs Creek are adjacent to each other in the forelands of the Hadley Glacier. Hadley Creek drains glacier melt in the watershed and Dobbs Creek drains predominantly snow melt and rain runoff. The difference in their streams are most noticeable in the turbidity of the water, where Hadley Creek is much more turbid than Dobbs Creek (Figure 4.9). The most turbid samples of both Hadley Creek and Dobbs Creek was on 8/3/15, where they reached 103 NTU and 18.4 NTU, respectively. This period was marked by prolonged above-average air temperature that likely induced snow and glacier melt. The least turbid samples of both creeks were in late summer when air temperatures were lower. The turbidity at Sholes was consistently a few orders of magnitude greater than that at Hadley Glacier, with the highest turbidity of 858 NTU on 8/12/15 (Figure 4.10). Although the data has not been thoroughly analyzed, it is apparent that turbidity and SSC at the snow-fed creeks (Bagley and Dobbs) are several magnitudes lower than for Sholes and Hadley creeks because they are for the most part not glacier fed. The difference between Sholes and Hadley relates to a larger portion of Hadley's watershed is glacier-free, while most of the Sholes Creek watershed is glacier covered. More sediment is carried in Sholes than Hadley for this reason (Table 4.2). Figure 4.10 shows how turbidity increases from the snowmelt period to the glacier ice melt period. The higher turbidity values likely relate to sediment released from on top of and within the melting ice of the glacier as well as erosion and entrainment of sediment in newly exposed areas around the margin of the glacier due to melt and recession. Sediment-discharge-turbidity curves will be developed for each creek with combined data from previous years and will be presented in our analysis in 2016.

5. Conclusions

Hadley Glacier watershed has greater un-glaciated watershed area and higher mean elevation than the Sholes Glacier, which resulted in lower overall ablation,discharge, and turbidity. Much of the Hadley Glacier watershed is vegetated and contains a wide area of glacial sediment which could be contributing groundwater sources to the stream, thereby causing the measured discharge to be much higher than the modelled discharge. The Sholes Glacier measured discharge was also higher than the modelled discharge, but not the same extent as the Hadley Glacier. The Sholes watershed is much more confined and nearly 90% glaciated, so measurements at this site are likely more reflective of glacier contribution than of the Hadley Glacier.

Table 5.2. Suspended sediment and turbidity sample collection dates and times.

Sample Number	Site	Date	Turbidity (NTU)	SSC (mg/L)
Bag1-15	Bagley	7/10/15 13:25	0.923	3
Bag2-15	Bagley	7/10/15 16:20	1.533	3
Bag3-15	Bagley	7/24/15 10:40	1.113	2
Bag4-15	Bagley	8/12/15 9:07	1.533	1
Bag5-15	Bagley	8/22/15 15:03	1.49	1
Bag6-15	Bagley	9/2/15 13:40	0.65	1
D1-15	Dobbs	6/25/15 10:45	N/A	2
D2-15	Dobbs	7/20/15 19:55	12.867	7
D3-15	Dobbs	8/3/15 12:15	14.467	5
D4-15	Dobbs	8/3/15 14:15	18.433	4
D5-15	Dobbs	8/25/15 16:19	14.4	4
D6-15	Dobbs	9/9/15 15:42	6.45	3
D7-15	Dobbs	9/9/15 18:54	4.79	2
H10-15	Hadley	9/10/15 10:48	9.36	2
H1-15	Hadley	6/25/15 11:10	N/A	10
H2-15	Hadley	7/20/15 20:25	80.033	61
H3-15	Hadley	7/21/15 7:23	53.333	41
H4-15	Hadley	8/3/15 11:35	91.467	74
H5-15	Hadley	8/3/15 13:30	108.667	94
H6-15	Hadley	8/25/15 16:57	106.6	69
H7-15	Hadley	8/25/15 21:01	47.4	36
H8-15	Hadley	9/9/15 16:18	36.6	15
H9-15	Hadley	9/9/15 19:23	33.4	19
S1-15	Sholes	6/11/2015 13:53	10.27	28
S2-15	Sholes	7/8/15 18:48	44.9	285
S3-15	Sholes	7/14/15 14:30	84.12	194
S4-15	Sholes	7/15/15 11:10	139	287
S5-15	Sholes	7/29/15 10:00	110	430
S6-15	Sholes	7/29/15 15:10	160	1668
S7-15	Sholes	8/7/15 14:00	283	1191
S9-15	Sholes	8/12/15 14:44	858	1953
s8-15	Sholes	8/12/15 15:40	519.7	1248
S10-15	Sholes	8/13/15 11:45	335.2	5039
S11-15	Sholes	8/18/15 13:45	523.2	7214
S12-15	Sholes	8/18/15 18:50	306	2058
S13-15	Sholes	8/25/15 12:50	251	2994
s14-15	Sholes	9/7/15 12:13	461.3	853
s15-15	Sholes	9/7/15 16:16	644	1190

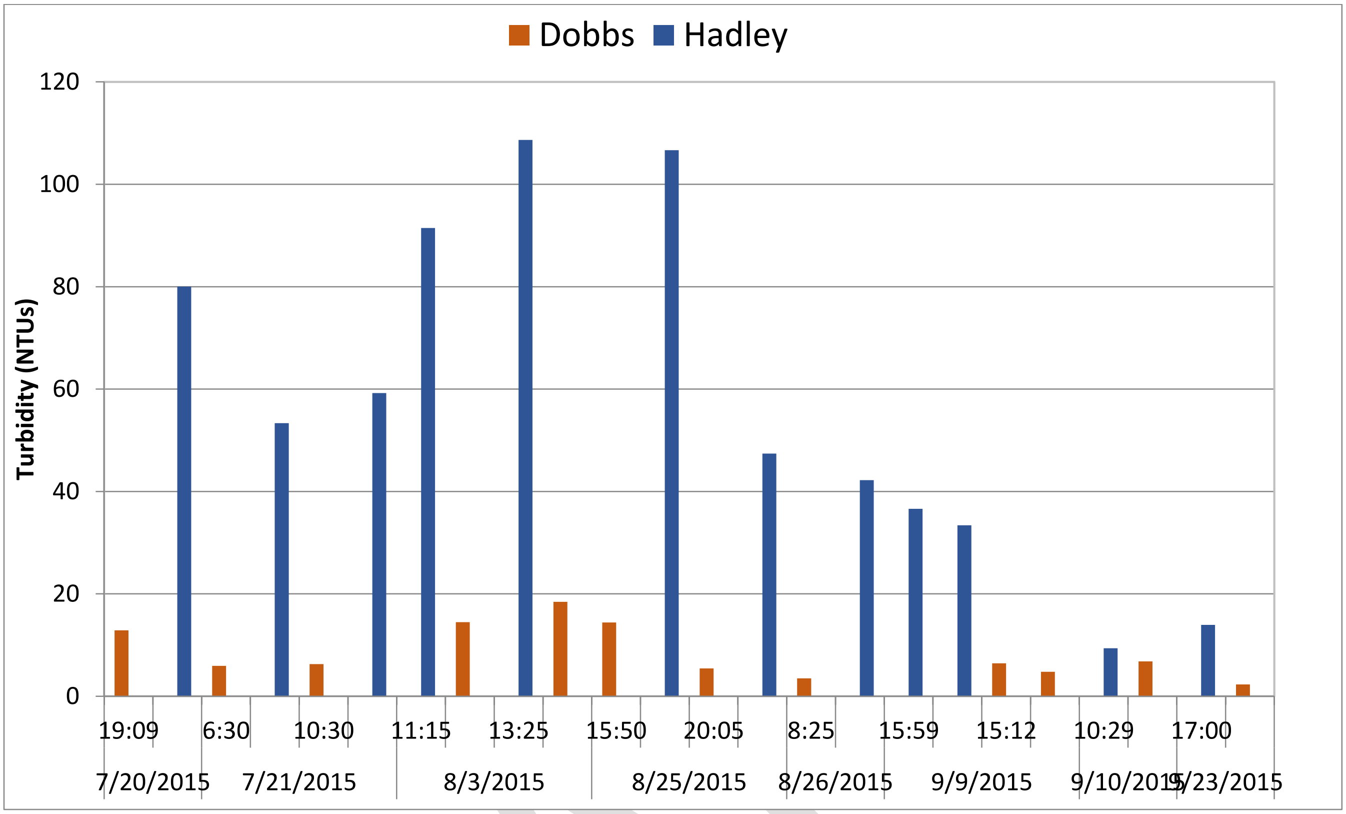

Figure 5.9. Turbidity samples collected at the Hadley Glacier (blue bars) and Dobbs Creek (orange bars).

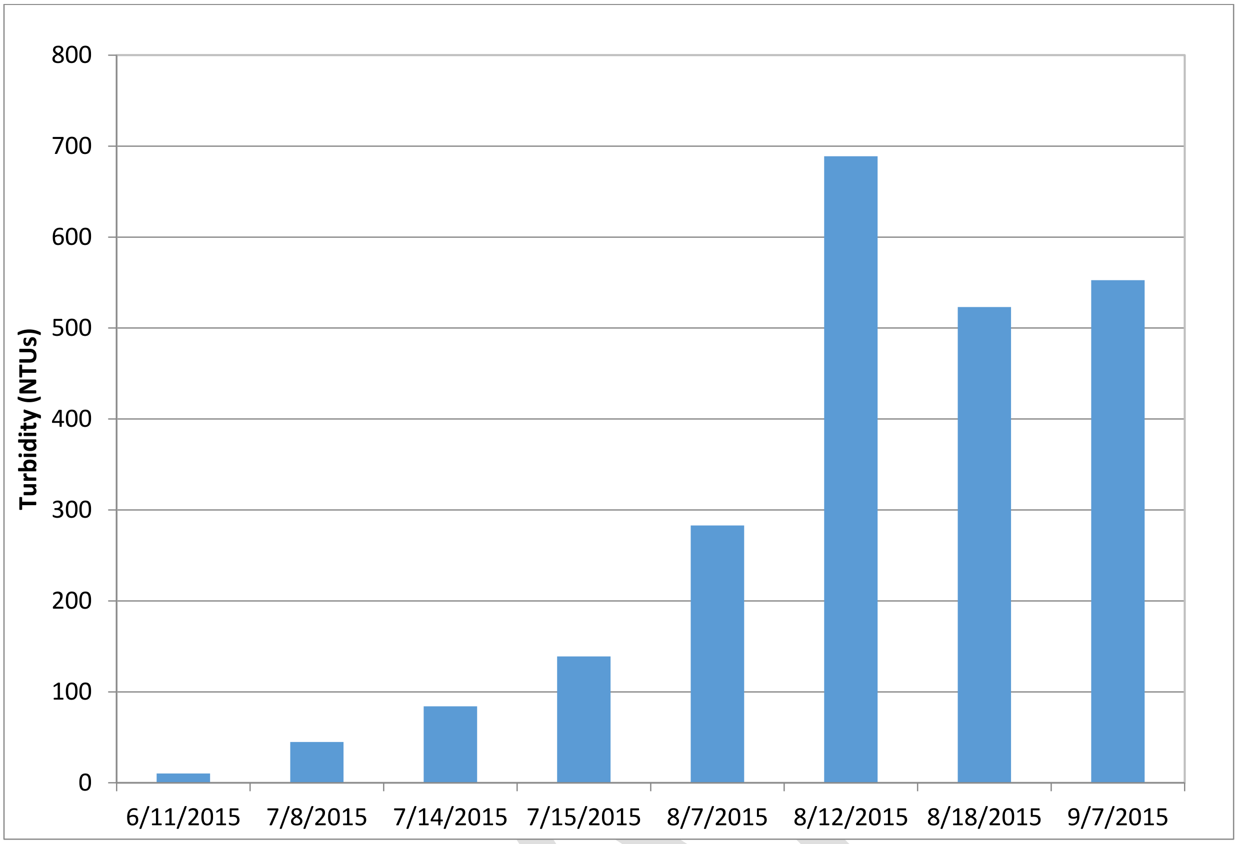

Figure 5.10. Turbidity samples collected at the Sholes Glacier.

General trends in stream temperature, discharge and air temperature were very similar amongst all glacier streams. Rain events in summer caused large increases in Q, and decreases in ST and AT. The heavy precipitation event on August 29th likely facilitated snow and ice melt in all watersheds, resulting in large spikes in discharge. When normalized for their watershed areas, it is apparent that Hadley Glacier watershed produces more stream discharge per area than Dobbs throughout the baseline summer period. Suspended sediment concentrations at each glacier stream have yet to be analyzed; however, turbidity samples can be compared between the field sites. Sholes Creek was the most turbid of all the streams, particularly during high air temperature events. Hadley Creek was much more turbid than Dobbs, even though Dobbs had overall greater discharge and watershed area. Bagley Creek and Dobbs Creek had SSC lower than 10 mg/L, which is representative of a snow and rain dominated watershed. Time series turbidity data for Sholes Glacier indicates that there is a marked spike in turbidity from snow melt to glacier ice melt periods—snowmelt laden waters have less turbidity that glacier melt laden waters. Although general trends in discharge, turbidity, air temperature and stream temperature were similar among the glacier creeks, the setup of each field station was slightly different resulting in variations of results. Not every field site can be identical in instrumentation, making comparison between sites less clear. However, trends are discernable in discharge, stream temperature, and turbidity between the glacier-fed streams and the non-glacier fed streams.

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Photo Log

Appendices

Photo Log