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The effect of climate change on glacier ablation and baseflow support in the Nooksack River basin and implications on Pacific salmonid species protection and recovery

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Abstract The Nooksack Indian Tribe (Tribe) inhabits the area around Deming, Washington, in the northwest corner of the state. The Tribe is dependent on various species of Pacific salmonids that inhabit the Nooksack River for ceremonial, commercial, and subsistence purposes. Of particular importance to the Tribe are spring Chinook salmon. Since European arrival, the numbers of fish that return to spawn have greatly diminished because of substantial loss of habitat primarily due to human-caused alteration of the watershed. Although direct counts are not available, it is estimated that native salmonid runs are less than 8 % of the runs in the late 1800's. In addition, climate change has caused and will continue to cause an increase in winter flows, earlier snowmelt, decrease in summer baseflows, and an increase in water temperatures that exceed the tolerance levels, and in some cases lethal levels, of several Pacific salmonid species. The headwaters of the Nooksack River originate from glaciers on Mount Baker that have experienced significant changes over the last century due to climate change. Melt from the glaciers is a major source of runoff during the low-flow critical summer season, and climate change will have a direct effect on the magnitude and timing of stream flow in the Nooksack River. Understanding these changes is necessary to protect the Pacific salmonid species from the harmful effects of climate change. All nine salmonid species that inhabit the Nooksack River will be adversely affected by reduced summer flows and increased temperatures. The most important task ahead is the planning for, and implementation of, habitat restoration prior to climate change becoming more threatening to the survival of these important fish species. The Tribe has been collaboratively working with government agencies and scientists on the effects of climate change on the

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hydrology of the Nooksack River. The extinction of salmonids from the Nooksack River is unacceptable to the Tribe since it is dependent on these species and the Tribe is place-based and cannot relocate to areas where salmon will survive.

1 Introduction

Glaciers in the North Cascades Mountains of Washington State are a critical water supply source, serving as water storage reservoirs, and their response to climate change will impact the region's water resources and fish habitat over the next century and beyond. The North Cascades occur in the north central and western portion of the State of Washington and are a very likely place for the occurrence of glaciers because of the high amount of winter precipitation (~80 % of annual mean) and relatively high altitude terrain that occurs in the snow accumulation zone (Hamlet et al. 2005). More than 700 glaciers cover 225 km^2 and yield approximately 800 m^3 of runoff each summer on the average (Post et al. 1971; Riedel and Larrabee 2011).

Air temperature, alpine snowpack, glacier extent, and streamflow in Washington have already experienced significant changes since 1950. Glacier area and volume loss have been extensive throughout the 20th century, and have been well documented by many researchers (e.g. Granshaw and Fountain 2006; Nolin et al. 2010; Riedel and Larrabee 2011; and Pelto 2010). The timing and magnitude of streamflow in a high relief, snow-dominated basin, such as the Nooksack River basin, is strongly influenced by changes in temperature and precipitation (Elsner et al. 2010; Bach 2002). The Nooksack River (Fig. 1) is comprised of three forks (North, Middle, and South) that converge near Deming, Washington, and is fed by glaciers on Mount Baker, Mount Shuksan, and other nearby peaks of the North Cascades. There are at least eight source glaciers within the Nooksack River watershed on Mt. Baker and include the Deming, Thunder, Coleman, Roosevelt, Mazama, Sholes, Heliotrope and Hadley glaciers (Fig. 1). If glacial recession continues at its present rate, many of these glaciers may disappear entirely and their contribution to streamflow could be lost (Bach 2002).

Forecasts developed from regional general circulation models (GCM) predict increases in temperature and variable changes in precipitation over the next century that will affect snow accumulation, snow melt, glacier size, and streamflow. Of particular concern in the Nooksack River is the substantial loss of glacier-melt contribution to streamflow during the low-flow summer season. Summer baseflows have already decreased and stream temperatures have increased thereby adversely impacting Pacific salmonid habitat and fish survival (Elsner et al. 2010; Mantua et al. 2010). Several of the nine salmonid species and populations (i.e., evolutionarily significant units, or ESU's) are protected under the federal Endangered Species Act (ESA). Of particular importance to the Tribe is spring Chinook salmon that return to hold, spawn, and rear in the Nooksack River. These fish are vital resources to the Tribe for ceremonial, subsistence, and commercial uses. Understanding the importance and magnitude of climate change effects on glacier-generated streamflow and fish habitat is imperative to effective planning for the restoration of damaged habitat under the current climate conditions and the future recovery and protection of fish in the Nooksack River watershed under future climate conditions. Since European arrival, the numbers of fish that return to spawn have greatly diminished because of substantial loss of habitat primarily due to human-caused alteration of the watershed. Although direct counts are not available, it is estimated that native salmonid runs are between 2 and 8 % of the runs in the late 1800's (Lackey 2000). Declines in salmon and habitat due to the

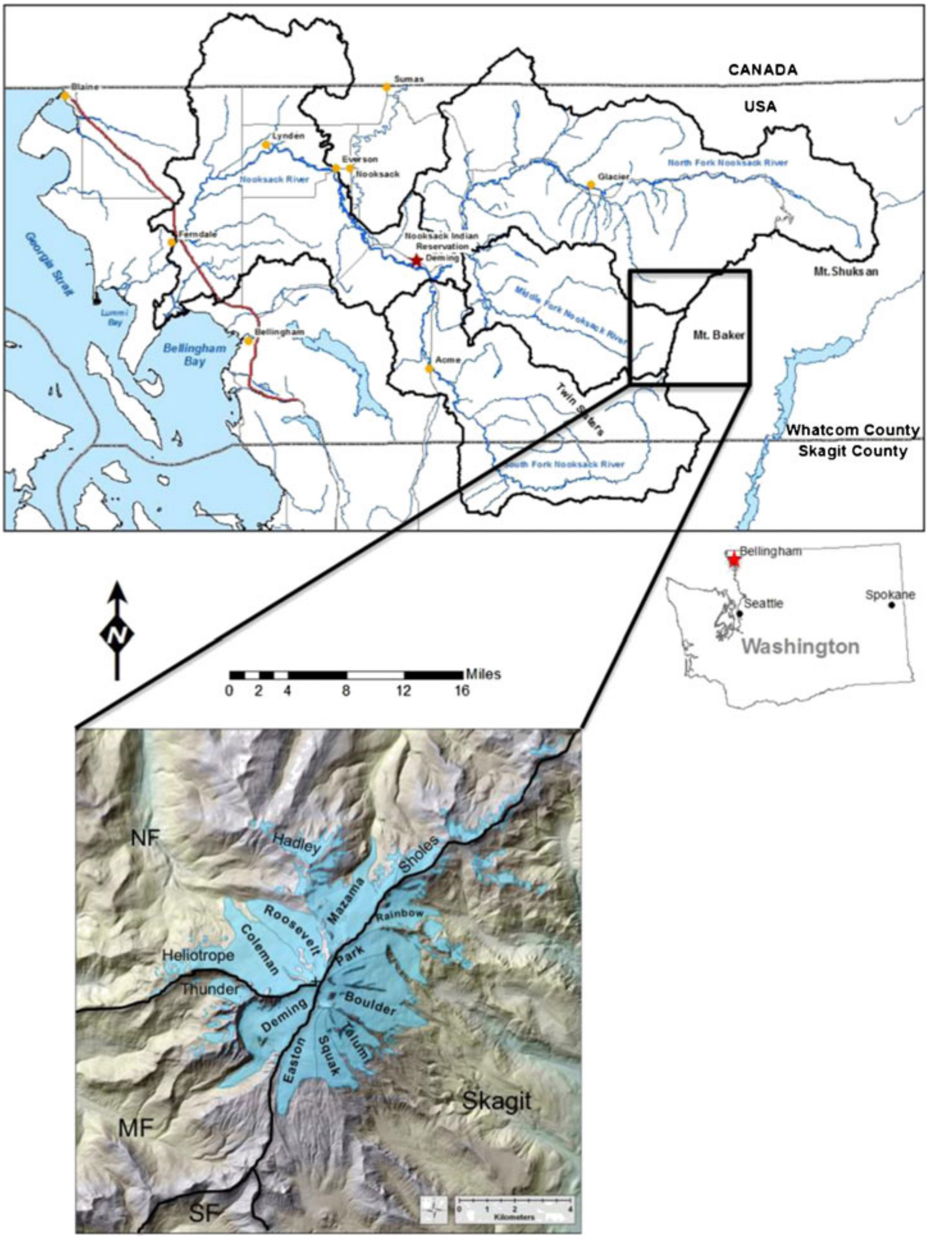

Fig. 1 Geography of the Nooksack River basin near Bellingham, WA and glaciers on Mount Baker (data source: http://glaciers.research.pdx.edu/glaciers-washington)

adverse effects of land use and climate change pose immediate risks to Tribal rights and their way of life (Colombi 2009; Dittmer 2013). The potential extinction of salmonids from the Nooksack River is unacceptable to the Tribe. The Tribe is dependent on salmon in the Nooksack River, is place-based, and thus cannot move their base to where salmon are located.

2 Recorded trends in climate, streamflow, and glaciers

2.1 Climate trends of the PNW

Climate in the Pacific Northwest (PNW) is dominantly affected by atmospheric-oceanic circulation patterns like the Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO) because of its proximity to the Pacific Ocean. Within the Nooksack River watershed, elevation rises from sea level to 3,285 m on Mt. Baker over a distance of approximately 53 km. This relatively steep elevation gradient creates substantive orographic effects that intensify these weather patterns. Mean annual temperature has increased 0.8 °C between 1920–2003, with most warming occurring since 1975 (Hamlet and Lettenmaier 2007; Mote 2003). This rate is 50 % greater than the average global warming during the same period (Mote 2003). Between 1920 and 2000, annual precipitation in the PNW increased approximately 14 %, with a 37 % increase in spring, 12 % increase in winter, 9 % increase in summer, and a 6 % increase in autumn (Mote 2003). The intensity of precipitation has slightly increased, and is more prominent during winter months.

The western slopes of the North Cascades receive approximately 1,250 mm of precipitation annually that predominantly falls as snow during the cool season (October–March). This region relies on melting snowpack and glaciers to sustain runoff during the warm season from April–September (Elsner et al. 2010). Snowpack is sensitive to both temperature and precipitation, but temperature is the dominant driver of changes in snowpack and glacier extent (Elsner et al. 2010; Mote et al. 2005; Hamlet et al. 2005; Mote and Salathé 2010). Because of its maritime climate, a large part of the North Cascades that accumulates snow is only a few degrees below freezing during the winter months, making snowpack much more vulnerable to small increases in winter temperature (Stewart 2009). The observed increases in winter temperature have caused more precipitation to fall as rain rather than snow, which has resulted in declining glacier mass balance and altered streamflow regimes (Mote et al. 2008; Pelto 2008; Elsner et al. 2010).

Snowpack is commonly measured as snow water equivalent (SWE, ratio of depth of liquid water to depth of snow containing that water), and is determined near its peak on April 1st. Between 1950–2006, snowpack has declined 25 % in the North Cascades, with the largest decreases at low to mid elevations (<2,000 m) (Mote et al. 2008). Lower elevations (<1,000 m) have experienced decreases in SWE by 40 % or more, and higher elevations (>2,000 m) have experienced decreases in SWE of 15 % to 35 % relative to the 1916–1970 period (Mote et al. 2008). This gradient is strongly correlated with the observed increases in temperature and declines in snow precipitation (Mote 2003; Mote et al. 2005). Casola et al. (2009) and Minder (2010) have estimated that approximately 15 % loss of snowpack occurs per 1 °C increase in air temperature.

2.2 Climate trends in the Nooksack River watershed

Meteorological data has been collected within the Nooksack River watershed at various locations and elevations, with a varied range of record lengths. The Clearbrook weather station has the longest record dating back to 1895, and is located approximately 42 km west-northwest of Mount Baker at an elevation of 20 m. This station is useful for low-elevation climate trends, but is not necessarily representative of the climate conditions affecting the glaciers. Snow telemetry (SNOTEL) stations within the watershed are at higher elevations on the flanks of Mount Baker, yet have shorter record periods making trends, if any, more difficult to discern. The most valuable high-elevation records are those of the Wells Creek and Schreiber's Meadow stations, dating back to 1995 and 1959, respectively. The Wells Creek station (1,228 m) is located on the north side of Mount Baker and Schreiber's Meadow station (1,036 m) is located on the south side. High elevation observations of temperature and precipitation are crucial for assessing meteorological effects on glaciers and streamflow in the lower elevations of the watershed, but longer records are necessary to interpret trends.

Mean annual temperature at Clearbrook has increased 1.4 °C from 1895 to 2010 at a rate of 0.12 °C per decade (OWSC 2012), whereas Wells Creek has only experienced a slight increase (~0.3 °C) in mean temperature from 1995 to 2010 (NRCS2012). Overall, summer temperatures have increased more than winter temperatures, which is consistent with trends in the region. Compared to the state average, the Nooksack River watershed has lower than average summer temperatures and higher than average winter temperatures due to its maritime climate.

Annual precipitation at Clearbrook has decreased by 11 % from 1895 to 2010, with summer precipitation increasing 11 % and winter precipitation decreasing by 26 %. This is not consistent with other regional trends, as winter precipitation has generally increased more than summer precipitation throughout the state (OWSC 2012). Winter precipitation at Wells Creek has also slightly decreased from 1995 to 2010, which is not obvious from 2010 to 2012 when there exists a positive trend in winter precipitation due to the La Nina phase of ENSO. April 1st SWE at Schreiber's Meadow has decreased nearly 26 % from 1959 to 2012, but decreased nearly 31 % prior to La Nina in 2010 (NRCS 2012). This is consistent with trends throughout the North Cascades at elevations below 2,000 m. Longer-term records and higher elevation weather stations are necessary for a more meaningful analysis of climate trends in the Nooksack River Basin.

2.3 Trends in glacier mass balance

Glaciers have long been the most visible and sensitive indicators of climate change and serve as one of the most useful proxies for measuring such change. Regional and local climate affects the magnitude of accumulation and ablation (or loss of ice volume and extent due to melt and sublimation), or mass balance, on a glacier depending on temperature and types and amounts of precipitation. The North Cascades glaciers are losing mass not only because of an extended melting season, but because they are receiving less snow accumulation. Precipitation is more frequently falling as rain rather than snow, resulting in a snowpack that cannot retain meltwater internally by refreezing, thereby reducing the amount of ice lenses and overall glacial ice accumulation (Kaser and Osmaston 2002). Estimates from Granshaw and Fountain (2006) suggest that ice cover in the North Cascades National Park, located approximately 8 km east of Mt. Baker, has reduced by 50 % in the last 100 years. Pelto (2006) states that 75 % of the North Cascade glaciers are rapidly thinning in their accumulation zone and are in disequilibrium with the current climate. The remaining 25 % generally occur at higher elevations and could approach equilibrium under the current climate without further warming. Pelto (2010) concluded that glacial retreat and declining mass balance is ubiquitous, rapid and increasing, with widespread thinning across the entire length of the glaciers suggesting that retreat will continue in the foreseeable future with continued climate change.

Mount Baker is the most northerly stratovolcano in the North Cascades with 12 main glaciers (including two small glacierets) covering an area of 38.6 km^2 and ranging in elevation from 1320 to 3270 m (Pelto and Brown 2012). Approximately 22 km^2 of glaciated area drains into the Nooksack River (Table 1). Pelto and Brown (2012) show that the average retreat of glacier termini has been approximately 370 m over the period of 1979–2009. Mt.

Table 1 Characteristics of Mount Baker glaciers, including retreat from 1979 to 2009, the drainage basin (Middle Fork (MF), North Fork (NF), or Skagit (SK)), and cumulative mass balance (MB) and survival factor (SF) for the period 1990–2008 (Easton and Sholes) and 1986–2008 (Rainbow). Table adapted from Pelto and Brown (2012) and Pelto (2010)

Glacier Name	Area (km^2)	Elevation Range (m)	Aspect (deg)	Retreat (m)	Drainage	Cumulative MB (m)	SF
Deming	4.79	1350–3200	215	−360	MF	–	–
Easton	2.87	1680–2900	195	−320	SK	−9.41	Yes
Squak	1.55	1700–3000	155	−300	SK	–	–
Talum	2.15	1800–3000	140	−240	SK	–	–
Boulder	3.46	1530–3270	110	−520	SK	–	–
Park	5.17	1385–3270	110	−360	SK	–	–
Rainbow	2.03	1340–2200	90	−480	SK	−8.16	Yes
Sholes	0.94	1610–2110	330	–	NF	−10.59	No
Mazama	4.96	1480–2970	10	−410	NF	–	–
Coleman	4.13	1380–3270	320	−340	NF	–	–
Roosevelt	3.57	1584–3270	320	−340	NF	–	–
Thunder	0.81	1870–2490	295	–	MF	–	–
Hadley	0.78	1880–2237	30	–	NF	–	–
Heliotrope	1.68	1885–2362	0	–	MF	–	–

Baker mass balance and accumulation area ratio (AAR) values are generally higher than the rest of North Cascade glaciers because of higher elevations and greater amounts of winter precipitation. As a result, the accumulation zones on Mt. Baker glaciers have experienced minimal thinning, although termini have seen significant retreat (Pelto and Brown 2012). Rainbow, Easton and Sholes glaciers have been observed since 1990, though only the Sholes Glacier drains into the Nooksack River. The mean annual balance of these glaciers has been −0.51 m w.e. from 1990 to 2010, which corresponds to a mass loss of 12–20 %, assuming the mean thickness of is 50–75 m (Post et al. 1971; Harper 1993; Pelto and Brown 2012). Rainbow and Easton glaciers are not experiencing significant thinning in their accumulation zones, suggesting that they are undergoing an equilibrium response to the current climate. Although retreating, they could theoretically approach a new stable position, but it is unlikely. It is uncertain whether the same response applies to future climatic conditions. There are minimal field observations of the glaciers that directly feed the Nooksack River, emphasizing the need for more thorough investigation.

Despite localized differences in glacier behavior, all North Cascades glaciers are responding to regional climate change. Correlation coefficients between each glacier exceed 0.8 indicating a widespread similar response amongst all glaciers (Pelto 2010). This does not depreciate the importance of local orographic effects that control amounts of precipitation delivered to the glaciers. Mt. Baker receives the most snowfall in the North Cascades, which buffers increasingly negative glacier mass balances, relative to other North Cascade glaciers. Precipitation trends in the Nooksack River watershed indicate that winter precipitation is overall decreasing, which is not consistent with regional trends. If this trend continues, glaciers on Mount Baker will accumulate increasingly less snow, ultimately having many implications for mass balance and streamflow.

2.4 Trends in Nooksack River streamflow and temperature

The effects of changes in snow accumulation and glacier mass balance on streamflow in the river have been measured in response to climate change. Studies by Pelto (2008) throughout the watershed compare the historical average discharge of the North Fork (NF) Nooksack River, Middle Fork (MF) Nooksack River, and main stem of the Nooksack River during the ablation season (July–September). From 1963 to 2003, average summer streamflow decreased by nearly 30 % and winter flows increased approximately 1 % (Bach 2002; Pelto 2008). The average decreases in summer flows were 21 % in the NF Nooksack River at Glacier and 28 % in the main stem at Ferndale. Flows in the MF Nooksack River have consistently decreased between 1934 and 2003, but measurements are made below a diversion dam, so trends are not purely representative of climate conditions or glacier behavior. The mean meltwater contribution of high elevation snowpack to summer flow in the Nooksack River basin is estimated to be nearly 30 % of the mean daily discharge (Bach 2002). This estimate is similar to the heavily glaciated Thunder Creek basin in North Cascades National Park (NPS 2012; Pelto 2008). If the current climate trend continues, and glacier mass is absent, there will be 20–30 % less summer flow and spring peak runoff will occur earlier in the year. Mean annual discharge has not significantly increased as a result of increased glacier contribution suggesting that precipitation levels and snowcover are decreasing at approximately the same rate (Bach 2002).

Adverse changes in streamflow caused by climate change also exacerbate stream temperatures. A study by Isaak et al. (2011) and others assessed long-term stream temperature trends in the PNW from 1980 to 2009. They detected a cooling trend in the spring and a warming trend in the summer, fall and winter, with net warming of +0.22 °C (Isaak et al. 2011). Air temperature was responsible for 82–94 % of the variability in stream temperature. These results suggest that many streams in the PNW are responding to climate change (Isaak et al. 2011).

The Tribe has been measuring stream temperatures throughout the Nooksack River watershed since 1999 to establish a baseline and to detect trends in temperature. Data indicates that stream temperatures closely mirror air temperature, but no discernible trends in stream temperatures are evident (NIT 2012). However, this relationship emphasizes that under climate change, when atmospheric temperatures increase, stream temperatures may also increase.

3 Climate projections with climate change

3.1 Climate projections for the PNW

In the PNW, mean annual temperature is projected to increase 1.1–2.9 °C and annual precipitation will likely increase 1.3–3.8 % by the 2080s, averaged and compared to 1970–1999 (Mote and Salathe 2010). Temperature will increase for all seasons, with most warming in the summer months, but changes in precipitation are less certain than changes in temperature (Mote and Salathe 2010). Summer precipitation will likely decrease 14–40 % by 2080s, and winter precipitation will increase on average by only 8 % by the 2080s. There will likely be an increase in frequency and duration of extreme precipitation, though variable in magnitude (Salathe 2006; Rosenberg et al. 2010; Tebaldi et al. 2006), and an increase of 5–10 % in storm intensity for the North Cascades (Salathe et al. 2010). Models project there will be between 27–65 % decrease in annual snowpack by the 2080s relative to the 1971–2000 average (Elsner et al. 2010). By the 2080's, snowpack will decrease 36–71 % below 1,000 m, 25–63 % at mid-elevations between 1,000–2,000 m, and 15–54 % above 2,000 m

(Elsner et al. 2010). The 0 °C isotherm will continue to retreat to higher elevations, resulting in a reduced area of snow accumulation and earlier snowmelt.

3.2 Projections for the North Cascade and Mount Baker glaciers

Those glaciers with accumulation zone thinning, emergence of new outcrops, recession of margins, which includes 10 of 12 North Cascade glaciers with annual measurements, are not forecast to survive the current climate (Pelto 2010). Accumulation area ratio (AAR) observations are frequently below 30 % suggesting a lack of consistent accumulation, which will continue in the foreseeable future (Pelto 2010). Also, those glaciers with the lowest mean elevation have, and will likely experience, the most dramatic changes in volume. Conversely, higher elevation glaciers, like those on Mt. Baker, have the capacity to approach equilibrium with the current climate conditions, though it is unlikely if mean temperature continues to increase. Once glaciers retreat to their accumulation zones, they are substantially less sensitive climate and their retreat rate declines (Hoffman et al. 2007).

If precipitation projections exhibit net increases, higher elevation glaciers may still accumulate significant amounts of snowfall. Although snowpack is projected to decrease overall, it may still remain robust at the highest elevations. Increased summer temperatures will result in higher melt rates, but increased winter precipitation may result in greater snow depth at higher elevations that could potentially buffer the direct melt of glacial ice (Bach 2002). Alternatively, if winter temperatures increase enough to cause precipitation to dominantly fall as rain rather than snow at elevations above 2,000 m, glacial ablation could eventually occur during all seasons, significantly increasing glacier loss. The combined influence of increased temperature and increased precipitation on higher elevation glaciers with climate change is still uncertain because most monitoring has occurred at low to mid-elevations, and downscaling methods are too coarse in scope. There is a perceived inconsistency between the trends seen over the last half century, which indicate that winter precipitation is decreasing, and the projections for the region, which indicate that winter precipitation will increase. This must be addressed with finer-scale downscaling models in order to infer changes to glacier accumulation and its subsequent effect on streamflow and salmon habitat. The Tribe has initiated studies that will focus on higher elevations on the glaciers of interest.

3.3 Projected changes in streamflow

As a result of changes in the timing of precipitation, declining snowpack, and glacier retreat, streamflow timing will likely shift significantly to earlier spring runoff. Increases in stream temperature are also expected as there will be less snow and ice contribution to summer runoff (Elsner et al. 2010). Summer baseflows in the PNW will initiate earlier in the summer and will diminish further into late summer and early fall. The warm season (April to September) runoff is projected to decrease by 16–19 % by the 2020s, 22–28 % by the 2040s and 34–43 % by the 2080s (Elsner et al. 2010). This will result in depleted Pacific salmonid summer and fall habitat due to reduced quality and quantity of flow, which limits spawning and rearing habitats and overall ecosystem health. The degree of adverse impact will depend on the specific species, stock, and life stage. By 2040, 16 watersheds in the Cascades, including the Nooksack River watershed, are characterized as critical basins with water shortages for fish habitat that will experience a significant to severe impact on summer low flows (Fig. 2). The cool season (October to March) runoff is projected to increase by 10–13 % by the 2020s, 16–21 % the 2040s and 26–35 % by the 2080s as a result of projected increased winter rain precipitation and melting snowpack. Because of increased winter

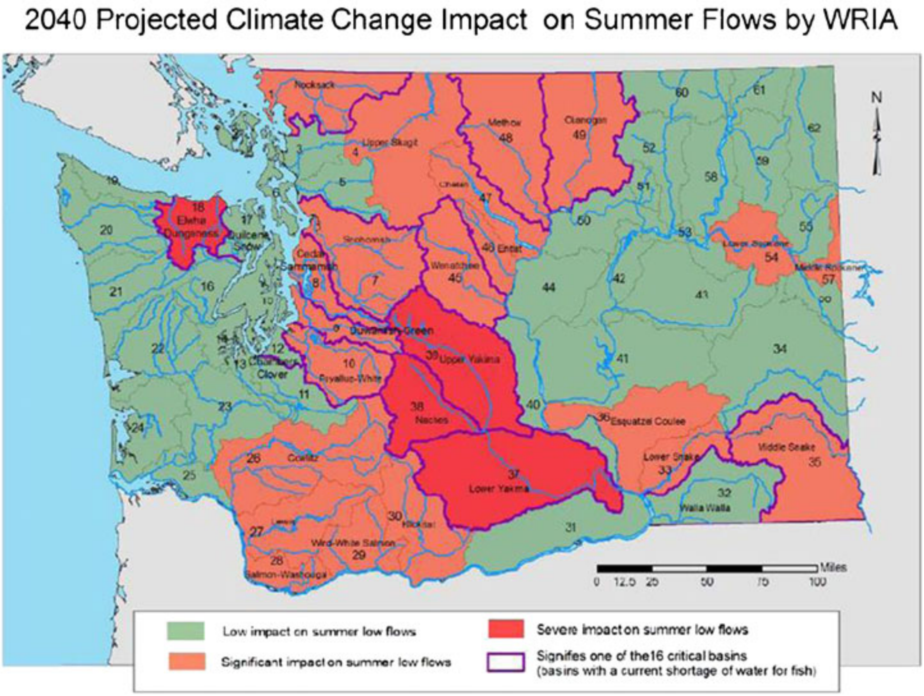

Fig. 2 Projected impact of climate change on summer low flows by the year 2040 for major watersheds in Washington State (From WTAGBI Report 2010)

flows, the total annual streamflow is expected to increase on average across the state by 0–2 % by the 2020s, 2–3 % by the 2040s, and 4–6 % by the 2080s (Elsner et al. 2010). Though modest, these changes will be primarily driven by increases in winter precipitation, regardless of whether it falls as rain or snow.

Dickerson and Mitchell (2012, in review) have modeled the effects of climate change on streamflow in the Nooksack River watershed, where they simulated future streamflow in the entire Nooksack River watershed by utilizing a range of future climate conditions produced by GCMs. Their results from three model simulations predict that a substantial increase in winter (30 to 97 % increase), spring (23 to 32 % increase), and fall (21 to 30 % increase) streamflow, and a substantial decrease in summertime flows (up to 40 % decrease) will likely occur by the year 2075. The Climate Impacts Group (2013) downscaled models suggest similar changes in streamflow. Spring snowmelt peak runoff will likely shift to earlier in the year and eventually combine with the winter peak runoff generated by rainfall as the snow-dominant portion of the watershed trends toward a transitional watershed, and the transitional portion of the watershed trends toward a rain-dominant watershed. Thus, the shape of the hydrograph will change, with one broad peak occurring from December through May, and quick recession to baseflow levels in July. As such, baseflows will initiate earlier in the summer and extend through October.

The glacial melt contribution to streamflow will eventually decrease as atmospheric temperatures increase and glacial extent decreases (Dickerson and Mitchell 2012, in review); however, the proportion of the summer baseflows contributed by glacier melt will increase due to reduction in precipitation in the summer time with climate change (Riedel and

Larrabee 2011). Seasonal snowpack, however, has the most control of streamflow in a changing climate. Simulations indicate that maximum SWE will decrease through time and shift to earlier in the season resulting in earlier spring melt peak, which is consistent with other regional research (Elsner et al. 2010; Mote and Salathe 2010; Hamlet et al. 2005). Additionally, warmer winter temperatures will lead to more rain-on-snow events that cause more frequent and higher peak flow events (Dickerson and Mitchell 2012, in review).

Mitchell (2013) found that the glacial meltwater component of late summer streamflow in the MF Nooksack River varied considerably for a range of climate conditions and scenarios. Glacier meltwater contribution was between 8.4 % and 26.1 % of total flow for the present climate conditions and 33.7 % for the predicted climate conditions. The results of the study further suggest that late-summer runoff could be reduced by anywhere between 3.1 % and 8.6 % as a result of a 17 % reduction in glacier size predicted for the next 50 years, and a reduction ranging from 6.7 % to 19.4 % as a result of a 48 % reduction in glacier size predicted for the year 2150. Overall, there will likely be an increase in glacier melt contribution to summer baseflows, followed by a substantial reduction once the glaciers entirely recede.

Similar studies have been conducted in other PNW watersheds that quantify the glacier melt contribution to streamflow. Pelto (2011) assessed glacier retreat and summer runoff in the Skykomish River Basin in Washington from 1950 to 2009 and found that the 45 % reduction in glacier area over this period led to a 38 % reduction in glacier runoff. The decline in glacier contribution to river discharge was only pronounced during low flows in late summer. A study conducted in the Hood River Basin of Oregon showed that 41–73 % of late summer streamflow is derived from glacier melt (Nolin et al. 2010). The study found that although projected temperature increase will increase glacier melt contribution to streamflow, widespread glacier recession will ultimately lead to substantial declines in streamflow during the summer months. However, glacier runoff will stay the same or increase if the glacier-covered area decreases <15 % for every 1 °C increase in temperature (Nolin et al. 2010). The methodologies of these studies should be incorporated into future research and planning in the Nooksack River watershed to fully assess the impact of climate change on glacier ablation, streamflow, and subsequent loss of fish habitat. The Tribe is implementing studies on Mt. Baker glaciers to better determine their behavior in response to recent climatic trends and subsequent climate changes in regard to glacier melt contributions to the Nooksack River.

4 Implications for salmonids

The Nooksack River watershed supports nine species of salmonids including populations of Chinook (spring and fall), riverine sockeye, chum, pink (even- and odd-year), and coho salmon, steelhead/rainbow, cutthroat, and bull trout, and Dolly Varden (WRIA1 SRB 2005). The abundances of two spring Chinook populations are 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 ESU's; both populations are considered essential for recovery of the ESU (WRIA1 SRB 2005; WDFW 2002). It is clear that abundances of several local salmonids populations have diminished substantially from historic levels (WRIA1 SRB 2005), as only two of 16 salmonid stocks identified by Washington State Salmonid Stock Inventories are currently considered healthy (WDFW 2002). Further, although direct counts are not available, it appears that native salmonid runs are less than 2 to 8 % of the runs in the late 1800's (Lackey 2000).

Habitat degradation is the leading cause of decrease in salmonid populations in the Nooksack River watershed. Both decreasing summertime stream flows as a result of decreased glacier melt contribution and increasing stream temperatures with climate change will further reduce habitat and stress salmonids. Low summer flows will cause a lack of deep pools and side channels for thermal refugia, and will cause even further warming of stream temperatures alongside the warming due to increased air temperatures. Periods of high flow due to increased glacier-melt during warm summers will cause increased sediment load (particularly fine sediment), redd scour, and altered stream networks that may disconnect side channels thereby stranding juveniles. Spring Chinook are of particular concern to the Tribe and are especially limited by these factors because they are the most endangered (WRIA1 SRB 2005). Predicted decreases in summertime low flows will further reduce available habitat by 10 % for spring Chinook during the summer holding period based on weighted usable area habitat curves presented by WRIA1 (2000). Climate change-induced increases in frequency of rain-on-snow events and intensity of precipitation events during the winter may cause debris-flow events that result in channel and habitat changes that further adversely effect salmonids.

Increased air temperatures as a result of climate change combined with deteriorating riparian cover as a result of land-use will produce higher water temperatures that are lethal to salmonids. Water temperature has already increased alongside population growth in the area, yet climate change has exacerbated this dynamic. High water temperatures during summer represent an important limiting factor for spring Chinook and other salmonids in the Nooksack River watershed, especially in the South Fork of the Nooksack River, which is a Clean Water Act (CWA) Category 5 303(d) listed for high temperatures. High water temperatures in the South Fork frequently exceed optimal temperature ranges and approach lethal limits for salmonids (WRIA1 SRB 2005). Stream temperatures frequently exceed 20 °C, and sometimes exceed 24 °C well in excess of the temperature ranges considered optimal for Chinook incubation (11–15 °C) and juvenile rearing (14.2 °C –16.8 °C) (Beechie et al. 2012). High temperatures stress holding and spawning fish, and increase susceptibility to disease, which can cause pre-spawn mortality or otherwise reduce reproductive success (WRIA1 SRB 2005). Continued increases in stream temperatures and reduced meltwater from glaciers with climate change will further stress all nine species of Nooksack River salmonids during all of their life history stages including migration, holding, spawning, intra-gravel development, rearing, and out-migration (Currence 2013). Spring Chinook salmon are especially susceptible to further habitat loss and are particularly important to the Tribe for cultural, subsistence, and commercial uses. Thus extinction of this species is not an option.

Continued increases in heat loading and reduced contribution of snow and ice melt to streams will result in increased water temperatures in the PNW with subsequent impact on aquatic habitats. Statewide, the annual maximum average water temperature will likely raise 1 °C by the 2020s, and 2–5 °C by the 2080s (Mantua et al. 2010). These projections suggest that stream temperature will increase at rates 50–100 % faster than recent decades (Mote et al. 2008; Mantua et al. 2010). According to Poole et al. (2001) and Mantua et al. (2010), stream temperatures in the Nooksack River watershed that are favorable for salmon under the current condition will transition to stressful habitat; and areas that were stressful for salmon will transition to fatal areas. The temperature increases would push temperatures in excess of the optimal and lethal thresholds and the duration of exceedances would likely increase, both of which would pose challenges to the survival and persistence of salmonids. Habitat quality and quantity will continue to decline as summer flows decrease and water temperatures increase, ultimately disrupting the timing of spawning and migration of salmonid species and increasing competition for habitat. As such, reducing the exacerbating effect of human activities and climate change, and implementing effective restoration activities will be fundamental to the survival of salmonids.

Beechie et al. (2012) have evaluated a menu of restoration techniques in the face of climate change and developed a decision support process for adapting salmon recovery plans that incorporates (1) local habitat factors limiting salmon recovery, (2) scenarios of climate change effects on stream flow and temperature, (3) the ability of restoration actions to ameliorate climate change effects, and (4) the ability of restoration actions to increase habitat diversity and salmon population resilience. They found that restoring floodplain connectivity, restoring stream flow regimes, re-planting deforested riparian zones, and re-aggrading incised channels are most likely to ameliorate stream flow and temperature changes and increase habitat diversity and population resilience. Restoring riparian shading along important salmon-bearing streams will be essential to ameliorating increased stream temperatures since current riparian shading is well below that needed to ameliorate high temperatures (Coe 2001). Given that conditions for salmonids in the Nooksack River watershed could transition from favorable to stressful with climate change, as opposed to lethal (Mantua et al. 2010), there is a likelihood that restoration actions could increase the probability of salmon survival in the face of climate change. However, planning for such restoration adapted to climate change must occur immediately to have the benefits of restoration in place before climate change has a substantial effect on stream temperature and flows.

Determining which restoration tools are most effective in the face of continued climate change will be essential to effective and successful restoration following a similar approach to Beechie et al. (2012). Further, climate change is beginning to be considered in temperature TMDLs, such as the South Fork Nooksack River TMDL, but such studies are limited by existing technology and protocol. The EPA and the Tribe (Klein et al. 2013) have initiated a pilot research project that is focused on how to evaluate, design, and implement restoration tools in a temperature TMDL that will address the increase in stream temperatures, loss of glacier melt contributions, decreased baseflows, and increased winter-time flows that adversely affect fish and habitat. This is one of a very few such projects being implemented in the United States. The outputs of the pilot research project will be a set of recommendations that will inform development of the TMDL, and that recommends updates to salmon recovery planning and other land use and restoration planning efforts taking climate change into direct consideration.

5 Conclusions

The Nooksack River is fed by snow and glacier melt that provides critical water resources that support Pacific salmonids. Climate trends generally show an increase in temperatures throughout the year and an increase in precipitation during the winter and spring, less overall snow accumulation, earlier snow melt and runoff, and reduced baseflows. There are significant trends in glacier loss at low elevations, with more negative balances for glaciers below 2,100 m. Lower elevation glaciers are at a greater risk of disequilibrium, but higher elevation glaciers, like those on Mt. Baker could theoretically approach equilibrium with current climatic trends. Because of Mt. Baker's unique response to regional climate trends, it is crucial that future investigations focus on higher elevation climate conditions and develop models that will constrain glacier response to future climate scenarios in the Nooksack River basin. This will allow more accurate predictions of reduced stream flows and integrate those effects with increased stream temperatures.

Existing temperatures during the summer and early fall already reach stressful levels for all nine salmonid species in the Nooksack River. With climate change, increased stream temperatures are predicted that could push temperatures to the lethal level for salmonids. Effective watershed restoration will be essential to promote the survival, persistence, and recovery of salmonids in the face of climate change. The most effective watershed restoration tools include: re-establishment of riparian forests, reconnection of floodplains, and reintroduction of large woody debris in the stream that will facilitate resilient channel response to changes in hydrology, sediment input, and temperature brought on by climate change. Such restoration should be implemented as soon as possible so that the effects of such restoration will be in place by time climate change causes challenging conditions for salmon, particularly spring Chinook salmon. Since the Tribe is place-based and cannot relocate to where the salmon will be, the extinction of salmonids from the Nooksack River is unacceptable. The Tribe has been collaboratively working with various governmental agencies and scientists regarding climate change effects on the hydrology of the Nooksack River so that restoration efforts can reduce the chance that continued climate change will cause extinction of salmonids from the Nooksack River.

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