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MEMORANDUM

TO:	**Nechako Water Engagement Initiative *Technical Working Group***
FROM:	**Jennifer Carter, M.R.M, R.P.Bio. and Jayson Kurtz, R.P.Bio., Ecofish Research Ltd.**
DATE:	**November 30, 2022**
FILE:	**1316-09**
RE:	**Review of Water Temperature Effects on Salmon**

1. INTRODUCTION

During Main Table and Technical Working Group (TWG) meetings of the Nechako Water Engagement Initiative (WEI), concerns were raised about potential effects of water temperature on salmon. The TWG asked Ecofish Research Ltd (Ecofish) to review scientific studies and other information and summarize key factors with recommendations for WEI consideration on how Rio Tinto Alcan (RTA) operations affect salmon through temperature effects in the Nechako River. This memo provides an overview of water temperature and salmon species in the Nechako River, describes how water temperature affects salmon, reviews scientific research linking water temperature thresholds to mortality, and offers practicable recommendations to inform water management decisions to minimize the negative effects of temperature on salmon in the Nechako River.

2. BACKGROUND

2.1. Nechako River Water Temperature

The Nechako River originates in the Coastal Mountains and has a hydrograph dominated by snowmelt with a spring freshet (Hernández-Henríquez *et al.* 2017). Water temperature in the river is well studied; however, natural water temperature is less understood since most of the data includes the effects of Rio Tinto water impoundment and controlled release (see Section 2.1.2). Recent studies have investigated water temperature across the Fraser River watershed (Islam *et al.* 2019), and results suggest that natural river temperatures often exceed 18°C and sometimes 20°C (Figure 1) and that the observed water temperatures in the Nechako River are similar to nearby rivers (Figure 2).

Figure 1. **Number of days when simulated daily summer water temperatures exceeded the critical temperature of 20°C during 1950-2015 in the Fraser River watershed. From (Islam *et al.* 2019).**

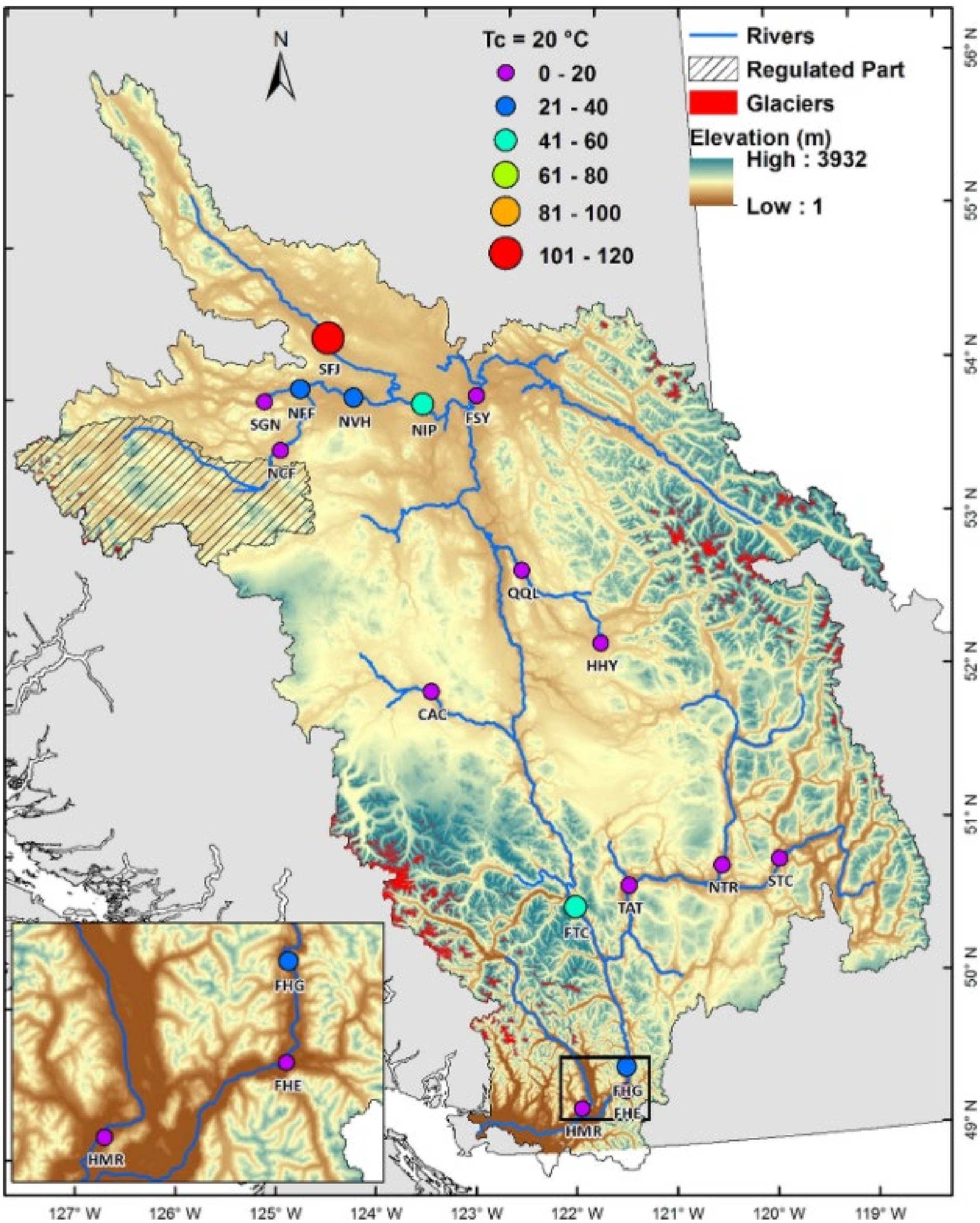
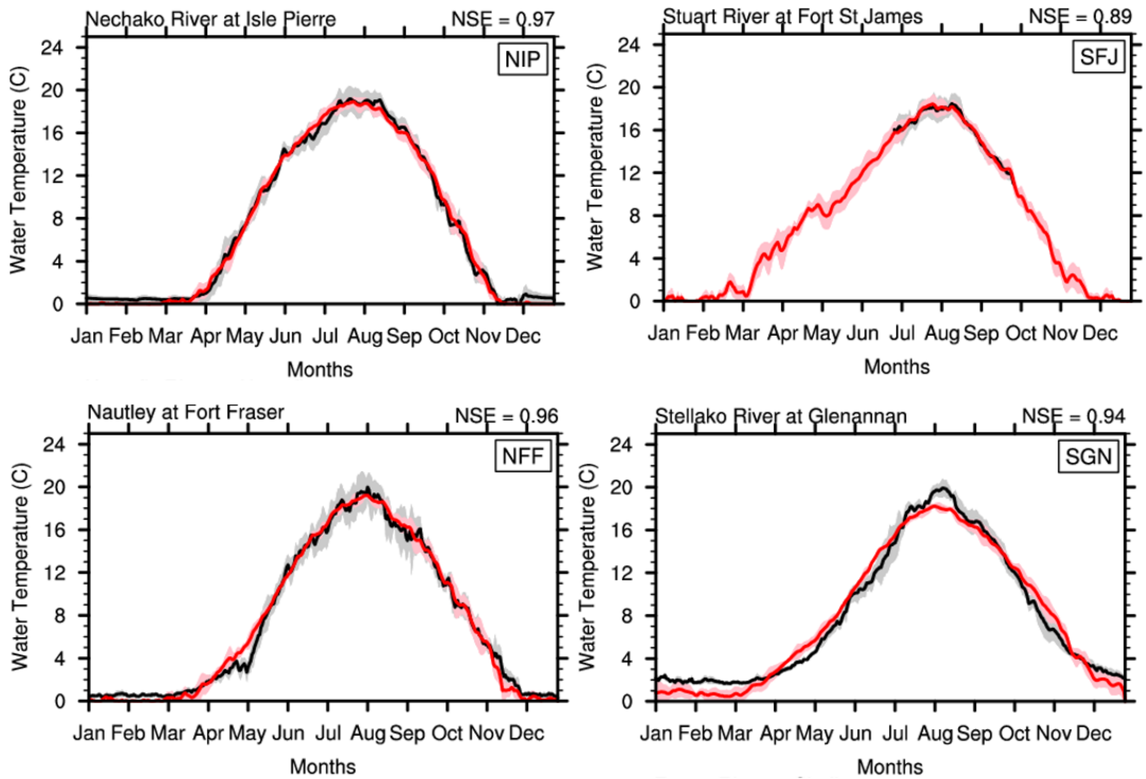


Figure 2. Observed (black) and simulated (pink) daily mean water temperatures in the Nechako River watershed. Shading represents daily water temperatures in individual years for 5-95% ranges. From (Islam *et al.* 2019).



2.1.1. Climate Change and Other Temperature Influences

Salmon migrating through the Fraser and Nechako Rivers are experiencing higher river temperatures than in the past due to climate change and resource development. Over the past 40 years, climate change has caused an estimated increase of more than 1.5°C in average peak summer water temperatures in the Fraser River (Patterson *et al.* 2007a). A recent study looking at climate change impacts on the Fraser River Basin reconstructed the historic thermal regime of the Nechako River and showed that the frequency of temperature extremes has increased in recent decades in the Nechako River and more broadly in the Nechako watershed (Islam *et al.* 2019). For example, results showed that between 1956-1976 temperatures exceeded 18°C 100 days in the Nechako River at Vanderhoof and 194 days between 1996 and 2015 (Islam *et al.* 2019). Land clearing for agriculture, forestry, and residential development has accelerated along the Nechako and Fraser Rivers and is linked to higher water temperatures via reductions in riparian shading (Beschta 1997). All Fraser River summer-migrating salmon currently experience river temperatures that routinely exceed 20°C at some point during their upriver migration, and some stocks experience average water temperatures that are 4°C warmer than historical levels (Patterson *et al.* 2007b).

2.1.2. Summer Temperature Management Program

By altering flow and reducing discharge, hydroelectric facilities also influence water temperature (Brett *et al.* 1982). In the 1980s, the Department of Fisheries and Oceans and others expressed concern about negative effects on Sockeye Salmon from warm river temperatures due to low flows, and starting in 1987, Rio Tinto was obliged to reduce temperature-related risks to returning Sockeye by releasing cooling water flows during July and August (NFCP 2016). At that time, a threshold of 20°C was considered the highest safe daily mean temperature for migrating adult Sockeye Salmon (Macdonald *et al.* 2012); thus, this temperature has been a target for management. However, recent research indicates that thermal tolerances differ across salmon species, populations, and life stages, underscoring the importance of assessing these differences to inform management (Eliason *et al.* 2011). An overview of the effects of temperature on salmon and a summary of temperature tolerances follows later in this report.

2.2. Nechako River Salmon

Three anadromous pacific salmon (Sockeye (*Oncorhynchus nerka*), Coho (*Oncorhynchus kisutch*), and Chinook (*Oncorhynchus tshawytscha*) Salmon)) utilize the Nechako River for migration, spawning, or rearing (Table 1).

2.2.1. Coho Salmon

There is little scientific study or other information on Nechako River Coho Salmon populations or habitats. The conservation unit (Interior Fraser) is considered threatened (COSEWIC 2021), but there is insufficient data to assess biological status (PSF 2021). Generally, Coho migrate to spawn in the late fall October and November, but specific migration timing is not known. Anecdotal information suggests Coho may spawn near Cheslatta Falls (Salewski, pers. comm. 2021). Coho Salmon fry emerge in the spring and generally rear in freshwater for a year prior to migrating to the Pacific Ocean. Although fry will utilize mainstem habitats, parr generally prefer to occupy tributary or off-channel areas with structural complexity (i.e., large substrate and woody debris) (COSEWIC 2013).

There is no temperature-related research on Coho Salmon in the Nechako River, but timing of expected migration suggest that warm water temperatures are unlikely to negatively affect adult Coho, even considering near-term climate projections (Sharma and Déry 2015). Therefore, further discussion on adult Coho Salmon is not included in this report. Although there is no information specifically on Nechako River juvenile Coho, these fish are discussed in general terms below because there is potential for warm water related effects during rearing in the mainstem.

2.2.2. Sockeye Salmon

Sockeye Salmon generally spawn in watersheds with large lakes, their preferred rearing habitat, although some "river-type" populations exist where fry rear in rivers and "sea-type" populations where fry migrate downstream to the Pacific Ocean directly after emerging (McPhail 2007). In the Nechako watershed, there are several Sockeye stocks that migrate through the mainstem during early summer (mid-July) or mid-summer (late-July and August) to spawn in tributary watersheds (i.e., Nadina, Early Stuart, Late Stuart, and Francois stocks) (NFCP 2016). These stocks include Endangered and Special Concern conservation units (COSEWIC 2021). Anecdotal information suggests a few Sockeye may also occasionally spawn in the Nechako River itself (Salewski, pers. comm. 2021).

Nechako watershed Sockeye populations have been well studied, including understanding effects of high temperature exposure on migrating adults, and this life stage is further discussed in this report. Water temperature effects of juvenile Sockeye in the Nechako River is less studied; however, juveniles rear in tributary lakes unaffected by Rio Tino operations and out-migrate through the Nechako River in the spring, which minimizes potential temperature effects; therefore, juvenile Sockeye are not discussed further in this report.

2.2.3. Chinook Salmon

Chinook Salmon are the most-studied fish in the Nechako Watershed, predominately through the Nechako Fisheries Conservation Program that provides useful information on population dynamics, fish distribution and habitat use, and movement patterns. Adult Chinook Salmon migrate to the Nechako River during mid-summer and spawn between Vanderhoof and Cheslatta Falls through early October (NFCP 2014). Juvenile Chinook emerge in the spring and a majority out-migrate to Fraser River rearing habitats as fry by July; however, some can rear a year or two in the Nechako River or tributary streams prior to out-migrating to the ocean as smolts (Bradford 1994; Quinn 2005; NFCP 2014; St. Hilaire *et al.* 2020). Juvenile Chinook in the Nechako River utilize both margin and mid-channel habitat (Triton 2010), as well as side channel and tributary habitat (Envirocon 1984). The Nechako River Chinook population is part of the Mid-Fraser Summer Chinook Conservation Unit, which have been designated as Threatened (COSEWIC 2021).

The Nechako River Chinook Salmon population has been well studied, including understanding effects of high temperature exposure on migrating adults, and this life stage is further discussed in this report. Water temperature effects of juvenile Chinook in the Nechako River is less studied; however, a portion of the juvenile population is susceptible to summertime warm water conditions, so this life stage is also discussed further in this report.

Table 1. Life history periodicity for anadromous pacific salmon in the Nechako River (excludes tributaries).

Inferred for the Nechako River | Confirmed for the Nechako River | Temperature sensitive period

Species	Lifestage/Period	January		February		March		April		May		June		July		August		September		October		November		December	
Coho Salmon	Adult Migration																								
	Juvenile Rearing																								
	Juvenile Outmigration																								
Sockeye Salmon (Early Summer)	Adult Migration																								
	Juvenile Rearing																								
	Juvenile Outmigration																								
Sockeye Salmon (Mid-Summer)	Adult Migration																								
	Juvenile Rearing																								
	Juvenile Outmigration																								
Chinook Salmon	Adult Migration																								
	Juvenile Rearing																								
	Juvenile Outmigration																								

3. GENERAL TEMPERATURE EFFECTS ON SALMON

3.1. Adult Salmon: Migration, Holding, and Spawning

Upstream migration is a physically demanding, once-in-a-lifetime occurrence. Because adult salmon cease feeding prior to migrating, they have a finite amount of energy available not only to propel themselves upstream for days or weeks, sometimes over challenging obstacles, but also to fuel reproductive maturation (i.e., acquisition of sexual characteristics, gonad growth) and to respond to stressors including predators, fishing pressure, and suboptimal water temperature and river velocity. Any one stressor or combination of stressors can deplete a fish's energy reserves quickly enough to impact individual migration and spawning success (i.e., whether a fish survives or successfully reproduces).

High water temperatures can affect the ability of migrating salmon to efficiently convert energy to maintain physiological functions (McCullough 1999) and can have major ramifications for fish health. For instance, water temperatures exceeding 17°C can increase susceptibility to parasites and disease, increase stress, and reduce swimming performance of migrating salmon (Macdonald *et al.* 2000; McCullough *et al.* 2001; Wagner *et al.* 2005). Adult spring Chinook held at 19°C for approximately two weeks prior to spawning produced smaller eggs with greater pre-hatch mortality, developmental abnormalities, and smaller alevins (Berman 1990). Jeffries *et al.* (2013) observed that frequent exposure to water temperatures ≥19°C increased mortality of adult Pink and Sockeye salmon.

In 2004, extremely high river temperatures were identified as a key factor explaining the estimated 57% overall en-route mortality rate of Fraser River Sockeye Salmon (Southern Salmon Fishery Post-Season Review Committee 2005; Mathes *et al.* 2010).

3.2. Juvenile Salmon: Rearing and Migration

Once salmon hatch and emerge from spawning substrate, they are small and vulnerable to predation and therefore must seek out suitable habitat to rear. While juvenile salmon are rearing, they feed, grow, and prepare to undergo the complex process of smoltification – a series of physiological changes that occur to prepare them for out-migration and survival in the ocean. Juvenile growth rates generally increase as water temperature rises; however, beyond an optimal temperature, growth declines as food conversion efficiency or food availability is reduced, and juveniles must increase food intake to meet higher energy demands when water temperatures are warm (Brett *et al.* 1982). Elevated freshwater temperatures can also hinder the smoltification process, delay outward migration to the ocean, and decrease survival in the marine environment (Sykes *et al.* 2009; McCullough *et al.* 2001). Increasing temperature can affect behaviour, salinity tolerance, body moisture and lipid content, and overall growth, and condition (Johnston and Saunders 1981; Sauter *et al.* 2001; McCullough *et al.* 2001; Sharron 2015). High temperatures can also delay or prevent downstream migration by blocking the gill ATPase osmoregulatory enzyme (crucial for seawater survival) (Sauter *et al.* 2001). ATPase is stimulated by growth hormones, which are reduced at high temperatures (Handeland *et al.* 2000). Insufficient body size and ATPase activity can in turn lower survival during outward migration (Johnston and Saunders 1981; McCullough *et al.* 2001).

4. QUANTIFYING THERMAL TOLERANCES

To quantify thermal tolerance, we need to understand how temperature affects physiology (or behaviour) that in turn affects a health outcome. Below we summarize scientific research that investigates the mechanistic links between both short- and long-term exposure to high temperatures and adverse impacts on salmon survival and growth, for both adult and juvenile salmon. Where possible, we apply this research to the Nechako River to infer thermal tolerances for Nechako Chinook and Sockeye Salmon.

4.1. Short-term Exposure: Aerobic Scope

Aerobic scope is an estimate of the total amount of energy available for activity. As such, aerobic scope is a general indicator of fish health and the relationship between water temperature and aerobic scope can be used to define population- and species-specific thermal tolerances for salmon over short periods of time (0-96 hours)

Aerobic scope has a dome-shaped relationship to temperature that peaks at an optimum temperature (T_{opt}) and is zero at very low and very high temperatures (T_{crit}) (Appendix A). Short-term exposure (0 to 96 hrs; e.g., Farrell *et al.* 2008) to high temperatures near T_{crit} can cause aerobic collapse, during which the total amount of aerobic energy available is insufficient to support activity demands and anaerobic metabolism can completely replace aerobic metabolism, leading to oxidative stress and possible immediate death (Pörtner and Knust 2007; Keefer *et al.* 2008; Steinhausen *et al.* 2008).

4.1.1. Adult Salmon (General)

Laboratory and field-based studies have investigated the relationship between aerobic scope and water temperature for different populations of adult migrating salmon (Lee *et al.* 2003; Farrell *et al.* 2003; Eliason *et al.* 2011; St. Hilaire *et al.* 2020). These studies have measured fishes' oxygen consumption while fish swim continuously until exhaustion at defined temperatures (Little *et al.* 2020; Eliason *et al.* 2011; Farrell *et al.* 2003). For example, stock-specific thermal tolerances have been developed for eight Fraser River Sockeye Salmon populations (or groups of populations that spawn within close proximity of each other) (Appendix A), which illustrate population-specific adaptations to temperature.

Population-specific variability in thermal tolerances can be attributed to physiological adaptations to different migration conditions and challenges (Lee *et al.* 2003; Farrell *et al.* 2008; Eliason *et al.* 2011). For example, summer-migrating stocks, which experience the warmest river temperatures, have higher thermal tolerances than fall-migrating stocks (Eliason *et al.* 2011). Weaver Sockeye (fall-run) T_{opt} and T_{crit} metrics range from 14.3 to 15°C and 20.4 to 21°C, respectively (Lee *et al.* 2003; Farrell *et al.* 2008;

Eliason *et al.* 2011; St. Hilaire *et al.* 2020) whereas Chilko (summer-run) T_{opt} and T_{crit} metrics are higher and range from 16.8 to 17°C and 29 to 29.5°C (Appendix A; Eliason *et al.* 2011; St. Hilaire *et al.* 2020). Among summer-run stocks, those that migrate over greater distances and elevations tend to have larger heart muscle and broader aerobic scope, which allows the fish to withstand a wider range of water temperatures (Eliason *et al.* 2011).

Preliminary results from aerobic scope research on Chilliwack and Shuswap Chinook indicate that, similar to Sockeye Salmon, summer-run adult Chinook have higher temperature thresholds than fall-run Chinook (St. Hilaire *et al.* 2020). Currently, results suggest that Chilliwack (fall-run) Chinook have a T_{opt} of 15°C, $T_{80\%}$ of 18°C, $T_{50\%}$ of 21°C, and T_{crit} of 23.1°C, whereas Shuswap (summer-run) Chinook have a T_{opt} of 15°C, $T_{80\%}$ of 19°C, $T_{50\%}$ of 23°C, and T_{crit} of 25.8°C (St. Hilaire *et al.* 2020). St. Hilaire *et al.* (2020) assumed that 50 to 80% aerobic scope is required to complete migration, which suggests thermal maximums of 19°C to 23°C (for periods of time <96 hours) for migrating Shuswap Chinook (St. Hilaire *et al.* 2020).

Telemetry studies have verified thermal tolerance ranges for various salmon stocks. For example, Farrell *et al.* (2008) found that predictions of migration mortality of Fraser River Weaver Sockeye using aerobic scope thresholds were similar to mortality estimates of empirical telemetry results in 2004 of migrants, when temperatures were extremely warm.

It is unknown exactly what percent aerobic scope is required to complete migration, but both laboratory and telemetry studies suggest that 50 to 80% aerobic scope is likely required to successfully migrate depending on the distance to the spawning grounds (Farrel *et al.* 2008; Martins *et al.* 2011; St. Hilaire *et al.* 2020). Other studies have suggested that perhaps 90% aerobic scope is required for long distance migrants (Eliason *et al.* 2011). This means that thermal maximums are probably between temperatures associated with 90% aerobic scope ($T_{90\%}$) and the temperatures associated with 50% aerobic scope ($T_{50\%}$).

4.1.2. Juvenile Salmon (General)

Aerobic scope thermal tolerances have been assessed for both juvenile Chinook and Coho Salmon and results are generally inconclusive. One study assessed aerobic scope in juvenile Coho from an Interior Fraser Coho stock (Seymour River) found aerobic scope was minimized at 13°C and 21°C, and T_{opt} was achieved at 17°C (Casselman *et al.* 2012). However, other studies (Poletto *et al.* 2016, 2017; Sungaila 2018) found no aerobic scope curve relationship across temperatures ranging from 12°C to 26°C (i.e., no T_{opt} was achieved) for either juvenile Chinook or Coho Salmon. There is ongoing research on aerobic scope thermal tolerances for juvenile Chinook Salmon (St. Hilaire *et al.* 2020) that may provide more information in the future.

4.1.3. Nechako River Salmon

Two of the eight Sockeye groups for which thermal tolerances have been developed are summer-run stocks that migrate through the Nechako River at Finmore. These include Early Stuart (comprised of 40 populations that spawn within 100 km of each other) and Nechako (comprised of Stellako, Nadina, Tachie, and Middle River populations that spawn within 100 km of each other). Temperature thresholds for Early Stuart were reported as T_{opt} ranging from 17.2 to 17.5°C, $T_{90\%}$ 19.9°C, $T_{80\%}$ 21 to 21.1°C, $T_{50\%}$ 23.3°C to 24°C, and T_{crit} of 25.8°C, while temperature thresholds for Nechako Sockeye were slightly lower and were reported as T_{opt} ranging from 16.8 to 17°C, $T_{90\%}$ 19.0°C, $T_{80\%}$ 20 to 20.5°C, $T_{50\%}$ 21.8°C to 22°C, and T_{crit} of 24°C (Eliason *et al.* 2011; St. Hilaire *et al.* 2020). The assumption that 50 to 90% aerobic scope is required to complete migration suggests thermal maximums of 19°C to 22°C and 19.9°C to 24°C (for periods of time <96 hours) for Nechako and Early Stuart migrating Sockeye, respectively.

There is no Nechako-specific aerobic scope research on Chinook (adult or juvenile) or Coho or Sockeye juveniles. There is also no similar research on adult Coho or Sockeye; however, these species-life stages are not exposed to acute warm temperatures in the Nechako River.

4.2. Long-Term Exposure

4.2.1. Adult Salmon (General)

Long-term migration survival can be negatively affected by chronic exposure (>96 hrs; e.g., Wagner *et al.* 2005; Crossin *et al.* 2008) to high water temperatures by accelerating the development of parasites and microbial infections and inducing thermal stress (Wagner *et al.* 2005; Crossin *et al.* 2008; Jeffries *et al.* 2013; Teffer *et al.* 2017, 2019). There has been less research mechanistically linking long-term exposure to high temperatures and mortality of adults, compared to the amount of research on aerobic scope and short-term exposure to high temperatures. We review key findings here.

Currently, studies suggest long-term exposure (one week or more) reaching 19°C is detrimental for adult migrating Sockeye and Chinook salmon. Another lab study showed Chilko River and Lower Adams Sockeye Salmon expressed heat shock and immune response genes when held at 19°C for a week (Jeffries *et al.* 2012a). Adult summer Chinook from the Puntledge River held at an average temperature of 17-19°C for three months experienced 57% pre-spawn mortality versus fish held at average temperatures of 8-9°C (Jensen *et al.* 2006). Furthermore, Berman 1990 found higher mortality in adult spring Chinook held at 19°C for approximately two weeks due to microbial infections than those held at 14°C (Berman 1990).

Laboratory studies show that one week of exposure to temperatures ≥18°C can cause physiological impairment and higher mortality in salmon (Teffer *et al.* 2019; Jeffries *et al.* 2012a, 2012b, 2013). Sockeye and Pink salmon, particularly females, exposed to 18 to 19°C for a week showed signs of thermal stress and had higher mortality than those exposed to temperatures ≤14°C

(Jeffries *et al.* 2012b, 2013). For summer-run female Sockeye Salmon specifically, mortality spiked after six days of experiencing temperatures of 19°C, and by ten days, more than 60% of all fish died (Jeffries *et al.* 2013).

Accumulated thermal units (ATUs) – the daily accumulation of temperature above 0°C, provides one useful measure of temperature exposure. ATUs greater than 500°C to 600°C during freshwater migration can result in severe development of the kidney parasite *Parvicapsula minibicornis*, which could impact migration success (Wagner *et al.* 2005).

Long-term exposure to high temperatures also increases susceptibility to infections. Severe microbial infection can lead to osmoregulatory impairment and chronic stress, which can cause mortality (Teffer *et al.* 2019; Jeffries *et al.* 2012a; Crossin *et al.* 2008). For example, in the Nechako River, Early Stuart Sockeye Salmon that died pre-spawn were found to have higher rates of microbial infection than those that survived (Teffer *et al.* 2017). Results from telemetry studies conducted across three years showed that chronic exposure to high temperatures decreases migration success (Martins *et al.* 2012). For example, when river temperatures were 19°C, migration survival decreased throughout the migration, especially in females (Martins *et al.* 2012).

4.2.2. Juvenile Salmon (General)

The relationship between long-term water temperatures and juvenile growth and smoltification has been well studied across salmon species. We focus here on juvenile Chinook Salmon, as juvenile sockeye out-migrate in spring and are not present in the Nechako during summer.

Generally, studies have suggested that growth and smoltification in Chinook Salmon can be impaired when fish are reared (over weeks to months) at temperatures above a broad range of 12 to 20°C (McCullough 1999; McCullough *et al.* 2001; Marine and Cech 2004). Of note, the higher range of 17 to 20°C was reported for a southernly distributed stock in the Sacramento River in California (Marine and Cech 2004), and this temperature may be higher than tolerances for more northern populations. Optimal growth has been reported between 15 and 20°C across populations of juvenile Chinook (McCullough *et al.* 2001). Marine and Cech (2004) reported a significant decrease in ATPase activity when juvenile Chinook were reared in temperatures above 20°C. The critical thermal limits reported for juvenile Chinook are 20 to 24°C (Zaugg and McLain 1976; McCullough *et al.* 2001).

Similar research has been done on juvenile Coho Salmon. Generally, growth and smoltification can be impaired when fish are reared at temperatures above 15°C, ATPase activity is restricted at 20°C, and 25°C has been reported as the critical thermal limit (McCullough *et al.* 2001).

4.2.3. Nechako River Salmon

A field study on juvenile Chinook in the Nechako River was conducted in 1982 to assess effects of temperature (Brett *et al.* 1982). The study assessed fish captured from 10 km downstream of Cheslatta Falls from March to September, and then assessed natural growing rates through the growing season. Optimal growth of juvenile Chinook in the Nechako River was found to occur at 14.8°C (Brett *et al.* 1982). Brett *et al.* (1982) further deduced that a 20% reduction in growth of Nechako River juvenile chinook would occur at 18 to 19°C, and no growth would occur at 21.4°C.

There is no Nechako-specific chronic temperature research on adult Chinook, or on juvenile Coho. There is also no similar research on adult Coho, or Sockeye adults or juveniles; however, these species-life stages are not exposed to chronic warm temperatures in the Nechako River.

5. DISCUSSION

Current knowledge of temperature tolerances may provide a basis for improving the STMP approach. In doing so, one must consider: 1) the certainty of the science and potential for additional research, 2) the natural thermal regime of the Nechako River, and 3) operational feasibility to reduce water temperatures.

5.1. Scientific Certainty

There is various information and uncertainty about the short- and long-term effects of warm water temperature on the salmon species and life stages present in the Nechako River. The short-term effects of water temperature on migrating salmon are certain and there is sufficient research on Nechako River Sockeye Salmon populations to recommend a thermal criterion and expected effects on fish based on aerobic scope. Based on current knowledge acute thermal limits for adult Nechako and Early Stuart migrating Sockeye are 19°C to 22°C and 19.9°C to 24°C, respectively. Although short-term effects on migrating and rearing Chinook Salmon in the Nechako River are less certain, there is ongoing research that may provide the basis for a thermal criterion soon (St. Hilaire *et al.* 2020). However, acute thermal criterion does not incorporate long-term exposure to temperature, which is important to consider. For example, Macdonald *et al.* (2012) showed that the reduction in water temperatures in the Nechako River from the STMP has a modest impact on pre-spawning mortality of Sockeye Salmon. This is likely because the STMP mainly controls for short-term exposure to warm water temperature in the Nechako River, where migrants typically spend only three to four days in the Nechako River en-route to spawning grounds in tributary watersheds (Macdonald *et al.* 2012). However, these salmon may have already been exposed to high temperatures for a longer period when migrating through the Fraser River. If fish have experienced exceptionally warm temperatures (i.e., over 19°C for ≥ 6 days or over 600°C ATUs) throughout their migration history, they likely have less aerobic scope available and have increased disease, therefore, an acute threshold may not be suitable. Assuming a larger aerobic scope is required for longer migrants is a conservative approach that may also account for potential effects of chronic exposure including earlier migration periods.

There is much less certainty about thermal tolerance for Chinook and Coho Salmon. Much of that uncertainty is due to insufficient information: there are few, if any, studies for these species on the Nechako River. Data from other watersheds are available, but it is unclear whether these data are relevant to the Nechako based on results for Sockeye Salmon that suggest there is considerable variability between stocks.

Additional research would improve our understanding of how exposure to elevated temperatures affect the fish of most concern (adult Chinook and Sockeye at the end of their migration and rearing juvenile Chinook and Coho). Using adult salmon from the Nechako River, a study that simulates the migration thermal history (i.e., Fraser River temperatures) and then the exposure to temperatures associated with 50-90% aerobic scope at the time they would be entering the Nechako River would provide managers a better understanding of the thermal maximum and duration of exposure that can negatively affect survival. Furthermore, we know that river temperature is not constant (there are tributaries and other temperature refugia) and understanding how fish movements and behaviour affect the real in-river exposure to acute warm water would allow us to refine potential effects. Additional research on Coho Salmon would help confirm whether this species has thermal risk in the Nechako River.

5.2. Natural Thermal Regime

It is also important to consider that optimal temperatures for fish are often exceeded in nature. As discussed in Section 2.1 rivers in the BC Interior are frequently at or near 20°C and the frequency of temperature extremes has increased in recent decades in the Nechako River and more broadly in the Nechako watershed (Islam *et al.* 2019). Although we may seek to reduce the consecutive days fish experience thermal extremes, it may not be natural to eliminate them completely. Furthermore, this highlights the complexity of managing a river's temperature in a warming climate.

5.3. Operational Feasibility

A target thermal regime for the Nechako River that may be beneficial for fish still needs to be operationally feasible. The large amount of water release necessary to cool water temperatures downstream is a trade-off for other management objectives; therefore, the temperature threshold must be justified and feasible from an operational perspective (i.e., to still have water left over for other uses). Nonetheless, changes to the current STMP may be feasible and may provide benefits during warm years.

6. RECOMMENDATIONS

Based on the status of current science and complexity of water temperature management on the Nechako River, we recommend the following for the TWG and Main Table consideration:

- Given the life history strategies of all the Nechako River salmon, focus on temperature tolerance for migrating adult salmon (juvenile salmon have significantly less risk).
- Adopt thermal limits based on the best current science to provide 50-90% aerobic scope for migrating salmon. A conservative limit of 19°C should be protective of the most at-risk and sensitive stock (Early Stuart Sockeye 19°C to 22°C).
- A less conservative limit of 20°C to 21°C, could be adopted to explore flow operations that appear generally protective of migrating salmon.
- Scientific research on aerobic scope for juvenile and adult Chinook is ongoing. Chronic exposure limit based on available information for juvenile Chinook growth suggests a thermal criterion of 18°C to 19°C; however, criteria should be re-evaluated once this research is complete.
- Consider research that would better our understanding of long-term temperature exposure of salmon including:
    - A study that simulates adult salmon migration thermal history (i.e., Fraser River temperatures) and then the exposure to temperatures associated with 50-90% aerobic scope at the time salmon would be entering the Nechako River.
    - A study that explores adult and juvenile salmon real exposure to warm temperatures in the Nechako River by understanding fish behaviour and habitat use, including thermal refugia.
- Consider research that would better our understanding of Coho Salmon use in the Nechako River, including population status and migration, spawning, and rearing timing and habitat use.
- Evaluate alternative approaches to the STMP such as the water release facility proposed at Kenney Dam.

7. CLOSURE

Ecofish was asked to support the WEI by reviewing the current scientific knowledge about effects of warm water on salmon in the Nechako River. The following key points summarize our current understanding of water temperature effects and tolerances for salmon species, populations, and life histories of concern:

- It is important to look at population-specific thermal tolerances as different species and populations have different physiological adaptations to water temperature regimes. However, juvenile salmon have significantly less risk that migrating adult salmon.
- Evidence suggests between 50% and 90% aerobic scope is required for salmon migration.
- Aerobic scope-temperature relationships have been developed for two adult Sockeye Salmon groups of concern. For Early Stuart Sockeye, an appropriate upper temperature range would be 19.9°C to 24°C, and 19°C to 22°C for all other Nechako Sockeye.
- Aerobic scope-temperature relationships have not been developed for Nechako Chinook Salmon. However, preliminary results from a similar population suggests an upper temperature range of 19°C to 23°C, which assumes 80% aerobic scope is required to complete migration.
- Aerobic scope-temperature relationships for juvenile Chinook and Coho are generally inconclusive; however, ongoing research may provide more information in the future.
- Chronic exposure to water temperatures 19°C or greater can lead to decreased spawning migration survival in Sockeye Salmon. Laboratory studies indicate a week of exposure can result in a large increase in mortality. Chronic exposure for Chinook Salmon is less well understood.
- General research suggest long-term water temperature (weeks to months of exposure) for juvenile salmon should not exceed 18°C.
- Ongoing research is likely to refine temperature tolerance thresholds for Nechako River salmon.

Yours truly,

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Personal Communications

Salewski, W. 2021. Verbal communications between Wayne Salewski and the Technical Working Group.

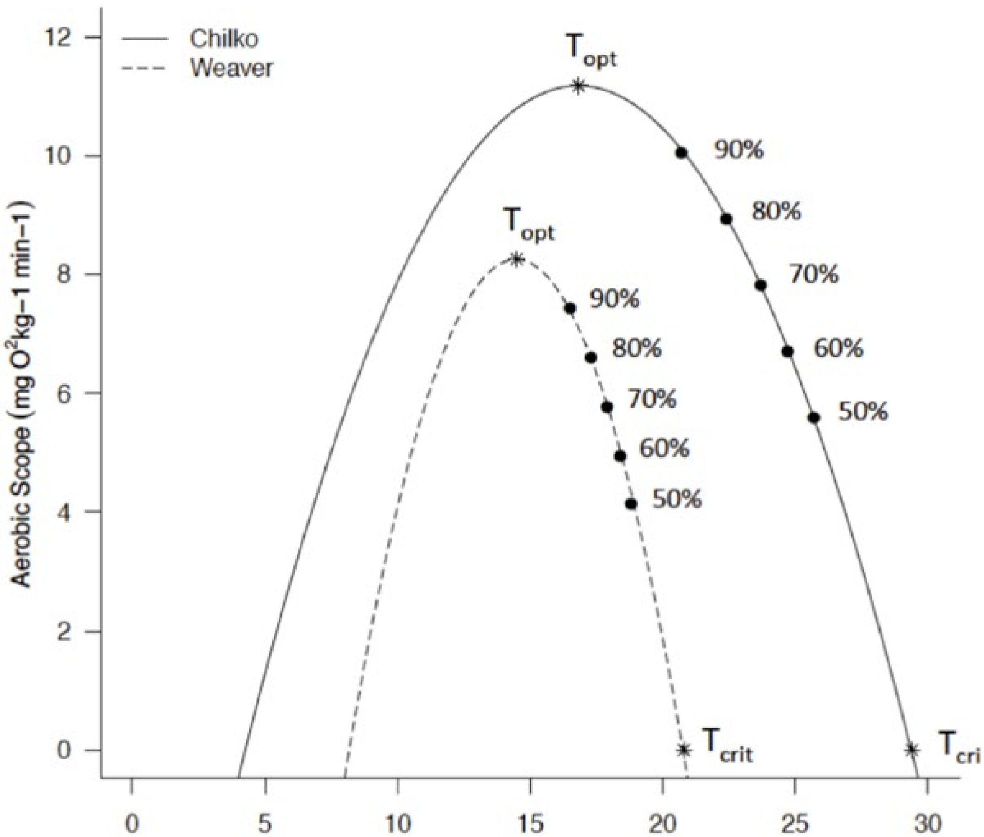
APPENDICES

Appendix A. Supplemental Figures

Appendix A. Supplemental Figures

LIST OF FIGURES

Figure 1. Aerobic scope as a function of temperature (°C) for Weaver Creek and Chilko Sockeye salmon populations, showing temperatures associated with 50 to 90% of maximum aerobic scope as well as optimal (T_{opt}) and critical (T_{crit}) temperatures. Recreated from data previously published in Lee *et al.* 2003[1] and Eliason *et al.* 2011[2].



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[2] Eliason, E.J., T.D. Clark, M.J. Hague, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, M.K. Gale, D.A Patterson, S.G. Hinch, and A.P Farrell. 2011. Differences in thermal tolerance among Sockeye Salmon stocks. Science 332: 109–12.

Figure 2. **Figures from Eliason *et al.* 2011[2] showing A) estimates of aerobic (colored lines), cardiac (black lines), and heart rate (gray lines) scopes for eight sockeye salmon populations in relation to water temperature, and B) map of the Fraser River and spawning locations of the eight sockeye salmon populations depicted in A.**