Water Temperature Conditions in the Snohomish River Basin

July 2021

Prepared for:

Snohomish River Basin Salmon Recovery Technical Committee

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Recommended Citation:

Kubo, J., A. Miller, and E. Davis. 2021. Water Temperature Conditions in the Snohomish River Basin. King County Department of Natural Resources and Parks, Water Land and Resources Division, Seattle, WA.

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Executive Summary

Aquatic temperature conditions affect all salmonid life-stages and influence their health, behavior, and survival. High water temperatures can be lethal to salmonids and warm temperatures can have a wide range of sub-lethal effects. The overarching importance of temperature conditions for salmonids in the Snohomish River basin emphasizes the need to fully address temperature impairments through conservation planning and strategy development. Human activities greatly impact aquatic temperature conditions and strategies which improve impairments and alleviate stressors will be critical for protecting and maintaining productive salmonid populations. Additionally, aggressive action may be needed in the near-term just to offset projected temperatures increases and impairments due to climate change.

Several factors impact aquatic temperature conditions in the Snohomish River basin including land use development (clearing and impervious surfaces), removal of riparian buffers and broader forest cover, channel engineering and alterations, dams, water withdrawals, point-source discharges, and human-caused climate change. These factors can influence temperature conditions by increasing the susceptibility of watercourses to heating and by limiting the exchange and availability of cooler water sources. Additionally, these factors can alter the timing and magnitude of hydrologic and thermal inputs, which influence temperature conditions and thermal regimes throughout the basin.

Various temperature monitoring efforts across the Snohomish River basin have provided useful insight into temperature conditions as well as potential strategies that may improve impaired watercourses. Continued temperature monitoring will be critical to further evaluate temperature conditions and trends moving forward. Observations across the Snohomish River basin indicate that there are widespread temperature impairments, primarily during summer months, with temperatures commonly exceeding Washington State water quality standards. Mainstem reaches of the Snoqualmie, Skykomish, and Snohomish rivers display frequent water quality temperature exceedances with impairments lasting up to several weeks or months. Additionally, several larger tributaries (e.g, Middle Fork Snoqualmie River, Pilchuck River, Raging River, Wallace River, and others) as well as smaller tributaries (e.g., Carpenter Creek, Cherry Creek, French Creek, Patterson Creek, Woods Creek, and others) also display consistent temperature exceedances and in some cases reach lethal levels. The Snohomish River Estuary also displays impaired conditions, partly due to natural condition (e.g., warming on mudflats), with summer temperatures at times being the highest across the entire Snohomish River basin. Observed temperature impairments across mainstem and tributary areas have largely been attributed to factors described above.

Despite the wide-spread occurrence and persistence of warm summer temperature conditions across the Snohomish River basin, several mainstem reaches, tributaries, and floodplain areas display considerably cooler and less impaired temperature conditions. Areas of relatively cooler temperatures may provide thermal refuge for salmonids and have the potential to lower temperature among adjacent watercourses and mainstem areas. Mainstem reaches with temperature moderation and cooling include the middle and lower reaches of the North and South Fork Snoqualmie River, upper mainstem Snoqualmie River from the South Fork Snoqualmie to Snoqualmie Falls, lower Snoqualmie River from Patterson Creek to downstream of the Tolt River, North Fork Skykomish River, Skykomish River around

the confluence with the Sultan River, as well as select middle reaches in the Pilchuck River. Cooling among these mainstem reaches is likely associated with decreased solar exposure due to topographic and riparian shading, cold groundwater inputs, tributary inputs, as well as increased exchange among surface and sub-surface waters (i.e., hyporheic exchange).

Tributaries with relatively cooler temperature conditions, compared to mainstem reaches, include the Tolt River and Sultan River, as well as several smaller tributaries (e.g., Boxley Creek, Griffin Creek, Tokul Creek, Worthy Creek, Quilceda Creek, and others). Cooler temperatures among these tributaries are likely due to less-degraded riparian and forest areas as well as adequate connections to floodplains and groundwater areas. Floodplain areas and side-channel networks among the Skykomish River, Pilchuck River, and Wallace River display moderated and cooler temperatures. Cooler temperatures among these areas may be due to tributary and groundwater inputs, channel complexity and sinuosity, well-shaded side-channel networks, and side-channel log jams, which promote hyporheic exchange and localized shading.

In order to address the widespread temperature impairments across the Snohomish River basin, it will be critical for restoration and protection strategies to not only focus on improving degraded conditions but to support and maintain existing thermal diversity among watersheds (i.e., suitable temperature conditions across space and time). Maximum temperatures are a well-established metric used to evaluate potential temperature impairments and impacts to salmonids. However, various additional aspects of thermal regimes including the timing, duration, rate-of-change, magnitude, and spatial variation of temperature conditions are also critical for salmonids. These thermal aspects can influence salmonid growth, development rates, timing of key life history transitions, and survival. Restoring and maintaining thermal diversity requires consideration of temperature conditions and complexity (i.e., number and diversity of features and their spatial organization) across reaches, floodplains, stream networks, and watersheds. Addressing and understanding temperature conditions and thermal diversity at multiple spatial and temporal scales as well as understanding how these affect salmonids, will be necessary to restore and protect watercourses.

Addressing the suite of human alteration impacting thermal regimes will require the adoption of multiple strategies as well as supporting implementation at both localized and basin-wide scales. The highest priority strategies for improving temperature conditions in the Snohomish River basin include riparian restoration/protection, increasing mainstem and floodplain channel complexity, as well as increasing connectivity within and among channels, floodplains, and tributaries. Riparian protection and restoration are needed basin-wide and may be the greatest near-term actions to provide long-term temperature improvements across the basin. However, riparian restoration alone won't be able to fully ameliorate temperature impairments and meet water quality standards. A suite of concurrent strategies is likely needed to maximize temperature improvements and to fully support localized and basin-wide thermal diversity.

Aside from basin-wide riparian restoration, watercourse-specific strategies may include increasing mainstem and floodplain channel complexity and connectivity though large wood installation, creation and maintenance of side-channel and off-channel areas, removal of bank stabilization, and restoration of tributaries and confluence areas. These approaches are likely beneficial among the Skykomish River, Snoqualmie River, Snohomish River, Tolt River, Sultan River, Pilchuck River, and others. Watercourse-specific strategies may also include increasing complexity in smaller tributaries, side-channels, and

floodplains through re-meandering, large wood placement, restoration/installation of beaver dams and analogs, as well as protecting and restoring wetlands. Additionally, reducing water use that detrimentally impacts late-summer low-flow periods among high water use areas may be needed. This could include limiting exempt wells and adopting water source switches, as well as moderating withdrawals and improving irrigation efficiency across agricultural areas throughout the Snoqualmie, Skykomish, and Snohomish river floodplains. Moving forward, it will be important to not only further understand the impacts of altered temperature conditions on aquatic resources but to also evaluate how the suite of improvement strategies could impact other resource needs in the basin such as agricultural drainage and water availability.

The increased awareness of wide-spread temperature impairments throughout the Snohomish River basin requires an elevated prioritization of strategies that address temperature conditions. It may be necessary to increase actions at a magnitude and scale comparable to the degree and urgency of apparent temperature issues. Additionally, conservation efforts may also need to focus on multiple time horizons for various strategies. Strategies in the near-term may include planting riparian vegetation and increasing groundwater and hyporheic exchange, which could help in slowing warming trends. Strategies in the long-term could focus on restoring/protecting water flow processes, ensuring adequate cold-water refuges, and supporting connectivity throughout a watershed, which could help in providing benefits and protections as the landscape and climate conditions continue to change.

Why is water temperature important for salmon recovery?

The influence of temperature conditions and thermal regimes on all salmonid life-stages emphasize the importance of addressing modifications to natural temperature regimes through salmon conservation planning and strategy development. As cold-blooded species, salmonids' metabolic and physiological processes are greatly affected by water temperature. Water temperature can influence salmonids throughout all life stages including egg and juvenile development, growth rates, life-stage transitions, predominance of life histories, geographic distribution, age at maturity, timing of migration and reproduction, as well as survival across all life stages (Crozier et al. 2008; Quinn 2018). Not only does water temperature govern the distribution, behavior, and health of aquatic life but thermal regimes can be greatly impacted by human activities (Stohr et al. 2011).

High water temperatures can impact salmonid survival across all life-stages (Hicks 2002). High water temperatures (e.g., above 23°C) can be lethal to salmonids and warm temperatures (e.g., 16-23°C) can cause significant sub-lethal effects such as increased susceptibility to disease, metabolic stress, developmental issues, and thermal blockages to migration (McCullough et al. 2001; Hicks 2002).

Specific to adult Chinook salmon, temperatures between 14-20°C can result in decreased energy reserves which impact migration, reproduction, and immune responses (McCullough et al. 2001, 2009; Richter and Kolmes 2005) (refer to Figure 1 and Table 1 for temperature impacts on Chinook salmon). Extended exposure to lethal and sub-lethal temperatures can result in direct pre-spawn mortality as well as indirect effects including increased stress, increased disease susceptibility, altered spawn timing, and decreased reproductive success (Hicks 2002; Quinn 2018). Specifically, prolonged thermal exposure to higher temperatures has been directly correlated with pre-spawn mortality (Keefer et al. 2009; Eliason et al. 2011) and can delay migration and holding resulting in higher energetic costs and lower survival (Caudill et al. 2007; Isaak et al. 2018; Crozier et al. 2020). During spawning and incubation, constant temperatures in the range of 8-10°C and daily maximum temperatures below 13-15°C are necessary to ensure that fertilized eggs have high survival success and so embryos develop properly (Hicks 2002). Higher water temperatures during development can alter fry emergence timing which can influence survival rates due to predation, disease, and starvation (Richter and Kolmes 2005; Crozier et al. 2008).

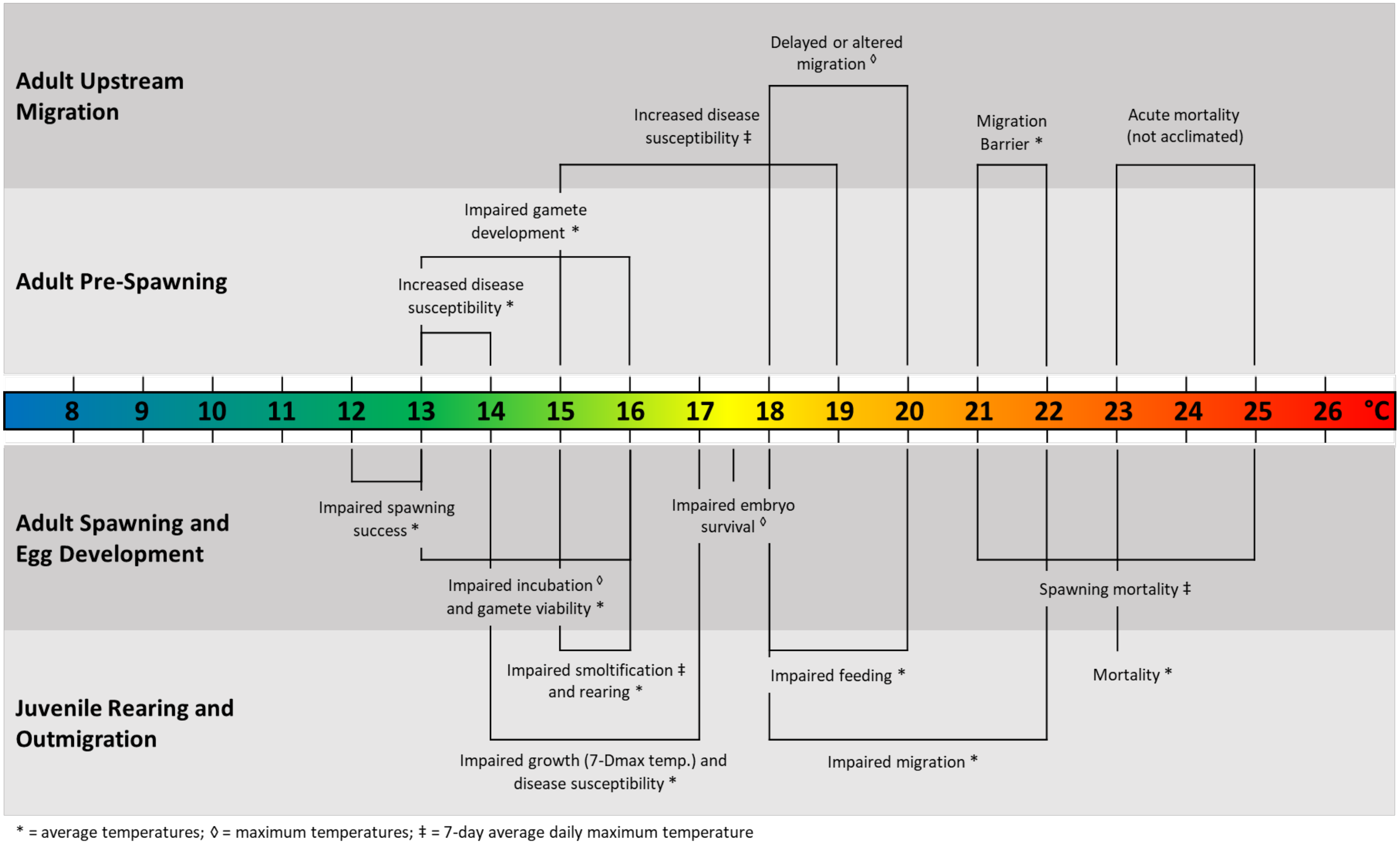

***Figure 1**: Temperature impacts on juvenile and adult Chinook salmon; * = average temperatures; ◊ = maximum temperatures; ‡ = 7-day average daily maximum temperature (i.e., the arithmetic average of seven consecutive measures of daily maximum temperature). Refer to Table 1 for additional information.*

***Table 1**: Temperature impacts on juvenile and adult Chinook salmon. The 7-day average daily maximum temperature (7-DADMax) is the arithmetic average of seven consecutive measures of daily maximum temperature.*

Life Stage	Impaired and Detrimental Temperature Range	Potential Temperature-related Impacts	Citations
Adult Upstream Migration	• Delayed or altered Migration: average >15°C, maximums >18-20°C, 7-DADMax >20°C • Complete migration barrier: average 21-22°C • Disease susceptibility: average >17.5°C, 7-DADMax >15-19°C • Acute mortality (not well acclimated): 23-25°C • Instant mortality: 32-33°C	• Increased metabolic demand • Delayed migration • Increased disease exposure • Direct lethality	Hallock et al. 1970; Fryer and Pilcher 1974; Alabaster 1988; Schreck et al. 1994; McCullough 1999; Materna 2001; McCullough et al. 2001; Farrell et al. 2008; Keefer et al. 2018; Crozier et al. 2020
Adult Pre-spawning	• Disease susceptibility: average >13-14°C, maximums >17-18°C • Gamete development: average >13-16°C	• Increased susceptibility to pathogens (e.g., *Ichthyophthirius multifillis*, *Ceratomyxa shasta*, columnaris disease) • Increased disease virulence • Decreased immune system condition • Reduced gamete quality and quantity	Fryer and Pilcher 1974; Schreck et al. 1994; Clarke and Hirano 1995; McCullough 1999; McCullough et al. 2001; Farrell et al. 2008
Adult Spawning	• Gamete viability: average >13-16°C • Spawning: average >12-13°C, 7-DADMax >12-14°C • Mortality: 7-DADMax 21-25°C, maximum 24-25°C	• Reduced fertilization success • Reduced gamete viability • Reduced embryo survival to emergence	Clarke and Hirano 1995; McCullough 1999; McCullough et al. 2001; U.S. Environmental Protection Agency 2007; Farrell et al. 2008; Elsner et al. 2010
Egg	• Incubation: average >8-10°C, maximum >13-15°C • Embryo: maximum >17.5°C	• Reduced embryo success, hatching-emergence, condition, and survival • Increased abnormalities and mortality • Altered metabolic rates, metabolic energy deficits	Johnson and Brice 1953; Seymour 1956; Healey 1979; Heming 1982; Murray and Beacham 1987; McCullough 1999; McCullough et al. 2001; Fuhrman et al. 2018
Juvenile rearing and outmigration	• Growth: average >13-15°C, 7-DADMax >14-17°C, maximum >17-19°C • Rearing: average >16°C, 7-DADMax >15-18°C • Disease susceptibility: average >14-17.5°C • Feeding: average >18-20°C • Smoltification: average >15.5°C, 7-DADMax >15-16°C • Migration: average >18-22°C • Mortality: average >23°C	• Reduced growth and feeding rates • Reduced competitive advantage with warm-water species • Reduced survival • Increased susceptibility to disease • Altered development and migration timing • Accelerated onset of smoltification and desmoltification	Seymour 1956; Brett 1958; Fryer and Pilcher 1974; Wedemeyer et al. 1980; Baker et al. 1995; Clarke and Hirano 1995; Marine and Cech Jr 1998; McCullough 1999; Materna 2001; McCullough et al. 2001; Richter and Kolmes 2005

Optimal temperatures for juvenile salmon rearing and growth (across multiple species) tends to occur around 10-17°C, with temperatures higher than 18°C increasing susceptibility to diseases, density-dependent interactions, and starvation (U.S. Environmental Protection Agency 2003). Warm temperatures have the potential to shift juvenile Chinook emergence timing, outmigration, mass, and survival across life stages (Hawkins et al. 2020). Additionally, high water temperatures can reduce juvenile growth rates, reduce swimming speed, and alter readiness for smoltification (Brett 1958; McCullough 1999; Hicks 2002). Juvenile salmonids adapted and acclimated to certain temperature ranges can actually benefit from relatively warm temperatures through accelerated metabolism and growth (Brett and Shelbourn 1982; Quinn et al. 2004). However, growth is only optimized if food resources are available and abundant (Rosenfeld 2003; Beauchamp 2009; Naman et al. 2018).

Altered growth rates and life-stage transitioning during relatively warmer springs and summers may result in earlier juvenile Chinook outmigration, which can result in potential asynchronies with food resources as well as truncated growth seasons (Fullerton et al. 2017; Munsch et al. 2019; Hawkins et al. 2020). When food resources aren't abundant enough to fuel a heightened metabolism, body condition can become impaired and survival may be reduced. Additionally, altered growth and life-stage transitioning may result in emergence and outmigration occurring during unsuitable flow conditions and may result in increased competitive or predator interaction as well as spatiotemporal overlap with native and non-native fish species (Steel et al. 2019). Warmer water temperatures in spring, as well as prolonged warm periods, likely confer a competitive advantage to warm water predators, which may become more active and effective at preying on salmonids (Seattle Public Utilities and U.S. Army Corps of Engineers 2008; Tabor et al. 2010; Steel et al. 2017).

Variation in temperature regimes has a strong influence on salmonid behavior, distribution, and life-history (Fullerton et al. 2017; Steel et al. 2019). The magnitude, frequency, duration, rate-of-change, and timing of water temperature can vary considerably, resulting in diverse temperature conditions across a river network (Steel et al. 2012, 2016; Fullerton et al. 2015). Thermal diversity helps in supporting juvenile and adult salmonids by providing optimal temperature conditions (both cooler and warmer) for growth, survival, and reproduction (Armstrong et al. 2013; Brewitt and Danner 2014). Variance in thermal conditions also plays a role in determining lethal and sub-lethal events, stress, and the phenology of key life-history transitions (Steel et al. 2012). Diversity among and across river networks can also provide patches of cooler and warmer water, which act as thermal refuges when temperature conditions exceed upper and lower tolerances (Torgersen et al. 1999). Temporal and spatial temperature patterns across reaches (Torgersen et al. 1999, 2012), floodplains (Tonolla et al. 2010), stream networks (Isaak et al. 2015), and watersheds (Fullerton et al. 2015; Woltemade 2017) characterize thermal diversity and influence salmonids across all life-stages.

Exposure to high temperatures near thermal limits can cause salmonids to seek areas of thermal refuge (i.e., cold-water refuge) (Berman and Quinn 1991; Torgersen et al. 1999; Goniea et al. 2006). Behaviors can include changes in vertical distribution (Olson and Quinn 1993), holding in estuaries and delay in upriver migration (Wendler 1958; Kristinsson et al. 2015), as well as use of cool tributaries, confluence areas, and/or deep pools (Berman and Quinn 1991; Goniea et al. 2006; Rice et al. 2008; Keefer et al. 2018). Elevation, topography, surficial geology, channel slope, and interactions with surface and subsurface hydrology can drive the spatial and temporal distribution and extent of cold-water refuges (Torgersen et al. 2012; Leonetti 2015a; Steel et al. 2016). Cold water refuges, including their spacing and magnitude (size and temperature), can be influenced by reach-scale drivers including tributary

confluences, alluvial valley segments, floodplain channel morphology, as well as habitat-scale drivers including stratified pools, side-channels, beaver ponds, hyporheic exchange, and diel fluctuations (Caissie 2006; Leonetti 2015b; Leonetti et al. 2015).

Frequent and persistent warm temperatures across riverine landscapes can also limit habitat availability and accessibility (Welsh Jr et al. 2001). Salmonids may avoid watercourses with high temperatures, which can limit potential accessible river miles and habitats. Watercourses with impaired temperature conditions may result in reduced rearing capacity and salmonid densities, which may limit overall habitat capacity and productivity across a riverine landscape. Temperature-related reductions in habitat availability and accessibility could have long-term impacts on salmonid populations.

In addition to riverine landscapes, temperature conditions among estuaries can have considerable impacts on salmonid behavior and ecology. Salinity and temperature are two primary factors governing the structure of estuarine areas, which influence salmonid habitat use and distribution (Simenstad and Cordell 2000; McCullough et al. 2001). The spatial and temporal variation of temperature conditions may have a strong influence on the distribution, densities, rearing duration, and growth potential of juvenile salmonids (Armstrong et al. 2013; Roegner and Teel 2014; David et al. 2014). With temperatures showing considerable variation across estuarine networks and across seasons (Hall et al. 2018), temperature not only impacts growth potential for juvenile salmon but also survival and transitioning to later life stages. Although optimal temperature ranges vary by salmonid species and life stage, estuarine temperatures between 10-16°C have the potential to impair smoltification, decrease densities, and reduce fish condition (U.S. Environmental Protection Agency 2003; Richter and Kolmes 2005; Roegner and Teel 2014).

Water temperature also controls several chemical characteristics in aquatic habitats that, in turn, impact aquatic life. For example, dissolved oxygen concentrations decrease with increasing temperature since the solubility of oxygen decreases as temperature increases (i.e., cold water can hold more dissolved oxygen than warm water). Dissolved oxygen is necessary for respiration and metabolism in salmonids. Dissolved oxygen levels less than 4.25 mg/L can be stressful to salmonids and levels less than 2 mg/L can be lethal (Davis 1975; Seattle Public Utilities and U.S. Army Corps of Engineers 2008). Additionally, dissolved oxygen below 5mg/L can result in avoidance or delay among migrating Pacific salmon (Hallock et al. 1970; Alabaster 1988). However, salmonids tend to prefer cooler temperatures over higher dissolved oxygen and can use areas with dissolved oxygen as low as 3 mg/L as long as they are cool (D. Beauchamp per comm. in Seattle Public Utilities and U.S. Army Corps of Engineers 2008).

Drivers of Water Temperature

Water temperature is governed by several factors including weather drivers, riparian buffer characteristics, watercourse characteristics, hydrologic inputs, and microclimate conditions (Table 2). Primary weather drivers include solar and atmospheric radiation, which can directly heat waterbodies through energy transfer (Poole and Berman 2001; Johnson 2003). Atmospheric radiation and related air temperatures can influence long-term stream temperatures as well as inter-annual variability (Isaak et al. 2012). Wind speed can influence heat exchange between the atmosphere and water surfaces with reduced wind speed trapping air against the water surface and buffering heat exchange (Naiman et al. 1992). Precipitation provides direct thermal inputs (e.g., rain or snow) and can also influence temperatures through hydrologic cycle processes (e.g., snowmelt and runoff) (Isaak et al. 2012).

***Table 2**: Primary drivers influencing water temperatures and thermal regimes across watercourses.*

Primary Driver	Driver Attributes	Impacts to Water Temperatures and Attribute Details	Citations
Weather	Solar radiation (sunlight)	• Heat transfer from short-wave radiation • Primary driver of watercourse heating	Sullivan and Adams 1991; Poole and Berman 2001; Johnson 2003
	Atmospheric radiation/air temperature	• Heat transfer from long-wave radiation • Influences long-term stream temperatures and inter-annual variability	Sullivan and Adams 1991; Isaak et al. 2012
	Precipitation	• Heat gains and losses from rain and snow • Water volume and temperature inputs	Sullivan and Adams 1991; Isaak et al. 2012
	Wind speed	• Influences rate of heat exchange between atmosphere and water	Naiman et al. 1992
Riparian buffer characteristics	Vegetation presence	• Limits heat input to watercourses from solar-atmospheric radiation • Insulates thermal inputs from groundwater mixing, streambed heat conduction, tributary inputs, and hyporheic exchange • Decreases wind throw exposure among adjacent riparian areas • Provides sources of large wood which can create pools and provide potential areas of thermal refuge • Can influence hydrologic connectivity	Steinblums 1977; Beschta et al. 1987; FEMAT 1993; DeWalle 2010; Groom et al. 2011; Stohr et al. 2011; Sweeney and Newbold 2014; Reeves et al. 2018
	Density and height	• Influences amount of solar and atmospheric radiation transmitted to a waterbody • Taller and denser vegetation can provide relatively greater shade than short and less-dense vegetation • Influences wind impacts	Vezina and Pech 1964; Reifsnyder and Lull 1965; Black et al. 1991; DeWalle 2010
	Width	• Influences amount of solar radiation transmitted to a waterbody (greater width increases shade density) • Influences wind impacts • Influences microclimate presence and extent	Brazier and Brown 1973; FEMAT 1993; DeWalle 2010; Groom et al. 2011; Sweeney and Newbold 2014; Reeves et al. 2018
	Length and continuity	• Influences the longitudinal buffering capacity from solar and atmospheric radiation • The greater the continuous length of a buffer the more effective the buffer is at moderating temperature • Decreases wind impacts	Barton et al. 1985; Naiman et al. 1992; Davies et al. 2004; Rutherford et al. 2004; Cole and Newton 2013

Primary Driver	Driver Attributes	Impacts to Water Temperatures and Attribute Details	Citations
	Microclimate (presence and extent)	• Microclimate can moderate temperatures around a watercourse • Microclimate can shield watercourses from temperature extremes from nearby landscapes • Can influence the thermal and moisture environments under the forest canopy • Microclimate extent and presence is related to riparian buffer composition, dimensions, and continuity	Brosofske et al. 1997; Moore et al. 2005; Olson et al. 2007; Reeves et al. 2016, 2018
Watercourse characteristics, channel morphology, and landscape topography	Watercourse type and morphology	• Governs channel characteristics and the diversity of channel forms • Channel characteristics and complexity can influence thermal diversity through variation in depths/width, velocity, shade potential, and proximity to tributary/groundwater inputs	Beechie et al. 2010, 2012
	Watercourse volume and depth	• Watercourses with less volume are more sensitive to thermal inputs • Low flows can increase the effects of solar radiation and minimizes a waterbody's ability to buffer warm air temperatures • Decreased depth increases the effects of solar radiation and minimizes the ability to buffer air temperatures	Adams and Sullivan 1989; Sullivan and Adams 1991; Poole and Berman 2001
	Watercourse width	• Determines the amount of shade that can be provided by topography and riparian vegetation • Wider-shallower channels are more susceptible to solar and atmospheric radiation; have proportionally greater contact with stream bed substrates (potential warming from conduction)	Poole and Berman 2001; Cole and Newton 2013; Goss et al. 2014; Quinn 2018
	Watercourse velocity	• Lower velocity watercourses more susceptible to heating	Rutherford et al. 2004; Cole and Newton 2013; Quinn et al. 2018
	Substrate composition and color	• Direct conduction from the stream bed to waterbody • Dark, large, and dense substrate absorb and retain heat longer • Can influence amount of hyporheic exchange and related heat gains/losses; particularly among floodplain relic channels and alluvial fans.	Poole and Berman 2001; Cole and Newton 2013
	Aspect and orientation	• Orientation affects the amount of direct solar radiation reaching the water's surface	Johnson 1971; Davies et al. 2004
	Topography	• Shading from channel banks, hills, and mountains can influence daily and seasonal temperature fluctuations	Steinblums 1977; Beschta et al. 1987
	Elevation	• Higher elevations tend to have cooler water temperatures and winter precipitation is more likely to fall as snow	Isaak et al. 2010; Ruesch et al. 2012; Fullerton et al. 2015; Leonetti 2015b

Primary Driver	Driver Attributes	Impacts to Water Temperatures and Attribute Details	Citations
Hydrologic inputs and hyporheic exchange	Tributaries	• Heat gains or losses from tributary inputs • Tributaries can create areas of cool/warm temperatures in receiving waterbodies • Volume and related temperature of tributary can influence water temperatures in receiving waterbodies	Poole and Berman 2001; Rice et al. 2008; Leonetti 2015a
	Groundwater	• Heat gains or losses from groundwater inputs • Influence overall channel temperatures (maximums, minimums, and averages) • More likely to influence low-elevation headwaters during periods of lower flows; contributions from low-elevation headwaters may create areas of cool/warm temperatures in receiving mainstem waterbodies	Rutherford et al. 2004; Gomi et al. 2006; Tague et al. 2007; Leonetti 2014; Quinn et al. 2018
	Hyporheic exchange	• Conductive heat gains and losses from stream bed and hyporheic zone • Transient hyporheic storage protected from direct solar heating • Influence the diel range in watercourse temperatures (maximum and minimum temperatures) • More likely to influence mainstem temperatures during periods of lower flows	Rutherford et al. 2004; Loheide and Gorelick 2006; Gomi et al. 2006; Arrigoni et al. 2008; Torgersen et al. 2012; Steel et al. 2016; Quinn et al. 2018
	Saltwater exchange and riverine inflows (specific to estuaries)	• Heat gains and losses from saltwater exchange and freshwater inputs • Volume and related temperature of freshwater inflows can influence water temperatures in estuaries • Cooler freshwater mixes with warmer estuarine saltwater during summer • Warmer freshwater mixes with cooler estuarine water during fall-winter	Brown et al. 2016; Vroom et al. 2017; Hall et al. 2018
Ecological interactions	Beaver dams and structures	• Promotes pools, side-channels, wetlands, and channel complexity which influences hyporheic exchange and groundwater recharge, storage, and exchange (resulting in related hyporheic and groundwater heat gains and losses) • Can decrease temperatures and dampen diel variability • Supports spatiotemporal thermal heterogeneity • Promotes cold-water refuge in deeper waters and in areas of downstream upwelling	Pollock et al. 2003; Ham et al. 2006; Shaw 2009; Błędzki et al. 2011; Janzen and Westbrook 2011; Bouwes et al. 2016; Weber et al. 2017; Dittbrenner et al. 2018; Dittbrenner 2019
	Ungulate herbivory	• Grazing of riparian vegetation can reduce vegetation diversity and composition (influencing shade potential) • Can change stream channel morphology including widening and shallowing (increasing susceptibility to warming from solar-atmospheric radiation)	Kauffman and Krueger 1984; Beschta and Ripple 2016

Riparian buffers can influence water temperatures by providing shade which limits heat exchange between watercourses and solar-atmospheric radiation (Rutherford et al. 2004; Cole and Newton 2013; Goss et al. 2014). Instream temperatures generally trend away from baseline groundwater temperature towards atmospheric temperatures in the downstream direction (Sullivan et al. 1990). Riparian buffers help to moderate this pattern by insulating thermal inputs from groundwater, streambed heat conduction, tributary inputs, and hyporheic exchange. In addition to the presence/absence of riparian vegetation, the composition, height, width, density, and connectivity of riparian areas have a direct influence on watercourse temperatures (Barton et al. 1985; Beschta et al. 1987; DeWalle 2010). Generally speaking, the taller, wider, denser, and more connected riparian areas are the greater the potential for temperature insulation and moderation. Additionally, riparian vegetation is most likely to protect streams from solar radiation during summer when leaves are on trees and when the sun is directly overhead.

Watercourse characteristics and landscape topography can affect watercourse temperatures by influencing susceptibility and sensitivity to thermal inputs. Climatic drivers largely determine heat and water delivery to stream networks; however, the physical structure of streams determine their resistance to warming or cooling (Poole and Berman 2001). Watercourses with lower velocities and less flow volume are generally more susceptible to solar-atmospheric heating and are more sensitive to tributaries and groundwater inputs (Poole and Berman 2001; Rutherford et al. 2004; Cole and Newton 2013). Low flows in addition to shallower depths minimize a waterbody's ability to buffer air temperatures. The orientation of a watercourse as well as adjacent topography (i.e., shading resulting from channel banks and/or hills and mountains) can also influence the amount of direct solar radiation reaching a waterbody (Steinblums 1977; Beschta et al. 1987; Davies et al. 2004). The width of a watercourse can determine the amount of shade that topography and riparian vegetation can provide, with narrower watercourses being easier to shade (Cole and Newton 2013; Goss et al. 2014; Quinn et al. 2018).

Hydrologic inputs including tributaries and groundwater can influence water temperatures through heat transfer between source and receiving waterbodies (Poole and Berman 2001). These inputs can result in mainstem rivers having gaining reaches (augmented with groundwater and/or tributary inputs) as well as losing reaches (mainstem discharges to groundwater) (Stohr et al. 2011). Tributaries and groundwater can influence mainstem waterbodies by contributing water that can either cool or warm receiving waters (Poole and Berman 2001; Rutherford et al. 2004; Gomi et al. 2006). Groundwater tends to maintain a constant temperature that can warm a waterbody in winter and cool it in the summer (Swanson et al. 2012). Tributaries can influence receiving water temperatures if there is enough of a temperature difference and if they contribute enough volume/flow to overcome the heat-mass balance in the receiving waterbody. Cooler tributaries can either shift mainstem temperatures or create localized plumes of cooler temperatures across mainstem reaches (Poole and Berman 2001; Stohr et al. 2011; Leonetti 2015a; Leonetti et al. 2015). Specific to estuaries, heat transfer between riverine freshwater and oceanic saltwater can influence temperature gradients and conditions (Brown et al. 2016; Vroom et al. 2017; Hall et al. 2018). The volume and related temperature of freshwater inflows can influence the extent and magnitude of temperature gradients across estuaries. Generally, cooler freshwater mixes with warmer estuarine waters during summer and warmer riverine water mixes with cooler estuarine waters throughout fall and winter (Hall et al. 2018).

Hyporheic exchange (i.e., surface water mixing with subsurface water flowing in the underlying and adjacent substrates) can influence water temperatures through heat transfer between substrates and subsurface waters (Gooseff et al. 2006; Wondzell 2006; Arrigoni et al. 2008). During summer months, groundwater inputs have the potential to reduce overall channel temperatures (maximums, minimums, and averages), while hyporheic exchange has the potential to reduce the diel range in channel temperatures (reduce maximum and increase minimum temperatures) as well as influence the phase of temperatures (timing of maximum and minimum temperatures) (Johnson 2004; Loheide and Gorelick 2006; Arrigoni et al. 2008). Hyporheic exchange and/or groundwater inputs are more likely to shift mainstem temperatures during low-flow periods. Hyporheic exchange in a river system depends on variations in streambed topography and geomorphology, as well as the range, frequency, and spatial variation in hydrologic conductivity and hydraulic gradients (Wondzell and Swanson 1999; Gooseff et al. 2006; Wondzell 2006). Localized hyporheic exchange and groundwater inputs may be associated with areas where valley walls narrow creating constriction points for upwelling, floodplain areas where aquifers interact with relict floodplain channels, as well as in areas such as alluvial fans and bedrock outcrops where substrate differences influence exchange rates and gradients. Hyporheic exchange is also associated with complex, braided, and sinuous reaches where sediment and large wood promote vertical and horizontal hyporheic exchange.

Microclimate is produced by a combination of variables including sunlight exposure, wind exposure (i.e., magnitude and direction), precipitation, and moisture content, all of which help to control air and soil temperatures (Davies-Colley et al. 2000). Microclimate can moderate temperatures and can shield waterbodies from temperature extremes among nearby landscapes (Brosofske et al. 1997; Moore et al. 2005; Rykken et al. 2007). The extent and presence of microclimate conditions are related to the composition, dimension, and continuity of riparian buffers. Additionally, microclimate conditions are strongly influenced by wind speed, macroclimate (i.e., the overall weather pattern and climate of an area), and adjacent landscape temperatures.

Ecological interactions including beaver dams and structures can directly influence water temperature conditions through increased water storage, maintained summer streamflow, groundwater recharge, and hyporheic exchange (Błędzki et al. 2011; Janzen and Westbrook 2011; Bouwes et al. 2016). Additionally, beaver dams and structures can extend hyporheic zones (Shaw 2009), raise groundwater levels (Ham et al. 2006), and increase exchange of cooler groundwater (Weber et al. 2017). These processes can result in cooling across watercourses, moderation of temperature extremes, dampening of diel variability, and the creation of channel-scale temperature refuge. Beaver dams and structures promote higher thermal heterogeneity and provide cold-water refuge in deeper pools as well as in areas of downstream upwelling (Dittbrenner et al. 2018). The thermal benefits of beaver structures are especially apparent during baseflow periods. In addition to direct thermal benefits, beaver dams can also influence valley floor morphology and enhance salmonid habitat quality and quantity (Pollock et al. 2003).

Additional ecological interactions such as ungulate herbivory can limit riparian vegetation composition, diversity, and growth (Kauffman and Krueger 1984; Beschta and Ripple 2016). As highlighted in the riparian buffer discussion, the alteration and removal of riparian vegetation can limit shade potential and have a direct influence on watercourse temperatures. The removal of riparian vegetation through ungulate herbivory can also influence channel morphology resulting in wider and shallower channels, which can increase a watercourse's susceptibility to warming from solar-atmospheric radiation.

While not discussed in detail, it is worth noting that there are several additional drivers that can influence heat loading and thermal regimes in aquatic systems. Some of these include geothermal activity, as well as natural disturbances such as landslides, wildfire, debris flows, and flooding.

Human Alterations to Aquatic Thermal Regimes

Human alterations across a watershed can have significant impacts on water temperature conditions and thermal regimes among aquatic environments. Human activities can alter temperature conditions and thermal regimes by changing the timing and magnitude of thermal inputs as well as affecting when and how much water is traveling downstream (Poole and Berman 2001). Alterations and contributing factors include nonpoint source inputs (e.g., land use and development, removal of riparian buffers and forest vegetation, channel engineering, dams, water withdrawals, and climate change) as well as point source inputs (e.g., domestic wastewater, combined sewer, storm water systems) (Table 3).

***Table 3**: Human alterations to aquatic thermal regimes. All alterations/factors are non-point source inputs except the last row which includes point source inputs (e.g., domestic wastewater, combined sewer, storm water systems).*

Alteration/Factor	**Impacts to Water Temperatures and Thermal Regimes**	**Citations**
Land use and development (e.g., land clearing, impervious surfaces, and related development)	• Affects the interaction between watercourses and alluvial aquifers • Alters hydrologic regime • Decreases infiltration and recharge • Reduces storage of higher winter flows • Increases bank erosion/instability and sedimentation which can fill in gravels and reduce hyporheic exchange	Poole and Berman 2001; Brown and Vivas 2005; Caissie 2006; Nelson and Palmer 2007; Somers et al. 2013
Removal of riparian buffers and forest vegetation	• Reduces insulating and buffering properties • Limits blocking of solar radiation • Streams rapidly trend away from groundwater temperature and toward atmospheric temperatures • Alters infiltration and hydrologic dynamics • Increases peak stream power and fine sediment load which fill in gravels and reduces hyporheic exchange • Limits large wood recruitment critical for creation and maintenance of channel complexity • Loss of microclimate temperature buffering	Li et al. 1994; McCullough et al. 2001; Poole and Berman 2001; Moore et al. 2005; Rykken et al. 2007; Reeves et al. 2016
Channel engineering (e.g., straightening, widening, dredging, bank hardening, diking, levees, related incision)	• Decreases connectivity to tributaries, side-channels, floodplain areas, as well as connectivity between surface water and hyporheic/groundwater • Confines flow that would otherwise interact with floodplains and alluvial aquifers • Severs subsurface flow paths • Limits large wood recruitment critical for channel complexity • Reduces habitat complexity and variability • Widened and consolidated channels are less easily shaded and have increased surface area susceptible to solar-atmospheric radiation	Jurajda 1995; Steiger et al. 1998; Poole and Berman 2001; Fernald et al. 2006; Burkholder et al. 2008; Hester et al. 2009
Human-built dams	• Reduces recharge of alluvial aquifer • Reduces thermal and flow variability (removes peak flows and fluctuations in flow) • Reduces hyporheic flows • Alter thermal dynamics from storage reservoirs • Contributes cool or warm water depending on reservoir release depth	Ward and Stanford 1995; Poole and Berman 2001; Olden and Naiman 2010; Poff et al. 2010

Alteration/Factor	Impacts to Water Temperatures and Thermal Regimes	Citations
Water withdrawals	• May reduce in-stream flow which limit the ability of watercourses to withstand thermal inputs (particularly in areas where groundwater inputs are limited) • Draws hyporheic water away from the stream • Reduces stream and tributary flow during low-flow periods	Hibbs and Sharp 1992; Dauble 1994; National Research Council 1996; Poole and Berman 2001; Meier et al. 2003
Human-caused climate change	• Increases air and water temperature • Reduces snow storage (influencing summer low flows) • Alters precipitation and flow regime (frequency and timing of events) • Reduces rearing and suitable habitats availability • Alters ecological temperature-specific timing across life stages • Increases stress on riparian vegetation	Eaton and Scheller 1996; Mote et al. 2005; Knowles et al. 2006; Battin et al. 2007; Isaak et al. 2010; Mantua et al. 2010; Leonetti 2015c; Mauger et al. 2015
Point source discharge (e.g., domestic wastewater, combined sewer, storm water systems)	• Contributes sources of heat loading • Alters flow and temperature regimes including localized warming, thermal barriers, and transient impacts	Smith 1972; Webb 1996; Stohr et al. 2011

Land uses such as impervious-related development can affect hydrologic processes and interactions between reaches and alluvial aquifers (Caissie 2006; Hardison et al. 2009; Somers et al. 2013). Development can alter hydrologic regimes by decreasing infiltration and recharge which can influence thermal regimes (Brown and Vivas 2005; Nelson and Palmer 2007; Somers et al. 2013). Bank erosion and instability due to road building and altered hydrologic regimes can increase sedimentation, which can embed spawning gravels and reduce hyporheic exchange (Everest et al. 1987; Nguyen et al. 1998; Montgomery 2007). Landslides and erosion can alter the width and shape of river channels resulting in wider-shallower channels, which may be more exposed to sunlight (Ice 1985; Kaje 2009). Additionally, development-related impacts such as the filling of wetlands, altering of watercourses, water diversions/withdrawals, and point source inputs can all influence water temperature conditions.

Removal of riparian vegetation and forest cover reduces insulating properties, which increases watercourse susceptibility to solar-atmospheric radiation (McCullough et al. 2001; Moore et al. 2005). Shade from riparian vegetation can alter daily and seasonal temperature fluctuations (Steinblums 1977; Beschta et al. 1987). In the absence of riparian/forest cover and during warm summer months, watercourses trend away from groundwater temperatures and towards atmospheric temperatures (Poole and Berman 2001). Trending towards atmospheric temperatures can result in significant watercourse warming during summer months (Beschta et al. 1987; Webb 1996; Hester et al. 2009). Additionally, the removal of riparian and forest vegetation can alter infiltration and hydrologic dynamics. The removal of riparian and upland vegetation, specifically related to land development, decreases watershed infiltration and can lower baseflows (Poole and Berman 2001). This results in reduced groundwater discharge which can decrease cooler groundwater thermal inputs during low-flow periods and can lower the ability of a watercourse to withstand warm thermal inputs (Dauble 1994).

Removal of vegetation can destabilize streambanks which influences erosional processes and can increase sediment loading (Beeson and Doyle 1995; Thorne et al. 1998; Simon and Collison 2002). Reduced streambed permeability from sediment inputs can restrict hyporheic flow and altered sediment processes can change the physical structure of streams and related groundwater/hyporheic exchange (Li et al. 1994; Poole and Berman 2001). The removal of riparian and forest vegetation can limit large wood inputs which reduces the formation, maintenance, and complexity of channel features such as pools, multi-threaded channels, and meanders, which all provide thermal diversity (Harmon et al. 1986; Bilby and Ward 1991; Bilby and Bisson 1998). Reductions in channel and hydraulic complexity limits hyporheic exchange, which can alter temperature regimes and thermal exchange. Removal of riparian vegetation can also provide opportunities for widespread invasive vegetation colonization, which can frequently inhibit natural riparian vegetation and result in decreased riparian function, including optimal shade potential and aquifer infiltration.

Channel engineering (e.g., straightening, dredging, bank hardening, diking, related incision, etc.) can decrease the interaction of watercourses with floodplains, alluvial aquifers, and hyporheic areas (Jurajda 1995; Steiger et al. 1998; Poole and Berman 2001). Additionally, channel engineering can influence riverine-riparian interactions including decreased large wood supply and retention. Confining flows reduces the opportunity for floodwaters to recharge alluvial aquifers and blocking surface/sub-surface flow paths can result in decreased groundwater discharge as well as altered hyporheic exchange, especially during low-flow periods. Simplifying watercourses and bank hardening can reduce habitat variability and complexity (Jurajda 1995; Poole and Berman 2001). A lack of heterogeneity in channel pattern and streambed topography directly alters vertical and horizontal hyporheic exchange. Decreases

in groundwater discharge and hyporheic exchange due to channel engineering can lower the ability of waterbodies to withstand thermal inputs and may result in warmer summer water temperatures (Fernald et al. 2006; Burkholder et al. 2008; Hester et al. 2009). Confining flows can also increase their erosive forces towards the middle of the channel which encourages downcutting and further disconnects flows from floodplain areas (National Research Council 1996). Consolidation of channels and increased peak flows can result in channel widening which increases width to depth ratios (LeBlanc et al. 1997; Poole and Berman 2001). Wider channels have greater surface areas available to heat loading and decreased shade potential, especially during baseflows.

Channel modification can also influence the connectivity among watercourses, tributaries, and off-channel areas. Changes in connectivity alter hydrologic flows which influence temperature dynamics and can result in watercourse warming. Additionally, channel engineering within floodplain areas, to facilitate agricultural uses, results in the draining of shallow groundwater during spring. This can result in decreased recharge and hyporheic exchange during summer months, which can negatively impact temperature conditions.

Human-built dams can impact flow and temperature conditions across riverine environments. Dams related to water supply reservoirs can reduce overall flow through evaporation loss and flow diversions. Addition water supply dams can alter flow variability including the magnitude, frequency, timing, and duration of flow events. Flood control dams general have less of an impact on overall flows but do alter flow variability including all of the aforementioned flow attributes. Large reductions in flow can reduce a waterbody’s ability to withstand thermal inputs and reduces the complexity of alluvial systems, thereby reducing hyporheic exchange and temperature moderation (Ward and Stanford 1995; Olden and Naiman 2010; Poff et al. 2010). Dam-related reductions in flow can be even more impactful when reduction aligns with low-flow periods (Dauble 1994; Poole and Berman 2001). Flow reductions and thermal conditions in storage reservoirs can dampen seasonal and annual temperature cycles in downstream reaches, especially when reservoir releases are from variable depths (Ward 1985; Webb 1996; Caissie 2006; DeGasperi 2017). Dams can also impact downstream channel morphology and geomorphology through altered sediment and hydrologic processes, which decrease groundwater and hyporheic connectivity and exchange (Simons 1979; Church 1995; Ward and Stanford 1995).

Beaver-built dams also influence flow and temperature conditions; however, in contrast to human-built dams, beaver dams support multiple beneficial processes across aquatic environments. Beaver dams function considerably different than human-build dams due to differences in location, size, scale, and impact-magnitude. For example, human-built dams tend to be associated with bedrock canyons where impounded water does not interact with sub-surface aquifers whereas beaver-built dams can occur across floodplains where impounded water can actively recharge sub-surface aquifers.

Water withdrawals directly reduce stream and tributary flows and result in a reduced ability for watercourses to withstand thermal inputs (Dauble 1994), particularly in areas where groundwater inputs are limited. Water withdrawals not only reduce base flows but can also draw down water tables (Poole and Berman 2001). Decreased flows due to water withdrawals result in a loss of water across groundwater and hyporheic systems (Hibbs and Sharp 1992). Changes in the net water exchange between a watercourse, hyporheic zone, and groundwater areas impact hydrologic and thermal conditions (Long and Nestler 1996). Sometimes water withdrawals are returned to streams after use;

however, the returned water can often be warmer than initial withdrawal temperatures (Dauble 1994; National Research Council 1996).

Climate change has a myriad of impacts on aquatic ecosystems. In-depth discussion of climate change impacts in the Snohomish River basin are included in the Snohomish Basin Protection Plan (Snohomish County Surface Water Management et al. 2015) as well as the WRIA 7 Climate Change Impacts to Salmon issue paper (leDoux et al. 2017). While not discussed in detail in this document, a summary of climate-related impacts include projected increases in air and water temperatures, reduction of snow storage, altered precipitation and flow regimes, reduced summer rearing area and suitability of habitat, and altered ecological temperature-specific timing across life stages (Battin et al. 2007; Isaak et al. 2010; Mantua et al. 2010). Climate change impacts can result in reduced summer low flows, altered frequency and timing of precipitation events, and reduced groundwater flows and hyporheic exchange, which all influence water temperatures and thermal regimes. Warmer watercourse temperatures, lower summer flows, higher air temperatures, and increased stress on riparian vegetation are all expected to negatively influence salmonid populations (Mauger et al. 2015).

Point source heat loading from human-influenced sources include discharges from domestic wastewater, hatcheries, gravel operations, combined sewer overflows, and separate storm sewer systems. Other potential permitted discharges include those operating under general permits for stormwater. These point sources can contribute sources of heat loading and can alter flow and temperature regimes (Stohr et al. 2011). Permitted discharges can include effluent discharges from municipal wastewater treatment plants, power plants, and industrial activities, which can all warm receiving waterbodies (Smith 1972; Webb 1996). Waste load allocations (i.e., the maximum amount of heat inputs allowed to be released into a particular waterway) are developed for point sources that discharge to temperature impaired waterbodies or discharge into water bodies that drain to temperature impaired water bodies (discussed further in section: *Water Temperature Standards in the Snohomish River Basin*). Waste load allocations aim to limit the amount of heat loading that a point source is allowed to contribute.

Water Temperature Standards in the Snohomish River Basin

Washington State water quality standards are set forth in Chapter 173-201A of the Washington Administrative Code (WAC). Numerical temperature criteria included in the water quality standards are designated based on aquatic life uses among different waterbodies (different designated uses have different standards). The criteria are focused on protecting conditions that support aquatic life. The water quality standards include aquatic life uses specific to key species (e.g., salmonids) and detail criteria for multiple life stages (e.g., spawning, rearing, migration, etc.). The Snohomish River basin supports various salmonid aquatic life uses which results in different water quality criteria across watercourses. Differences among watercourses are meant to protect conditions critical to specific life stages in those areas. For example, areas important for spawning and rearing have different standards than areas where spawning is unlikely to occur.

Temperature criteria for designated salmonid life uses in the Snohomish River basin include char spawning and rearing, core summer salmonid habitat, salmonid spawning, rearing, and migration, and spawning and incubation (Table 4, Figure 2 - Figure 4). The supplemental spawning and incubation criteria were developed to protect areas where salmonid spawning and egg development occurs. This

criterion applies when the standard temperature criteria are insufficient in protecting spawning and incubation temperature needs. Tributaries are subject to the same standards as the receiving water, unless otherwise specified in the WAC.

The temperature criteria for designated uses are based on a 7-day average of the daily maximum temperatures (7-DADMax), i.e., the arithmetic average of seven consecutive measures of daily maximum temperatures. The temperature criteria focus on a 7-DADMax rather than instantaneous temperate maximums to reflect short-term tolerance of high temperatures as well as acclimation. The 7-DADMax reflects persistent exposure to detrimental temperature conditions where harm is more likely to occur (Stohr et al. 2011). While maximum temperatures are a predominant factor limiting salmonid growth and survival, various aspects of thermal regimes including the timing, duration, rate-of-change, magnitude, and spatial variation of temperature conditions can have a myriad of sub-lethal impacts on salmonids (Fullerton et al. 2015; Steel et al. 2016, 2017; Tsang et al. 2016). Variation in these aspects across a landscape can influence salmonid behavior, distribution, growth, and survival. Since the 7-DADMax criteria isn't comprehensive, it may be beneficial to consider multiple aspects of thermal regimes as well as spatial and temporal variation when evaluating temperature conditions and impairments across the Snohomish River basin (e.g., regime-based water quality standards, as described in Poole et al. 2004).

Washington State Ecology (WA Ecology) is required to assess all available water quality data to determine if a given watercourse meets water quality standards for designated uses (Section 303[d] of the Clean Water Act). The Clean Water Act of 1972 authorized the U.S. Environmental Protection Agency (EPA) to implement pollution control programs to improve and protect waterbodies. The watercourse assessments result in assignment to several categories including: Category 1 (meeting tested standards), Category 2 (waters of concern), Category 3 (insufficient data), Category 4 (impaired waters that do not require a TMDL), and Category 5 (polluted water that require cleanup). Watercourses that are assigned to Category 5 are placed on the 303(d) list with WA Ecology required to follow up with the development of a clean-up plan and/or determination of Total Maximum Daily Loads (TMDLs) that would bring a watercourse back into compliance. Total Maximum Daily Loads are based on a waterbody's loading capacity, which is the maximum inputs of pollutants that still allow a waterbody to meet water quality standards.

Over the last 15 years, temperature TMDLs have focused on riparian shade goals (system-potential riparian shade). This focus has been emphasized since riparian shade is the primary strategy used to address temperature increases in a river system. Temperature TMDL load allocations (allowable heat loading) are based on the site potential maximum achievable effective shade in a given reach, which is the fraction of the incoming solar radiation blocked by vegetation and topography (Stohr et al. 2011). Areas with effective shade deficits, difference between mature riparian shade and current riparian shade, indicate reaches where riparian restoration as well as other strategies are needed to reduce/mitigate warm water temperatures. Once a watercourse has an EPA-approved TMDL plan, it is placed in Category 4a (already has an EPA-approved TMDL plan in place and implemented). Ecology currently has a temperature TMDL for the Snoqualmie River (Stohr et al. 2011) with ongoing development of additional temperature TMDLs in the Skykomish River (Svrjcek et al. 2013; Restivo 2020) as well as French Creek and Pilchuck River (Swanson et al. 2012).

Table 4*: Washington State watercourse designated uses and water temperature criteria. Criteria are based on the seven-day average of the daily maximum temperatures (7-DADMax).*

Designated Aquatic Life Use	**Washington Ecology Temperature Criteria**	**Date Range**	**Additional Information**
Char spawning and rearing	7-DADMax ≤12°C (53.6°F)*	Varies by location	Spawning or early juvenile rearing by native char (bull trout and Dolly Varden). Summer foraging and migration of native char. Spawning, rearing, and migration by other salmonid species.
Core summer salmonid habitat	7-DADMax ≤16°C (60.8°F)*	Year-round	Salmonid spawning or emergence, adult holding, summer rearing habitat by one or more salmonids, or foraging by adult and sub-adult native char. Other protected uses include spawning outside of the summer season, rearing, and migration by salmonids.
Salmonid spawning, rearing, and migration	7-DADMax ≤17.5°C (63.5°F)*	Sep. 16 – Jun. 14	This use protects salmon or trout spawning and emergence that only occurs outside of the summer season. Other uses include rearing and migration by salmonids.
Spawning and incubation	Char: 7-DADMax ≤9°C (48.2°F)** Salmon and Trout: 7-DADMax ≤13°C (55.4°F)**	Year round	Special protection for spawning and incubation in waterbodies where the other established temperature criteria would not protect these life stages.

* Temperature must not exceed threshold more than once every ten years on average.
** At the initiation of spawning and at fry emergence for char.

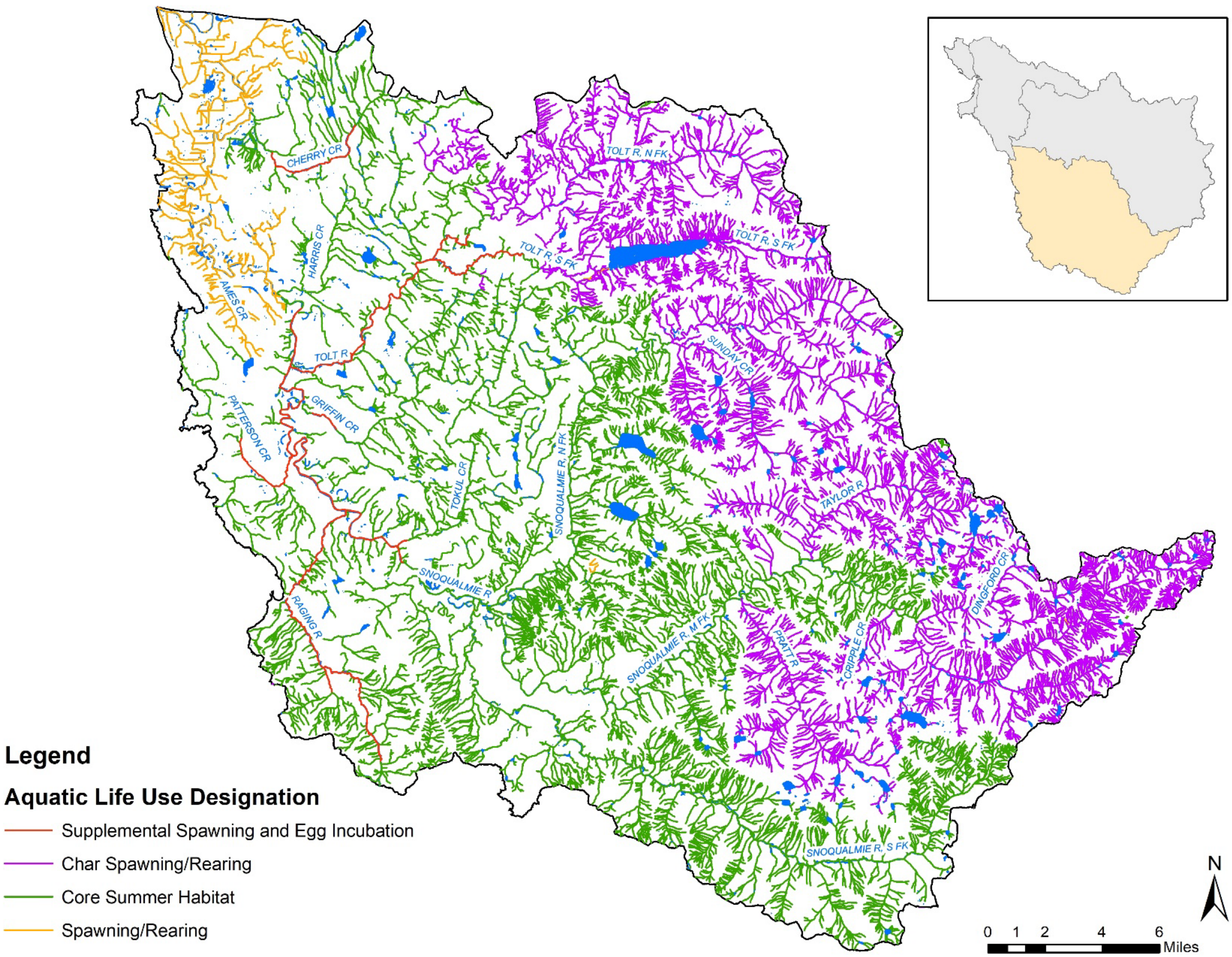

***Figure 2**: Snoqualmie River watershed aquatic life uses. The datasets for the freshwater beneficial uses originated with the Washington State Department of Ecology for the Supplemental spawning and Incubation data, Washington Department of Fish and Wildlife prepared the source data (SASSI). Input for updates and improvements were made by federal and tribal entities. Ecology complied the final dataset.*

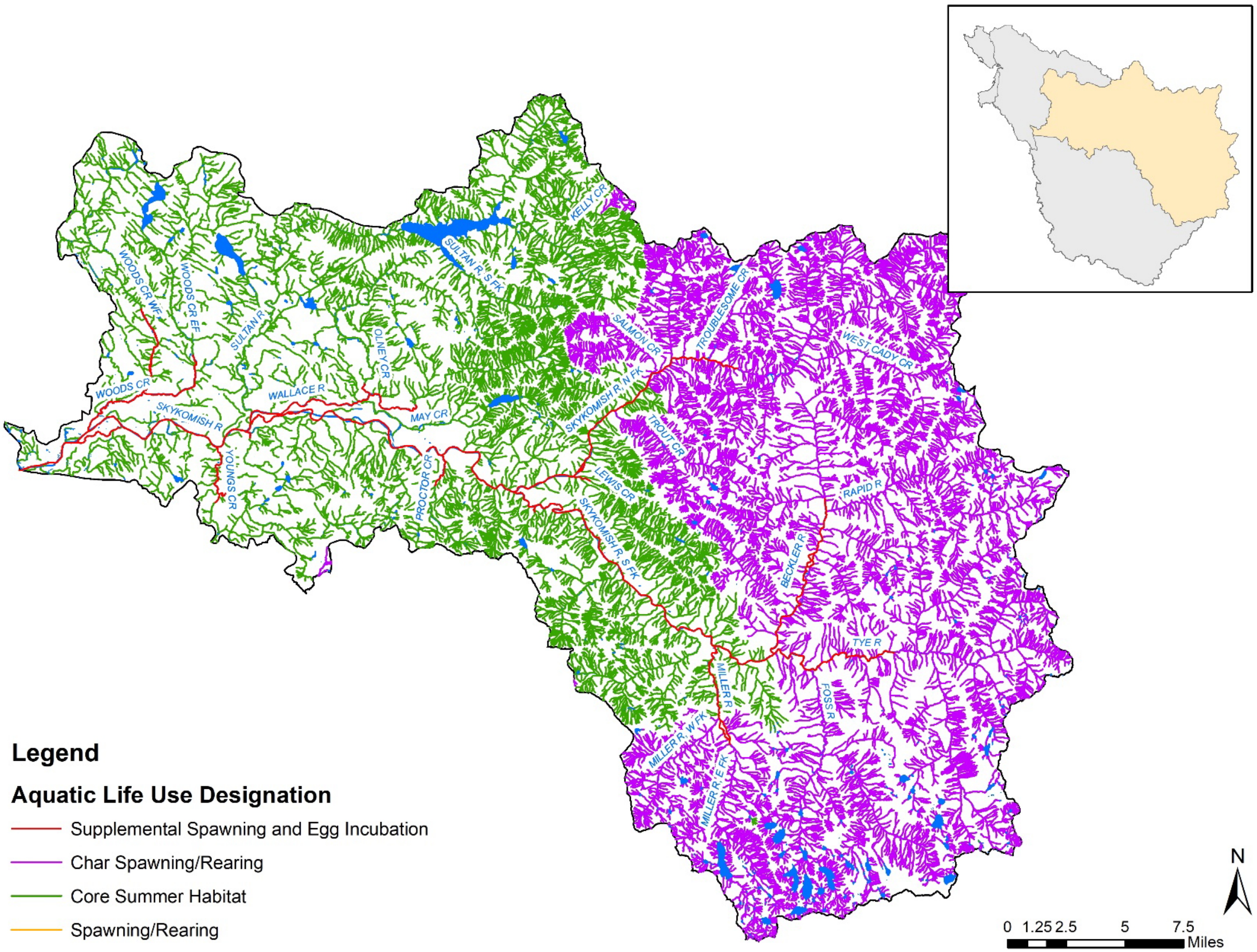

Figure 3: *Skykomish River watershed aquatic life uses. The datasets for the freshwater beneficial uses originated with the Washington State Department of Ecology for the Supplemental spawning and Incubation data, Washington Department of Fish and Wildlife prepared the source data (SASSI). Input for updates and improvements were made by federal and tribal entities. Ecology complied the final dataset.*

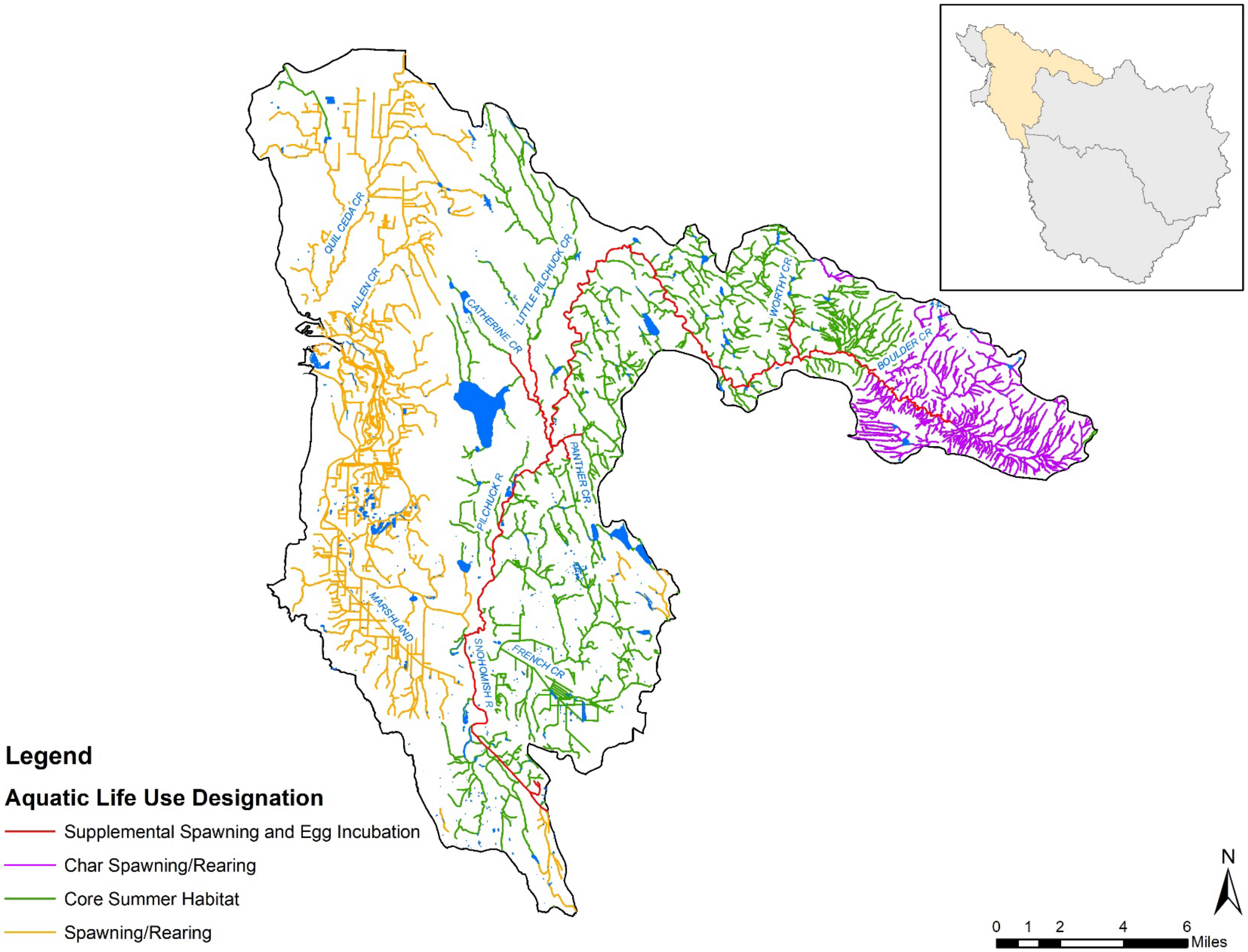

Figure 4*: Lower Snohomish River aquatic life uses. The datasets for the freshwater beneficial uses originated with the Washington State Department of Ecology for the Supplemental spawning and Incubation data, Washington Department of Fish and Wildlife prepared the source data (SASSI). Input for updates and improvements were made by federal and tribal entities. Ecology complied the final dataset.*

Water Temperature Conditions in the Snohomish River Basin

Overview of the Snohomish River Basin

The Snohomish River basin covers 1,856 square miles and is situated in both Snohomish and King counties. The Snohomish River basin has two primary contributing sub-basins including the Skykomish River and the Snoqualmie River. The Snohomish River basin contains various land uses including agriculture, forestry, as well as urban and rural residential areas. Aquatic habitat throughout the Snohomish River basin supports diverse aquatic resources including several salmonid species: Chinook (*Oncorhynchus tshawytscha*), chum (*Oncorhynchus keta*), coho (*Oncorhynchus kisutch*), and pink salmon (*Oncorhynchus gorbuscha*); steelhead (*Oncorhynchus mykiss*), rainbow (*Oncorhynchus mykiss),* cutthroat (*Oncorhynchus clarki*), Dolly Varden (*Salvelinus malma*), and bull trout (*Salvelinus confluentus*); as well as mountain whitefish (*Prosopium williamsoni*). Among these salmonids, three are listed as "threatened" under the Endangered Species Act (ESA) including Chinook salmon, steelhead trout, and bull trout char. These species are all listed because of declining and depressed populations in the Snohomish River basin and across the greater Puget Sound. While not listed as "threatened" under the ESA, coho salmon in the Snohomish basin are considered a species of concern as populations have shown considerable decline. Salmonid habitat degradation throughout the basin has been attributed to a several factors including fish passage barriers, floodplain modification, loss of wetlands, altered channel conditions including large woody debris removal, and altered riparian functions and conditions (Haring 2002).

Water temperatures across the Snohomish basin tend to increase proceeding downstream from forested headwaters to mainstem channels. However, there is considerable variation in spatial and temporal patterns in temperature conditions across riverine reaches, watercourses, and sub-basins. Temperature conditions throughout the Snohomish basin have been significantly impaired due to various factors including land use and development, removal of riparian buffers and forest vegetation, channel engineering, dams, water withdrawals, point source inputs, and climate change (discussed in section: *Human Alteration to Aquatic Thermal Regimes*). While there are some exceptions, water temperature impairments in the Snohomish basin tend to worsen moving east to west from the headwater down to the lower mainstem watercourses. However, projected climate change is expected to result in greater temperature changes among the upper watershed, compared to the lower watershed (i.e., upper watershed will warm at a greater degree) (Snoqualmie Tribe, pers. comm.). Temperature impairments tend to be seasonal with exceedances of temperature criteria generally occurring between late spring and early fall. Exceedances tend to align with periods of low flow and high air temperatures. The Snohomish basin supports various aquatic life uses (Figure 2 – Figure 4) with several watercourses listed as impaired for temperature on WA Ecology's 303(d) list, and additional watercourses listed as waters of concern. Many of the watercourses in the basin have not been assessed for temperature impairments, due to insufficient data. There are likely several additional watercourses that have temperature impairments across the basin; however, widespread and thorough temperature assessments are often limited or absent. While inference from evaluated watercourses may be beneficial for other watercourses, the extent and degree of temperature impairments remains incomplete.

Temperature Conditions - Snoqualmie River

Overview of the Snoqualmie River Watershed

Temperature conditions throughout most of the larger watercourses in the Snoqualmie River watershed are impaired with several smaller tributaries also showing temperature impairments. Details of impairments and temperature conditions are included in the 2011 WA Ecology TMDL study (Stohr et al. 2011) as well as other investigations and evaluations (discussed in detail in the following sections). Most temperature impairments have been attributed to a lack of riparian and forest cover, widespread channel modification and engineering, wetland filling, land development, climate change, and other factors. Non-point source impacts from land use changes and increased residential and commercial development are presumed to not only threaten temperature conditions but also overall water quality conditions in the Snoqualmie River watershed (Joy 1994; Stohr et al. 2011).

The Snoqualmie River watershed drains nearly 700 square miles from the crest of the Cascade Mountains down to the confluence with the Skykomish River near Monroe, where they form the Snohomish River. The three main forks of the Snoqualmie River (North Fork, Middle Fork, and South Fork) meet near the city of North Bend and combine to form the mainstem Snoqualmie River before flowing past the city of Snoqualmie. At approximately river mile 38.5 the Snoqualmie River drops 268 feet over the Snoqualmie Falls and continues flowing northward past Fall City, unincorporated agricultural areas, and the cities of Carnation and Duvall. The upper Snoqualmie watershed is dominated by forests in public and private ownership. After forestry, agriculture and unincorporated rural residential areas are the most prevalent land uses in the Snoqualmie River watershed, with incorporated cities representing just 2% of overall watershed area. The Snoqualmie River watershed is an important area for aquatic habitats, domestic water supply uses, forestry, agricultural, and recreational activities (e.g., swimming, rafting, tubing, fishing and wildlife viewing). Additionally, the Snoqualmie has many residential, commercial, and industrial uses.

While nearly 70% of the watershed is still forested (NOAA CCAP 2011 data), the lower portion of the Snoqualmie mainstem has only a fraction of its historic forest cover. As of the late 1990s, over 60% of the mainstem Snoqualmie River had little to no riparian cover, and only 33% had a riparian buffer width equal to or greater than 20 feet (Pentec 1999; Haring 2002). The historic floodplain of the Snoqualmie River featured many oxbows and wetlands (Collins and Sheikh 2002); however, many of these wetland features have either been disconnected or no longer exist due to conversion of the floodplain from a forested condition to one dominated by agricultural uses.

The Snoqualmie River watershed has a temperate marine climate with warm, dry summers and cool, mild, wet winters (Stohr et al. 2011). The climate, hydrology, and landscape characteristic of the Snoqualmie have direct influence on temperature conditions in the watershed. Precipitation falls unevenly across the watershed, falling largely as snow in the higher elevations and as rain in the lowlands with an intermediate rain-snow zone in mid-elevations. Snowmelt runoff contributes to stream flows in May and June and low flows generally occur from August to September when snowmelt runoff and precipitation are minimal. Summer low-flow and high-water temperatures commonly co-occur. During summer, much of the Snoqualmie River baseflows come from low elevation precipitation as well as groundwater expressed from lower elevation aquifers across sub-basins (Bethel 2004; McGill et al. 2021).

Above the Snoqualmie Falls

Mainstem Snoqualmie River
• North and South forks have a cooling influence on the mainstem Snoqualmie River during summer periods. • Middle Fork contributes 50-60% of flow to mainstem Snoqualmie during summer periods. • Middle Fork is consistently the warmest of the three forks and drives temperatures in the mainstem Snoqualmie River during summer. • Cooling occurs from groundwater upwelling and can contribute up to ~20% of mainstem flow. • Water extraction by municipalities and permit exempt domestic groundwater wells could reduce the buffering capacity of the mainstem Snoqualmie and its three forks during summer low flows.
North Fork Snoqualmie River

• Consistent temperature exceedances during summer months across the headwaters and around the downstream confluence with the Middle Fork.
• Temperature cooling and/or buffering across middle and lower reaches likely due to:
    ○ Decreased solar exposure through canyon reaches (topographic shading).
    ○ Increased cooler groundwater contribution in lower reaches.
    ○ Contribution from cooler tributaries near downstream confluence, which may also serve as thermal refuges.

South Fork Snoqualmie River
• Regular temperature exceedances at the downstream confluence with the Snoqualmie River from July through August (shorter during cool years); exceedances up to 24 miles upstream, but only in extremely warm-dry years. • Temperature buffering in middle reaches and cooling in lower reaches (Twin Falls to North Bend) possibly due to cooler groundwater and tributary inputs (e.g., Boxley Creek). • Limited cooling in upper reaches possibly due to shallow bedrock, which may limit groundwater inputs.
Middle Fork Snoqualmie River

• Wide-spread temperature exceedances; lower reaches exceeding from early June to mid-September; tributaries also displaying exceedances (e.g., Dingford Creek, Pratt River, and Taylor River).
• Cooler than North and South forks during winter, suggesting poor buffering from limited exchange with alluvial aquifer.
• Warm summer temperature conditions, especially in middle and lower reaches, likely due to:
    ○ Change in stream aspect from NE-SW to E-W (increasing solar exposure).
    ○ Broadening of river valley and increased channel width (decreasing riparian and topographic shading).
    ○ Few springs and cool tributaries in middle reaches.
    ○ Legacy clear-cut logging (recovering riparian corridors and channel characteristics).
    ○ Lack of instream large wood (limiting pool formation and hyporheic exchange).
    ○ Revetments and levees near the city of North Bend (limiting hyporheic exchange in the lower reaches of the river).

Approximately 54 percent of the Snoqualmie River watershed is located above Snoqualmie Falls, a 268-foot waterfall that serves as a barrier to anadromous fish. The upper Snoqualmie River basin is predominantly forested (91%) with all residential, commercial, and agricultural development concentrated around the cities of North Bend and Snoqualmie (Snohomish County Surface Water Management et al. 2015). The upper Snoqualmie River basin is primarily drained by the North, Middle, and South forks with their headwaters starting as steep streams in high alpine landscape before transitioning to lower gradient, meandering rivers (Thompson et al. 2011).

In spite of the heavily forested and relatively high elevation of the upper Snoqualmie River basin, recent monitoring has documented summer water temperatures that exceed State standards every year, in reaches on all three forks and the mainstem Snoqualmie River between the confluence of the three forks and Snoqualmie Falls. Much of the focus on the impacts of warm summer water temperature to salmonids has occurred below Snoqualmie Falls due to the presence of anadromous fish and the extent of riparian areas with limited vegetation in the lower valley. However, recent studies suggest that flow from the upper Snoqualmie basin, particularly the Middle Fork, drives water temperature downstream in the mainstem Snoqualmie River where anadromous fish are present (Figure 5) (Thompson et al. 2011; Kubo and leDoux 2016). This underscores the need to include and address the upper Snoqualmie watershed to support thermal conditions that are sufficient for salmonid survival.

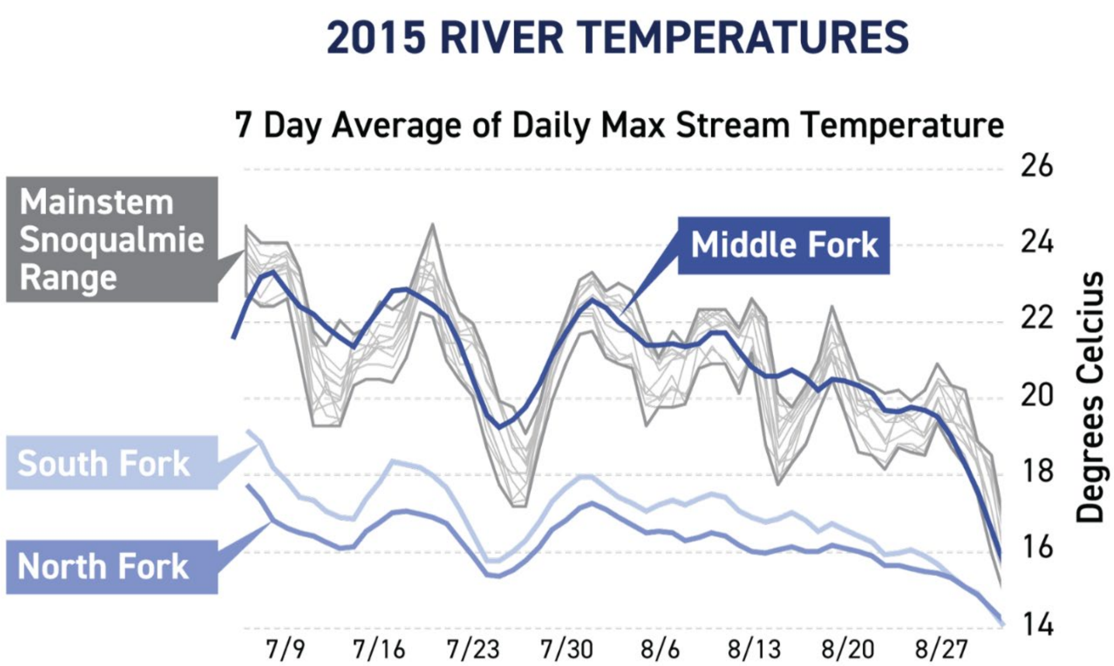

***Figure 5**: 7DADMax for the mainstem Snoqualmie River and the North, Middle, and South forks during the summer of 2015. Water temperature in the Middle Fork of the Snoqualmie is substantially warmer than the North and South forks and closely tracks with the range of temperatures observed in the Snoqualmie River below Snoqualmie Falls. This suggests that the Middle Fork is a major driver of downstream water temperature, especially since 50-60% of the combined flow out of the three forks of the Snoqualmie comes from the Middle Fork. Adapted from (Kubo and leDoux 2016).*

Middle Fork Snoqualmie River

The Middle Fork is the largest of the three forks, draining a 170.5 square mile watershed extending from the west slopes of the Cascade crest to the town of North Bend. The basin is predominantly forested (97%), with much of the upper basin in federal or state-owned lands. The thermal regime of the Middle Fork is due to a combination of natural and anthropogenic factors (Kaje 2009; Miller 2020). Many of the anthropogenic factors are likely also affecting the North and South forks, but the Middle Fork's geology, hydrology, and larger basin area may result in more pronounced impacts to stream temperature.

Exceedances of State water temperature standards are widespread throughout the basin in all years where monitoring has occurred. Headwater reaches and tributaries, such as Dingford Creek and the Pratt and Taylor rivers, routinely exceed the 12.0°C *char spawning and rearing* standard for extended periods during summer (Steel et al. 2016; Miller unpub. data). The 16.0°C *core summer habitat* standard applies to the mainstem of the Middle Fork from Dingford Creek to the confluence with the North and South forks. The Middle Fork below Dingford Creek (RM 25.0) generally meets State standards (except in 2015) but prolonged exceedances from late July to early September were observed in the Middle Fork just above the Taylor River confluence at RM 20.5 (Stohr et al. 2011; Miller unpub. data). In the lower reaches of the river, exceedance of the State standard can last from early June to mid-September and water temperature can reach levels lethal to cold-water fish in extreme years, a threshold not surpassed in the either of the South or North forks (Kubo and leDoux 2016; Fullerton unpub. data). Daily minimum temperature in the lower Middle Fork exceeds State standards in most years (Kaje 2009); in 2015, water temperature in the lower Middle Fork never dropped below 16.0°C from late June to late July (Steel et al. 2019).

Citing 2006 data from Stohr et al. (2011), Kaje (2009) assigned most of the summer thermal gains to the reach between Burntboot Creek (RM 30.0) and the Pratt River (RM 15.4). A 2006 thermal infrared survey of surface water temperature from the Taylor River to the mouth of the Middle Fork showed the greatest gains occurring further downstream, between RM 10.6 to RM 3.3 and attributed the warming to increased solar inputs and decreased cool water inflows (Watershed Sciences, Inc. 2007; Stohr et al. 2011). Subsequent monitoring confirmed that during summer, most thermal gains occurred in the middle reaches of the river between RM 20.5 and RM 4.0, while there was very little warming in the highest (RM 31.0 and RM 25.0) and lowest (RM 4.0 to mouth) reaches (Miller unpub. data). The reach between RM 20.5 and RM 4.0 also experienced the largest diurnal fluctuations (Miller unpub. data), suggesting limited exchange between the channel and the alluvial aquifer (Leibowitz et al. 2016). Unlike the North and South forks that show temperature decreases from their middle to lower reaches, the Middle Fork appears to just maintain temperatures (Thompson et al. 2011; Miller unpub. data). Several levees and revetments are present on the lowest reaches of the Middle Fork; these structures generally limit lateral channel movement and disconnect the channel from the floodplain, but the degree to which they are impacting thermal regimes on the Middle Fork is unclear.

The Middle Fork has a unique thermal regime compared to the North and South forks during winter. In contrast to the North and South forks which generally warm as they flow downstream, water temperature in the Middle Fork is very similar along its length during winter (Thompson et al. 2011; Miller unpub. data). The Middle Fork in winter is the coldest of the three forks (Thompson et al. 2011, Steel et al. 2019); during a prolonged period of below freezing air temperature in the winter of 2009, the lower Middle Fork froze completely while the North and South forks did not (Thompson et al. 2011).

Elucidating the various drivers of water temperature on the Middle Fork and how thermal regimes have changed from pre-European settlement is difficult but important for understanding the degree to which Snoqualmie salmonids are imperiled. The presence of several warm and hot springs in the headwaters of the Middle Fork suggest there could be additional warm-water inputs to the river (Kaje 2009), though subsequent temperature monitoring by Stohr et al. (2011) and (Miller unpub. data) did not detect warming attributable to geothermal inputs. Stohr et al. (2011) noted that the increased longitudinal heating rate observed in the middle reaches of the river correspond to a change in stream aspect (from NE-SW to E-W) and broadening of the river valley. Stohr et al. (2011) also noted that there are fewer springs and cool water tributaries entering the Middle Fork in this portion of the river, compared to upstream reaches.

Legacy impacts of clear-cut logging and related road and rail building during the early- and mid-twentieth century are likely still affecting the morphology of the Middle Fork, as well as other WRIA 7 streams, in ways that will impact water temperature. After widespread timber harvest from riparian areas and hillslopes in the early 1900s, many Puget Sound rivers widened relative to their pre-settlement channels (Legg and Olson 2014). Aerial photo analysis documented channel widening in the Middle Fork basin after clear cut logging, though this phenomenon was not ubiquitous across the basin (U.S. Forest Service 1998). High channel width-to-depth ratios are present in the middle and lower reaches of the Middle Fork resulting in increased solar exposure as well as decreased buffering and cool water refuges in these reaches (Stohr et al. 2011; Thompson et al. 2011). These wide, shallow riffles may be a natural feature of the Middle Fork, but could be exacerbated by increased sediment delivery due to previous logging (Thompson et al. 2011). Scott and Wohl (2018) noted that the Middle Fork is likely suffering from a large woody debris (LWD) deficit compared to pre-logging conditions and low LWD among lower and middle reaches of the Middle Fork may be limiting pool formation and habitat complexity (Cascades Environmental Services, Inc. 1997, Thompson et al. 2011). Thompson et al. (2011) observed that reaches of the lower Middle Fork with simplified habitat and warm water temperature coincided with limited trout growth, production, and distribution.

North Fork Snoqualmie River

The North Fork drains a 103.5 square mile watershed that is predominantly forested (97%), much of which is managed private timber stands (Kaje 2009). Exceedances of the 12.0°C *char spawning and rearing* standard are consistent in the headwaters during summer months, including Sunday and Lennox creeks, with exceedances generally occurring between early summer and early fall, often with little respite (Fullerton unpub. data).

During summer, there appears to be a cooling and/or buffering influence between the middle and lower reaches of the North Fork. Fullerton (unpub. data) observed lower daily maxima (by as many as 3.0°C) and daily minima between the mouth of the North Fork and a site 11.3 river miles upstream. Thompson et al. (2011) observed only reduced daily maxima. Thompson et al. (2011) hypothesized that this pattern was due to a combination of warm lake water (from Lake Hancock and Calligan) influencing the upper site and decreased solar exposure through Black Canyon and the lower North Fork channel buffering the lower site, though the mid-basin NOAA monitoring site is above both lakes. Increased groundwater contribution in the lower North Fork may also contribute to the observed cooling. During winter months, the river generally warms in a downstream direction (Thompson et al. 2011; Fullerton unpub. data).

Water temperature at the mouth of the North Fork regularly exceeds State standards. Based on data from 2012-2018, exceedances generally began in late June or early July and persisted until mid-August during warm years but durations were much shorter during cool years (Fullerton unpub. data). Several tributaries near the mouth of the North Fork, including Tate Creek, are cooler than the mainstem North Fork and could serve as cool-water refuge for fish and other biota (Kaje 2009).

The drivers of these exceedances are not clear but are likely a result of both anthropogenic disturbance and natural variability. Clear-cuts and immature timber stands are prevalent throughout the watershed, though a forested riparian buffer has been maintained along the mainstem of the North Fork. Channel migration zones in the upper North Fork are wide, which allow warming from increased solar input (Stohr et al. 2011). Riparian vegetation and effective shade in the lowest reaches is reduced due to encroachment from residential development (Stohr et al. 2011) and extraction of water from Canyon Springs by the city of Snoqualmie may be redirecting groundwater that would further cool the lower North Fork.

South Fork Snoqualmie River

The South Fork drains an 85.4 square mile watershed, starting at Snoqualmie Pass. The basin is predominately forested (84%) with developed areas generally concentrated in the lower reaches near the city of North Bend and the upper basin near the Alpental ski-resort and community. Levees and revetments armor the banks of the South Fork near the city of North Bend and the river is paralleled by Interstate 90 for much of its length.

Like the North Fork, the South Fork generally warms as it travels downstream during summer months but is buffered in its middle reaches and cools between the reach above Twin Falls and a downstream reach near North Bend during summer months (Thompson et al. 2011, Steel et al. 2016). Thompson et al. (2011) attributed the pattern to reduced groundwater contribution at the upper site due to shallow bedrock and cooling from Boxley Creek, which is fed by spring flow from Chester Morse Lake, and additional groundwater flow from Cedar River reservoirs through the Cedar moraine buffering the lower site.

Exceedances of the 16.0°C *core summer habitat* standard have been observed as far upstream as river mile 24.0, but only during extremely warm-dry years such as 2015 (Steel et al. 2019). Exceedances near the downstream confluence with the Snoqualmie River have been observed regularly, generally occurring in July and August, though exceedances are short-lived in cool years (Thompson et al. 2011; Fullerton unpub. data). Longer duration and greater magnitude exceedances have been observed in the mainstem reach above Twin Falls (Thompson et al. 2011; Fullerton unpub. data).

Upper Mainstem Snoqualmie River and Three Forks Confluence

The mainstem Snoqualmie River is formed at the confluence of the Middle and North forks, with the South Fork confluence occurring 0.6 miles further downstream. The mainstem flows over Snoqualmie Falls approximately 3.3 miles below the South Fork confluence.

Over half of the flow in the mainstem Snoqualmie River above Snoqualmie Falls originates from the Middle Fork, the largest of the three upper Snoqualmie basins (Kubo and leDoux 2016). The Middle Fork is consistently the warmest of the three forks during the summer low flow period and drives

temperatures in the mainstem Snoqualmie River (Figure 5) (Thompson et al. 2011; Kubo and leDoux 2016).

During summer, the North Fork is several degrees cooler than the Middle Fork (Stohr et al. 2011; Thompson et al. 2011; Fullerton unpub. data), creating a plume of cooler water on the right bank below their confluence (Watershed Sciences, Inc. 2007). The South Fork also has a cooling influencing on the mainstem Snoqualmie River during summer (Stohr et al. 2011; Thompson et al. 2011; Kubo and leDoux 2016), forming a plume that is approximately 2.0°C cooler than mainstem water and its influence is persistent for some distance downstream (Watershed Sciences, Inc. 2007). Water temperature in the mainstem Snoqualmie River decreases from the North Fork to Snoqualmie Falls (Figure 6), by as much as 2.0°C (Watershed Sciences, Inc. 2007). Groundwater upwelling in the approach to Snoqualmie Falls contributes to this cooling as approximately 20% of the flow comes from sub-surface sources (Turney et al. 1995).

It is important to note that the mainstem Snoqualmie River above Snoqualmie Falls and the Middle, North, and South forks are all impacted by water withdrawals from municipalities (e.g., North Bend and Snoqualmie) and permit exempt domestic groundwater wells. Water withdrawals can reduce streamflow during summer low flow, thereby decreasing a watercourse’s buffering capacity of thermal inputs (Dauble 1994). Municipalities are required to offset withdrawals to maintain minimum instream flows on the Snoqualmie River (Golder Associates 2007) and the recently passed Streamflow Restoration law seeks to mitigate the impact of permit exempt wells on instream flows. Projections of increased water demand and decreased water availability underscore the need to protect minimum flows during summer to preserve flows and thermal conditions suitable for cold-water fishes.

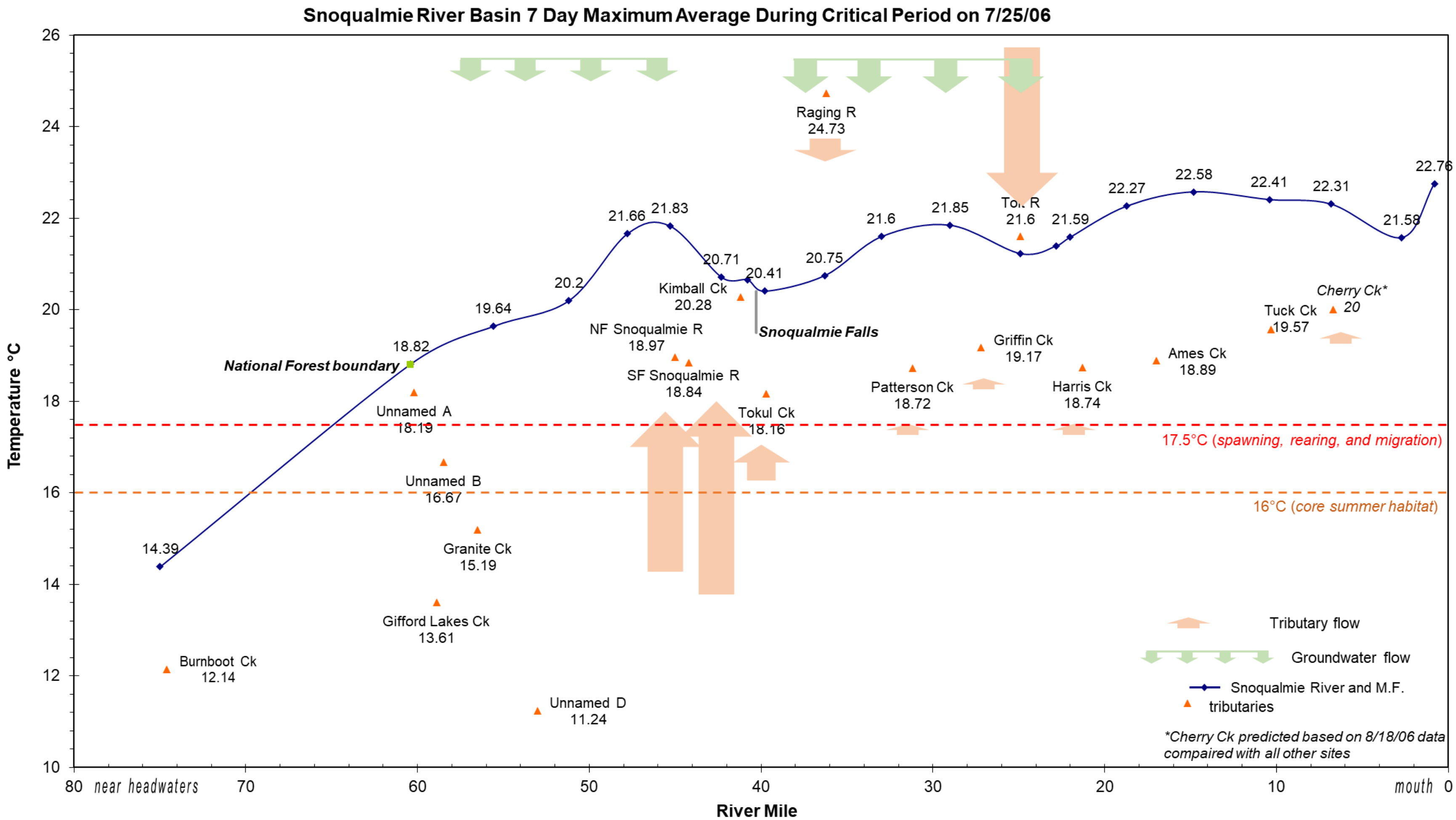

Figure 6*: Snoqualmie River longitudinal profile 7-DADMax during the 2006 critical period, July 22 to 28, 2006. Adapted from Figure 9 in Stohr et al. (2011). Water temperature steadily increases in the lower reaches of the Middle Fork before the inflows from the South and North forks cool the river before the Snoqualmie Falls. Temperatures are also decreased from inputs from the Tolt River. Mainstem Snoqualmie River temperatures consistently exceeded State standards including the 16°C criteria (core summer habitat) and the 17.5°C criteria (salmonid spawning, rearing, and migration). All monitored tributaries below the Snoqualmie falls exceeded both criteria. Tributary inputs with the greatest flow contribution include the North and South Fork Snoqualmie River as well as the Tolt River.*

Below the Snoqualmie Falls

Mainstem Snoqualmie River

• Widespread temperature exceedances, especially during summer periods.
  ○ Primary thermal input from air temperature and solar radiation.
  ○ Extensive removal of riparian and forest vegetation has resulted in vegetation conditions and extents unable to provide sufficient shade benefits.
  ○ Sensitivity to air temperature and solar radiation pronounced during low-flow periods.
  ○ Reach-scale temperature cooling from smaller tributaries is likely minimal.
• Snoqualmie River gains groundwater (potential thermal cooling) along its length except in downstream reaches from Carnation to Monroe.
• Areas of temperature moderation and cooling:
  ○ Cooling in reaches between Patterson Creek and downstream of the Tolt River (due to groundwater inputs, hyporheic exchange, and Tolt River inputs).
  ○ Cooling more pronounced during low-flow periods.
  ○ Exchange between surface and sub-surface waters likely occur where the valley walls narrow (constriction points) as well as around bedrock outcrops and alluvial fans (increased exchange rates from sediment and channel characteristics).
• Snoqualmie River is projected to have maximum water temperatures averaging 22.8°C and in some locations exceeding the 23°C lethal threshold.
• A 180-ft wide riparian buffer of mature vegetation could shade up to 50% of the Snoqualmie River and decrease maximum temperatures by ~1.9°C (additional 0.4°C with microclimate benefits).

Snoqualmie River Tributaries

• Larger tributaries generally less impaired for temperature include Tuck Creek, Ames Creek, Harris Creek, Langlois Creek, North and South Fork Tolt River, Griffin Creek, and Tokul Creek.
• Larger tributaries generally more impaired for temperature include Cherry Creek, lower Tolt River (downstream of the North/South fork confluence), Patterson Creek, and the Raging River.
• Tributaries that cross the exposed valley-floor floodplain display major increases in temperature, likely due to minimal riparian shade and channel modifications.
• Tolt River delivers water at relatively similar temperatures to the mainstem Snoqualmie River.
  ○ Minimum temperatures can be several degrees cooler than the mainstem Snoqualmie River; when cooler, the Tolt River can decrease mainstem Snoqualmie temperatures.
• Raging River delivers considerably warm water to the mainstem Snoqualmie in the summer; however, it has a limited influence due to minimal flow-volume contribution.
  ○ Warm temperatures may act as barriers to upstream migration in the Raging River during early fall, which may be confounded when low flows go subsurface through the gravel fan at its mouth.
  ○ During fall/winter, the Raging River has a wide active channel; however, during summer base-flow periods, the width of the active channel is considerably narrower resulting in limited riparian shading.
• During the warm and low-flow year of 2015, several tributaries displayed temperature exceedances; however, some tributaries were cooler than the mainstem Snoqualmie and may provide thermal refuge.
• There are many smaller unnamed tributaries where the water temperature regime is unknown.

Mainstem Snoqualmie River

Temperatures in the Snoqualmie River were first determined to exceed State standards based on temperature data collected by Puget Sound Energy (formerly Puget Power) in 1991 and by WA Ecology in 2001 (Stohr et al. 2011). After initial evaluation and input from Snohomish basin stakeholders, WA Ecology decided to rank the Snoqualmie River as the highest priority for completion of a TMDL, due to its high level of temperature impairment as well as the watershed's importance to salmon stocks. The TMDL process included characterization of the water temperature in the basin, establishing load and wasteload allocations for heat sources, and detailing corrective actions needed to meet water quality standards for river water temperature (Stohr et al. 2011). The Snoqualmie TMDL did not assign load allocations to waterbodies upstream of the National Forest Lands boundary under the assumption that practices from the U.S. Forest Service and Department of Natural Resources would be protective of standards. However, as discussed previously in the *Above the Snoqualmie Falls* section, continued research and temperature monitoring highlights that temperature conditions in select reaches above the Forest Lands boundary and directly downstream can exceed temperature standards (Stohr et al. 2011; Thompson et al. 2011; Steel et al. 2019; Fullerton unpub. data; Miller unpub. data).

The mainstem Snoqualmie River exceeds water temperature standards throughout much of its length below the Snoqualmie Falls during summer base-flow months. Stream temperature data from 2006, collected and evaluated by WA Ecology, indicated that water temperatures exceeded criteria throughout the watershed (Figure 6) (Stohr et al. 2011). Specifically, temperature exceedances above the 16°C criteria (*core summer habitat*) and/or the 17.5°C criteria (*salmonid spawning, rearing, and migration*) were common across mainstem and tributary locations. The majority of the highest 7-DADMax water temperatures were recorded in late July, which coincided with periods of relatively high air temperatures (Stohr et al. 2011).

During the particularly warm summer of 2015, record low flows and warm temperatures were ubiquitous across the Snoqualmie River watershed (Kubo and leDoux 2016; Steel et al. 2019). That year highlighted the relative sensitivity of the Snoqualmie River to air temperatures and solar radiation during low-flow periods. Observed temperatures in the mainstem Snoqualmie, Middle Fork Snoqualmie (discussed above), and several tributaries (discussed below) were consistently above state standards for designated uses, often by several degrees Celsius (Kubo and leDoux 2016). With projected climate change impacts (discussed in section: *Human Alterations to Aquatic Thermal Regimes*), the wide-spread temperature exceedances and detrimental temperature conditions observed during the summer of 2015 may provide insight into what future conditions may look like, especially if temperature improvement strategies are not adequately implemented across the landscape.

After passing over Snoqualmie Falls, temperatures in the mainstem Snoqualmie appear to increase in a downstream direction until areas upstream and around the Tolt River, where tributary and groundwater inputs decrease temperatures (Figure 6). Downstream of the Tolt River, temperatures in the mainstem Snoqualmie continue to increase (Stohr et al. 2011). While water temperatures generally increase from upstream to downstream, during base-flow periods there can be variation in this pattern, especially at a localized scale among groundwater gaining reaches and across areas of hyporheic exchange (Fullerton et al. 2015; Kubo and leDoux 2016; Kubo 2017). For example, during the warm-dry summer of 2015, Kubo and leDoux (2016) observed localized decreases in mainstem Snoqualmie temperatures between Fall City and Carnation as well as downstream of Carnation, in areas just upstream of Tuck Creek.

Additionally, in 2016 Kubo (2017) continued to observe decreases in water temperature between Patterson Creek and the Tolt River (Figure 7). Observations across 2015 and 2016 showed that localized temperature moderation primarily occurred during base-flow periods. For example, prior to base-flow periods in 2016, water temperature increased from upstream to downstream (Figure 7a); however, during base-flow periods (August and September) localized decreases in temperature were observed (Figure 7b). The percent contribution of hyporheic exchange and/or groundwater inputs may only be significant enough to influence mainstem temperatures during low flow periods (Kubo and leDoux 2016; Kubo 2017; McGill et al. 2021). The temperature patterns along this reach indicate that improvement strategies focused on improving groundwater expression, watershed-wide retention of water to augment low-flow periods, as well as improved hyporheic exchange may help to moderate further decrease temperatures within the reach and further downstream.

It was hypothesized that the localized cooling may have been attributed to groundwater and hyporheic exchange, both influenced by surrounding topography, geology, and riverbed morphology (Kubo and leDoux 2016; Kubo 2017). Areas where the valley walls narrow can create constriction points for upwelling and areas such as alluvial fans and bedrock outcrops can influence exchange rates and gradients. Across the mainstem Snoqualmie River, groundwater contributes up to 30% of the total surface water flow (Haring 2002; Stohr et al. 2011). The Snoqualmie River appears to gain groundwater along its entire length except for downstream reaches from Carnation to Monroe. From Fall City to Carnation, the Snoqualmie River gains approximately 11-13% of its surface flow from groundwater upwelling (Turney et al. 1995). During summer base-flow periods, groundwater inputs have the potential to mitigate surface water temperatures, especially at localized scale. While large tributaries can influence mainstem Snoqualmie River temperatures (e.g, Tolt River), localized reach-scale temperature moderation from smaller tributaries is likely minimal, as the percent contribution of smaller tributaries during base-flow periods is generally low. For example, during 2016 in the Snoqualmie River reach from Patterson Creek to the Tolt River, the contribution of primary tributaries including Griffin Creek and Patterson Creek was less than 2% of the mainstem flow.

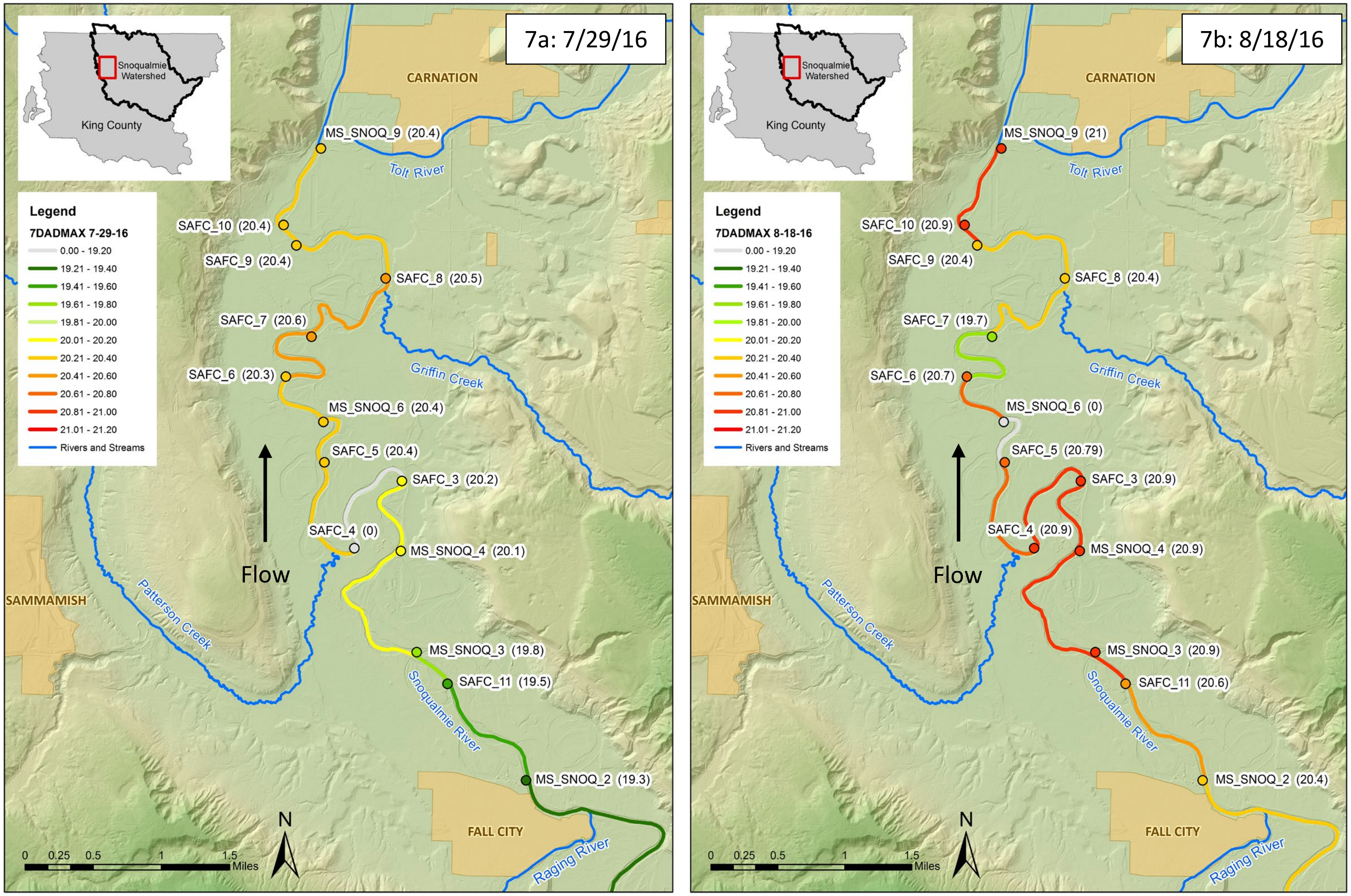

Figure 7a & 7b*: Snoqualmie River 7-DADMax temperatures on 7/29/16 (prior to base flows) and 8/18/16 (during base flows). Labels for sample points include a site code and the 7-DADMax temperature in parentheses (°C). Temperature ranges for both 7a and 7b are binned in similar 0.2°C intervals. Segment colors align with the temperature measured at the downstream sample location for ease of interpretation and segments with missing data are colored grey. The mainstem Snoqualmie River cooling reach, with decreased temperatures compared to adjacent upstream and downstream reaches, can be observed in Figure 7b from SAFC_6 (20.7°C) downstream to SAFC_9 (20.4°C). Figure 4 in Kubo (2017).*

The primary source of heat loading across the Snoqualmie River watershed is solar-atmospheric loading due to lack of riparian shade. Several assessments and evaluations (discussed below) have highlighted that the lower Snoqualmie River not only has degraded riparian and forest conditions but that these conditions significantly impact water temperatures. Temperature improvement strategies will need to prioritize the restoration of riparian and forest vegetation as well as protect intact and functioning areas (further discussed in section: *Strategies to Improve Water Temperature Conditions*).

Prior to European settlement, much of the Snoqualmie River floodplain upstream of Duvall and downstream of the Snoqualmie Falls was forested (Collins and Sheikh 2002). By the early 2000s, forest cover throughout the lower Snoqualmie floodplain was only 16% of historic extents mapped in the 1870s (Collins and Sheikh 2002). Additionally, by the late 20th century, only 25% of the lower Snoqualmie River shoreline had riparian buffers greater than 200-ft wide, with around 86% of the riparian corridor being cleared or in early seral stages (Gersib et al. 1999; Pentec 1999). Land cover analysis comparing early 2002 to 2015 indicated that ~60% of the 150-ft riparian corridor on the mainstem Snoqualmie was characterized as land cover types other than trees (i.e., agriculture, bare ground, impervious surfaces, shrubs, and other) (Kubo 2018). The percentage of tree coverage had modestly increased (~4%) from 2002 to 2015, which highlighted vegetation growth or plantings as well as areas of alluvial deposition and subsequent vegetation establishment and growth. While tree coverage has increased, the Snoqualmie River is still far from its riparian canopy potential.

An extensive riparian survey from WA Ecology in 2006-2007 indicated that effective shade was less than 30% across the majority of the mainstem Snoqualmie River. The Snoqualmie River is too wide for current riparian vegetation to have significant shading benefits and many riparian areas are in early seral stages and/or dominated by non-native species. Aerial photograph interpretation conducted by Pentec (1999) indicated that mature riparian forests could shade 50% of the Snoqualmie River helping to maintain and buffer temperature conditions. Temperature model scenarios conducted by Stohr et al. (2011), in association with the Snoqualmie River TMDL, indicated that under current riparian conditions and during low-flow periods, the Snoqualmie River is expected to have maximum water temperatures averaging 22.8°C and in some locations exceeding the 23°C lethal threshold. Compared to current conditions, a 180-ft wide riparian buffer of mature vegetation could decrease these daily maximum temperature averages by about 1.9°C (Stohr et al. 2011). In the Snoqualmie River watershed, mature vegetation around 100-yrs old has the potential to reach 225 feet tall (i.e., site potential tree height of mature vegetation) (FEMAT 1993; Reeves et al. 2016). The microclimate conditions associated with a 180-ft wide mature riparian buffer could further lower the daily average maximum water temperatures by about 0.4°C.

In addition to the restoration of riparian and forest vegetation, consideration of channel modifications and floodplain management, specifically among agricultural areas, may be needed to address temperature impairments. With current agricultural practices focused on draining floodplains during spring, opportunities for groundwater recharge, base-flow groundwater expression, and hyporheic exchange may be limited. Since reductions in groundwater and hyporheic exchange can impact temperature conditions (Fernald et al. 2006; Burkholder et al. 2008; Hester et al. 2009), strategies which mitigate these impacts including controlled drainage and seasonal water retention, may be beneficial in improving temperature conditions.

In the Snoqualmie River, point sources are not considered to be highly impactful to temperature conditions. Four point-source discharges from wastewater treatment plants (WWTPs) in Snoqualmie, North Bend, Carnation, and Duvall were evaluated by Stohr et al. (2011) and monitoring indicated that there were no measurable cumulative temperature effects from these sources. Additionally, two hatchery facilities (Tokul and Boxley creeks) were monitored and also had minimal impacts on stream temperatures. The spatial separation and volume of input across WWTPs and hatcheries likely influenced their minimal temperature effects. Stormwater heat loading was calculated by Stohr et al. (2011) from permitted discharges operated by King County, Snohomish County, Washington State Department of Transportation, and the cities of Duvall and Sammamish. Results indicated that stormwater had little, if any, effect on temperatures across watercourses in the Snoqualmie River basin. However, as development continues, heat loading from stormwater may become a more significant contributor to temperature problems. Stohr et al. (2011) also determined that sand and gravel permittees were not a major issue to heat loading; however, sediment discharges associated with these practices could have impacts on temperature conditions by filling in substrates and limiting groundwater and hyporheic exchange.

Snoqualmie River Tributaries

Below the Snoqualmie Falls, there are several small and large tributaries that feed into the mainstem Snoqualmie River. Tributaries listed by WA Ecology as impaired for temperature include North/Middle/South Fork Snoqualmie River (discussed in the *Above the Snoqualmie Falls* section), Burnt Boot Creek, Kimball Creek, Tokul Creek, Raging River, lower Tolt River (downstream of the North/South fork confluence), Patterson Creek, Weiss Creek, Tuck Creek, Harris Creek, Griffin Creek, Ames Creek, Adair Creek, and Cherry Creek. The largest tributaries of the Snoqualmie River (excluding the forks above the falls) include the Tolt River and Raging River, which drain 101 square miles and 32.8 square miles, respectively.

Among tributaries monitored in 2006 by Stohr et al. (2011) as part of the TMDL study, Tokul, Patterson, Griffin, Harris, Ames, Tuck, and Cherry creeks all had 7-DADMax temperatures below those in the mainstem Snoqualmie River (Figure 6). Tributaries that had 7-DADMax temperatures above those in the mainstem Snoqualmie included the Raging and Tolt rivers. Kaje (2009) indicated that watercourses which were relatively less impaired for temperature included Tuck Creek, Ames Creek, Harris Creek, Langlois Creek, North and South Fork Tolt River, Griffin Creek, and Tokul Creek. These watercourses commonly displayed cooler temperatures and generally remained below criteria thresholds (Kaje 2009). Tributaries more impaired for temperature included Cherry Creek, lower Tolt River (downstream of the North/South fork confluence), Patterson Creek, and the Raging River.

Water temperature impairments in Cherry Creek appear to primarily occur within the lower extents where the tributary transitions from canyon-like, wooded areas to the agricultural valley floor (Kaje 2009). Much of the Snoqualmie floodplain is severely altered with widespread removal of riparian vegetation as well as channel modification intended to drain the floodplain in early spring. Cherry Creek, as well as other tributaries, appear to display major increases in temperature as they cross these exposed valley-floor floodplain areas.

The Tolt River is the largest tributary below the Snoqualmie Falls and contributes around 20% of the mainstem Snoqualmie River flow gaged at Carnation (Stohr et al. 2011). Temperatures in the lower Tolt

River, measured just upstream of the confluence with the Snoqualmie River, are generally similar to temperatures in the mainstem Snoqualmie, but in some cases can be cooler (Stohr et al. 2011). Observations from Kubo and leDoux (2016) indicated that 7-DADMax temperatures in the lower Tolt River can be similar to the mainstem Snoqualmie River; however, minimum temperatures can be several degrees cooler. When the tributary water is cooler, the Tolt River appears to decrease mainstem Snoqualmie River temperatures (Stohr et al. 2011; Kubo and leDoux 2016). This pattern is especially apparent during warm summer months as well as during baseflow periods.

The Raging River is the second largest tributary and is frequently warmer than the mainstem Snoqualmie River during summer months (Stohr et al. 2011; Kubo and leDoux 2016; Steel et al. 2016). Observations from Stohr et al. (2011) indicated that the Raging River reached a peak 7-DADMax of 25.1°C in 2006. While the Raging River can deliver considerably warm water to the mainstem, minimal flow volume and a low percent contribution limits its influence on mainstem Snoqualmie River temperatures (Stohr et al. 2011; Kubo and leDoux 2016). Sub-surface hyporheic flow near the mouth can have cooler temperatures (Matt Baerwalde Snoqualmie Tribe pers. comm.); however, the percent contribution is still limiting. The warm water temperatures at the mouth of the Raging River in addition to low flows going subsurface through the gravel fan at its mouth may pose a barrier to migrating adult salmonids. The Raging River is rain-dominated with flows largely driven by precipitation and possibly groundwater, as compared to snowpack (Steel et al. 2019). Additionally, the underlying bedrock geology in the upper watershed of the Raging River may limit the depths and extent of hyporheic zones which can influence recharge potential and hyporheic exchange (Macneale 2017). With the Raging River being largely rainfall dominated and having an underlying bedrock geology, it experiences flashy and high-volume flows during fall and winter and then relatively low-volume flows during summer periods. The differences in flow volumes results in fall/winter periods having a wide active channel while the summer period has a relatively narrow active channel. Additionally, the bedrock geology limits hyporheic exchange and potential aquifer recharge. Subsequently, during summer base-flow periods, the narrow active channel has limited tree canopy cover and limited hyporheic exchange, which increases susceptibility to warming from solar-atmospheric heating. Additionally, timber harvest in the upper watershed impacts forest vegetation which limits shade potential, and Highway 18 impacts groundwater and hyporheic connectivity. Near its mouth, the Raging River crosses a largely rural to suburban residential floodplain, which has been severely altered with degraded riparian areas and revetment/levees along both banks of lower 1.5 river miles (Kubo 2018).

Monitoring during the warm, dry year of 2015 indicated that several tributaries (e.g., Raging River, Tolt River, Cherry Creek, Patterson Creek, Tuck Creek, and Griffin Creek) consistently exceeded State standards for designated uses (Kubo and leDoux 2016). Water temperatures across many tributaries were consistently above State standards up until the end of August, coincident with a rainstorm event. Many of the smaller tributaries still surpassed State standards for designated uses but remained below the thresholds for acute lethality and barriers to migration (Kubo and leDoux 2016). During 2015, several tributaries (e.g., Raging River, Cherry Creek, Tuck Creek, and the Tolt River) were well within the range of temperatures observed in the mainstem Snoqualmie River, while some of the smaller tributaries were noticeably cooler than the mainstem (Kubo and leDoux 2016). Among smaller tributaries, Harris, Tokul, Griffin, and Ames were at times cooler than the mainstem Snoqualmie. While the thermal influence of these smaller tributaries on the mainstem Snoqualmie River is likely minimal (due to small relative percent contribution), they may provide localized plumes of cooler temperatures that could serve as

thermal refuges for salmonids (Matt Baerwalde Snoqualmie Tribe pers. comm.). For example, (Stohr et al. 2011) noticed a plume at the mouth of Tokul Creek that was considerably cooler than adjacent mainstem temperatures. In addition to plumes along the mainstem, salmonids could also take refuge in the tributaries themselves.

Temperature Conditions - Skykomish River

Skykomish River

• Several reaches and tributaries of the Skykomish River display temperature exceedances.
  ○ Frequent mainstem temperature exceedances near Monroe; exceedances near Gold Bar generally occurring from mid-July to mid-September.
  ○ Less-frequent exceedances in the mainstem around the confluence with the Sultan River (Sultan River provides discharge at cooler temperatures during low-flow periods).
  ○ Less-frequent exceedances in the North Fork Skykomish River.
  ○ Temperature exceedances largely attributed to degraded riparian areas, hydrologic changes, channel engineering, and timber harvest.
• During the warm and low-flow years of 2015, temperature exceedances were widespread across mainstem reaches and tributaries.
• Skykomish River floodplain has considerable temperature variation.
  ○ Floodplain side-channels, tributaries, and wall-based channels can be considerably cooler than the mainstem.
  ○ Cooler floodplain areas are likely due to tributary inputs, groundwater inputs, well-shaded side-channel networks, and side-channel log jams, which promote hyporheic exchange and provide localized shading.

Skykomish River Tributaries

• Carpenter Creek (tributary to Woods Creek) has frequent temperature exceedances, largely attributed to degraded riparian conditions.
• Woods Creek, including the East and West forks below Carpenter creek, frequently exceed temperature standards with exceedances being more prevalent moving downstream.
• Sultan River general has cooler summer water temperatures that largely remain below State temperature standards.
  ○ Provides enough flow volume and temperature difference to cool the mainstem Skykomish River around the confluence (reservoir releases have provided increasing summer low-flow discharge, relative to the Skykomish River).
  ○ Longitudinal warming along 6-mile dam bypass reach can result in occasional exceedances of water quality criteria at points furthest downstream within the bypass.
  ○ Exceedances of water quality criteria are infrequent in the lower 9.7 miles of the river.
• Wallace River primarily displays temperature exceedances from late July through August.
  ○ Olney Creek (tributary to Wallace River) shows summer exceedances; however, considerably less frequent than Wallace River.
  ○ Side-channels within Wallace River commonly remain below temperature standards with minimal increases during summer months.
• Small tributary sub-basins with greater riparian and forest cover have considerably cooler temperatures than watershed with degraded riparian and forest areas.
• During the warm and low-flow year of 2015, there were widespread temperature exceedances across Skykomish River tributaries.
  ○ Several tributaries and side-channel areas displayed temperature exceedances across multiple critical thresholds.
  ○ Select smaller tributaries remained relatively cooler including Worthy Creek, a tributary to West Fork Woods Creek, and a tributary to Carpenter Creek.

Overview of the Skykomish River Watershed

Several waterbodies in the Skykomish River watershed are impaired for temperature (Svrjcek et al. 2013). Since these waterbodies do not meet State water quality standards, a Skykomish River TMDL is currently in progress. Temperature impairments in the watershed have largely been attributed to degraded riparian areas as well as hydrologic changes, channel engineering, timber harvest, as well as other factors (Svrjcek et al. 2013). These landscape alterations have impaired temperature conditions across several waterbodies and limit mainstem, tributary, and floodplain functions.

The Skykomish River watershed drains ~835 square miles and is situated in northeastern King County and southeastern Snohomish County. The river includes a North and South fork which flow through Washington State Parks and Recreation lands in the northern Cascades down to where they converge just downstream of Index. The Skykomish River includes numerous tributaries and continues downstream through primarily unincorporated agricultural areas as well as the cities of Gold Bar, Sultan, and Monroe. It converges with the Snoqualmie River around river mile 15 forming the Snohomish River. Evergreen forest and grassland areas dominate the watershed and a large portion is managed by the U.S. Forest Service and Washington State Parks and Recreation (Svrjcek et al. 2013). Approximately 4% of the watershed is developed including Index, Skykomish, Gold Bar, Sultan, and Monroe.

The Skykomish River watershed is primarily comprised of undeveloped and agricultural lands (~96%) with most of the undeveloped non-agricultural lands residing within the Mt. Baker-Snoqualmie National Forest (Svrjcek et al. 2013). Of the 96% undeveloped and agricultural lands, 78% includes deciduous, evergreen, and mixed forest cover and 15% includes grasslands and scrub/shrub lands. The watershed includes a major dam (Culmback Dam) and associated reservoir (Spada Reservoir) on the Sultan River, which is operated by the Snohomish County Public Utility District. This facility provides water to the city of Everett, electricity to Snohomish County, instream flows for fish, and incidental flood control. A small diversion dam is located on the Sultan River approximately 6.8 miles downstream from Culmback Dam. Volitional, unimpeded, year-round fish passage was initiated in 2016 and under current conditions the dam is only used to divert water under emergency conditions. Implementation of fish passage was one measure tied to issuance of the new operating license in 2011 (Snohomish County Public Utility District No. 1 2011). Prior to project completion in 2016, the diversion dam blocked 6.8 miles of the Sultan River since the early 1900s. Prior to issuance of the new license, past mitigation efforts focused on providing additional downstream habitat, providing cooling waters during summer months, and by normalizing flows (Haring 2002; Snohomish County Public Utility District No. 1 2011).

Prior to European settlement, the majority of the Skykomish River watershed was forested, aside from alpine areas, prairies, and wetlands (Svrjcek et al. 2013). As previously mentioned, the majority of the Skykomish watershed is still forested; however, after European settlement forest lands decreased, forestry practices converted older forests to earlier seral stages, and evergreen-dominated forests transitioned to mixed forests. While logging practices have declined, the Skykomish River watershed still supports abundant timber harvest and forestry practices.

The climate of the Skykomish River watershed has a temperate marine climate due to its year-round precipitation and moderate temperatures (Pentec Environmental and GIS NW 1999). The climate is characteristic of warm, dry summers and cool, mild, wet winters. Snowfall occurs at higher elevations and is generally less common than rainfall. Annual precipitation increases from west to east across the

watershed, from 48 inches in Monroe (in the western watershed) to 89 inches in Index (in the center of the watershed) (Western Regional Climate Center 2006a, 2006b).

Mainstem Skykomish River

The Skykomish River was listed as impaired for temperature in a 2008 303(d) listing and proposed 2010 303(d) listing (Svrjcek et al. 2013). Several segments of the Skykomish River as well as its tributaries consistently exceed water quality temperature standards (Haas et al. 2007; Svrjcek et al. 2013). Additionally, Water Quality Index Scores assessed by Snohomish County suggest that temperature may be a primary water quality limiting factor for salmonids in the lower mainstem Skykomish River (Snohomish County and SLS Executive Committee 2017). During select summer periods from 2001-2006, temperature monitoring in the Skykomish River at Monroe indicated that the average 7-DADMax frequently exceeded the 16°C criteria (*core summer salmonid habitat*) during summer months (Svrjcek et al. 2013). Between July and September in 2001-2006, temperature exceedances at Monroe ranged from 60% - 100%, with 2006 being the year of 100% temperature exceedances. Snohomish County temperature monitoring in the North Fork Skykomish River during the summer of 2010 indicated that the overall exceedance of the 12°C criteria (*char spawning and rearing*) was around 17.4% (Svrjcek et al. 2013). Monitoring in 2005 by Snohomish County near the city of Gold Bar indicated that 7-DADMax temperatures were below the 16°C criteria (*core summer salmonid habitat*) up to mid-July and after mid-September, with exceedances generally occurred between those periods (Haas et al. 2007). Downstream near the confluence with the Sultan River, temperature monitoring conducted by the Snohomish County Public Utility District in 2011-2012 showed that the 16°C criteria (*core summer salmonid habitat*) was exceeded 2.3% of the time in the mainstem above the Sultan River and 4.2% of the time below the Sultan River. Low exceedances around the confluence with the Sultan River were attributed to cool water inputs from the Sultan River (Haas et al. 2007; Svrjcek et al. 2013). During the warm and low-flow year of 2015, temperature exceedances throughout the Skykomish River watershed were relatively wide-spread across mainstem and tributary locations (Leonetti and Rustay in prep.). Not only were exceedances common, but 7-DADMax temperatures reached levels that may have been barriers to migration as well as potential single day lethal temperature peaks.

Across the Skykomish River floodplain, there appears to be considerable temperature heterogeneity among large and small tributaries as well as in side-channel areas (Haas et al. 2007). Side-channel complexes upstream of the Sultan River appeared to have high temperature variability over relatively short distances. Snohomish County was able to identify several area of relatively cool water temperatures associated with tributary inputs as well as in well-shaded side-channel networks. Side-channels, tributaries, and wall-based channels along the margins of the floodplain were noticeably cooler than mainstem Skykomish River temperatures. In some side-channels, Snohomish County observed lower temperatures at the downstream extent, compared to the upstream extent. Temperature differences were hypothesized to be related to hillslope groundwater and tributary inputs, which may decrease watercourse temperatures among floodplain margin areas (Haas et al. 2007). Additionally, log jam features throughout side-channel areas may influence temperature conditions by promoting hyporheic exchange and providing localized shading. However, some side-channels including wide and poorly shaded watercourses frequently exceeded State standards (Haas et al. 2007; Snohomish County and SLS Executive Committee 2017). Watercourses and side-channel areas that

consistently had warm temperatures may be less influenced by groundwater inputs, more influences by mainstem flows, and less buffered by surrounding riparian vegetation.

During the ongoing development of the Skykomish River TMDL study, wasteload allocations will be evaluated for relevant point source discharges in the Skykomish River watershed. For relevant point sources, discharge monitoring data and permit limits will be reviewed in detail for sources that may impact water temperature conditions (Svrjcek et al. 2013). Discharges and point source loading from Spada Reservoir and the PUD's hydroelectric operation on the Sultan River are currently managed by Federal Energy Regulatory Commission Licensing and the Clean Water Act Section 401 Water Quality Certification. Additional point source discharges may include sewage and wastewater treatment plants in Monroe, Sultan, and Everett as well as hatcheries (e.g., Reiter Ponds and Wallace River) and gravel facilities. Based on observation from previous TMDL efforts, WA Ecology predicts that thermal contributions from hatcheries and gravel facilities are likely minimal, similar to the situation in the Snoqualmie; however, they will still aim to evaluate loading and allocations. Stormwater discharges have been permitted for King County, Snohomish County, Washington State Department of Transportation, Monroe, and Everett (issuance of Phase 1 and 2 stormwater permits). As long as these discharges are less than 1% of the receiving waterbody, they will not be assigned allocations through the TMDL processes.

Skykomish River Tributaries

Tributaries within reaches listed by WA Ecology as impaired for temperature (or as watercourses of concern) include Bear Creek, Cripple Creek, Beaver Creek, Olney Creek, Pekola Creek, Riley Slough, Carpenter Creek, and West Fork Woods Creek. Tributary monitoring throughout the Skykomish River watershed have indicated that there is considerable variation among tributary temperature conditions (Flint et al. 2013; Svrjcek et al. 2013).

Carpenter Creek is a tributary to Woods Creek and frequently exceeds the 16°C temperature criteria (*core summer salmonid habitat*) during summer months. For example, observation from 2008-2010 indicated that the percent exceedance across locations in Carpenter Creek ranged from 10% – 60% (Svrjcek et al. 2013). Exceedances in a given year were noted to be relatively similar across the watercourse. An extended water temperature evaluation (2008-2015) found similar results with Carpenter Creek exhibiting 10 – 64% exceedances, specifically during summer periods (Snohomish County and SLS Executive Committee 2017). Much of the water temperature impairments have been attributed to degraded riparian conditions (Flint et al. 2013).

Woods Creek flows through forest lands and then agricultural and urban residential lands before joining the Skykomish River near the city of Monroe. Woods Creek, including its East and West forks downstream of Carpenter Creek, frequently exceed the 16°C temperature criteria (*core summer salmonid habitat*) as well as the supplemental 13°C criteria (*spawning & incubation*) (Flint et al. 2013; Svrjcek et al. 2013). Specifically, Snohomish County water quality monitoring indicated that the percent exceedance across summer periods from 2008-2010 ranged from 37 – 77% in the East Fork to 47 – 94% in the West Fork (Svrjcek et al. 2013). Additionally, percent exceedance in Woods Creek from 2009-2011 ranged from 24 – 93%. During the summer of 2010, all stations along Woods Creek were found to exceed temperature criteria with exceedances tending to be more prevalent moving downstream (Flint

et al. 2013). Similar to Carpenter Creek, impaired temperature conditions were largely attributed to degraded riparian condition across the sub-basin.

The Sultan River originates in the headwaters upstream of Spada Reservoir (aka Spada Lake) and flows through lands of varied and mixed ownership before joining the Skykomish River near the City of Sultan. The Snohomish County Public Utility District No. 1 (Snohomish County PUD) operates Culmback Dam to regulate Spada Reservoir to meet license requirements tied to municipal water supply, fish flows, incidental flood control, and the generation of electricity. Mitigation for dam operations include improvements to downstream salmonid habitat conditions by normalizing flow, habitat creation, and by providing cool releases during summer-fall periods when the reservoir is stratified. Temperature impacts from the Henry M. Jackson Hydroelectric Project are addressed through a Clean Water Act Section 401 Water Quality Certification (Snohomish County Public Utility District No. 1 2011). Generally, the Sultan River has cooler summer water temperatures that largely remain below the 16°C temperature criteria (*core summer salmonid habitat*). For example, monitoring data collected by U.S. Geological Survey and Snohomish County PUD showed that from 2011 to 2012 the Sultan River exceeded the 16°C temperature criteria only 0 – 1.4% of the monitored period (Svrjcek et al. 2013). These observations were further supported by Snohomish County PUD in 2018 which showed few exceedances downstream of the Culmback Dam aside from a few days in September at the most downstream station (Snohomish County Public Utility District No. 1 2019). However, longitudinal warming along the 6-mile bypass reach of the dam has been observed, which can increase temperatures and related exceedances in the most downstream points in this particular reach (Snohomish County Public Utility District No. 1 2019). The Sultan River appears to have enough flow and temperature difference to cool the mainstem Skykomish River around the vicinity of the confluence (Haas et al. 2007).

Over the last 35 years, reservoir releases in the Sultan River have provided increasing summer low-flow discharge, relative to the Skykomish River. Specifically, summer low flow yield (minimum 7-day average of average daily flow divided by square mile) from the Sultan River has increased substantially over time compared to other local and regional rivers (Figure 8) (Frank Leonetti pers. comm). These trends suggest that flow management and reservoir releases in the Sultan River have normalized flows relative to other rivers, which as previously highlighted, can alter temperature dynamics in adjacent Skykomish River reaches. Additionally, due to an estimated increase in flow subsidy of ~146 cfs (for the 7-day minimum low flow) from the Sultan River to the lower Skykomish River, the ratio of Skykomish River to Sultan River low-flow discharge has changed from 3 times to only 1.5 times (Snohomish County Surface Water Management unpub. data).

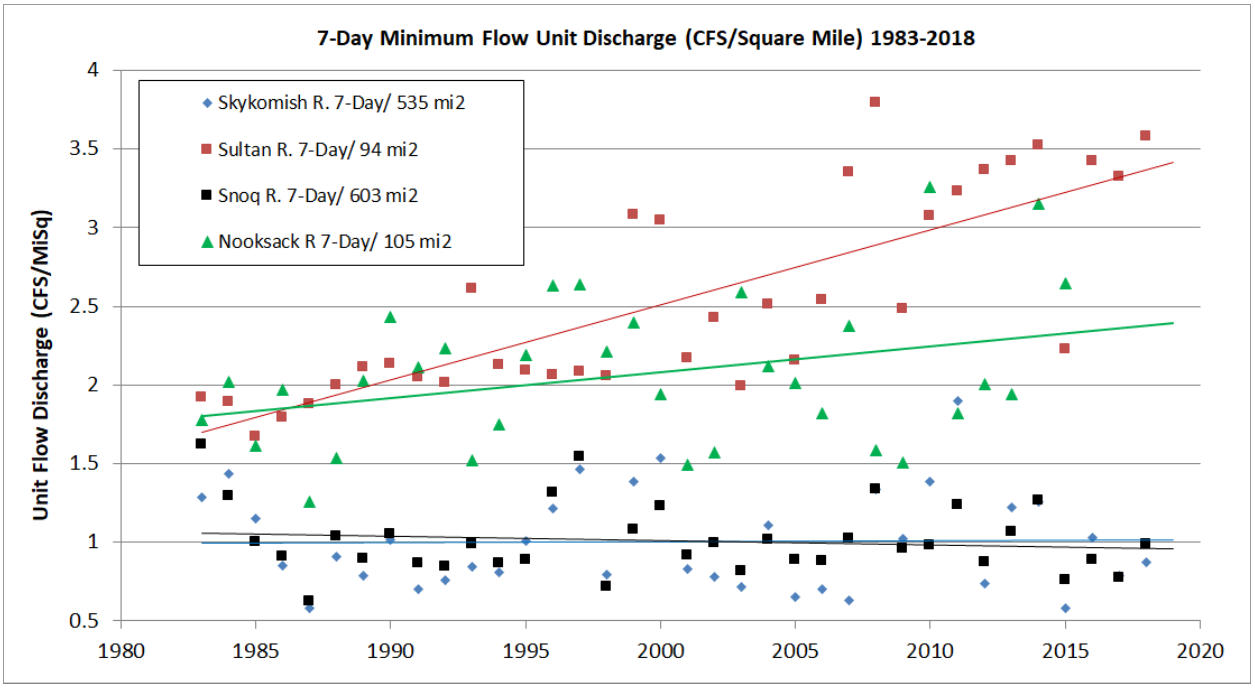

Figure 8. *Summer low flow yield (minimum 7-day average of average daily flow divided by square mile) from the Skykomish River, Sultan River, Snoqualmie River, and Nooksack River. Figure provided by Frank Leonetti.*

The Wallace River (including its tributary, Olney Creek) flows through mostly undeveloped evergreen forest lands, including the Wallace Falls State Park, and enters the Skykomish River just upstream of the Sultan River. Monitoring by Snohomish County in 2005 indicated that the Wallace River remains below the supplemental 13°C criteria (*spawning & incubation*) until July and returns to the range in mid-September (Haas et al. 2007). However, the 16°C temperature criteria (*core summer salmonid habitat*) was frequently exceeded from late-July through August. Additional Snohomish County temperature monitoring in 2008 and 2010 indicated that the Wallace River exceeded temperature criteria between 15 – 71% of the monitored summer-fall period (Svrjcek et al. 2013). Olney Creek also shows summer exceedances; however, the percent exceedances were considerably lower at 7 – 22% of the time. Select side-channels complexes within the Wallace River appear to have considerably lower temperatures than the mainstem, with temperatures remaining below criteria and showing little rise through summer months (Haas et al. 2007). In addition to the Sultan River, the Wallace River appears to have enough flow to result in localized cooling in the mainstem Skykomish River (Haas et al. 2007).

Other tributaries to the Skykomish River have showed variation in temperature exceedances. For example, during periods of 2008 – 2010, McCoy Creek exceeded criteria 28 – 76% of the monitored period and in 2000, Barr Creek, Elwell Creek, and Kinsee Creek exceeded criteria 31%, 68%, and 14% of the monitored period, respectively. Additionally, in 2004, Richardson Creek, Sister of Friar, and Roesiger Creek exceeded temperature criteria 66 – 80%, 27 – 69%, and 100% of the monitored period, respectively. Temperature conditions in smaller tributaries appear to be related to the riparian conditions and forest cover in a given watershed. For example, monitoring conducted by Snohomish County indicated that a tributary coming from a forested watershed was considerably cooler (~2.5°C)

than Wagley Creek, a tributary coming from a developed watershed (Haas et al. 2007). The difference in canopy cover between the forested and developed watershed was hypothesized to be a primary driver in observed temperature differences.

During the warm and low-flow summer of 2015 (second lowest among 87 years of data in the Skykomish River), there were wide-spread exceedances of temperature criteria across the Skykomish River watershed as well as among tributaries to the Snohomish River (Figure 9) (Leonetti and Rustay in prep.). Temperature conditions across Snohomish River tributaries (e.g., Pilchuck River, French Creek, Quilceda creek, and others) are discussed in detail in the following *Snohomish River Tributaries* section. Observed temperature exceedances in 2015 included mainstem, tributary, and side-channel watercourses with temperatures surpassing multiple critical thresholds. As mentioned in the *Mainstem Snoqualmie River* section, the temperature conditions observed in 2015 may provide insight into potential future conditions associated with projected climate change and land use impacts. Select tributaries across the Skykomish River watershed were relatively cool, compared to other tributaries. These select tributaries included Worthy Creek, a tributary to West Fork Woods Creek, as well as a tributary to Carpenter Creek (Figure 9) (Leonetti and Rustay in prep.).

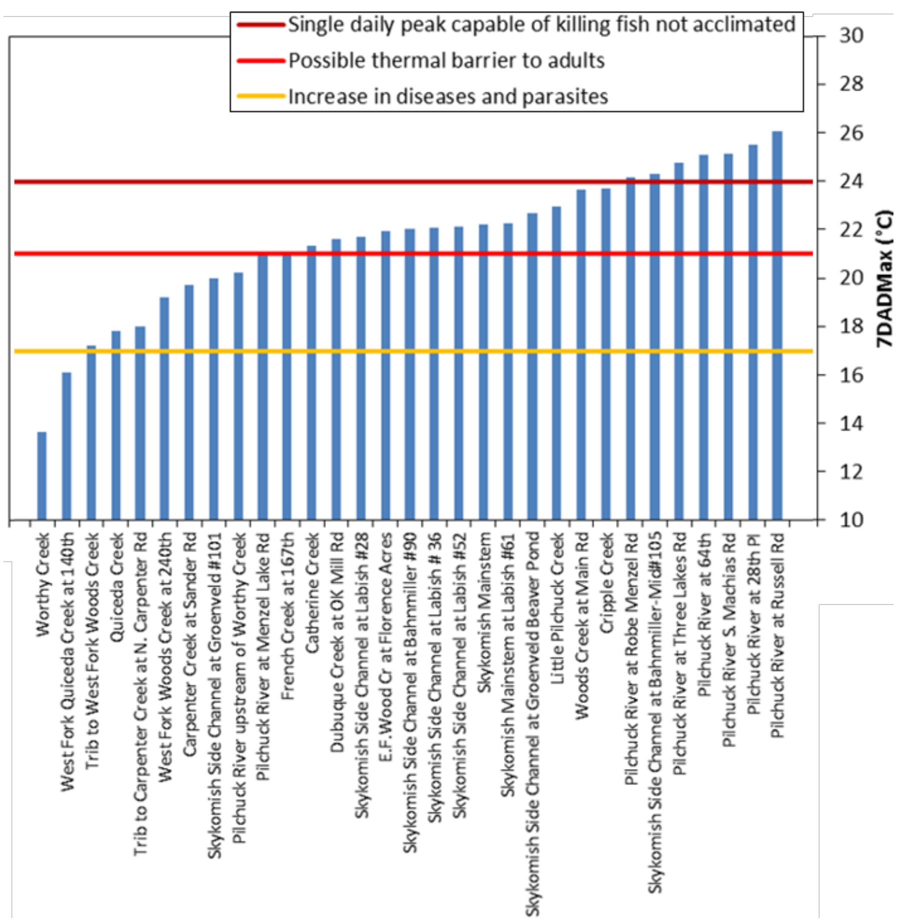

***Figure 9**: 7-DADMax temperatures in 2015 at sites across the Snohomish River basin (Snohomish County portions of basin). Physiological thresholds for salmonids from Hicks (2002). Figure from Leonetti and Rustay in prep.*

Temperature Conditions - Snohomish River and Estuary

Snohomish River and Estuary

• The lower Snohomish River and Snohomish Estuary consistently have the warmest temperatures across the entire Snohomish River basin.
    o Temperature exceedances in Snohomish Estuary occur from July through September
• Temperatures generally increase moving downstream throughout most months; reversed after August, with temperatures becoming cooler with increasing proximity to the Puget Sound.
    o Cooler riverine waters mix with warmer ocean waters up until August, when warmer riverine waters mix with cooler water of the Puget Sound throughout fall and winter.
• Considerable temperature variation across the Snohomish Estuary (primarily from May to August) with differences from the upper to the lower estuary ranging from 1.5 – 1.7°C.

Snohomish River Tributaries

• The Pilchuck River frequently exceeds temperature standards across middle and lower reaches with exceedances occurring from July to August.
• High water temperature conditions in the middle Pilchuck likely due to:
    o Broad and shallow channel (increasing susceptibility to solar-atmospheric heating).
    o Few tributary inputs (limiting potential cold-water thermal inputs).
    o Degraded riparian areas and reduced shading.
    o Limited connectivity to groundwater and aquifer areas due to levees and revetments.
• The Pilchuck River displayed widespread temperature exceedances during the warm and low-flow summer of 2015; some locations displayed temperatures above the single-day mortality threshold.
• The lower Pilchuck River has several tributaries (e.g., Little Pilchuck Creek, Catherine Creek, and Dubuque Creek) which can be cooler at times, compared to the mainstem Pilchuck River; however, these tributaries are generally warm and appear to have a minimal effect on mainstem Pilchuck River temperatures.
• Select reaches of the middle Pilchuck River display localized cooling.
    o Reaches near Schwarzmiller Road can be cooler than downstream reaches (up to 5°C cooler) as well as upstream reaches (up to 2°C cooler).
    o Some side-channel complexes display cooler temperatures than the mainstem Pilchuck.
    o Localized reach-scale and side-channel cooling are likely due to hyporheic flow, groundwater inflow, or shallow floodplain aquifer exchange.
• French Creek displays frequent temperature exceedances, primarily during summer months.
• Compared to the Pilchuck River, French Creek shows a broader range in the frequency of temperature exceedances.
• Areas of temperature moderation and cooling:
    o Reaches in the middle Pilchuck River near Schwarzmiller Road.
    o Side-channels throughout the Pilchuck River.
    o Little Pilchuck Creek near 108th St., French Creek near Spada Rd., tributary to Mallard Lake, and the Pilchuck River near 236th Ave N.E.
    o Select tributaries of the Snohomish Estuary (e.g., middle and west fork of Quilceda Creek and Allen Creek near 4th Ave).

Overview of the Snohomish River and Estuary

The Snohomish River begins at the confluence of the Skykomish River and the Snoqualmie River (around river mile 21) and travels downstream till it discharges into Puget Sound. Aside from the Skykomish and Snoqualmie rivers, the only other major tributary in the Snohomish River is the Pilchuck River, which drains approximately 136 square miles and enters near the city of Snohomish. The Snohomish River is a low-gradient watercourse with a broad floodplain extending approximately 1 mile wide in its upper extents to 2 miles wide in its lower extents (Snohomish County and SLS Executive Committee 2018). The Snohomish River becomes the Snohomish Estuary around river mile 8, where Ebey Slough diverges from the mainstem. The Snohomish Estuary includes three primary sloughs (Ebey, Steamboat, and Union) as well as a network of blind tidal channels. The hydrologic, hydraulic, and flood characteristics in the Snohomish Estuary are determined by the interaction between river flow and tidal cycles. Specifically, the Snohomish River and Estuary are affected by tidal backwater conditions upstream to river mile 16 (Collins and Sheikh 2002) with saltwater intrusion extending up to river mile 9.9 (Hall et al. 2018). Below the confluence of the Skykomish and Snoqualmie, the lower Snohomish River watershed includes the cities of Snohomish, Everett, Marysville, Lake Stevens, and parts of Granite Falls.

Non-native settlers began inhabiting the Snohomish River valley in the mid-1850s and with the expansion of settlements came dramatic landscape changes. These included logging of riparian forests, stream ditching and straightening, wetland draining, removal of instream wood, construction of dikes and levees, and extensive clearing of vast areas for agriculture (Snohomish County and SLS Executive Committee 2018). Prior to non-native and European settlement, the lower Snohomish River Estuary consisted of approximately 9,760 acres of wetland and estuarine habitats with roughly 400 acres of blind tidal sloughs (Haas and Collins 2001). With the dramatic landscape changes from non-native and European settlers came a significant loss in estuarine habitat area and extent. For example, compared to the mid-nineteenth century, only 23% of the historic estuarine extent remained by the late-twentieth century (Haas and Collins 2001). This included a 95% loss in the forested riverine tidal zone, a 68% loss in the emergent-forested transition zone, as well as a 38% loss in the estuarine-emergent marsh zone. By the 1950s, an extensive dike, levee, and revetment networks was constructed along the Snohomish River and Estuary to protect adjacent lands from flood impacts. These modifications disconnected the mainstem Snohomish River from floodplain, tidelands wetland, and marsh areas resulting in significant loss to critical salmon habitats (Snohomish Basin Salmon Recovery Forum 2005). The lower Snohomish River and Estuary continues to be a highly modified landscape with large portions converted to agricultural, urban, and industrial land uses. Additionally, the floodplain is crisscrossed with several transportation corridors including Interstate-5, U.S. Highway 2, State-route 529, and the BNSF rail line.

Climate in the Snohomish River and Estuary differ quite a bit from the contributing Skykomish and Snoqualmie watershed. The lowlands in the Snohomish River basin typically receive 30 to 40 inches of precipitation annually, compared to over 150 inches in the Cascades Range. This results in considerable variation in stream flows throughout the year. Due to the contributing watershed areas, the lower Snohomish River experiences winter storm flooding as well as melting snowpack floods in spring and summer. The Snohomish River and Estuary provide a diversity of aquatic habitats which support the various salmonids of the Snohomish basin. The diversity of habitats provides areas for rearing, migration, and transitioning between freshwater and saltwater.

Mainstem Snohomish River and Estuary

Areas in the Snohomish River and Estuary listed by WA Ecology as impaired for temperature (or a watercourse of concern) include the mainstem Snohomish River, Steamboat Slough, Marshlands, Ebey Slough, and Deadwater Slough.

Temperature monitoring across the mainstem Snoqualmie, Skykomish, and Snohomish rivers indicate that the lower Snohomish River and Estuary consistently have the warmest temperatures across the Snohomish River basin (Haas et al. 2007). Temperatures in the lower Snohomish River and across the Snohomish River Estuary tend increase along a downstream gradient throughout most months (Hall et al. 2018). However, this pattern is reversed in August when temperatures become relatively cooler with increasing proximity to the Puget Sound. This pattern is likely due to relatively cooler freshwater mixing with warmer ocean waters up till August when relatively warmer riverine waters mix with cooler water of the Puget Sound throughout fall and winter (Hall et al. 2018). Water temperatures across the Snohomish Estuary are generally spatially homogenous throughout winter months with gradients and variation in spatial temperature patterns primarily occurring between May and August.

Observations from Hall et al. (2018) indicated that mean monthly temperatures across distributary channels of the Snohomish Estuary varied from 8.3 – 12.0°C in May to 16.5 – 20.0°C in August. Temperatures exceeding 16°C appear to occur throughout the estuary from July through August and temperatures exceeding stress thresholds for salmonids appeared to occur throughout the estuary from July through September (Hall et al. 2018). Previous observations by Haas et al. (2007) also found that temperatures across the estuary exceeded 16°C from the middle of June through September. Haas et al. (2007) also noticed that 20°C was surpassed in mid-July and didn't drop below 20°C until early September. Temperature variation across the Snohomish Estuary can be considerable with average monthly temperature differences from the upper to the lower estuary ranging from 1.5 – 1.7°C (Hall et al. 2018). Additionally, temperature ranges within and between distributary channels can vary by several degrees Celsius during summer periods.

Snohomish River Tributaries

Snohomish River tributaries listed by WA Ecology as impaired for temperature include French Creek, Swifty (Ferguson) Creek, Pilchuck River, Little Pilchuck Creek, Catherine Creek, and Dubuque Creek.

The Pilchuck River is the largest tributary in the lower Snohomish River and flows from Mt. Pilchuck and Bald Mountain near Spada Lake down to where it joins the Snohomish River just upstream of the City of Snohomish. The Pilchuck River is largely designated as *core summer habitat* (16°C criteria), aside from the upper extents, which are designated as *char spawning and rearing* (12°C criteria). Temperature in Pilchuck River generally increase moving downstream with most exceedances occurring from July to August (Figure 10) (Snohomish County Surface Water Management 2012). Only locations in the upper watershed (upstream of Menzel Road) occasionally meet State temperature standards. Across the Pilchuck River, high water temperatures were commonly observed in 2001-2002 among the middle and lower reaches, with those areas frequently exceeding the 16°C criteria (Savery and Hook 2003). Data collected by Snohomish County across the Pilchuck River watershed, during select periods from 1994 – 2009, indicated that temperature exceedances ranged from 32 – 41%, primarily occurring during summer months (Snohomish County Surface Water Management 2012). These exceedances were

supported by Snohomish County data from 2004 – 2011, which found temperature exceedances ranging from 32 - 47% during summer periods (Swanson et al. 2012). Data collected by WA Ecology further noted that temperature exceedances ranged from 17 – 42% during critical summer periods (Swanson et al. 2012).

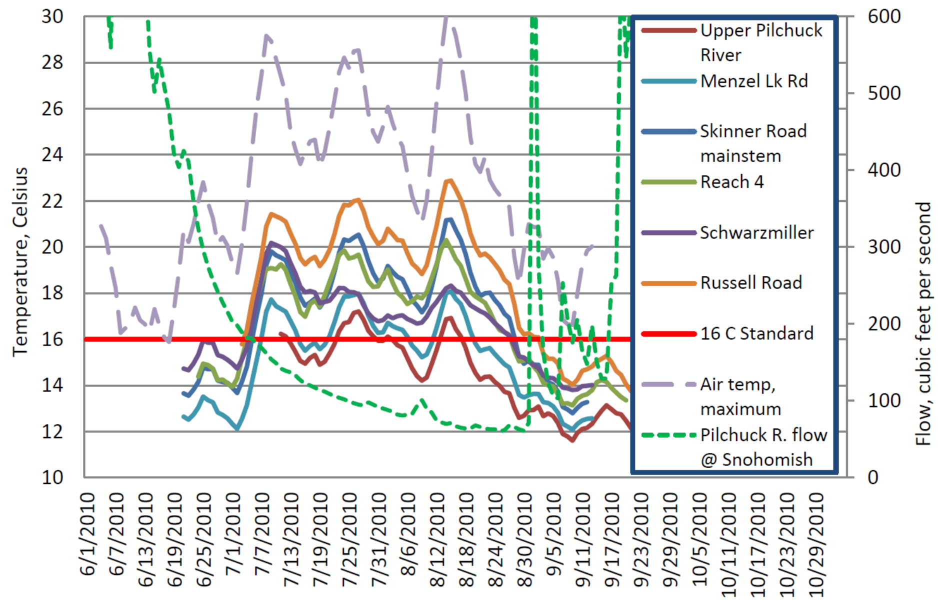

***Figure 10**: 7-DADMax temperatures among the Pilchuck River mainstem location – the list reading upstream to downstream. Also shown are the applicable Washington State temperature standard of 16°C, 7-DADMax air temperature, and Pilchuck River flow. Temperature exceedances across locations occurred from July to August during low flow periods with water temperatures generally tracking air temperatures. The figure highlights that the Schwarzmiller location was at times 5°C cooler that the adjacent downstream location (Russel Road) as well as even 2°C cooler than upstream locations (Reach 4 and Skinner Road mainstem). Figure 3-13 from Snohomish County Surface Water Management (2012).*

High temperature conditions throughout the middle Pilchuck River (downstream of Menzel Lake Road) has largely been attributed to the watercourse being broad and shallow, having few tributary inputs, degraded riparian areas, as well as having limited connectivity to floodplain and aquifer areas due to levees and revetments (Savery and Hook 2003; Snohomish County Surface Water Management 2012; Leonetti and Rustay in prep.). The middle Pilchuck River is of particular concern for future drought and hot water conditions. For example, increases in air temperature beyond 20°C in combination with low flows (e.g. < 200 cfs) appear to cause significant spikes in water temperatures (Snohomish County Surface Water Management 2012). During the warm and low-flow summer of 2015, several sites across the Pilchuck River surpassed several critical temperature thresholds with select locations even displaying temperatures high enough to cause potential single-day mortality (Figure 9) (Leonetti and Rustay in prep.). The lower Pilchuck River (downstream of Russel Road) has several tributaries including Little Pilchuck Creek, Catherine Creek, and Dubuque Creek, which at times can provide cool water inputs. However, Little Pilchuck Creek and Catherine Creek are generally warm and commonly exceed temperature criteria (Swanson et al. 2012; Snohomish County and SLS Executive Committee 2018). These tributaries appear to have a minimal effect on mainstem Pilchuck River temperatures.

Localized temperature moderation and variation in thermal conditions has been observed in select reaches of the Pilchuck River. Snohomish County observed that reaches near Schwarzmiller Road in the middle Pilchuck River were at times 5°C cooler than the adjacent downstream reach (near Russel Road bridge) and even 2°C cooler than upstream reaches (Figure 10) (Snohomish County Surface Water Management 2012). Much of the observed temperature moderation was attributed to cooler groundwater, floodplain, and/or hyporheic water sources. Several side-channels across the middle Pilchuck River have displayed considerably cooler temperatures compare to the mainstem Pilchuck River (Figure 11) (Snohomish County Surface Water Management 2012). Temperature moderation in side-channel areas were likely influenced by hyporheic flow, groundwater inflow, or shallow floodplain aquifer areas (Snohomish County Surface Water Management 2012). Restoring and supporting geomorphically diverse and active river segments throughout the Pilchuck River may help in improving structural habitat quality and quantity, which could provide cold-water refuge for rearing salmonids.

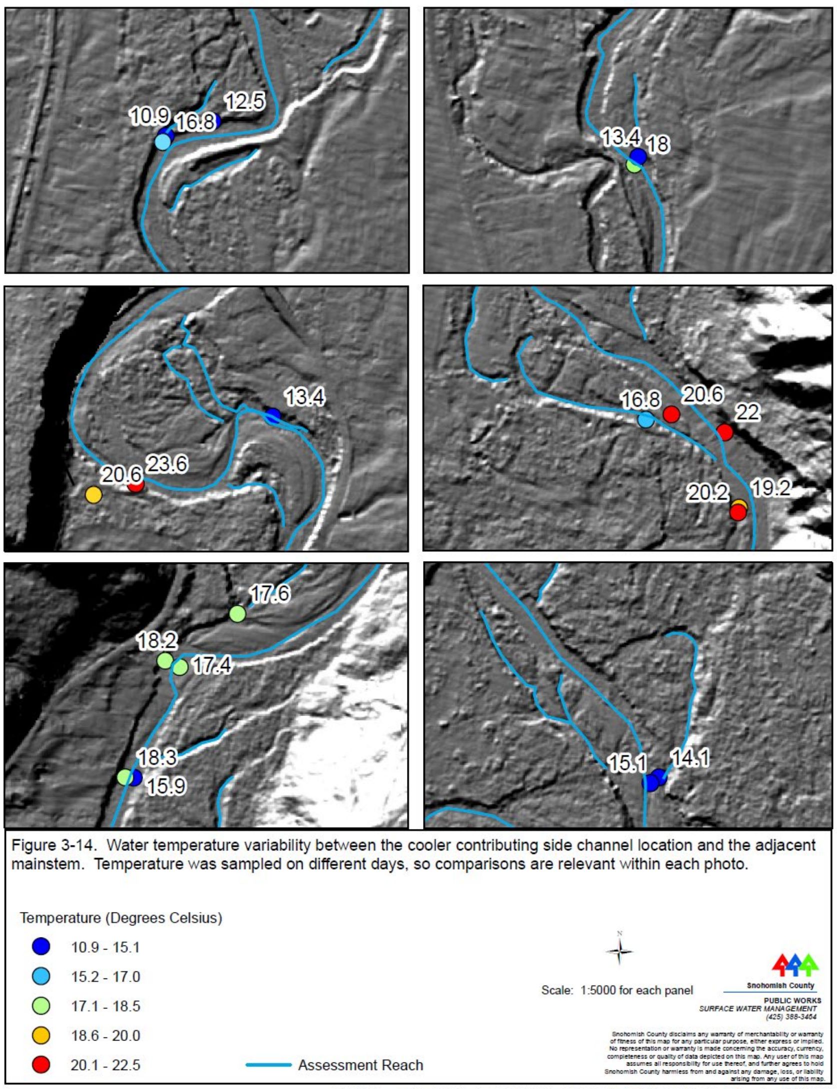

Figure 3-14. Water temperature variability between the cooler contributing side channel location and the adjacent mainstem. Temperature was sampled on different days, so comparisons are relevant within each photo.

Figure 11: *Water temperature variability between side-channel and mainstem Pilchuck River locations. Side-channels across locations appear several degrees cooler than adjacent mainstem temperatures. Figure 3-14 from Snohomish County Surface Water Management (2012).*

French Creek is largely designated as *core summer habitat* (16°C criteria) and observations from Snohomish County (select periods from 1993 – 2009) indicated that temperature exceedances in French Creek ranged from 30 – 45%, primarily occurring during summer months (Swanson et al. 2012). Data collected by Snohomish County during select periods from 2004 – 2011 also supported temperature exceedances from 16 – 49%. Observations from Swanson et al. (2012) suggested that temperature exceedances in French Creek may have a wider range than the mainstem Pilchuck River. Swanson et al. (2012) indicated that 43% of daily temperature measurements in French Creek exceeded water temperature criteria during summer critical periods.

Areas with relatively cooler temperatures (difference of 2.5°C) have the potential to provide thermal refuge for salmonids (Berman and Quinn 1991; Torgersen et al. 1999, 2012; Goniea et al. 2006; Steel et al. 2016). As discussed above, reaches near Schwarzmiller Road in the middle Pilchuck River show considerably lower temperatures, compared to upstream and downstream reaches (Snohomish County Surface Water Management 2012). Additionally, side-channels throughout the Pilchuck River appear to display relatively cooler temperatures, compared to the mainstem Pilchuck River. Additional areas of relatively cooler temperatures across the Pilchuck River and French Creek watershed include Little Pilchuck Creek near 108th St., French Creek near Spada Rd., a Mallard Lake tributary, and the Pilchuck River near 236th Ave N.E. (Snohomish County and SLS Executive Committee 2018). Tributaries to the Snohomish Estuary with relatively cooler temperatures include the middle and west fork of Quilceda Creek as well as Allen Creek near 4th Ave (Snohomish County and SLS Executive Committee 2018). Even during the warm and low-flow summer of 2015, these select tributaries were consistently cooler than other tributaries (Figure 9) (Leonetti and Rustay in prep.).

Across the Pilchuck River and French Creek watersheds, potential point source inputs for heat loading include stormwater pollution, sand and gravel pits, wastewater treatment plants, and agricultural practices (e.g., dairy operations). Similar to the Snoqualmie River TMDL processes, it's thought that these inputs are likely negligible sources of heat loading to the watersheds. However, the ongoing Pilchuck River and French Creek TMDL process has highlighted the potential impact of permit-exempt wells on water temperature condition (through decreases in stream flow). Subsequently, the TMDL process will include potential temperature impacts from water withdrawals and reduced streamflow. WA Ecology has already noted that streamflow restoration will likely be needed to address temperature exceedances during baseflow conditions.

Strategies to Improve Water Temperature Conditions across the Snohomish River Basin

Improving Temperature Conditions and Thermal Diversity
• Restoring/preserving temperature conditions and thermal diversity requires consideration of multiple spatial and temporal scales. • Thermal diversity constitutes temperature variation within riverine reaches, across floodplains, throughout stream networks, and across watersheds. • It will be critical to consider various aspects of thermal regimes (aside from just maximum temperatures) including the timing, duration, rate-of-change, magnitude, and spatial variation of temperature conditions. • A suite of concurrent strategies is needed to maximize temperature improvements and to fully support localized and basin-wide thermal diversity.
Strategies to Improve Water Temperature Conditions

• Highest priorities for improving temperature conditions across the Snohomish River basin include riparian restoration/protection, increasing channel and floodplain complexity, as well as increasing channel, floodplain, and tributary connectivity.
• The protection of intact functioning riparian/forest areas as well as the restoration of degraded riparian areas may be the greatest near-term action for providing long-term temperature improvements.
• Restoring channel, floodplain, and tributary complexity and connectivity includes large wood installation, creation and maintenance of side-channel and off-channel areas, removal of bank stabilization, protection/restoration of wetlands, promoting beaver dam complexes, and restoration of tributaries and confluence areas.
• Conservation efforts need to focus on multiple time horizons:
    o Near-term strategies include planting riparian vegetation and increasing groundwater/hyporheic exchange.
    o Long-term strategies include restoring/protecting water flow processes, ensuring adequate cold-water refuges, and supporting connectivity throughout watersheds.

The impacts of degraded temperature conditions on salmonid growth, reproduction, and survival emphasize the urgency of addressing temperature impairments across the Snohomish River basin. While the 2005 Snohomish River Basin Salmon Conservation Plan discusses temperature conditions and potential strategies, the increased awareness of widespread temperature impairments requires an elevated prioritization of strategies which address temperature conditions across the basin.

Restoring and preserving temperature conditions and thermal diversity across watersheds requires consideration of several water temperature aspects including seasonal cycles, daily variation, network-scale longitudinal patterns, and small-scale thermal refuges (Poole et al. 2004; Steel et al. 2017). The spatial complexity of geomorphic, hydrologic, riparian, and landscape features influence multiple aspects of thermal regimes and watercourse temperature conditions. Thermal diversity constitutes temperature variation within riverine reaches (Torgersen et al. 1999, 2012), across floodplains (Tonolla et al. 2010), throughout stream networks (Isaak et al. 2015), and across watersheds (Fullerton et al.

2015; Woltemade 2017). Addressing temperature conditions and thermal diversity at multiple spatial and temporal scales will be necessary to restore and protect watercourses.

In order to address the suite of human alterations impacting temperature impairments in the Snohomish River basin (discussed in section: *Human Alterations to Aquatic Thermal Regimes*) it will be necessary to adopt multiple strategies and support implementation at both local and watershed scales. Additionally, it may be necessary to increase conservation and restoration actions at a magnitude and scale comparable to the degree and urgency of apparent temperature issues. Conservation efforts and strategies may also need to focus on multiple time horizons. Strategies in the near-term may include planting riparian vegetation and increasing groundwater/hyporheic exchange, which could help to slow warming trends. Strategies in the long-term could focus on restoring/protecting water flow processes, ensuring adequate cold-water refuges, and supporting connectivity throughout a watershed, which could collectively provide benefits and protections as the landscape and climate conditions continue to change (Beechie et al. 2012; Fullerton et al. 2017).

General concepts for strategies and actions to improve temperature conditions can be described for different spatial scales (Table 5) (Snohomish County Surface Water Management 2015). The general management concepts could include: 1) the sub-basin (Assessment Units – analogous to Sub-basin Strategy Units), where flow and temperature are influenced by protection and restoration of water flow process components, notably recharge, discharge and groundwater connectivity, 2) the whole-river or stream-reach scale, where heating is broadly limited by the presence and absence of shading, surface-groundwater interactions (flow gain or loss), as well as hyporheic exchange, and 3) the habitat-unit scale where the frequency, source, magnitude, and habitat quality of thermal refuges may be manipulated structurally to increase temperature benefits (Snohomish County Surface Water Management 2015).

Table 5: *Multi-scale water temperature management concepts. Adapted from Snohomish County Surface Water Management (2015) with assessment units described in Stanley et al. (2012).*

Spatial Scale	**Large: Assessment Unit (AU) (1 – 10 km^2)**	**Medium: River/stream reach scale (100 – 1000m^2)**	**Small: In-channel Habitat Units (10 – 100m^2)**
Goals Supporting information and data	Protecting and restoring water flow processes (delivery, surface storage, recharge, discharge)	Improving shading, future large wood recruitment, complex channel patterns and flow routing in floodplain	Enhancing habitat hydraulic complexity and connections for thermal refuge at point locations of cold discharge
Supporting information and data	Watershed Characterization (WA Ecology); hydrogeology; flow measurements (e.g., seepage runs and baseflow analyses)	Shade deficits; bank armoring; channel morphology; floodplain connectivity; seepage runs; FLIR imagery-mapping; longitudinal thermal profiling	Site-based summer temperature; pool formation and stratification; side channel connectivity; tributary junctions; thermal profiling; TIR imagery
Action and Activities	Promote AU-scale solutions for targeted water flow processes protection and restoration; focus on recharge and discharge	Riparian planning; floodplain acquisition and restoration; removal of armoring to restore flow routing and channel forming processes	Construct log jams; connect side channels; enhance tributary confluences
Response Time	Long-term (>20 years)	Medium term (5-20 years)	Short-term (1-10 years)

Rather than focusing solely on maximum temperatures, it will be critical to consider various aspects of thermal regimes including the timing, duration, rate-of-change, magnitude, and spatial variation of temperature conditions. Integrating multiple aspects of thermal regimes as well as spatial and temporal variation among temperature conditions may provide the greatest ability to support temperature restoration and protection. Supporting thermal diversity will provide salmonids with opportunities to optimize growth, reproduction, and survival across all life-stages. Integrating and supporting various aspects of thermal regimes may be beneficial in improving the favorableness of temperature conditions at various spatiotemporal scales (Torgersen et al. 2012). For example, Snohomish County Surface Water Management (2015) describes this approach as a "More, Bigger, and Better" strategy which aims to improve favorableness of temperature conditions across a range of channel and habitat types (Table 6).

Supporting thermal diversity and temperature improvements across multiple spatial scales and time horizons likely requires a suite of strategies (Table 5, 6, & 7). Among these strategies, riparian restoration/protection, increasing channel and floodplain complexity, as well as increasing channel, floodplain, and tributary connectivity are among the highest priorities for improving temperature conditions across the Snohomish River basin (priority strategies discussed in detail below). The protection of intact functioning riparian/forest areas as well as the restoration of degraded riparian areas may be the greatest near-term action for providing long-term temperature improvements in the Snohomish River basin (Stohr et al. 2011; Svrjcek et al. 2013). However, a suite of strategies is likely needed to maximize temperature improvements to fully support localized and basin-wide thermal diversity. Additionally, the suite of strategies may vary across the Snohomish River basin as location, watercourse size, geomorphology, hydrology, and adjacent land use all vary considerably within and across watercourses.

TABLE 6: *Application of concepts in Table 5 within a more, bigger, better strategy focused on improving temperature and habitat conditions within a river continuum. Adapted from Snohomish County Surface Water Management (2015).*

Habitat Type	**More Refuges** (increase the frequency of refuges and decrease spacing)	**Bigger Temperature Effects** (greater size of temperature effects including changes in flow volumes, mixing, and/or temperature differences)	**Better Habitat** (improved cover, depth, flow, substrate, vegetation, shading, wood complexity)
Tributary	Generally, can't form new tributaries to increase frequency. Historical flow routing of tributaries may have been reduced due to road, railroad, ditch, or other linear conveyance and modifications altering discharge(s). Kurylyk et al. (2014) describe groundwater pumping that could generate a focused discharge location (much like a tributary outlet).	Shading at tributary assessment unit (AU) - and river-reach scales; smaller streams will show bigger effect in shorter time from shading effectiveness; Flow increase due to AU-scale restoration is uncertain but may be possible where water withdrawals can be mitigated.	Instream and confluence restoration based on stream size, channel classification, and habitat condition, prioritized by cooler temperature and size effect, where summer low flow is high relative to drainage area.
Side Channel & Floodplain	Short-term, connect remnant habitat if isolated and prioritize if fed by tributary, hillslope, or floodplain/spring-brook discharge. Long-term, side channel formation and floodplain complexity from restoration helps mitigate effects of changing climate (Beechie et al. 2012).	Increasing length, width, flow, and shading increases existing capacity for rearing due to a temperature and area effect.	Depends on habitat impairment of existing or potential side channels – restoration of cover, wood, edge habitat quality, pools, and riparian functions increase potential density of use by fish, thereby increasing capacity.
Mainstem	Short-term by increasing scour in flow-gaining reaches to reduce spacing between cold-water inflow sources. Long-term, through floodplain reconnection, channel migration and backwater formation, channel aggradation, increased local scour, increased floodplain recharge, hyporheic exchange, and shading to reduce longitudinal gaps in suitability for salmon rearing and migration.	Cool inflow to mainstem either from upstream locations or reduce/delay mixing of cool water with flow shadowing effect (Kurylyk et al. 2014). Long-term, through floodplain reconnection, channel migration, and backwater formation to increase area of better conditions.	Habitat improvement at existing mainstem locations of cold-water inflow from discrete locations or in flow-gaining reaches to improve cover, depth, velocity, structural complexity to support greater fish capacity.

***Table 7**: Strategies and recommendations for improving temperature conditions in the Snohomish River basin.*

<table>
<tr><th>Strategy</th><th>Action</th><th>Effects of Strategies and Actions</th><th>Example Areas and Watercourses</th><th>Citations</th></tr>
<tr><td rowspan="2">Riparian restoration and protection</td><td>Planting riparian vegetation</td><td rowspan="2">• Riparian vegetation provides shading which blocks solar-atmospheric radiation
• Riparian restoration in headwaters and along mainstems provides temperature buffering
• Reduces stream temperatures locally and reduces diel variability
• Supports microclimate conditions
• Can also provide large wood which enhances channel complexity and creates pools</td><td rowspan="2">Snohomish River basin (including mainstem, tributary, and headwater areas)</td><td rowspan="2">Poole and Berman 2001; Beechie et al. 2010; Stohr et al. 2011; Sun et al. 2015; Kubo and leDoux 2016; Woltemade and Hawkins 2016; Steel et al. 2017, 2019; Fullerton et al. 2017; Kubo et al. 2019</td></tr>
<tr><td>Protecting existing riparian buffers</td></tr>
<tr><td rowspan="4">Increasing channel and floodplain complexity (i.e., number and diversity of features and their spatial organization)</td><td>Installation of large wood</td><td>• Large wood directly influences channel complexity
• Increases hyporheic exchange and groundwater inputs, particularly in locations with strong gradients
• Increases number of large pool and potential thermal refuge
• Local decreases in thermal range</td><td>Watercourses with gradient conductive to sediment transport and large wood accumulation (e.g., Skykomish River, Tolt River, Pilchuck River); particularly among flow gaining reaches and areas of hyporheic exchange</td><td rowspan="4">Poole and Berman 2001; Pollock et al. 2003; Ham et al. 2006; Haas et al. 2007; Seedang et al. 2008; Kaje 2009; Shaw 2009; Beechie et al. 2010; Blędzki et al. 2011; Janzen and Westbrook 2011; Stohr et al. 2011; Snohomish County Surface Water Management 2012; Svrjcek et al. 2013; Bouwes et al. 2016; Kubo and leDoux 2016; Woltemade and Hawkins 2016; Steel et al. 2017; Weber et al. 2017; Fullerton et al. 2017; Dittbrenner et al. 2018; Dittbrenner 2019</td></tr>
<tr><td>Restoring beaver dams, install beaver dam analogs, augment beaver populations</td><td>• Promotes pools, side-channels, and channel complexity
• Supports water storage and infiltration recharging aquifers and increases hyporheic and groundwater exchange
• Can decrease temperatures and dampen diel variability
• Supports spatiotemporal thermal heterogeneity</td><td>Watercourses and areas where beaver dams can engage floodplains and side-channels (e.g., smaller tributaries, side-channels, floodplain channels); particularly where tributary inflow to floodplains can be captured by dammed locations</td></tr>
<tr><td>Wetland protection, enhancement, and creation</td><td>• Maintains/increases cool groundwater inputs and aquifer recharge during low-flow periods
• Helps to capture and infiltrate stormwater
• Supports spatiotemporal thermal regimes in floodplain areas</td><td>Floodplain areas (e.g., Snoqualmie River, Skykomish River, Tolt River, Pilchuck River, Wallace River)</td></tr>
<tr><td>Creation and maintenance of side-channel and off-channel areas</td><td>• Provides areas of thermal refuge
• Provides areas for hyporheic exchange and groundwater inputs
• Provides habitat complexity
• Supports spatiotemporal thermal diversity</td><td>Side-channel areas (e.g., Pilchuck River, Wallace River, Skykomish River, Snoqualmie River)</td></tr>
</table>

Strategy	Action	Effects of Strategies and Actions	Example Areas and Watercourses	Citations
Increasing channel, floodplain, and tributary connectivity	Removing bank stabilization (revetments, levees, etc), reduce channelization, and promote channel meandering	• Increases channel formation processes that creates complex, diverse, and connected areas for water flow, storage, and surface/sub-surface exchange • Increases hyporheic exchange and groundwater discharge among mainstem, floodplain, tributary areas • Restores spatiotemporal thermal regimes in floodplain areas • Increases mainstem and off-channel spatiotemporal thermal diversity and thermal refuges • Decreases temperature extremes and fluctuations	Area with revetments and levees (e.g., Snohomish River, Snoqualmie River, Skykomish River, Tolt River, Pilchuck River, Raging Rivers) Floodplain areas that have been dredged, channelized, and straightened (e.g., Snoqualmie, Skykomish, and Snohomish floodplains)	Poole and Berman 2001; Haas et al. 2007; Seedang et al. 2008; Kaje 2009; Beechie et al. 2010; Tonolla et al. 2010; Stohr et al. 2011; Snohomish County Surface Water Management 2012; Svrjcek et al. 2013; Kubo and leDoux 2016; Steel et al. 2017; Fullerton et al. 2017
	Restoring tributaries and confluences; protecting cool tributaries	• Increasing connectivity between tributaries and mainstem reaches can enhance the potential of tributaries to provide cool water refuge • May support localized plumes of cold water near confluences • Supports natural pathways of water, wood, and sediment	Tributaries to mainstem watercourses	
Reducing and modifying surface water use	Reducing consumptive water use and withdrawals during summer low-flow periods; buyout water rights; improve irrigation efficiency and timing	• Increase in stream flows in local watercourses during critical periods • Increase in side-channel and off-channel habitat area and related thermal refuge • Decrease in temperature maximums and diel variability	Areas with a high frequency of exempt wells (e.g., Pilchuck watershed) and areas with increasing consumptive water use during spring-summer periods (e.g., Snoqualmie and Skykomish river floodplains) Floodplain areas with agricultural drainage needs (e.g., Snoqualmie, Skykomish, and Snohomish river floodplains)	Poole and Berman 2001; Stohr et al. 2011; Swanson et al. 2012; Kubo and leDoux 2016; Woltemade and Hawkins 2016; Steel et al. 2017
	Controlled drainage and modified seasonal drainage	• Supports seasonal water retention, especially during spring • Reduces irrigation needs with water retention from controlled drainage • Supports groundwater recharge and base-flow groundwater expression		

Strategy	Action	Effects of Strategies and Actions	Example Areas and Watercourses	Citations
Improving flow and sediment regimes	Human-built dam removal or restorative management of flows	• Restores natural flow and sediment regimes • Restores migratory pathways to thermally suitable habitats • Restores natural seasonal and diurnal temperature variation as well as availability of cold-water refuge • Selective reservoir depth releases (e.g., hypolimnetic withdrawals) can provide cooler waters during critical periods	Pilchuck River (dam removal) as well as the Sultan River and Tolt River (ongoing and updated flow management)	Poole and Berman 2001; Moore et al. 2004, 2005; Sherman et al. 2007; Waples et al. 2009; Beechie et al. 2010; Stohr et al. 2011; Svrjcek et al. 2013; Woltemade and Hawkins 2016; Steel et al. 2017; Sun et al. 2018
	Forest management such as revegetation, limiting clear cuts, promoting canopy gaps, longer harvest cycles, etc.	• Increases forest and riparian cover which provides shading and temperature buffering • Provides a diversity of vegetation age classes (reduced evapotranspiration from predominantly younger stands) • Improves microclimate conditions • Improved hydrology (reduced peak flows, increased water recharge and storage, etc.) • Canopy gaps can improve snow retention and extend the snowmelt period (supporting spring water availability and cool water sources)	Upper sub-basin areas across the greater Snohomish River basin	
	Riparian restoration and land use management	• Provides bank stabilization and limits unnatural rates of sedimentation • Re-aggrading incised channels helps restore alluvial aquifer, increase stream flow, and decrease summer temperatures	Snohomish River basin including mainstem, tributary, and headwater areas	
	Stormwater retrofits and management	• Reduction in stormwater discharge volumes and alterations to hydrologic and sediment regimes • Restoring natural flow and sediment regimes • Stormwater infiltration and aquifer recharge	Watercourses and watersheds near cities including Monroe, Sultan, Everett, Snoqualmie, North Bend, Carnation, Duvall, and others	
Limiting thermal loading from point sources	Management of wastewater treatment plants, hatchery facilities, and gravel facilities	• Ensures thermal discharges are controlled • Reduction of municipal water discharge volumes and heat loading • Reduce sedimentation	Discharge areas near sewage and wastewater treatment plants across the Skykomish River (e.g., Monroe, Sultan, and Everett) and Snoqualmie River (e.g., Snoqualmie, North Bend, Carnation, and Duvall); discharge areas near Hatcheries (e.g., Skykomish River, Wallace River, Tokul Creek)	Hester et al. 2009; Stohr et al. 2011; Svrjcek et al. 2013

Riparian Restoration

Riparian restoration and protection are considered among the highest priorities for improving temperature impairments across the Snohomish River basin (Stohr et al. 2011; Svrjcek et al. 2013). Riparian restoration provides multiple benefits (Table 2 & 7) and protecting functioning riparian areas will likely help buffer the impacts of projected land use and climate changes. The benefits of riparian plantings on temperature conditions have been characterized by WA Ecology for the mainstem Snoqualmie River with ongoing efforts progressing in the Skykomish River, Pilchuck River, and French Creek (Stohr et al. 2011; Swanson et al. 2012; Svrjcek et al. 2013; Restivo 2020). Scenario modelling by Stohr et al. (2011) indicated that establishing a 180-ft-wide mature (100yr old) riparian buffer along the mainstem Snoqualmie River could reduce solar radiation, lower localized air temperatures, and subsequently reduce average daily water temperatures by 1.9°C. Furthermore, restoration of tributaries and headwaters, as well as changes in microclimate from mature riparian vegetation could further reduce temperature by 0.9°C. These modelling efforts emphasize the importance of riparian restoration and highlight the additional benefits of utilizing multiple strategies. Planting mainstem reaches has the potential to significantly reduce water temperature; however, concurrent plantings of headwaters and tributaries will likely be needed to maximize temperature improvements and to support basin-wide restoration/protection of cold-water sources. The protection of intact and high-quality riparian areas, especially among headwater areas, will help maintain functioning riparian corridors and may provide the greatest near-term benefit towards minimizing further degradation. Additionally, increased hyporheic and groundwater exchange may provide additional sources of cold water, especially at a localized scale, which established riparian vegetation could buffer from heat loading.

Increasing Channel and Floodplain Complexity

Restoring channel and floodplain complexity (i.e., number and diversity of features and their spatial organization) can increase the ability of watercourses and watersheds to withstand thermal inputs (Poole and Berman 2001). Increased channel complexity can result in greater water storage, hyporheic exchange, and groundwater discharge, which moderate temperature maximums and minimums, decrease average daily temperatures, and influence diel temperature fluctuations. Structures like large wood and log jams influence hydraulic processes such as transient storage and local hydraulic gradients, which can stimulate vertical and horizontal hyporheic and groundwater exchange (Seedang et al. 2008; Stohr et al. 2011). Sediment trapping and pool formation associated with large wood increases water exchange with sub-surface water in the gravels and adjacent floodplain areas. The deep pools associated with large wood provides areas for groundwater discharge, which may provide temperature refuges for juvenile and adult salmonids (Haas et al. 2007; Leonetti 2015a). Increasing structural habitat quality and quantity can support reach-scale cooling as geomorphically diverse and active river segments promote interaction between surface and sub-surface waters (Snohomish County Surface Water Management 2012). Additionally, river segments bordered by strong water recharge and discharge processes (sensu Stanley et al. 2012) promote the presence and extent of cold-water refuges (Leonetti 2015b). Restoring channel complexity can also influence deposition and aggradation processes. Where channels are incised into alluvial fill, restoring sediment deposition and re-aggradation is expected to restore the alluvial aquifer, increase summer stream flows, and decrease summer temperatures (Beechie et al. 2010).

Across a riverine network, restoring and maintaining side-channel and off-channel areas can also promote thermal diversity and provide cold-water refuges (Haas et al. 2007). Restoring side- and off-channel areas can provide temperature heterogeneity, moderate temperature conditions, and provide areas of cooler temperatures, compared to mainstem reaches. Riverine networks with complex side-channel and off-channel areas promote thermal diversity, especially when these are well-shaded or associated with tributary inputs, wall-based channels, or hillside groundwater discharge (Haas et al. 2007; Snohomish County and SLS Executive Committee 2017). Maintaining side-channel complexity and connectivity to mainstem reaches and adjacent tributaries may help promote hyporheic exchange and groundwater inputs, which support cold-water refuges.

Protecting and restoring wetland areas is critical to support groundwater infiltration and aquifer recharge (Kaje 2009; van der Kamp and Hayashi 2009; Mitsch et al. 2009). Restoring wetlands, especially in floodplains and recharge areas, promotes infiltration, which maintains groundwater recharge and discharge processes. Supporting these processes maintains cold-water inputs, which can decrease temperatures across watercourses, especially during summer low-flow periods. In addition to restoration, the protection of wetland areas through regulations, acquisitions, incentives, and other strategies is critical to maintain functions and benefits into the future.

Beaver dams and ponds can directly influence water temperature conditions through increased water storage, maintained summer streamflow, groundwater recharge, and hyporheic exchange (Pollock et al. 2003; Błędzki et al. 2011; Bouwes et al. 2016; Weber et al. 2017; Dittbrenner et al. 2018; Dittbrenner 2019). These processes can result in cooling across watercourses, moderate temperature extremes, and dampen diel variability. Supporting beaver population and related beaver structures can maintain thermal diversity by extending hyporheic zones (Shaw 2009), raising groundwater levels (Ham et al. 2006), and increasing exchange of cooler groundwater (Weber et al. 2017). The thermal benefits of beaver structures are especially apparent during baseflow periods and among off-channel habitat areas. For example, Snohomish County conducted a comprehensive survey of side channels throughout the Stillaguamish River and noted that beaver pools formed ~50% of the total pool area, had the greatest residual pool depth by pool form type, and were on average 3.9 °C cooler than the adjacent mainstem river (Leonetti unpub. data). Restoring and promoting beaver dam complexes across riverine networks can subsequently increase surface water thermal heterogeneity as well as potential cold-water refuges. Restoring beaver dam complexes may require supporting beaver populations (through protection and/or augmentation), allowing beaver structures to persist on the landscape, and even provide beaver-dam analogs in areas where beavers are less common or have been removed.

Increasing Channel, Floodplain, and Tributary Connectivity

Similar to complexity, restoring connectivity among channels, floodplains, and tributaries can also increase the ability of watercourses to withstand thermal inputs. Increased connectivity supports the movement and influence of groundwater discharge, hyporheic exchange, and tributary inputs on thermal conditions across watercourses and floodplains (Poole and Berman 2001; Tonolla et al. 2010; Steel et al. 2017). Additionally, improved connectivity allows salmonids to distribute to preferred areas and optimize thermoregulatory needs (Radinger et al. 2017; Snyder et al. 2019). Restoration actions including levee setbacks and revetment removals help to promote channel migration and lateral floodplain connectivity, which increase sub-surface floodwater storage, aquifer recharge, groundwater discharge during base-flow periods, and hyporheic exchange. Restoring these processes helps to support

spatial and temporal thermal diversity across floodplain and mainstem areas (Tonolla et al. 2010; Steel et al. 2017). Additionally, channel migration promotes the recruitment of large wood from riparian areas, which as previously discussed, directly influences channel complexity and related temperature conditions.

Restoring connectivity between mainstem, side-channel, and tributary areas supports thermal diversity and the availability of cold-water refuges (Stohr et al. 2011; Svrjcek et al. 2013). Restoring and maintaining connectivity allows salmonids to move across thermally suitable habitats (Radinger et al. 2017; Snyder et al. 2019) and supports the movement and exchange of surface and subsurface waters. Side-channels can provide areas of localized temperature moderation and can at times be several degrees cooler than adjacent mainstem reaches (Haas et al. 2007). Restoring and protecting tributary connectivity also supports pathways of water, wood, and sediment to mainstem reaches, helping to create and maintain thermal diversity (Steel et al. 2017). Thermal inputs from tributaries can influence daily and seasonal temperature fluctuation and increased connectivity supports flow and temperature exchange during base-flow periods.

Tributaries across the Snohomish River basin appear to have considerable variation in temperature conditions, with several tributaries characteristic of relatively cooler summer temperatures compared to mainstem reaches (Haas et al. 2007; Stohr et al. 2011; Snohomish County Surface Water Management 2012; Svrjcek et al. 2013; Kubo and leDoux 2016). The protection of cooler tributaries may be critical to maintain thermal diversity and to provide potential cold-water refuge. While only a few tributaries have enough flow to considerably influence mainstem temperatures, smaller tributaries can provide localized plumes of cooler temperatures in mainstem reaches and cooler tributaries themselves can provide thermal refuges (Snyder et al. 2019). The benefits of tributary restoration were highlighted in scenario modeling for the mainstem Snoqualmie River (Stohr et al. 2011), which indicated that the restoration of tributaries and headwater areas could reduce mainstem temperature by 0.5°C. This reduction, in combination with temperature reduction from a mature riparian buffer (1.9°C) and microclimate benefits (0.4°C) emphasize the importance of tributary restoration as well as the collective benefits of multiple temperature improvement strategies.

Current Monitoring

Current Monitoring
• Water temperature is one of the most intensively studied water quality parameters in the Snohomish River basin. • De-siloing monitoring information will reduce duplication of effort and may enable more impactful salmon recovery via comprehensive analysis. Aggregating data into a single, publicly available database would facilitate analysis, coordination, and tracking by multiple basin stakeholders. • Appendix 1 contains a first-iteration attempt to centralize water temperature datasets in the Snohomish River Basin. • Continuous, multi-year timeseries of water temperature are most useful for salmon recovery, compared to point measurements. • Monitoring itself is a critical strategy.

Across the Snohomish River basin, a host of entities monitor temperature at different levels of spatial and temporal resolution and effort (see Appendix 1). While there is plenty of temperature monitoring and research underway, much of it is siloed, and institutional knowledge about past or ongoing efforts is often not written down. Thus, the first and most important data gap regarding water quality monitoring in the Snohomish River basin is knowing all the respective previous and current monitoring and research efforts. While a data clearinghouse, centralized database like NorWEST, or interactive online map would be ideal, even just a tabular list of who is doing what, where, and how to get in contact with them would be beneficial. As a starting place, an initial summary table can be found in Appendix 1. The hope is that partners in the Snohomish River basin will take on the task of completing, updating, and maintaining this list as a first step to de-silo information, in support of cohesive, watershed-wide analysis of salmon recovery performance. The rest of this section is an overview of the information contained in Appendix 1, which contains more detail.

Water temperature monitoring efforts generally take two forms:

1. Single observations of water temperature taken monthly or annually, usually in tandem with other water quality parameters.
2. Continuous time series of water temperature recorded by data loggers deployed in watercourses.

Water temperature time series are of much greater utility for salmon recovery as they are able to capture important metrics like maximums, minimums, and daily variation that single observations are limited in representing. Similarly, multiple years of data are important to be able to account for natural inter-annual variation (“noise”) that can swamp the detectability of change due to restoration projects or land use change (“signal”). Annual time series capture winter-spring thermal regimes that may be particularly important to understand as the climate continues to warm, because warmer winter-spring temperatures may alter development and growth rates for juvenile salmonids.

Paired water and air temperature loggers have been deployed extensively throughout the Snoqualmie River watershed by multiple entities; the National Oceanic and Atmospheric Administration (NOAA), U.S. Forest Service (USFS), and King County networks cover much of the headwaters, mainstem, and major

tributaries. Seattle City Light and the U.S. Geological Survey (USGS) are collecting air and water temperature throughout the Tolt basin. King County water temperature monitoring for the Agriculture Drainage Assistance Program (ADAP) and upcoming monitoring by the Snoqualmie Valley Watershed Improvement District (SVWID) will provide additional information about water temperature regimes in smaller watercourses and modified/artificial drainage channels in the lower Snoqualmie valley floodplain. Much of the existing monitoring network is expected to continue indefinitely, though it is likely the King County, NOAA, and USFS network will be downscaled in the future without additional funding; the NOAA network was established as a joint effort between NOAA and USFS but is currently maintained solely by NOAA staff and volunteers. In addition, King County occasionally performs more focused temperature studies, such as the studies on low flow and thermal refuge in 2015 and 2016.

More recent temperature monitoring efforts in the Snoqualmie River watershed have largely been coordinated through an informal collaborative group called the Snoqualmie Science Coordination and Advisory Team (SnoSCAT). SnoSCAT members are sharing and leveraging data, knowledge, and resources to better understand water temperature regimes in the Snoqualmie River watershed. The NOAA logger network was used to build statistical and physical process-based models to examine spatial and temporal temperature variation (Steel et al. 2016), biological implications of extreme conditions (Steel et al. 2019), and climate change impacts (Lee et al. 2020). The USGS and Tulalip Tribes conducted aerial and floating water temperature surveys on the Snoqualmie and Skykomish Rivers in the summer of 2020, and analysis is ongoing. The Snoqualmie Indian Tribe is working on a modelling effort in collaboration with Pacific Northwest National Laboratory (PNNL) and NOAA to predict how implementing different riparian buffer scenarios might impact stream temperatures, and by extension, salmon populations.

Multiple entities are also monitoring in the Skykomish River watershed, the mainstem Snohomish River, major Snohomish River tributaries such as the Pilchuck and Sultan rivers, and the Snohomish Estuary. Snohomish County and Snohomish County PUD have several long-term temperature monitoring sites, visited on a rotating schedule. They also occasionally add more monitoring sites on a short-term basis for projects such as monitoring the 2015 drought year. The Tulalip Tribes are currently monitoring temperature on their reservation and have previously monitored water temperature within Skykomish River headwaters in order to assess the impact of beaver recolonization (Dittbrenner 2019). Water temperature monitoring in the Skykomish River watershed may benefit from a SnoSCAT-style collaborative group. Building a similar multi-agency temperature monitoring network might enable a more comprehensive approach that drives a collective conversation on research goals and directions, while leveraging complimentary datasets.

Monitoring is one of the most critically important strategies we have for determining if our efforts to reduce water temperature impairments are working, and if not, why not. Yet, adequate monitoring and follow up analysis and tracking is chronically underfunded. Monitoring is repeatedly recommended as an important strategy by the Department of Ecology in its TMDLs and TMDL effectiveness reporting (Sargeant and Svrjcek 2008; Stohr et al. 2011). Beyond the suggested expansions to monitoring programs in the following section, it is also critical that we work to fund and maintain existing monitoring networks, particularly long-term monitoring networks, of which there are comparatively few throughout the basin at present. This will ensure data continuity into the future.

Future Research

Future Research
• We do not need to wait for additional data before taking action on the strategies discussed in this document. • We lack a comprehensive hypothesis-driven monitoring strategy. • We should use the copious data we already have to answer questions. • Lack of hypothesis-based effectiveness monitoring and comprehensive restoration tracking hampers our ability to make causal inference. • More emphasis on effectiveness monitoring of best management practices is needed. • Continued investigation of thermal spatiotemporal heterogeneity and its drivers, including tributaries and groundwater, is important. • Data on thermal diversity can be leveraged to protect cold-water refuges, and to tailor strategies among particular areas. • It is important to link data on thermal regimes with fish use data. • We should continue to investigate specific watercourses of concern.

Efficiency Through Strategic Planning

It is important to frame this section, where we list existing data gaps, suggested additions to monitoring programs, and potential research projects, by stating that we do not need to wait for additional data before taking action on the strategies discussed earlier in this document. This white paper and a very large body of prior literature make it abundantly clear that riparian restoration, channel and floodplain restoration, improved channel and floodplain connectivity, and protection of existing functioning riparian/floodplain habitat are needed, and that these strategies work. Meanwhile, funds and available opportunities to implement these strategies—not data—is the limiting factor. We should not fall into the trap of hesitating to forge ahead with protection and restoration actions until all data gaps have been filled. However, additional research and monitoring will be valuable in improving salmon recovery strategies: it will continue to help tailor strategies effectively to specific locations, assess causal mechanisms for patterns, and expand information and knowledge.

However, data collection needs to be strategic, just as restoration and protection efforts need to be strategic. Since its inception, the Snohomish River basin Salmon Plan has lacked a strategic, well-sequenced basin-wide set of hypotheses or questions that would determine what, when, and how to monitor. Ideally, this overarching "monitoring strategy" would use observations to adapt, add, and change existing programs where possible, then seek more funding for those that work. As part of the ongoing 2020-2021 Snohomish Basin Salmon Conservation Plan update process, a monitoring chapter that may fulfill some of these needs is underway.

Partially because of the lack of an overarching monitoring strategy, there is no clear direction for how to use much of the temperature data already being collected across the Snohomish basin. The result is that data is sometimes not used to its full potential. King County and Snohomish County long term monitoring data are two prime examples of underutilized resources. Water temperature data from these two programs has not yet been used for effectiveness analysis or to answer specific questions. In addition, there is often a lack of funding or capacity for data analysis. Guaranteed funding in place for

increasing capacity for more large-scale analyses of data coming in from ongoing programs every three to five years would help with real-time adaptive management and leverage the data that is produced.

Given the volume of existing temperature monitoring data already being collected across the Snohomish basin, there is potential for answering questions with data that is already on hand. The opportunity to use this valuable data to answer questions is available to us and should be utilized. Many of the suggested questions in the remainder of this section could take at least partial advantage of existing data. After a strategic, hypothesis-driven basin-wide monitoring plan is developed, existing monitoring programs would ideally be restructured and redeveloped, if necessary, so that the data collected can more directly inform restoration and management actions.

The following sections describe potential future research ideas. This is not a complete list, nor does it stand in for a sequenced and prioritized overall strategy. With any of the suggested work that follows, it's important to note that it will be critical to focus not just on water temperature itself: we need to pair any water temperature measurements with air temperature data, flow data, and other hydrologic and meteorological data. This will enable us to make causal inferences and better separate signal from noise as we attempt to track patterns over time.

Improvements and Additions to Monitoring

Besides the lack of an overarching monitoring strategy or plan, two of the biggest gaps in monitoring are monitoring based on hypothesis testing, and monitoring that is able to establish cause-and-effect relationships—these two should go hand in hand, together with the monitoring strategy described above. Otherwise, collecting temperature data just informs what the temperature is and not what to do about it, if and how it's linked to problems we're interested in—like Chinook recovery— or what may be effective in fixing those problems. Monitoring based on hypothesis testing and monitoring that helps establish causal inference, not just correlation, will help to prioritize actions and distribution of resources.

We must conduct statistically robust, well-controlled long-term effectiveness monitoring of riparian and in-stream restoration projects, to ascertain if and how various best management practices (BMPs) function to mitigate or reverse temperature impairments. This is not to say that we need to spend monies trying to reinvent the wheel, but rather, that we should try to hone the efficacy of what we already know.

Select questions and suggested changes could include:

- How quickly and where are different types of habitat (channel, floodplain, riparian, etc.) changing? This includes gains from restoration efforts and natural and anthropogenic losses. Without being able to quantify net losses, we don't know if we're really making systemwide gains or still losing ground, and we weaken our own ability to make strong causal inferences and rule out natural interannual variation in effectiveness analyses.
    - One way to approach this type of centralized, comprehensive tracking would be through more regular land use/land cover assessments.
- How close are we at any given time to achieving various restoration 'targets' set-in documents like the Snohomish River Basin Salmon Conservation Plan or the Snoqualmie River TMDL? Having a decentralized network of practitioners and various ways of tracking restoration targets

makes meaningful, ongoing, incremental quantification a difficult task, and this question is not usually assessed very often. The result is that adjusting and adapting—e.g. speeding up implementation if we are behind our stated goals—is difficult to achieve in real time.

- Do riparian buffer plantings work to achieve temperature goals on smaller streams, such as naturally fed agricultural drainage channels or tributary channels?
    - King County's Agricultural Drainage Assistance Program (ADAP), which plants many of these types of channels, could perform long-term effectiveness monitoring to ascertain if and how those plantings may be making a difference to temperature; this information could be valuable in determining if and how planting projects should change in the future.

The literature is clear that riparian restoration is one of the best ways to reduce temperature impairments, but we also know that success tends to be uneven across different watercourses and locations in the basin. It will be important to know why, when, and how some riparian planting projects succeed while others do not. Additionally, it will be beneficial to know if there are common factors in site selection or implementation that produce better results.

Thermal Diversity

Thermal diversity across the Snohomish River basin may provide an important way to mitigate the continued impacts of development and climate change on overall temperature regimes. It is therefore critical that we continue to investigate the nature of thermal diversity throughout the system and leverage these data to help understand how different areas of the Snohomish River basin respond differently to climatic and hydrologic events. By understanding localized thermal variation among drainages and reaches, we can create a better framework for conservation and restoration prioritization, and tailor strategies to watercourses where they may work best. For example, mapping of cold-water refuges in the Stillaguamish system showed that the South Fork Stillaguamish was more reliant on tributary flow for refuge locations, whereas the North Fork had a diversity of cold-water refuge types (Leonetti et al. 2015). Therefore, the two forks need different strategies to protect their respective refugia: protection of tributary buffers for shading is important for protection of cold-water refuges in the South Fork, whereas protection and restoration of channel migration in the North Fork is relatively more important. It is reasonable to expect that detailed mapping in the Snohomish River basin would result in the same kind of important information for tailoring effective location-specific strategies. (See *Strategies to Improve Water Temperature Conditions across the Snohomish River Basin* section for examples of strategies appropriate for different watercourses.)

- Running hydrologic and stream temperature models to understand the thermal diversity across mainstems. Similar models exist for other water bodies in the Snohomish River basin, such as for the Tolt Reservoir. Seattle City Light has a CEQUAL W2 model of the Tolt Reservoir that has been updated to include 2015. They plan to apply different climate scenarios to see how the reservoir responds under different conditions. It may prove beneficial to conduct similar modelling efforts in other watercourses and subbasins throughout the Snohomish River basin.

Understanding Groundwater

An important part of understanding and leveraging thermal diversity is understanding groundwater. Current work being done by SnoSCAT members is beginning to elucidate some of these questions, but groundwater remains a relatively understudied component of thermal diversity across the Snohomish River basin.

Specific questions and suggested studies about groundwater include:

- Where are groundwater exchange zones, and how do they relate to different geomorphic and landscape features? Answering this question helps us distinguish which areas are appropriate for groundwater- or hyporheic-based restoration actions, based on surficial geology and geomorphology, vs. any areas where geology/geomorphology do not support such actions.
- What did groundwater exchange zones look like historically, and what actions would be required to return them to that condition?
- How do present-day relict channels and alluvial floodplain features relate to present-day hyporheic exchange zones and groundwater flow paths?
- What are the relative contributions of hyporheic and groundwater flow to surface water flow and temperature?
    - There are a variety of ways to assess this, including longitudinal profiles of temperature and conductivity and instream wells/piezometers, as well as synoptic flow measurements.
- We know that certain mainstem reaches are groundwater gaining reaches, while others are losing reaches. What are the mechanisms behind where gaining and losing reaches occur? For example, is the Carnation to Duvall reach a losing reach due to human alterations of the floodplain, or is it a natural condition? If it is human caused, what could be done to change that?
- How do anthropogenic changes in hydrology—such as intentionally draining the floodplain in early spring for agriculture, or building revetments/levees—impact groundwater discharge and recharge?
    - One way to assess this question would be an evaluation of revetment/levee influence on hyporheic flow and connectivity.
- Can aquifers in various subbasins be used to help supplement surface flow with cool groundwater, or be used in later summer for out of stream uses, allowing more surface water to stay in the system?
    - A starting point to explore these questions would be performing a low flow assessment to understand aquifers in various subbasins.
- How do changing snowfall and snow accumulation patterns influence groundwater recharge and discharge?

Understanding Cold-Water Refuges

Understanding groundwater is an important part of expanding our knowledge of cold-water refuges. Cold-water refuges provide potential for system resilience in the face of climate change; we can leverage knowledge of their location, sources, and variation to better protect and expand such refuges. Habitat restoration and/or protection projects in areas identified as cold-water refuges would provide a buffer for cold-water fish populations as thermal degradation continues.

Specific questions and suggested studies relating to cold-water refugia include:

- Where are cool water inputs, and what are their sources (e.g. springs, tributaries, groundwater inflow, hyporheic exchange)?
- How do cool water inputs vary over time and climatic conditions?
- Where cool water inputs occur, are they sufficient to provide refuge for cold-water fishes? Where could they be enhanced?
    - Collecting longitudinal profiles of stream temperature is one approach to answering the above questions. There are various ways to accomplish this, such as helicopter- or drone-mounted thermal infrared surveys, boat-mounted sensors (Vaccaro and Maloy 2006) or fiber-optic distributed temperature sensors (Gendaszek and Opatz 2016). Surveys could be completed during different parts of the year to evaluate thermal regimes under different hydrologic conditions.

Understanding Tributary Influence

Gaining a greater understanding of tributary influence—especially small tributaries—is another important component of thermal diversity. Understanding tributaries may help in understanding where salmonids might find refuge during hot years and to prioritize where riparian plantings may need to occur.

Specific questions and suggested studies related to tributaries include:

- What are the relative contributions of smaller tributaries, springs, and modified floodplain features (e.g. pipes and modified outlets from drainage systems) on mainstem temperatures?

- Which tributaries (especially small tributaries and seeps) provide cold water? When? How do these tributaries interact with mainstem temperatures and localized thermal regimes?

- For small tributaries that flow through floodplains, how much thermal gain occurs in tributary reaches flowing through the floodplain, and what is the mechanism of this gain?

- Why do some tributaries remain cool even in years of low flow and high air temperatures, while others of similar size do not?
    - One way to approach this question would be to compare 2015 temperature data across the Snohomish River basin with other datasets (e.g., land cover and surficial geology) to assess potential correlations.

Linking Fish Use Data to Thermal Data

Understanding thermal diversity is important because it will enable us to find, protect and enhance cold-water refuges for salmonids; however, we must link data on thermal regimes to fish use data. We currently have little direct (vs. inferred) understanding of how fish use across the Snohomish River basin corresponds to temperature. We lack empirical evidence to understand if and how temperature-altered growth and condition is limiting population productivity and survival. By better understanding specific impacts to adult and juvenile life stages of different species, we can better target which life stages are most at risk due to temperature, and which areas of the Snohomish River basin may have the greatest impact on population performance due to temperature. This does not mean that we should not proceed with the strategies we have, based on inference about fish-temperature relationships drawn from work in other systems. We should implement and accelerate existing work based on known strategies, while expanding understandings of how fish use and survival is linked to the thermal landscape in the Snohomish River basin. A small body of modeling work in the Snoqualmie River watershed reflects initial attempts to make this link; more empirical data will help.

Specific questions and suggested studies that link salmonids with thermal regimes include:

- Is temperature-altered growth and condition limiting population productivity and survival of some salmonid species in the Snohomish River basin?
- For a given salmonid species, what life stages and life history are most impacted or most at risk?
- Which areas of the Snohomish River basin have the greatest impact on population performance due to temperature?
- Aside from the often-focused-on metric of daily maximum temperatures during the summer critical period, where, when, and how frequently are biological thresholds for fish species being exceeded?
    - For example, using data we are already collecting all over the basin, we could examine trends over time for metrics such as temperature during the incubation period, daily minimums, etc.
- How do salmonids distribute themselves throughout the summer season and on a daily basis? Do certain species or life history types seek out certain types of thermal refuges?
    - A potential study could include PIT (passive integrated transponder) tagging or radio tagging salmonids and evaluating movement patterns during summer months. This would help to better understand how fish distribute through the season and on a daily basis.
    - Another way to approach this is by evaluating water column depth and fish body temperature from internal acoustic tags.
- How do stream temperature profiles impact spawner distribution?
    - It may be useful to overlay spawner and redd survey data on longitudinal temperature profiles.
- What are the direct and indirect impacts of drought years, such as 2015, to salmon survival? While the occurrence of low flow and warm water conditions in 2015 were apparent throughout the Snohomish River basin, the extent to which each of these conditions separately and conjunctly influenced juvenile and adult salmonids cannot be fully evaluated until we can analyze the survival and productivity of returning adults from the 2015 brood year.

    - This question will be difficult to answer, due to the tricky nature of parsing the confounding effects of high temperature and low flow, which occurred simultaneously in the basin. Reduced flow greatly reduced habitat capacity, irrespective of the direct and indirect impacts of temperature stress and disease to both adults and juveniles. One potential hypothesis to test, using data from otoliths, is whether cooler years produce more yearling Chinook, while warmer years produce fewer, due to temperature-induced early outmigration and mortality.

Investigating Watercourses of Concern

We should continue to investigate specific watercourses of particular concern. Specific questions and suggested studies include:

- The Middle Fork Snoqualmie displays considerably warmer temperatures than both the North and South forks and drives temperatures downstream of the Snoqualmie Falls. To what degree are observed conditions in the Middle Fork anthropogenically influenced, and to what degree are they natural?
    - An extensive water temperature logger network was deployed in the summer of 2018 and will collect year-round continuous temperature data for at least three years. This information may help to further understand how temperature is regulated in the Snoqualmie River and to what extent various conservation and restoration efforts may have in mitigating warmer temperatures.

- The Raging River is the warmest tributaries of the Snoqualmie River – daily maximum temperatures in excess of 25.0°C have been observed near its confluence with the Snoqualmie River (Stohr et al. 2011; Kubo and leDoux 2016; Steel et al. 2016). While natural conditions such as rain dominated hydrology, shallow bedrock, and a wide active channel contribute to the thermal regimes of the Raging River, several important questions remain about the lower reaches of the river are directly impacted by human development (Kaje 2009). Do extensive levees and revetments in the lower portions of the river limit hyporheic exchange with the alluvial aquifer that would serve as an important buffer during summer months? Do thermal barriers prevent the migration of adult Chinook during summer months? How do juvenile salmonids utilize different habitat types and thermal refuges to cope with thermal conditions?
    - Paired fish use and detailed thermal surveys of the lower reaches of the Raging River would begin to answer many of these questions. Spawner surveys paired with longitudinal temperature profiles would identify where thermal barriers exists and how (i.e., when) adult salmon are able to traverse these obstacles.
    - Thermal infrared surveys of water temperature and PIT tagging or radio tagging juvenile salmonids and evaluating movement patterns during summer months would elucidate how juvenile fish utilize different habitat types and thermal conditions throughout summer.

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Appendix 1 – Water Temperature Monitoring in the Snohomish River Basin

Agency	Project / Unit	Data Type	Interval	Start of Data	End of Data	Number of Sites	General location description	Public Access	
King County	Ambient Benthic Monitoring	Continuous time-series	Hourly	2017 [1]	ongoing	23	Small to moderate sized tributaries in the Snoqualmie River watershed (e.g., unnamed tributaries to the Middle Fork Snoqualmie)	Coming soon	https://green2.kingcounty.gov/hydrology/
King County	Field Hydrology Unit	Continuous time-series	15 minutes	1990 [2]	ongoing	12	Small to moderate sized tributaries primarily in the lower Snoqualmie River watershed (e.g., Ames, Cherry, Patterson)	Yes	https://green2.kingcounty.gov/hydrology/
King County	Special Study: Upper Snoqualmie Temperature	Continuous time-series	30 minutes	2018	ongoing	25	The upper Snoqualmie River watershed above the falls, primarily the Middle Fork	Yes	https://green2.kingcounty.gov/hydrology/
King County	Special Study: Summer of 2015 in the Snoqualmie River Watershed	Continuous time-series		June 2015	September 2015	27	17 mainstem Snoqualmie River sites; 10 major tributaries	Report available	https://green2.kingcounty.gov/ScienceLibrary/Document.aspx?ArticleID=336
King County	Special Study: Fall City to Carnation reach of Snoqualmie River	Continuous time-series		June 2016	September 2016	15	14 mainstem Snoqualmie River sites between Fall City and Carnation; 1 at Patterson Creek mouth	Report available	https://green2.kingcounty.gov/ScienceLibrary/Document.aspx?ArticleID=419
King County	Streams Ambient Water Quality	Monthly observation	Monthly	2011	ongoing	12	One on the mainstem Snoqualmie River at Duvall; all others moderate to large tributaries including 3 forks above the Falls	Yes	https://green2.kingcounty.gov/streamsdata/
King County	ADAP	Continuous time-series[3]	15 minutes	2018	ongoing	varies	Location and timing vary by year but mostly small channels serving as ag drainage during mid-summer	Upon request	Email Andrew Miller at andrew.miller@kingcounty.gov
NOAA/USFS	NW Fisheries Science Center	Continuous time-series	30 minutes	2011	ongoing	46	5 on mainstem Snoqualmie River; others on moderate to large tributaries	Coming soon	https://green2.kingcounty.gov/hydrology/

Agency	Project / Unit	Data Type	Interval	Start of Data	End of Data	Number of Sites	General location description	Public Access	
WDFW	Upper Snoqualmie River Game Fish Enhancement Plan	Continuous time-series		2008	2010	11	3 sites per fork of Upper Snoqualmie River; 2 sites on upper Snoqualmie River mainstem from 3 forks and Snoqualmie Falls	Report available	https://wdfw.wa.gov/sites/default/files/publications/01377/wdfw01377.pdf
USFS	Skykomish and Snoqualmie Ranger District	Continuous time-series[4]	30 minutes	installation summer 2020	NA	5	Skykomish River watershed; exact locations TBD	No	
USFS	AREMP	Continuous time-series	30 minutes	varies[5]	varies[5]	3	Lower Beckler River, Lower SF Skykomish River, and Upper NF Skykomish River	No	
USGS	Washington Water Science Center	Continuous time-series	15 minutes	2007 [6]	ongoing	7	Tolt basin - NF, SF, and mainstem; Sultan River watershed	Yes	https://waterdata.usgs.gov/wa/nwis/current/?type=flow
City of Seattle	City Light	Continuous time-series	30 minutes	2015	ongoing	23	Tolt River watershed - NF, SF, and mainstem	No	
USGS / Tulalip Tribes	Thermal Mapping	Thermal Infrared Survey	NA	August 2020	NA	NA	On Snoqualmie (upper MF to Chinook Bend) and Skykomish (Gold Bar to confluence) rivers	Coming soon	TBD
Snoqualmie Tribe	--	Continuous time-series	Hourly	2013	ongoing	3	Headwaters of Kimball Ck. on Snoqualmie Reservation	Upon request	Email Matt Baerwalde at Matt@snoqualmietribe.us
Snoqualmie Tribe	--	Monthly observation	Monthly	2010	ongoing	8	Headwaters of Kimball Ck. on Snoqualmie Reservation	Yes	https://www.waterqualitydata.us/
Tulalip Tribes	--	Continuous time-series	30 minutes	1994	ongoing	4	On Tulalip reservation	No	
Tulalip Tribes	--	Monthly observation	Monthly	2019	ongoing	21	On Tulalip reservation	Yes	https://www.waterqualitydata.us/
Ecology	Snoqualmie River Basin Temperature Total Maximum Daily Load	Thermal Infrared Survey		8/13/2006	NA	NA	Snoqualmie River from Taylor River to confluence with Skykomish River	In report	https://fortress.wa.gov/ecy/publications/documents/1110041.pdf
Ecology	Snoqualmie River Basin Temperature Total Maximum Daily Load	Continuous time-series		June 2006	September 2006	48	15 mainstem Snoqualmie River sites, various large and small tributaries	In report	https://fortress.wa.gov/ecy/publications/documents/1110041.pdf

Agency	Project / Unit	Data Type	Interval	Start of Data	End of Data	Number of Sites	General location description	Public Access	
Ecology	Long-term monitoring	Monthly observation	Monthly	1959	ongoing	4	Snohomish River (at Snohomish) Skykomish River (at Monroe) Snoqualmie River (at Snoqualmie and at Monroe)	Yes	https://ecology.wa.gov/Research-Data/Data-resources/Environmental-Information-Management-database
Ecology	Long-term monitoring	Continuous time-series	30 minutes	2001	ongoing	7	Skykomish and Snoqualmie mainstems, Snoqualmie tributaries like Patterson, MF, NF, Tolt	Yes	https://ecology.wa.gov/Research-Data/Data-resources/Environmental-Information-Management-database
Ecology et al.[8]	Watershed health monitoring	Annual observation	Annually	2009	ongoing	39	Only Griffin Creek is sampled annually. Other sites are sampled randomly every eight years.	Yes	https://apps.ecology.wa.gov/eim/search/WHM/WHMLocationResults.aspx?&LocationWRIAs=7
Snohomish PUD	Henry M. Jackson Hydroelectric Project: Water Quality Monitoring Plan	Continuous time-series		Formally in 2011, per License, but some stations have been in place since before 2011	ongoing	12	10 sites on Sultan River; 2 on Skykomish above and below Sultan	Reports available	
Snoqualmie Valley Watershed Improvement District	--	Continuous time-series	TBD	installation summer 2020	NA	24	Tuck, Langlois, Cherry, and Peason Eddy creeks[9]	Upon request	Email Andy Obst at andy@svwid.org
Snohomish County Surface Water Management	State of Our Waters	Monthly observation + Continuous Time Series [12]		2018	ongoing	40	Streams and rivers throughout Snohomish County with 24 consistent each year as trend sites	Yes	http://www.snoco.org/applications/login.html?publicuser=Guest#waterdata/stationoverview
Snohomish County Surface Water Management	Habitat Monitoring Program	Continuous time-series[11]		June 2004	September 2004	18	Woods Creek basin	Upon request	

Agency	Project / Unit	Data Type	Interval	Start of Data	End of Data	Number of Sites	General location description	Public Access	
Snohomish County Surface Water Management	Snohomish River Pollutant Diagnosis and Implementation Project	Continuous time-series[11]		May 2005	September 2005	39	Primarily Skykomish River and tributaries but a few sites on Snoqualmie, Snohomish, and Snohomish estuary	Report available	https://snohomishcountywa.gov/Archive/ViewFile/Item/2156
Snohomish County Surface Water Management	Habitat Monitoring Program	Continuous time-series[11]		April 2001	August 2001	19	Snohomish Estuary (main, distributary, blind tidal, estuarine emergent marsh)	Upon request	
Snohomish County Surface Water Management	Snohomish Status and Trend Monitoring Program	Continuous time-series[11]		June 2007	September 2007	14	Woods, Quilceda, Allen, Skykomish, French	Report available	https://snohomishcountywa.gov/ArchiveCenter/ViewFile/Item/2143
Snohomish County Surface Water Management	Wood Creek Watershed Habitat Conditions Report	Continuous time-series[11]		June 2009	September 2010	5	Woods Creek watershed	Report available	https://snohomishcountywa.gov/ArchiveCenter/ViewFile/Item/2173
Snohomish County Surface Water Management	Middle Pilchuck River Assessment	Continuous time-series[11]		June 2010	September 2010	11	7 on mainstem Pilchuck R.; 4 on tributaries	Report available	https://snohomishcountywa.gov/ArchiveCenter/ViewFile/Item/4269

1 oldest site begins in 2017, newest site begins 2019

2 oldest site begins in 1990, newest site begins 2013

3 temperature loggers only deployed during project construction in summer

4 temperature loggers only deployed during summer

5 Loggers are deployed on a rotating basis, usually for 1 to 2 year durations

6 SF Tolt monitoring begins in 2007; NF Tolt begins 2015; mainstem Tolt 2016

7 oldest site begins in 1959; newest site begins in 1977

8 Other agencies include King and Snohomish counties and the US EPA

9 Some sites prone to flooding may not be monitored during the wet season

10 Large Snohomish County river sites began in 2017, all other sites 2018. Monitoring sites rotate

11 Data only collected during critical period from June 15th to September 15th

12 Not all sites have continuous monitoring all years