Ecofish Research Ltd.
Suite 101 - 2918 Eby Street
Terrace, B.C. V8G 2X5
Phone: 250-635-7364
info@ecofishresearch.com
www.ecofishresearch.com

MEMORANDUM

TO: **Nechako Water Engagement Initiative Technical Working Group**

FROM: **Rachel Chudnow, Ph.D., William Twardek, Ph.D., Bill Rublee, B.Sc., R.P.Bio., and Adam Lewis, M.Sc., R.P.Bio., Ecofish Research Ltd.**

DATE: **December 12, 2022**

FILE: **1316-09**

RE: **Issues #20 - 23 – Nechako River Salmon – Review of Flow Effects on Chinook Salmon**

1. INTRODUCTION

During Nechako Water Engagement initiative (WEI) Main Table and Technical Working Group (TWG) meetings, concerns were raised about potential effects of Rio Tinto (Alcan; RTA) operations on fish populations in the Nechako River. One priority is to better understand how changes in flow affect Chinook Salmon habitats in the Nechako River. The TWG asked Ecofish Research Ltd. (Ecofish) to review literature and summarize the status of current knowledge regarding Nechako River Chinook Salmon, with focus on informing how changes in flow may affect spawning and rearing habitats (i.e., issues #20 – #23) and develop recommendations for WEI consideration. This memo provides an overview of flow related impacts on Chinook Salmon throughout their freshwater life history and offers practicable recommendations to inform water management decisions and minimize the negative effects of operational flows on Chinook Salmon in the Nechako River.

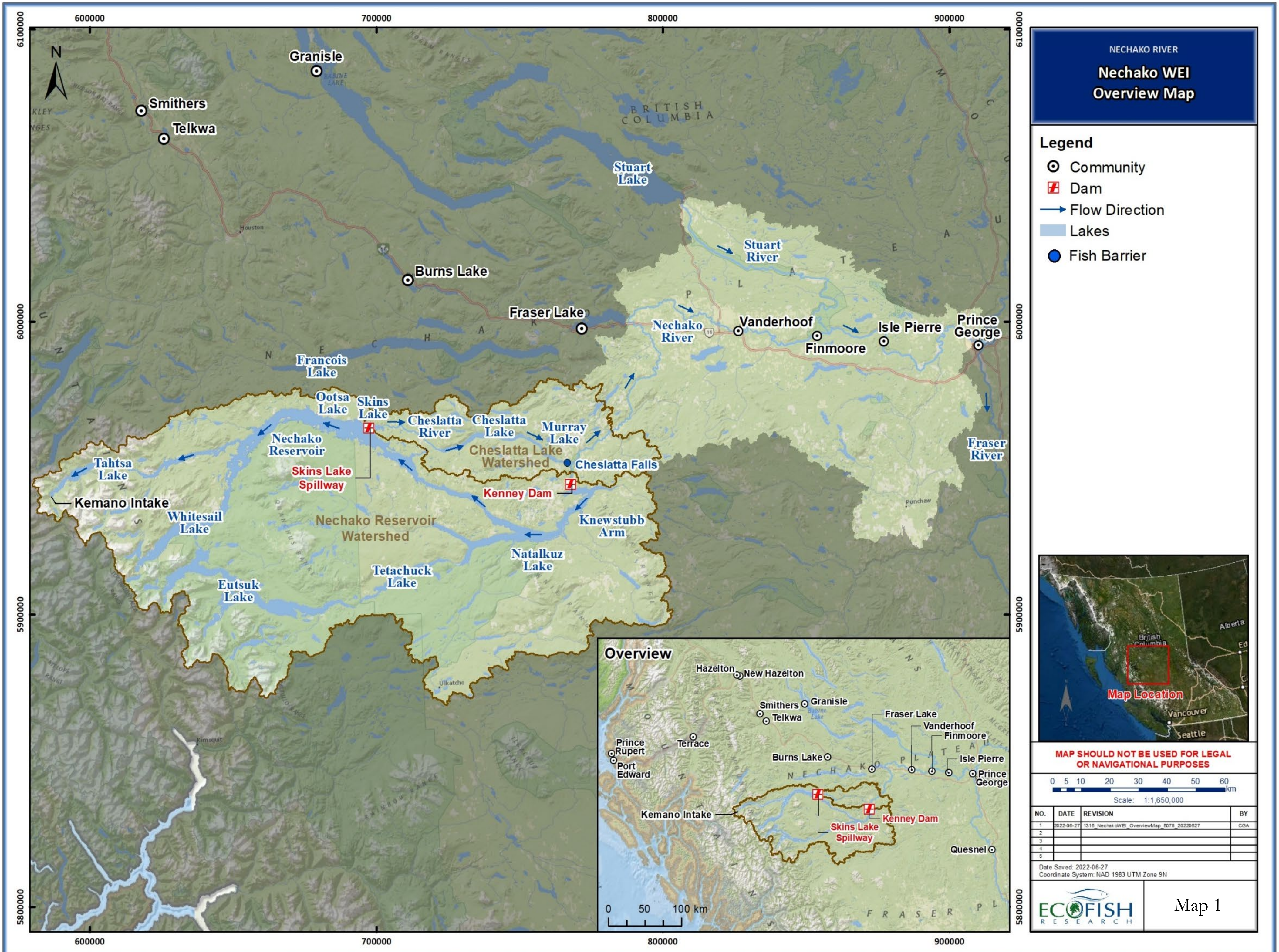
2. BACKGROUND

2.1. Geographic Scope

A hydrological overview of the Nechako watershed is provided by Beel *et al.* (2022), summarized here. The Nechako Reservoir is located approximately 200 km west of Prince George, British Columbia and was created to provide water for Rio Tinto Alcan's Kemano Hydroelectric Project, which was constructed in the 1950s to provide energy to operate an aluminium smelter in Kitimat, BC. The reservoir was formed by the construction of the Kenney Dam on the Nechako River (at the east end of the reservoir), which inundated a chain of six major lake and river systems (Ootsa, Whitesail, Knewstubb, Tetachuck, Natalkuz, and Tahtsa, ~420 km total length).

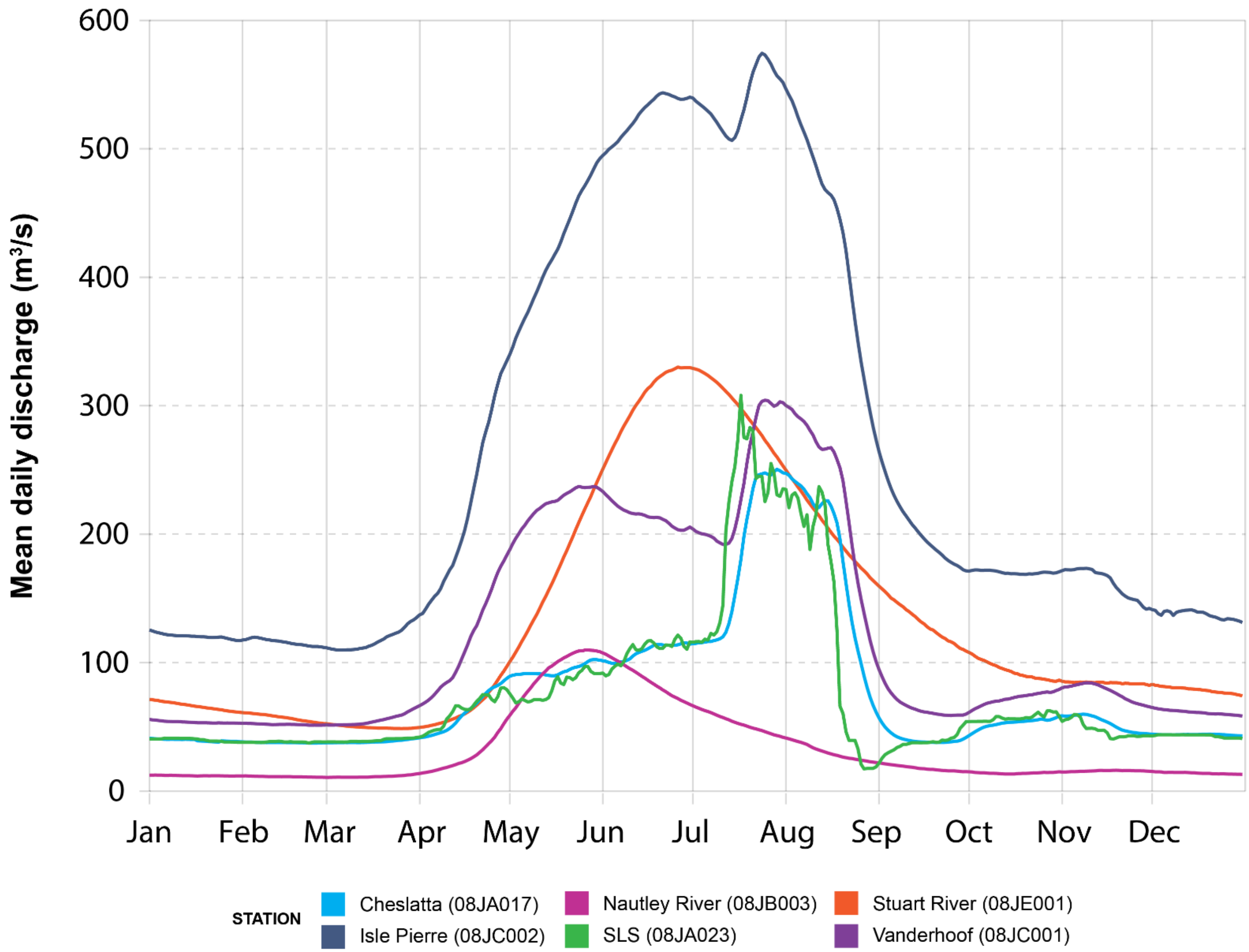
The Nechako Reservoir is ~910 km^2 with a normal annual drawdown of ~3 m (10 ft); low water is in late spring, and high water occurs in late summer. All flow from Nechako Reservoir to the Nechako River is currently via Skins Lake Spillway, which directs flow into the Cheslatta watershed, from where water flows into the Nechako River, downstream of Cheslatta Falls, located 9 km downstream of Kenney Dam (Map 1). The Nechako Reservoir provides the majority of flow in the upper

Nechako River (there is minimal local inflow); here, flow is reduced to ~30% of pre-dam conditions and mean flow ranges from ~40 to 240 m^3/s (Figure 1). The Nautley River (~95 km downstream of the dam) and local inflows together make moderate contributions and mean flow in the Nechako River at Vanderhoof (~150 km downstream of the dam) ranges from ~65 m^3/s to 270 m^3/s. The Stuart River contributes significant inflow and by Isle Pierre (~215 km downstream of the dam), mean flows range from ~120 m^3/s to 560 m^3/s. The Nechako River flows into the Fraser River at Prince George ~275 km downstream of the dam. The Nechako River has a hydrograph dominated by snowmelt with a summer freshet.



Path: M:\Projects-Active\1316\MXD\1316_NechakoWEI_OverviewMap_5078_20220627.mxd

Figure 1. Mean daily discharge during 1990 - 2020 at selected Nechako River monitoring stations.



2.2. Chinook Salmon Life History

Chinook Salmon, also commonly referred to as tyee, quinnat, king, or spring salmon, are one of North America's seven native anadromous and semelparous Pacific salmon (*Oncorhynchus spp.*) species (Healey 1991). The species demonstrates the general anadromous salmonid life history composed of six distinct life stages, a subset of which occur exclusively in freshwater or the marine environment (i.e., eggs, alevin, fry, smolt, adult, spawner; McPhail 2007). Chinook are unique among Pacific Salmon by demonstrating significant life history strategy diversity across all life stages, driven by both environmental conditions and genetics (Healey 1991; Quinn 2005; Brown *et al.* 2019; COSEWIC 2019). This diversity has resulted in substantial variation both between and within different populations, including those that use the same habitats. Notable variation surrounds the timing, duration, and habitat used during freshwater, estuarine, and ocean residency, the age at which individuals reach maturity, and spawning migration timing (Healey 1991; Waples *et al.* 2004; Brown *et al.* 2013). Population specific Chinook salmon life history patterns have historically been characterized by two distinct types (i.e., stream- and ocean-type, key differences between behaviour types presented in Table 1; Healey 1991; COSEWIC 2019). Today, it is generally accepted that individual population's behaviours vary from the stream- or ocean- archetypes and that instead, Chinook Salmon behaviour exists on a continuous spectrum. Nechako River Chinook Salmon are characterized as a stream-type population (Bradford 1994; COSEWIC 2019), and a discussion of each of the life history stages that use the Nechako River[1] are presented in Section 2.3 below.

[1] Note this memo excludes discussion of Chinook Salmon life history stages occurring outside the Nechako River (i.e., estuarine and ocean habitats).

Table 1. Life history variation between stream-type and ocean-type Chinook Salmon. Modified from Healey (1991).

Life Stage	Component	Characteristic	Behaviour Classification	
			Stream-type	Ocean-type
Juvenile (emergence to smolting)	Freshwater residency	Duration	1 year or more	< 1 year (generally within 3 months of emeregence)
		Individual variation in out-migration age	Years	Months
Adult	Ocean migration	Distance	Extensive	Limited
		Habitat	Offshore / open ocean	Near-shore / coastal
Spawner	Spawning migration	Run timing periodicity	Spring to summer (February - July)	Summer to winter (July - December)
		Migration distance	Longer (often to headwater tributaries)	Shorter
		Freshwater residency before spawning	Months	Days to weeks
	Spawning	Male precocity*	Present	Absent
		Age-at-maturity (Average, in years)	M: 3.7 - 5.6 F: 4.4 - 6.1	M: 3.0 - 3.9 F: 4.0 - 4.3
		Fecundity	High	Low

* A subset of males are freshwater residents that mature at age 1 (microjack) or age 2 (minijack) without making an ocean migration (Larsen *et al.* 2022).

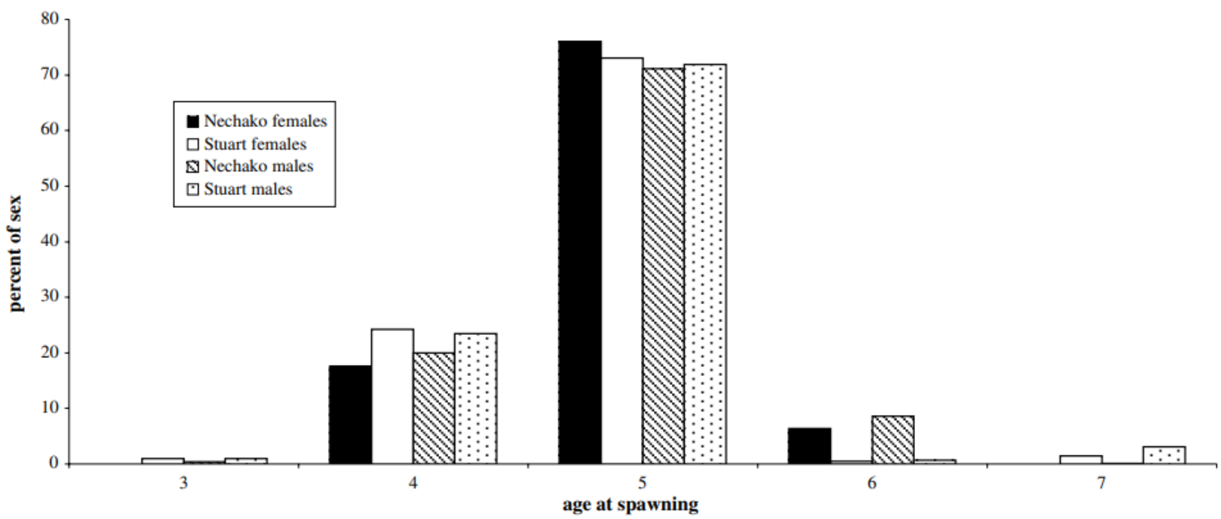
2.3. Life Stage Specific Nechako River Chinook Salmon Distribution and Habitat Use

Numerous population specific studies have characterized the temporal and spatial distribution and habitat use of Chinook life stages present within the Nechako River (i.e., alevin, fry, smolts, and spawners, summarized in Sections 2.3.1 and 2.3.2 below). Two distinct Chinook Salmon populations rely on the Nechako River for both juvenile and spawning life stages. The Stuart River (a major tributary of the Nechako River) population uses the Nechako River as a migratory corridor to spawning habitat in the Stuart River, whereas juveniles also use the lower Nechako River as rearing habitat and a migration corridor to the Fraser River and subsequently the ocean (Bradford and Taylor 1997; NFCP 2005). The Nechako River population spawns within the river mainstem upstream of Vanderhoof, with juvenile rearing occurring in the Nechako system or downstream within the mainstem Fraser River (NFCP 2005).

2.3.1. Spawners and Eggs

Chinook Salmon show significant variation in age at maturity[2], with 16 possible age classes identified (Brown *et al.* 2019). Most individuals reach sexual maturity between the ages 2+ to 6+ though a maximum age of 7+ has been recorded (Healey 1986, 1991; Quinn 2005; COSEWIC 2019). In the Nechako River, most individuals mature at age 5+ (73.1% of females and 65.8% of males; Figure 2; NFCP 2005).

Figure 2. Age composition of Nechako and Stuart River Chinook Salmon spawners, based on a combination of scale and fin ray analysis (resolved age), 1988 to 1998. Sourced from NFCP (2005).



Generally, Chinook Salmon spend two or three years in the ocean before returning to freshwater to spawn (Healey 1991), though individuals from the Nechako population typically remain in the ocean for four years prior to spawning (NFCP 2005). Males mature at younger average ages than females and in some populations, a proportion of males ("jacks") mature precociously at age 1+ to 3+ without leaving freshwater (Healey 1991; Quinn 2005; COSEWIC 2019; Koch *et al.* 2022). Early maturation can also occur in females ("jills"); however, the phenomenon is much less common than observed in males (COSEWIC 2019).

Chinook Salmon may return to their natal river mouth during almost any month of the year in preparation for spawning migrations (Snyder 1931; Rich 1942; Hallock *et al.* 1957). Stream-type Chinook adults generally return to spawn in freshwater earlier in the year than ocean-type populations

---

[2] It is important to note that age composition of spawners is not equivalent to the population's total maturation rate due to the loss of both immature and mature individuals to natural and anthropogenic sources (e.g., predation and fishing; Ricker 1980; Riddell 1986; Quinn 2005).

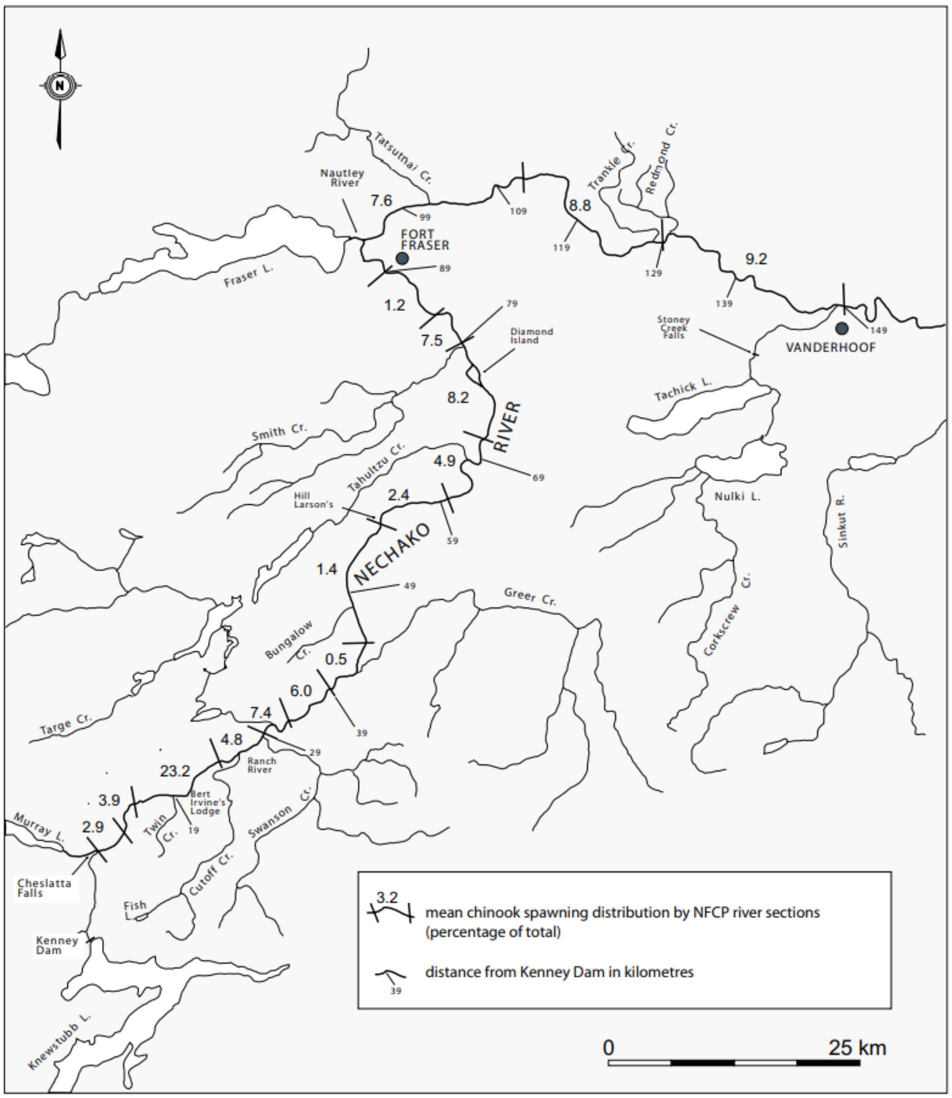
(see Table 1; Healey 1991; Ohlberger *et al.* 2018). Early entry allows these populations to take advantage of peak summer flows to reach spawning areas (Allen and Hassler 1986; Healey 1991). However, it also increases the energetic costs of ion balance maintenance in the osmotically rigorous freshwater environment and reduces feeding time in the ocean with little opportunity for feeding in the river (Healey 1991).

Typically, migratory activity peaks one to three times over the course of a year and the timing of, and number of migratory peaks varies both by river system and life history type (Rich 1925; Ball and Godfrey 1968). Northern populations (e.g., Kamchatka and Yukon rivers, Cook Inlet tributaries) are dominated by earlier runs (e.g., June peak with run extending from April to August; Yancey and Thorsteinson 1963; Vronskiy 1972; Brady 1983). Run timing occurs progressively later in more southern populations (e.g., peaks occurring from July to October; Slater 1963; Ball and Godfrey 1968; Fraser *et al.* 1982). Chinook migratory activity in the Fraser River is comprised of three migratory peaks; an early (i.e., July peak) and late run (September/October peak) that are similar in size with a third, smaller mid-summer run (i.e., August peak) (Ball and Godfrey 1968; Fraser *et al.* 1982). Nechako Chinook migrate into the Fraser River beginning in June and July and enter the Nechako River in August (Fraser *et al.* 1982; NFCP 2005). Spawning occurs from August through early October, with peak spawning in mid-September (Bradford 1994; NFCP 2005). Spawning habitat exists between Cheslatta Falls and Vanderhoof but most spawning typically occurs upstream of Fort Fraser and is most concentrated ~10 km downstream of Cheslatta Falls (Figure 3; NFCP 2005).

Spawning occurs in redds (i.e., gravel or cobble nests) which are constructed by females (Healey 1991). Within the redd, eggs are buried in the substrate in areas with moderate sub-gravel flow (Healey 1991). Females often dig multiple nests and deposit eggs over multiple spawning events, with successive events typically separated by several hours, or even days (Berejikian *et al.* 2000; Healey *et al.* 2003). In the Nechako River, spawning activity has been documented in water depths of 0.4 to 1.1 m and velocities of 0.30 to 1.05 m/sec over gravel substrate (i.e., mix of large and small gravel with <10% fines; (Envirocon Ltd. 1984; NFCP 1998c; NHC 2002). Individual fecundity is population-specific, varying by female size, latitude, and migration length (i.e., trade-off between the length of migration and gonadal investment; Healey and Heard 1984; Nicholas and Hankin 1988; Beacham and Murray 1993; McPhail 2007). Average Chinook Salmon fecundity has been assessed to range from 4,347 to 9,427 eggs with published egg counts ranging from less than 2,000 to over 17,000 eggs per female (Healey and Heard 1984; McPhail 2007). Fecundity of Nechako River Chinook Salmon ranges from 5,000 to 7,200 eggs/female (mean 5,769 eggs/female; Jaremovic and Rowland 1988). Chinook Salmon females generally deposit most of their eggs, although high levels of egg retention have been observed in some circumstances (Healey 1991; Bowerman *et al.* 2018; Twardek *et al.* 2022).

Eggs incubate in gravel over winter, with dissolved oxygen provided through sub-surface flows (McPhail 2007). During this period, eggs are subject to high mortality rates due to numerous factors including predation, disease, low egg quality, and/or unfavourable environmental conditions (e.g., high flows, siltation, freezing, desiccation; Healey 1991). Upon hatching, alevin[3] become mobile and move into the substrate (Healey 1991). The yolk sac is absorbed through winter with individuals leaving the gravel in spring as emergent fry (typically between early March and mid-May, Figure 4; NFCP 2005).

Figure 3. Nechako River Chinook Salmon spawner distribution. Black lines differentiate NFCP river sections and numbers represent the mean Chinook Salmon spawning distribution (as percentage of total) of each section. Sourced from NFCP (2005).



[3] i.e., Recently hatched, small fish with a yolk sac for food provision (McPhail 2007).

2.3.2. Rearing

Chinook Salmon demonstrate significant variation in the duration of their freshwater rearing period, and in the behaviours, they exhibit during this time. Early juvenile dispersal patterns vary both by and within systems, and juveniles can smolt[4] and out-migrate to the ocean at almost any time of year (Healey 1991; Bradford and Taylor 1997). In many stream-type populations, age 0+ juveniles out-migrate to the marine environment between the months of April and June, while in other populations, juveniles rear within freshwater habitats for their first year, undertaking a seaward out-migration at age 1+ (Healey 1987). Freshwater rearing can occur within natal streams, or individuals may make upstream or downstream movements to alternative non-natal habitats (Bourret *et al.* 2016).

Most[5] Nechako Chinook rear in freshwater their first year, emigrating to the marine environment at age 1+ (NFCP 1995, 2005). These individuals generally remain in the upper river until May (known as post-emergent fry), when they redistribute to alternative habitats in the Nechako River downstream (known as pre-migrant fry) prior to emigrating to alternative freshwater habitats in the mainstream Fraser River between June and July (known as migrant and post-migrant juveniles) (Healey 1987; Jenkins 1993a; NFCP 2005). A small proportion of the population remains within the Nechako River for their freshwater rearing period, emigrating as age 1+ individuals (estimated < 1.5% captured by electrofishing and <3% captured by rotary screw traps during 1989-1998; NFCP 2005).

2.3.2.1. Emergence and Post-emergent Fry

In unregulated systems, Chinook Salmon emergence generally corresponds with the spring freshet (Bradford 1994). The influx of flow provides fish access to suitable rearing habitats along stream margins and side channels with flooded vegetative cover (Murphy *et al.* 1989; Healey 1991; Bradford 1994; Brown *et al.* 2019). In the Nechako River, emergence occurs prior to the spring freshet in late April and early May (Figure 4; NFCP 2005; Bradford and Taylor 2021). Generally, emergence occurs earlier in the river's upper 20 km than further downstream due to a temperature gradient caused by reservoir releases (i.e., warmer water released from reservoir cools as it moves downstream; Bradford and Taylor 1997).

[4] Juveniles preparing for downstream migration and the transition to the marine environment undergo a series of physiological, behavioural, and morphological changes described as the 'smoltification process' or alternatively as 'smolting', or 'to smolt' (Healey 1991). The process corresponds to a period of downstream freshwater migration. The out-migration from freshwater rearing habitats occurs over days to weeks, but are dependent on fish length, flow, temperature, and migration length (e.g., smolts can travel rapidly downstream, up to 20-40 km/day; Healey 1991; Sykes *et al.* 2009).

[5] Greater than 99% of juveniles rear in freshwater until age 1+ (based on NFCP aging work; NFCP 1995, 2005).

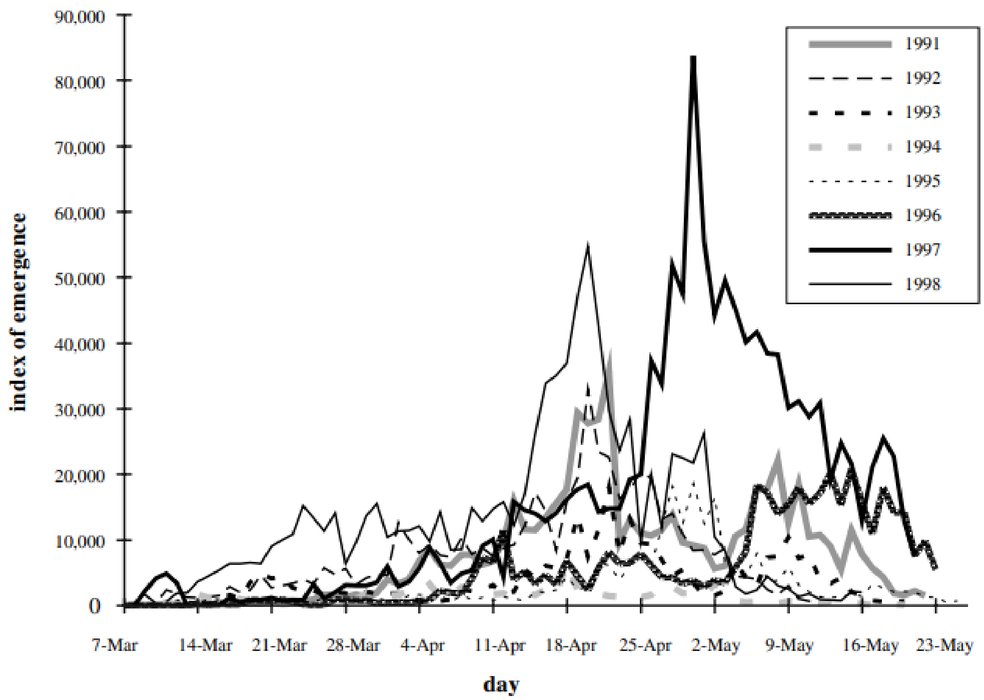
Immediately following emergence, Nechako Chinook disperse short distances to initial rearing habitats in the upper Nechako River where they remain for several weeks[6] (Envirocon Ltd. 1984; Healey 1987; Jenkins 1993a; Bradford and Taylor 1997). Individuals are generally strongly associated with river margins, but may also rear in available off-channel habitats or nearby tributaries (Envirocon Ltd. 1984; Healey 1987; Jenkins 1993a). This period of initial post-emergent juvenile residency contrasts that observed in the Stuart River, where freshet flows coincide with juvenile emergence. Here, individuals generally migrate significant distances immediately following emergence (i.e., 90-100 km; Bradford and Taylor 1997). Though previously thought to be solely flow driven passive downstream displacement, more recent literature suggests that initial post-emergent dispersal is active (Bradford and Taylor 2021). Drivers of its duration and where and when individuals take up residence are unknown but appear to be at least in part the result of density dependent mechanisms, in combination with flow regulation and the upper Nechako River's low gradient, which may lead to an abundance of low velocity near shore habitats for initial rearing (Lister and Walker 1966; Reimers 1968; Bradford and Taylor 1997).

Generally[7], newly emergent fry occupy near shore habitats characterized by low velocity (0 – 0.15 m/s; (Everest and Chapman 1972; Envirocon Ltd. 1984), shallow depth (0 – 0.5 m; Jenkins 1993a) near river margins and are often associated with vegetative cover (NFCP 2005). Highest fry densities are found along scalloped shorelines and side and back channels with lower fry densities commonly observed within 2-3 m of the wetted edge of lower gradient, straight, gravel shorelines (NFCP 2005). As fry grow and develop more competent swimming abilities (at ~45-50 mm length), individuals transition to deeper (≤ 4 m), higher velocity areas (0 – 0.5 m/s) with associated velocity refugia and cover during the day and shift toward nocturnal behaviour, foraging along river margins at night (Everest and Chapman 1972; Bovee 1982; NFCP 2005). This habitat use permits individuals to collect drifting food carried by the current while maintaining their position in the river and avoiding predation (Healey 1987).

[6] Juveniles observed during the summer dispersal period (i.e., June and July) are notably larger in size than observed in other similar populations (Rempel 2004; Bradford and Taylor 2021; NFCP 2022a). The later timing, and increased size of Nechako juveniles suggests that they rear and grow rapidly for a short period in the upper Nechako River before dispersing to habitats downstream in the lower Nechako and Fraser rivers (Bradford and Taylor 2021).

[7] Research conducted by the NFCP (see NFCP 20052005, 2022a; NFCP Technical Committee 2016) provided detailed assessments of rearing Chinook Salmon habitat in the Nechako River.

Figure 4. Daily index of Nechako River Chinook fry emergence at Bert Irvine's Lodge (19 rkm), 1991 to 1998. Sourced from NFCP (2005).



2.3.2.2. Pre-migrant and Migrant Juveniles

After several weeks, individuals redistribute from the upper river (upper ~80 km) to appropriate rearing habitats downstream (Figure 5; Envirocon Ltd. 1984; Bradford and Taylor 2021; Bradford *et al.* 2021). Most of these individuals exit the Nechako River and overwinter in the Fraser River before out-migrating to the ocean at age 1+ (Bradford and Taylor 2021). However, a small percentage[8] of individuals rear for one to two years in the Nechako River and associated tributary streams before smolting (Bradford 1994; NFCP 2005; Quinn 2005). Peak age 0+ dispersal from the upper river occurs between May and July (Envirocon Ltd. 1984; NFCP 2005), with maximum juvenile abundance in the Nechako River occurring in June (Bradford *et al.* 2021) and declining thereafter as the majority of age 0+ fish enter the Fraser River (Bradford and Taylor 2021; Bradford *et al.* 2021).

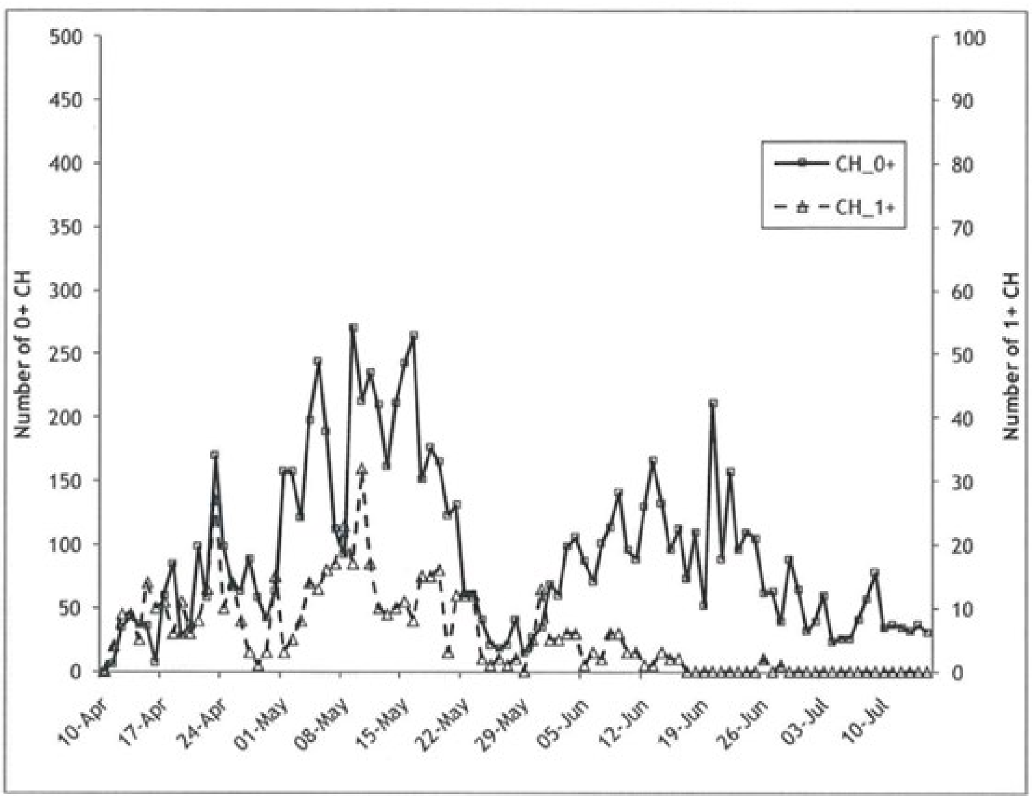
Drivers of individual dispersal are not well understood, and it is assumed that conditions required for successful rearing in spring, summer, and fall/winter seasons differ enough to necessitate the risk associated with undertaking large scale movements (Healey 1987; Bradford and Taylor 2021). The

[8] NFCP monitoring from 1989 to 1998 recorded age 1+ fish composing only 1.5% of electrofishing catches and <3% rotary screw trap catches (NFCP 2005).

Nechako River lacks some of the juvenile Chinook rearing habitat characteristics present in other river systems (e.g., complex instream cover; NFCP 1998a, 1998b; Beniston and Lister 2003). It is unclear if Nechako Chinook dispersal behavior is the result of the river's altered hydrograph as there is no historical information regarding juvenile dispersal timing prior to flow regulation (Bradford and Taylor 2021). However, in other populations, individuals dispersing in both summer and fall can make significant downstream movements from their previous residence locations to new, seasonally appropriate rearing habitats (Russell *et al.* 1983; Healey 1987).

During the day, pre-migrant juveniles are generally found in moderate to high velocity areas (i.e., high food delivery areas) with adjacent low velocity refugia and depth sufficient to avoid predation (Healey 1987). Temperature is also an important variable, with an appropriate thermal regime critical for continued growth (Healey 1987; Shelbourn *et al.* 1995). At night, individuals move and rest in lower velocity areas (Healey 1987).

Figure 5. Typical juvenile Nechako River Chinook Salmon dispersal pattern. The first node indicates post-emergent fry movement. Second node indicates older rearing juveniles leaving the upper river. Sourced from Triton Environmental Consultants Ltd (2010).



2.3.2.3. Post-migrant and Age 1+ Migrant Juveniles

Downstream dispersing Nechako Chinook Salmon juveniles rear in the Fraser River system during late summer, fall and winter, before out-migrating to the ocean as age 1+ fish the following spring (Envirocon Ltd. 1984; Bradford and Taylor 2021; Bradford *et al.* 2021). Summer rearing Nechako Chinook are common in both the mid and lower Fraser River mainstem, and Nechako juveniles are the only of five Fraser River tributary populations sampled found to migrate in June and July, timing coinciding with the Fraser River freshet flows (Rempel 2004; Bradford and Taylor 2021).

Only a small proportion of each age 0+ cohort remain in the Nechako River to overwinter each year (Bradford 1994; NFCP 2005; Quinn 2005). Early winter juvenile Nechako River Chinook monitoring has identified habitat use prior to ice formation (i.e., prior to ice formation in 1988 - 1990; Emmett 1989; Archipelago Marine Research Ltd. 1990; Emmett *et al.* 1992). Generally, during the day individuals were located in nearshore habitats with associated cover (i.e., shoreline or substrate cover) (Emmett 1989; Archipelago Marine Research Ltd. 1990; Emmett *et al.* 1992). At night, individuals were more active and most abundant in nearshore (< 4 m from shore), shallow (< 1 m), low velocity (< 15 cm/s) areas. Juveniles were most abundant in complex shoreline habitats including areas with shear zones, back eddies, scalloped shoreline, and near-shore cover (e.g., beaver lodges; Emmett 1989; Archipelago Marine Research Ltd. 1990; Emmett *et al.* 1992).

2.3.3. Population Structure and Conservation Status

Chinook Salmon populations in southern British Columbia are divided into 38 Conservation Units (CUs) / Wild Salmon Policy Conservation Units (CKs) (Brown *et al.* 2019). Nechako River Chinook are designated within the middle Fraser Summer 5_2 Conservation and Designatiable Units (CK-11/DU-10; COSEWIC 2019). Other spawning locations in this CU include the Bridge, lower Cariboo, Chilko, Endako, Kuzkwa, Quesnel, Seton, Stellako, and Stuart rivers and Kazchek Creek (DFO 2020a). All populations within the aggregate are dominated by 5-year-old spawners which have spent two full years in freshwater before migrating to the ocean and were assessed by COSEWIC (2019) as "Threatened".

2.4. Current Level of Knowledge

Nechako River Chinook abundance data are available as escapement estimates since the mid-1920s and the population has been well studied since the 1970s (Jaremovic and Rowland 1988; NFCP 2005; NFCP Technical Committee 2016; Levy 2020). Fisheries and Oceans Canada and collaborating consultants undertook numerous fisheries studies during the late 1970s and 1980s. Research related primarily to the Kemano hydroelectric project and Salmon Enhancement Program and focused on providing biophysical descriptions of the watershed, assessing the distribution and habitat use of juvenile and adult Chinook Salmon, and assessing past Chinook Salmon escapements (Jaremovic and Rowland 1988). This work ultimately formed the basis of the 1987 Settlement Agreement between the

Province of British Columbia, Government of Canada, and Rio Tinto (Alcan), and the establishment of the Nechako Fisheries Conservation Program (NFCP; NFCP 2005).

The NFCP mandate is to conserve Chinook and Sockeye Salmon within the Nechako River through physical and biological monitoring, ensure the annual "Conservation Goal"[9] is met, and to provide flow and summer water temperature (STMP) oversight and management (NFCP 2005, 2016). NFCP projects targeting Chinook Salmon can be grouped into three main areas: (1) Identifying stock performance and life history trends; (2) Assessing the status of in-river habitat and use of artificial and natural juvenile habitats; and (3) Applied research to fill knowledge gaps regarding Chinook Salmon in-river ecology. The bulk of NFCP directed work occurred prior to the cancelation of the Kemano Completion Project (KCP) in 1995 (NFCP Technical Committee 2016; NFCP 2022b). Following KCP cancelation, the NFCP has continued work in a reduced capacity to fulfill its mandate under the 1987 Settlement Agreement, with program and technical data review conclusions occurring in 2019, and an ongoing role in water allocation under the STMP (NFCP 2022b). Currently, Chinook Salmon monitoring is conducted by DFO stock management. Recent DFO and academic research external to Chinook Salmon escapement monitoring is limited primarily to the recovery potential assessment for Fraser River Chinook (DFO 2020b) and the recent work of Bradford and Taylor (2021) and Bradford *et al.* (2021).

Table 2 provides a high-level overview of work conducted under the tenure of the NFCP. Further information and relevant citations are available from NFCP (2005, 2022a) and NFCP Technical Committee (2016). The NFCP's work provides us with a strong background understanding of Nechako Chinook Salmon biology and the cause-and-effect relationships between physical and biological parameters impacting the population. Specifically, it clarified the ability of current flows to provide habitat and maintain productivity that would ensure conservation of Nechako Chinook Salmon. The use of detailed habitat assessments also clarified habitat preference for several life history stages and the efficacy of artificial habitats in supporting Chinook Salmon productivity (NFCP 2005). All NFCP work focused directly on its mandate surrounding the "Conservation Goal" and did not provide direct measures of habitat capacity within the Nechako River.

[9] *The "Conservation Goal" is defined as: … the conservation on a sustained basis of the target population of Nechako River Chinook salmon including both the spawning escapement and the harvest as referred to in paragraph 3.1 of the Summary Report….*(NFCP 2005).

Table 2. Summary of NFCP monitoring and research activities during the program's tenure. Information sourced from NFCP (2005).

Activity Type		Life Stage	Activity / Topic
Monitoring	Primary	Spawners	Escapement
			Female residence time
			Carcass recovery (enumeration, demographics, condition)
	Secondary	Juveniles	Fry emergence
			Out-migration
	Tertiary	Juveniles	Winter conditions
			Air & water temperature
			Discharge
			Dissolved oxygen
			Substrate composiiton
Remediation Studies			Artificial juvenile instream habitat
			Riparian bank stabilization
			Cheslatta watershed inflows
			Inorganic fertilization
			Sediment sources
			Flow management
			Riverbed survey / surface profiling
			Sand mapping
Applied Research		Juveniles	Pedator, competator, & prey interactions
			Winter habitat use
			Temperature effects (food & growth)
			Productivity limiting factors

3. METHODS

A literature review and data search were conducted to locate all known information on the influence of flow on Nechako River Chinook Salmon since the commencement of Kemano hydroelectric operations and flow releases through the Skins Lake Spillway. Specific efforts were undertaken to review British Columbia Utilities Commission (BCUC), Fisheries and Oceans Canada (DFO), Kemano Completion Project (KCP), Nechako Environmental Fund (NEEF), and Nechako Fisheries Conservation Program (NFCP) reports. Information was collected via online searches including Google, Google Scholar, federal government databases (e.g., CSAS, DFO 2021; Federal Science Libraries Network, DFO 2022), and organizational databases (e.g., NEEF 2022; NFCP 2022a; UNBC 2022), and review of scanned archival copies of government and organizational reports.

4. RESULTS

4.1. Overview of Potential Pathways of Effect

Chinook Salmon spawning, incubation, emergence, and rearing are greatly influenced by river flow (i.e., discharge), which has been called the 'master variable' for fish communities (Poff *et al.* 1997; Bergendorf 2002). Flow directly affects physical habitat through multiple mechanisms which govern the amount of physical space available for fish and their food and the quality of available habitats (i.e., by determining channel width, water depth, and velocity; Raleigh *et al.* 1986). The combination of water velocity and depth affect the 'fundamental ecological determinants' of temperature, dissolved oxygen, turbidity, and nutrient concentrations (Ryder and Kerr 1989). While in combination with meteorological conditions, flow also plays an important role in determining a river's winter hydrologic regime, contributing to ice formation processes and spring ice-break-up (Blachut 1988; Brown *et al.* 2011).

Temporal variation in flow is also a critical aspect shaping fish communities in riverine systems. Fish have evolved to natural variations in flow in ways that maximize their survival (Lytle and Poff 2004). Seasonal flow variation is also a defining factor in determining fish life history event timing, physiology, behaviour, and adaptations to local conditions. For example, seasonal flow patterns directly impact reproductive strategies, feeding, and growth, and ultimately play a role in individual survival (Bergendorf 2002).

Hydropower operations can alter the natural flow regime both in terms of the magnitude of water released and the timing of releases (Trussart *et al.* 2002). Although some hydroelectric facilities release constant flow year-round, variation is common. Further, even when hydroelectric flow release is constant, meteorological conditions and unregulated downstream inflows can impose flow variability (Blachut 1988; Davie and Mitrovic 2014). The time scale over which flow fluctuates also has important consequences for fish. Peaking plant operations may negatively impact fish habitat by stranding individuals or their food or by displacing them from preferred habitats, thereby reducing growth and/or survival. While the same change in flow magnitude occurring over a longer time period may have no negative effects on fish or fish habitat.

4.2. Identified Pathways of Effect

Here, we identify key pathways through which RTA operations could potentially effect Nechako River Chinook Salmon as the result of flow alteration. These can be summarized as flow-mediated changes to:

1. Hydraulically suitable habitat quality and availability;
2. Sediment input and flushing;
3. Temperature effects;

4. Dissolved oxygen effects;
5. Food availability;
6. Community structure;
7. Winter hydraulic regime; and
8. Access to tributaries and off-channel habitats.

In Sections 4.2.1 to 4.2.8 below, we discuss available evidence regarding the impacts of these threats/limiting factors.

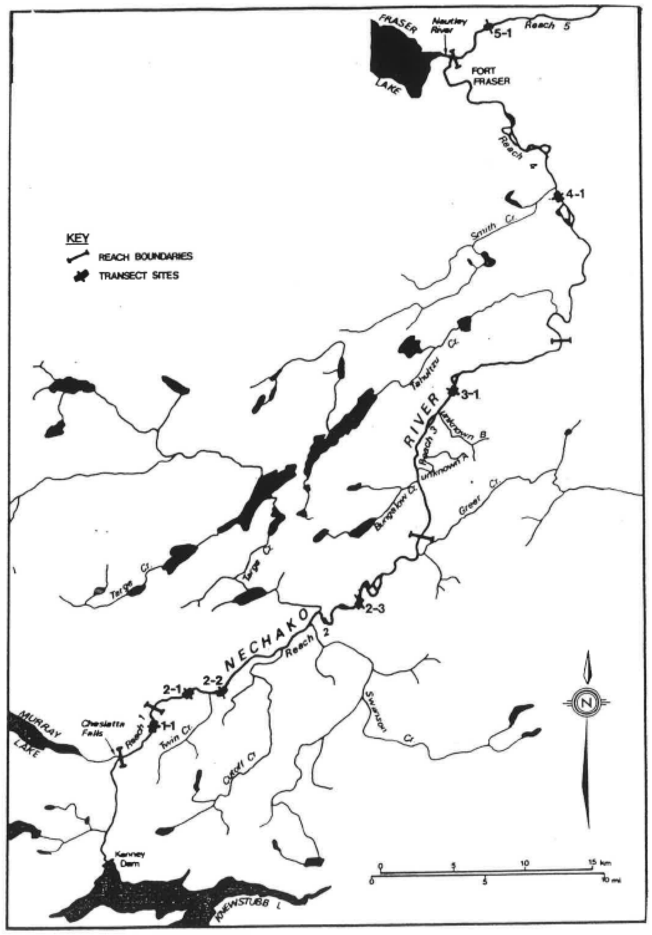
4.2.1. Hydraulically Suitable Habitat

Chinook Salmon tend to aggregate in optimal spawning habitats and compete for the 'best sites' (Healey 1991). When habitat is limited, Chinook Salmon spawning success may be compromised as the result of density-dependent mechanisms (Quinn *et al.* 2007). Although spawning site choices vary, spawning typically occurs over coarse gravel that will provide sufficient sub-surface flow to eggs (Healey 1991). In the Nechako River, spawning has been observed at a range of depths and velocities (Envirocon Ltd. 1984), and it is believed that flow releases influence spawner distributions (see Section 2.3.1; Bradford 1994).

Past decisions on Nechako River Chinook Salmon spawning habitat requirements were based on supporting a target population of 3100 individuals (1987 Settlement agreement; NFCP 2005). However, escapements over the past 40 years have demonstrated that the available habitat can support spawner returns exceeding 8,000 individuals. The 1984 Envirocon flow model (Jenkins 1993c; Mitchell 1993) estimated the relationship between flow and weighted usable area for spawning Chinook Salmon in the Nechako River for both a composite of Reaches 1 to Reach 5 and separately for Reach 2[10], the principal Chinook spawning habitat. This analysis found spawning habitat within the primary spawning reach (Reach 2; Figure 6) increased to a maximum at flows of approximately 50 m^3/s and decreased at higher flows. Later expert testimony by Healey (1987) as part of the DFO Expert Reports for the Nechako River Court Action suggested flows of 56.6 m^3/s in September would be required to flood spawning grounds and support Chinook Salmon fry rearing post hatch. NFCP carcass surveys provide further insight into Nechako River Chinook Salmon spawning habitat conditions over a range of flows, temperatures, and spawner abundances (surveys occurred from 1980 – 1998; NFCP 2005). Despite differences in spawning conditions, egg retention remained low across years, suggesting there was sufficient spawning habitat to accommodate all females across observed flows (retention rates ranging 0.02 – 5.18% total estimated fecundity; NFCP 2005).

[10] Reach 2 extends from approximately Twinn Creek at the upstream extent of the reach to approximately Greer Creek at the downstream extent of the reach.

Figure 6. **Location of test segments used within the 1984 Envirocon flow model. Sourced from Mitchell (1993).**



Nechako River Chinook Salmon egg incubation and hatching occurs over winter when annual flows are typically at their lowest (NFCP 2005), making these life stages a potentially sensitive period within the lifecycle. Low flows can compromise egg survival by reducing intra-gravel dissolved oxygen levels (discussed in Section 4.2.4) and by limiting the removal of waste products from redds (Bergendorf 2002), while habitat dewatering over fall or winter can result in egg desiccation or freezing (Bergendorf 2002). Although Chinook Salmon eggs can survive short periods of dewatering (Becker *et al.* 1982), chronic dewatering can result in high mortality rates (Harnish *et al.* 2014). In contrast, high flows can scour the streambed, which can expose eggs or alevins to predators or dislodge them from the substrate (Harvey and Lisle 1999). Envirocon estimates of intra-gravel water velocities in the Nechako River in 1980 – 81 ranged from 0.11 – 1.67 cm/s (average 0.70 ± 0.50 cm/s). This is higher than the threshold minimum value of 0.06 cm/s suggested by Bams and Simpson (1977) and comparable to velocities that have been demonstrated to result in 93.1 – 100% Chinook Salmon egg survival in a laboratory setting (Silver *et al.* 1963). Further, consistent incubation flows (ranging from ~30 – 40 m^3/s) likely limit dewatering and scour risk (Jenkins 1993a; NFCP 2005).

Juvenile Chinook Salmon are dependent on appropriate rearing habitats to facilitate their growth and survival (Nunn *et al.* 2012). However, the specific micro-habitat requirements for newly emergent and pre-migrant Chinook Salmon fry are complex and the causes of, and timing of fry dispersal events are uncertain. The interaction between flow and stream morphology is one of the fundamental factors determining the quantity and quality of rearing habitats (Raleigh *et al.* 1986). Low flows can decrease habitat quantity by reducing stream width or the wetted area of off-channel habitats or by reducing or eliminating connectivity between mainstem, tributary, and/or off-channel habitats. Together these factors can decrease a river's overall carrying capacity or decrease individual survival (Bergendorf 2002; Bradford and Taylor 2021).

Increased flow may also be an important mediator of juvenile fish survival during downstream dispersal periods. Increased flows can facilitate downstream movements, reducing dispersal or migration time (Raymond 1968; Thorpe and Morgan 1978; Berggren and Filardo 1993; Bergendorf 2002; Sykes *et al.* 2009; Sturrock *et al.* 2020). It can also result in increased turbidity which lowers predator efficiency, increasing survival (Gregory 1993). However, increased water velocity can also displace newly emerged fry due to their limited swimming ability. Loss of hydraulically suitable habitats can also modify juvenile behavior (e.g., see Bjornn 1971). Density dependent factors in combination with social factors (e.g., presence of aggressive, dominant individuals) may stimulate downstream movement of subordinate fish and ultimately negatively impact their survival (e.g., potential increased predation, lack of suitable habitat downstream; Lister and Walker 1966; Reimers 1968). Flow is also an important cue for the onset of juvenile out-migration and may also play a role in determining when migrations end (Sykes *et al.* 2009).

Multiple studies have characterized the relationship between juvenile Chinook Salmon rearing habitats and flow within the Nechako River (i.e., for post-emergent and pre-migrant juveniles; Envirocon Ltd. 1984; Hamilton 1987; Reid Crowther and Partners Ltd. 1987; Mitchell 1993). Two such investigations, measured multiple indices of juvenile Nechako Chinook spring and summer rearing habitat (i.e., wetted width, wetted area, side and back-channel length and area, and percent side channel flooded; Hamilton 1987; Reid Crowther and Partners Ltd. 1987). These studies found that across most indices measured (i.e., all those excluding length of some side channel habitat types) habitat quantity increased with increasing discharge to a maximum of the highest discharge level measured, approximately 163 m^3/s. Rate of habitat quantity increase was highest at low discharges, with rate of increase declining at flows exceeding 42.5 to 56.6 m^3/s (Hamilton 1987; Reid Crowther and Partners Ltd. 1987). At low flows, wetted cross-section decreased 23-44% (i.e., reduction from 56.5 to 14.2 m3/s; Hamilton 1987; Reid Crowther and Partners Ltd. 1987). This work also examined flow mediated impacts on off-channel habitat availability, discussed in Section 4.2.8 below.

4.2.2. River Geomorphology and Sediment Processes

Geomorphic changes, particularly to the sediment regime, are some of the most significant effects of flow regulation in the Nechako system (Neill 1987; Rood 1987). Flow diversion has led to significant levels of bank erosion in the Cheslatta River watershed and Nechako River, including two known avulsion events (i.e., major sediment erosion events; Hay and Company Consultants Inc. 2000; McAdam 2012). While flow regulation and decreased flow variation has limited the Nechako River's capacity to transport sediment (Neill 1987; Rood 1987). Together, these changes have resulted in significant increases in fine sediment throughout the river (Neill 1987; Rood 1987; McAdam *et al.* 2005; NHC 2015, 2016; Gateuille *et al.* 2019).

Increased sediment deposition in combination with resulting vegetative encroachment have narrowed the main river channel and led to losses of off-channel habitat connectivity (Neill 1987; Rood 1987; Johnson *et al.,* 2022a). Increases in fine sediment deposition and reduced sediment flushing can also decrease egg and alevin survival through entrapment or smothering (i.e., reductions or loss of intra-gravel flow decreasing both dissolved oxygen levels, discussed in Section 4.2.4 and metabolic waste flushing; Bergendorf 2002; NFCP 2005).

Several studies have assessed substrate composition at known Nechako River Chinook Salmon spawning and rearing sites (Jenkins 1993b; NFCP 1998c; Rood 1998; NHC 2002). This work found substrates to be comprised of low percentages of fines and that the amount of fines present has been relatively stable over time (Table 3). Given that Chinook Salmon fry percent emergence was estimated at 80 – 95% for substrate fine sediment proportions ranging from 0 – 10% (Reiser *et al.* 1985), it appears unlikely that sedimentation is a limiting factor impacting Chinook Salmon incubation or emergence in the Nechako River. However, the impact of increased sedimentation in rearing habitats, particularly relating to fish access to tributary habitats remains an uncertainty at this time.

Table 3. Percentages of fine sediment within known Chinook Salmon spawning, incubation, and post-emergent fry rearing habitats.

Year	River Section	rKm(s)	Fines (< 2mm)*		Source
			Surface Layer	Sub-Surface Layer	
1980	Reach 2	N/A	3.00 ± 2.90	N/A	Jenkins (1993b)
1989 - 1990	Reach 2	19.3	7.45 ± 5.56	17.59 ± 8.40	Rood (1998)
1990 - 1991	Reach 2	19	9.40	N/A	NFCP (1998c)
1992, 2000	Reach 2	15 - 40	9.16 ± 7.35	17.51 ± 5.29	NHC (2002)
	Reach 4	72 - 89	9.67 ± 6.32	17.01 ± 7.35	

N/A = Not available

* As mean proporation (%) ± standard devation

4.2.3. Altered Thermal Regime

One priority identified during the WEI process is to better understand how RTA operations affect salmon through temperature effects in the Nechako River (i.e., issues 18 and 19). As a result, this topic is given specific consideration in Carter and Kurtz (2022), which should be referred to for a detailed discussion.

In summary, flow is closely associated with temperature, a "master" variable influencing fish physiology (Brett and Groves 1979). Air temperature is a primary driver of water temperature. At low flows, river volume and subsequent thermal buffering of air temperature is reduced. This results in increased water temperature variation towards observed air temperatures as flow moves from a release point (such as Skins Lake spillway; Caissie 2006). Typically, in spring and summer, lower flow results in higher water temperature. While in fall and winter, low flows may lead to quicker cooling and may increase ice formation (discussed in Section 4.2.7; Faulkner *et al.* 2011). Temperature governs the rate of metabolic processes, influencing egg and juvenile development (Allen and Hassler 1986; Carter and Kurtz 2022). Across life stages, when water approaches Chinook Salmon's upper temperature limit, individuals can succumb to thermal stress and elevated mortality (Brett *et al.* 1982; Bowerman *et al.* 2018; von Biela *et al.* 2020).

Temperature also influences individual behaviour (e.g., migration or dispersal timing; Bergendorf 2002; Keefer *et al.* 2018; Carter and Kurtz 2022). Bradford (1994) suggested the proportion of Chinook Salmon spawning in the upper Nechako River was negatively correlated with flow magnitude. He hypothesized that during low flows, there was insufficient water to effectively cool the lower Nechako River, such that salmon would seek out spawning opportunities in the upper river where water was presumably cooler. Bradford (1994) also suggested juvenile Chinook survival throughout the river was lower when more fish spawned in the upper river. One hypothesis explaining this trend was that warmer fall and winter water temperatures could result in early emergence. More recent data collected through in-river monitoring throughout the period of record for the NFCP has not detected such a trend and available data[11] suggest temperatures are appropriate for spawning, incubation, and fry emergence (NFCP 2005; NFCP Technical Committee 2015).

4.2.4. Dissolved Oxygen

Appropriate intra-gravel and sub-surface dissolved oxygen levels are required for successful Chinook spawning, egg incubation, and juvenile rearing. In general, females bury eggs in gravel at depths ranging from 10-33 cm, with intra-gravel flows providing oxygen during incubation (Chapman *et al.* 1986). Chinook Salmon eggs have a small surface-to-volume ratio and are the largest of all Pacific salmon eggs (Raleigh *et al.* 1986; Healey 1991). Therefore, high intra-gravel flow and dissolved oxygen concentrations are critical for egg survival (Raleigh *et al.* 1986; Healey 1991). It has been estimated that dissolved oxygen concentrations below 2.5 mg/L can increase egg mortality (Bergendorf 2002) with evidence that concentrations of approximately 8 mg/L are necessary for high egg survival (Reiser *et al.* 1985).

Intra-gravel dissolved oxygen levels were measured in Nechako River Chinook Salmon redds in 1980 – 1981 at constant river discharge of approximately 38 m^3/s (Envirocon Ltd. 1984). This work found intra-gravel dissolved oxygen levels ranged from 7.5 – 11.4 mg/L and resulted in high estimates of egg-to-fry survival (i.e., 37 – 50% survival; Envirocon Ltd. 1984). More recent work on dissolved oxygen in the Nechako River was initiated by the NFCP as part of targeted monitoring in support of the proposed KCP. This work aimed to monitor for changes in dissolved oxygen concentrations in active Chinook Salmon redds as a result of a reduced flow regime (NFCP 2005). The project was abandoned following the cancellation of the KCP because it did not fall within the NFCP Technical Committee's mandate (NFCP 2005).

Low sub-surface dissolved oxygen levels have also been found to modify spawning and juvenile Chinook behavior. It has been estimated that spawners will cease upstream migrations if water column dissolved oxygen concentrations fall below 3.4 mg/L (Alabaster 1969), while juveniles have been found to avoid areas with water column dissolved oxygen concentrations below 4.5 mg/L (Whitmore *et al.* 1960). Surface dissolved oxygen levels were measured in Nechako River Chinook Salmon redds in 1980 – 1981 at constant river discharge of approximately 38 m^3/s (Envirocon Ltd. 1984). This work found dissolved oxygen concentrations did not vary significantly across depths measured, averaging approximately 10.2 ± 1.6 mg/L, with oxygen saturation ranging from 86.1 – 106.5% (measurements at 15, 30, and 45 cm; Envirocon Ltd. 1984). Therefore, available evidence suggests dissolved oxygen concentrations are not likely limiting spawning, egg survival. or

[11] For example, low egg retention rates observed in annual carcass surveys suggested that thermal conditions were not sufficiently stressful to influence female spawning ability.

rearing Chinook Salmon given previously recorded concentrations in the Nechako River (NFCP 2005).

4.2.5. Food Availability

The only Chinook Salmon life stage feeding within the Nechako River are juveniles (i.e., post emergent fry to out-migrating age 0+ and age 1+ fish), which are highly reliant on aquatic invertebrate prey (Envirocon Ltd. 1984; McPhail 2007). The effects of flow regulation on invertebrate communities has been well studied (e.g., Envirocon Ltd. 1984; Dewson *et al.* 2007; Bilotta *et al.* 2017; Rosero-López *et al.* 2020). Many of the mechanisms impacting aquatic invertebrates mirror those impacting the fish community (i.e., presence of hydraulically suitable habitat, sedimentation, thermal regime, dissolved oxygen levels, food availability, and icing processes; Envirocon Ltd. 1984). Habitat alteration as a result of these factors can modify invertebrate species composition, distribution, relative abundance, and individual size (Minshall and Winger 1968; Envirocon Ltd. 1984; Ward and Stanford 1987; Caldwell *et al.* 2018). This directly effects overall food availability and the abundance of preferred prey for aquatics species including Chinook Salmon and has the potential to result in decreased individual growth, increased intra- and inter-species competition, displacement, and increase predation risk due to prolonged prey search periods (Hilborn and Walters 1992). All these factors could ultimately reduce juvenile Chinook Salmon growth and survival, affecting overall production.

Johnson *et al.* (2022b) investigated the relationship between flow and productivity in the Nechako River but was unable to quantify how flow affects benthic invertebrates and their habitat. Given the aforementioned uncertainty, it appears rearing conditions for Nechako River Chinook Salmon have been relatively stable over time, given lack of variation in out-migrating juvenile Chinook Salmon size, growth, and condition factor as measured over a multi-year period as part of the NFCP Juvenile Chinook Out-Migration Project (NFCP 2005).

4.2.6. Community Structure

Altered stream flow as the result of flow regulation can cause complex changes within ecological communities (Bruce 1991; NFCP 2005). Bruce (1991) identified multiple flow-mediated mechanisms that could change competitive interactions or predation encountered by Nechako River Chinook including:

1. Changes in Chinook Salmon social behavior (discussed in Section 4.2.1);
2. Overcrowding as a result of changes to habitat quantity and quality;
3. Shifts in species' spatial and temporal distribution; and
4. Temperature mediated impacts on fish physiology resulting in shifts in competitive, predatory, or predator avoidance ability.

The NFCP conducted research on predatory and competitive interactions between Chinook Salmon and both fish and avian species in the early 1990s (Bruce 1991; Brown *et al.* 1994; Brown 1995; NFCP 2005). Of the 19 resident fish species found in the Nechako River, six were identified as Chinook Salmon predators with six additional species identified as potential predators (Table 4; Bruce 1991; NFCP 2005). Three species were identified as potential competitors based on research in other systems, while no literature support regarding potential competitive interactions between Chinook Salmon and the remaining 15 species were identified (Bruce 1991). Further, an ornithological survey of the Nechako River by Brown *et al.* (1995) identified nine of 49 species as piscivores. Of these, herring gulls and mergansers were identified as the largest threat to Chinook Salmon (Brown *et al.* 1995; NFCP 2005).

Table 4. Known and predicted Nechako River species with competitive and/or predatory relationships with Chinook Salmon*.

Family	Common Name	Scientific Name	Interaction
Minnows	Northern Pikeminnow	*Ptychocheilus oregonensis*	Predator
	Redside Shiner	*Richardsonius balteatus*	Competitor & Predator
Salmonids	Bull Trout	*Salvelinus confluentus*	Predator (Chudnow 2021)
	Rainbow Trout	*Oncorhynchus mykiss*	Competitor† & Predator
Sculpins	e.g., Prickly & Slimy Sculpin	*Cottus spp.*	Predator
Sturgeon	White Sturgeon	*Acipenser transmontanus*	Predator
Suckers	e.g., largescale, longnose, & white sucker)	*Catostomus spp.*	Competitior

* Interation information sourced from Bruce (1991) except where noted

† Tributary rearing individuals only

No directed research has been conducted in the Nechako River to date that has explored if, or how, known interactions between Chinook Salmon and the species identified above have been modified by flow regulation. However, expert opinion by Slaney (1987) suggested that lower discharge would decrease velocity and increase water temperature, to the benefit of many non-salmonid resident species (e.g., minnows, sculpins, and suckers). It is possible that flow regulation could result in an increase in the abundance of these species, increasing the potential for competition or predation to the detriment of the Chinook Salmon population. However, the likelihood and extent of such a shift in community structure is unknown.

4.2.7. Icing Processes

Both meteorological and flow regimes can be important factors contributing to Chinook Salmon overwinter survival due to their impact on ice formation processes within the river. Only incubating eggs and post-emergent fry are present in the Nechako River during periods when ice is present (icing is highly variable and ice coverage generally occurs between approximately October and early May annually; Blachut 1988; NFCP 2005). Therefore, the following discussion is limited to consideration of these life stages.

Eggs require suitable physical habitat conditions for successful incubation while rearing juveniles are reliant on adequate overwintering habitats to minimize energy expenditure, avoid adverse environmental conditions, and decrease the likelihood of predation (Raleigh *et al.* 1984; Brown *et al.* 2011). Decreased early winter flows can lead to quicker cooling and more severe ice formation (e.g., earlier and thicker formations of surface, frazil, and anchor ice which extend further distances upstream) (Blachut 1988; Faulkner *et al.* 2011; Brown *et al.* 2011). Together, these ice formation processes can negatively impact egg development and juvenile rearing through various mechanisms including modified water velocity, reduced or absent intra-substrate flow, streamflow diversion, habitat fragmentation, substrate freezing; and substrate scour, topics that are detailed in Blachut (1988); Faulkner *et al.* (2011); Brown *et al.* (2011), and summarized below.

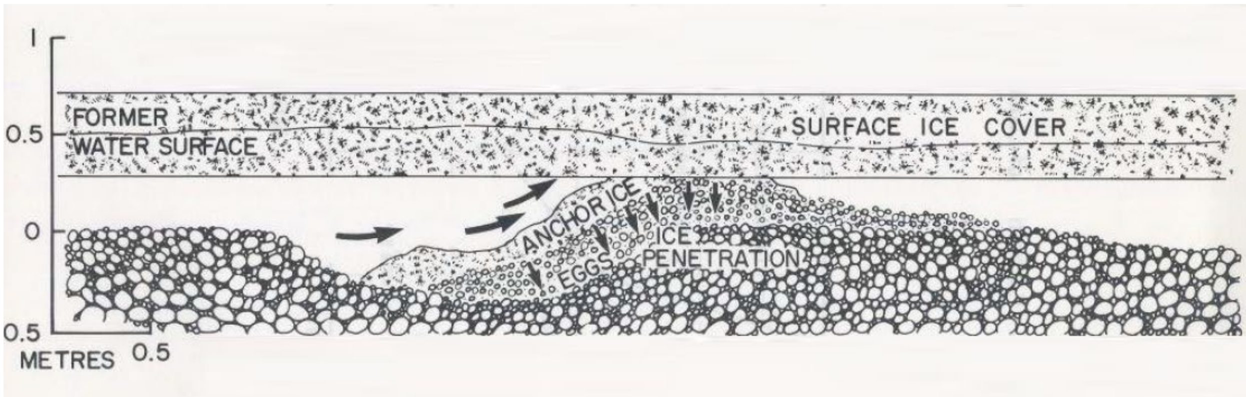
Ice formations can modify water velocity, a critical attribute of microhabitats, in multiple ways. Ice penetration into the water column can increase water velocities in adjacent open water areas or increase near-bed velocities resulting in fish avoidance or displacement (e.g., anchor ice, hanging dams, ice jams; Brown *et al.* 2000; Lindstrom and Hubert 2004). Anchor ice and surface ice formations can also decrease sub-surface water velocities or result in loss of flow, preventing intra-substrate water exchange (Blachut 1988). This decreases intra-substrate dissolved oxygen concentrations and increases waste accumulation in redds, decreasing egg survival (Healey 1987; Blachut 1988).

Several icing processes[12] can also result in habitat fragmentation or habitat loss due to the physical presence of ice structures within the water column or if ice formations upstream divert flow away from specific habitats (e.g., redds, shore zones, and off-channel habitats; Maciolek and Needham 1952; Blachut 1988; Brown *et al.* 2011). This can have several effects including: Redd dewatering (Healey 1987; Blachut 1988; Faulkner *et al.* 2011; Brown *et al.* 2011), loss of fish access to suitable overwintering habitats, or fish stranding (Maciolek and Needham 1952; Brown *et al.* 2011), all of which decrease overwinter survival (Cunjak 1996; Brown *et al.* 2000; Faulkner *et al.* 2011). Fish can also become isolated in pockets of open water (Brown *et al.* 2011) and subject to increased mortality due to freezing or high predation rates in spring, prior to complete ice break-up (Brown *et al.* 2000; Faulkner *et al.* 2011). Ice emergence above the water's surface can also permit frost penetration to the streambed and subsequent substrate freezing, which can result in high levels of egg mortality (Figure 7; Reiser and Wesche 1979; Walsh and Calkins 1986). While spring ice

[12] Examples of icing process that can lead to such impacts include surface ice contact with substrate, anchor ice formation extending from the streambed to underside of surface ice cover, hanging dams, and ice jams.

break up can result in substantial levels of substrate ice scour which can displace alevin and fry from rearing habitats (Healey 1987).

Figure 7. Schematic representation of ice penetration within a salmon redd as the result of surface and anchor ice formation. Flow direction is indicated by large arrows while direction of ice penetration is indicated by small arrows. Sourced from Blachut (1988).



Winter temperatures[13] and ice formation and distribution[14] have been recorded in the Nechako River over multiple decades (Blachut 1986a, 1986b, 1987, 1988; Blachut and Bams 1987; Faulkner 1994, 1999; Faulkner and Ennevor 1999; Wilkins and Faulkner 1999a, 1999b, 1999c; NFCP (Nechako Fisheries Conservation Program) 2005 p. 2005). However, this literature review was only able to identify Nechako River specific winter icing conditions data for the period of 1980 – 1996, and no contemporary information on surface or anchor ice formation was located.

Generally, the river has solid ice cover over a five-month period (as recorded at Vanderhoof; Blachut 1988). The date of freeze-up is highly variable, but generally occurs between October and January (Blachut 1988). Flow regulation generally prevents spring freshet driven ice-break up (NFCP 2005). Instead, ice break-up is slow with patchy melting along the river's length as ice "rots" in place with rising air and water temperatures (NFCP 2005). Shore ice is the last type of formation to melt in spring (NFCP 2005). Ice conditions in the upper river are highly variable and dependent on both reservoir discharge and meteorological conditions (Blachut 1988). Solid surface ice formation has been estimated to extend upstream to approximately 29 rkm below Cheslatta Falls (Blachut 1988;

---

[13] Water and air temperatures sourced from Water Survey of Canada stations at Bert Irvine's Lodge and Vanderhoof (Blachut 1988; NFCP 2005).

[14] A combination of aerial (1975 – 1996) and satellite photography (various dates between 1972 – 1985) and land-based observations (1975 – 1996) (Blachut 1986a, 1986b, 1987, 1988; Blachut and Bams 1987; Faulkner 1994, 1999; Faulkner and Ennevor 1999; Wilkins and Faulkner 1999a, 1999b; NFCP 2005).

NFCP 2005). Modeling of the winter regime under combinations of alternative flows and air temperature by Blachut (1988) suggested surface ice would extend further upstream at flows of 10.6 m^3/s vs. 31.1 m^3/s and that during severe winters, surface ice would likely encroach on a major spawning area at 10.6 m^3/s.

Extensive anchor ice formation has been documented throughout the upper and middle Nechako River, extending at least from 25 rkm upstream to 70 rkm (i.e., Diamond Island downstream; Blachut 1986a). Anchor ice within the river was described by Blachut (1988) as:

> *"Blanketing the streambed for several kilometres… emergent at the water surface, and attached to the underside of surface ice cover"* (at discharges of 30-35 m^3/s).

In the upper river, anchor ice was found to exceed 30 cm thickness, filling most of the free water space and limiting available shallow, nearshore habitats (Blachut 1986b). Several investigations have also documented anchor ice deposition occurring preferentially on Chinook redds (Tutty 1980; Blachut 1986a, 1986b, 1988). Surface and anchor ice have been observed to result in redd dewatering and to lead to substrate freezing in natural and artificially constructed redds located within the upper river (i.e., frost penetration into redds documented to depths of 20-30 cm; Tutty 1980; Johansen 1985; Jaremovic and Johansen 1986; and 1 m, Blachut 1988). Significant reductions in subsurface water velocity have also been observed in shallow nearshore areas at Diamond Island (Blachut 1988). While shore ice (≤ 25 cm thickness) has been observed extending to the substrate with no evidence of subsurface flow and evidence of nearshore scour (Blachut 1988).

Despite available evidence outlined above, winter ice conditions have not been implicated in the literature as a factor limiting Nechako Chinook productivity (Bradford 1994; NFCP 2005; Brown *et al.* 2013; Levy and Nicklin 2018; COSEWIC 2019; Levy 2020) or expert opinion (Rublee, pers. comm. 2022). Evidence that rearing habitats and incubation conditions in the Nechako River have been stable over time (see Section 4.2.1; Rood 1987; NFCP 2005; Levy 2020) provide further evidence that winter conditions are not a limiting factor for Chinook Salmon productivity, however the effect of icing processes on the population remains uncertain.

4.2.8. Loss of Fish Access to Tributary and Off-channel Habitat

A priority identified during the WEI process is to better understand how RTA operations affect fish access to tributary and off-channel habitats (i.e., issues 18 and 19). As a result, this topic is given specific consideration in Johnson *et al.* (2022a), which should be referred to for a detailed discussion. In summary, alteration of Nechako River flows has likely influenced river connectivity with tributary and off-channel habitats as well as modified habitat availability within off-channel habitats. This could occur as the result of multiple mechanisms:

1. Loss of lateral connectivity as the result of reduced flows, sedimentation, debris deposition, or vegetative encroachment;

2. Fish passage blockages as the result of debris deposition; or
3. Reduced off-channel habitat quantity as the result of reduced flows.

Information on fish access to Nechako River tributaries is limited (i.e., few streams investigated over a relatively short temporal window within the mid-1980s and late 1990s; Tredger *et al.* 1985; ARC Environmental Ltd. 1998). Flow mediated impacts to off-channel habitat availability have also been the subject of preliminary investigations (Hamilton 1987; Reid Crowther and Partners Ltd. 1987). This work found available off-channel habitat declined with decreased discharge. Specifically, off-channel wetted area decreased 22.5 – 72.8% with discharge reduction from 56.6 to 30.0 m^3/s, while higher flows inundated and provided fish access to off-channel habitats, until flow levels reached a point at which they 'flooded out' (Hamilton 1987; Reid Crowther and Partners Ltd. 1987). Literature review was unable to identify any work examining fish access to off-channel habitats. As a result, the impact of flow regulation on fish access to tributary and off-channel habitats remains uncertain.

5. DISCUSSION

5.1. Potential Limiting Factors and Associated Uncertainties

Eight potential pathways of effect have been identified (summarized below, see Section 4.2) that relate to the potential for flow-related factors to impact Nechako River Chinook Salmon. Each pathway is summarized separately, although interactions and trade-offs between the pathways should be considered when evaluating flow scenarios. Available evidence collated throughout this memo suggests that none of the eight pathways are limiting factors under the current flow regime. However, several could plausibly become limiting factors under an alternative flow regime and are therefore important considerations during the assessment of alternative flow scenarios.

- ***Hydraulically suitable habitat*** – Flow regulation can modify the quantity and quality of habitats important to all Chinook Salmon life stages present within the Nechako River. Changes in habitat quantity and quality impact Chinook Salmon by modifying individual spawning success, behaviour, growth, or survival or by modifying habitat carrying capacity (Raleigh *et al.* 1986; Healey 1991; Bergendorf 2002; Sturrock *et al.* 2020). The relationship between flow and mainstem habitat quantity and quality has been explored extensively within the Nechako River (Envirocon Ltd. 1984; Hamilton 1987; Healey 1987; Reid Crowther and Partners Ltd. 1987; Mitchell 1993). Available evidence suggests that in-river productivity is not limiting under the current flow regime and that spawning and rearing habitat conditions within the Nechako River mainstem have been relatively stable through time (NFCP 2005). Less information is available regarding the impacts of flow regulation on the quantity and quality of hydrologically suitable off-channel habitats, which appear to be less important to juvenile rearing than mainstem margins.

- ***River geomorphology and sediment processes*** – Flow diversion and regulation have significantly modified geomorphic and sediment transport processes within the Nechako system (Neill 1987; Rood 1987). Flow diversion has resulted in significant erosion (McAdam 2012), while flow regulation has decreased the Nechako River's capacity to transport sediment, resulting in increased fine sediment deposition within the river (Neill 1987; Rood 1987; NHC 2016; Gateuille *et al.* 2019). Though geomorphic and sediment processes have been identified as potentially critical limiting factors impacting Nechako River White Sturgeon habitat (discussed further in Chudnow *et al.* 2022a), they have not been implicated as factors limiting Nechako River Chinook Salmon production (Brown *et al.* 2013; Levy and Nicklin 2018; COSEWIC 2019; Levy 2020). Available evidence suggests fine sediment levels in spawning and incubation habitats is low and has been stable over time (Jenkins 1993b; NFCP 1998c, 2005; Rood 1998; NHC 2002). There is significantly more uncertainty surrounding the role of sedimentation processes and resulting vegetative encroachment on juvenile rearing habitats, specifically in off-channel habitats (discussed below).
- ***Altered thermal regime*** – All life stages of Chinook Salmon present within the Nechako River are sensitive to changes in water temperature which in turn, can be impacted by factors including flow. Lower flows have the potential to increase water temperatures during the growing season (Carter and Kurtz 2022). Operational flow scenarios that increase water temperatures may cause adverse physiological and behavioural effects to migrating, spawning, and rearing salmon (Brett *et al.* 1982; Bergendorf 2002; Bowerman *et al.* 2018; Keefer *et al.* 2018; von Biela *et al.* 2020). These considerations are addressed in another memo (Carter and Kurtz 2022), and therefore, are not considered in detail here. While lower flows in fall and winter can decrease water temperature and contribute to more severe icing processes (Faulkner *et al.* 2011), the impacts of which are discussed below.
- ***Dissolved oxygen*** **–** Chinook Salmon spawning, incubation, and rearing are dependent on appropriate dissolved oxygen levels. Reduced intra-gravel dissolved oxygen leads to increased egg mortality (Raleigh *et al.* 1986; Healey 1991; Bergendorf 2002), whereas reduced water column dissolved oxygen levels can impact both spawner and juvenile behavior (i.e., through habitat avoidance; Whitmore *et al.* 1960; Alabaster 1969). Available evidence supports that water column and intra-gravel dissolved oxygen levels within the Nechako River are appropriate for all Chinook Salmon life histories (Envirocon Ltd. 1984; NFCP 2005). Therefore, it is unlikely that dissolved oxygen levels are a limiting factor for Chinook Salmon within the Nechako River.

- ***Food availability*** **–** Flow regulation has the potential to impact productivity and aquatic invertebrate community's species composition and relative abundance (Minshall and Winger 1968; Envirocon Ltd. 1984; Caldwell *et al.* 2018). This may reduce available food resources for rearing Chinook Salmon and could result in increased intra- and inter-species competition, decreased growth rates, and increased predation (Hilborn and Walters 1992). Factors that ultimately could impact Nechako River Chinook Salmon production. Though the effects of flow regulation on invertebrate communities has been well studied, Johnson *et al.* (2022b), which investigated the relationship between flow and productivity in the Nechako River, was unable to quantify how flow affects benthic invertebrates and their habitat. It is also unclear what, if any resultant impacts possible changes to food availability have had on juvenile Chinook Salmon. These factors therefore remain a data gap. However, available evidence (i.e., fish growth and condition) suggest that food availability for juveniles rearing within the Nechako River has been relatively stable through time and changes in food availability have not been implicated as a factor limiting Nechako Chinook Salmon production (NFCP 2005; Brown *et al.* 2013; Levy and Nicklin 2018; COSEWIC 2019; Levy 2020).

- ***Community Structure*** **–** Flow regulation has the potential to modify the aquatic environment such that it results in shifts in the relative abundance, distribution, and species composition of the river's fish community or results in changes in species' competitive, predatory, or predator avoidance abilities (Bruce 1991). Expert opinion by Slaney (1987) suggested that reduced flows are likely to favor course fish species (e.g., minnows, sculpins, and suckers). This could potentially result in increase competitive interactions or predation by these species on Chinook eggs or juveniles. Further an ornithological survey identified two native bird species as a potential predatory threat to juvenile Chinook salmon (Brown *et al.* 1995). Though the scale at which community structure or competitive and/or predatory interactions have been modified by flow regulation remain a data gap, to date, available evidence does not suggest that changes to community structure are limiting Nechako River Chinook Salmon (NFCP 2005).

- ***Icing process and the winter regime*** – Flow regulation, specifically decreased flows in fall and winter have the potential to lead to earlier river cooling and more severe icing processes (Faulkner *et al.* 2011). The presence of surface and/or anchor ice can impact incubation as the result of redd dewatering, decreased dissolved oxygen availability, egg freezing, or redd scour (Blachut 1988; Faulkner *et al.* 2011; Brown *et al.* 2011). While icing processes can also impact overwintering juvenile Chinook by reducing the availability of hydraulically suitable habitats or through fish displacement or freezing (Blachut 1988; Faulkner *et al.* 2011). Available evidence from the 1980s demonstrates winter ice conditions do effect Nechako River Chinook

Salmon, with observations of extensive icing and preferential ice deposition on redds which was observed to penetrate the substrate (Tutty 1980; Johansen 1985; Blachut 1986a, 1986b, 1987, 1988; Jaremovic and Johansen 1986). However, the magnitude of ice's impact on Chinook Salmon productivity across a range of flows is uncertain. More recent work (e.g., NFCP 2005; Levy and Nicklin 2018; COSEWIC 2019; Levy 2020) has not highlighted winter conditions as a specific concern impacting Nechako Chinook Salmon production and it does not appear to be a limiting factor under the current flow regime. Despite this, the aforementioned observations of extensive icing under cold, low flow conditions indicates remaining uncertainty (i.e., extent winter ice conditions impact incubation survival) which could be further clarified by future monitoring activities if identified as a priority by the WEI process.

- *Access to tributary and off-channel habitats* – Flow regulation has the potential to impact fish access to tributary and off channel habitats through multiple mechanisms including decreased lateral connectivity, sediment and debris deposition, and vegetative encroachment. These considerations are addressed in another memo (Johnson *et al.* 2022a), and therefore are not considered in detail here. Given that in-river productivity is not limiting and that juvenile Chinook Salmon are strongly associated with mainstem river margins it does not appear that these pathways of effect are limiting factors under the current flow regime. However, there is little Nechako specific research available directly exploring the potential magnitude of effect of these pathways and therefore they remains an uncertainty (but see Hamilton 1987; Reid Crowther and Partners Ltd. 1987; Tredger *et al.,* 1985).

5.2. Rationale for Inclusion in Structured Decision-making Process

The development of performance measures (PMs) provides clear, quantifiable metrics that compare and communicate the effectiveness of specific operational actions in achieving desired goals, objectives, and outcomes. They are a key element to manage the risks associated with resource use trade-offs. Specific PMs can be identified using established values from the literature, comparison to relationships established in baseline studies, or through eliciting expert opinion. To be an effective tool, PMs must be capable of differentiating the effect of specific operational alternatives and their ability to achieve required objective(s).

Chinook Salmon optimize production by matching behaviour to stream conditions. Operations which modify stream conditions can elevate risks associated with known limiting factors or introduce new limiting factors. Changes in RTA operations within the Nechako system primarily affect stream flow, which in turn affects seasonal habitat quantity and quality, described in detail in Section 4. The impacts of operationally imposed modifications to the natural hydrograph impose different risk quantity and severity during the distinct time periods relating to different Chinook Salmon life history stages present in the river. The relationships between these flow-mediated factors and different relevant life history stages define the threshold for maintenance of Chinook Salmon productivity. Given the above considerations, the development of PMs representing the impact of flow on Nechako River Chinook Salmon life stages of interest is an appropriate and valuable tool for WEI decision-making.

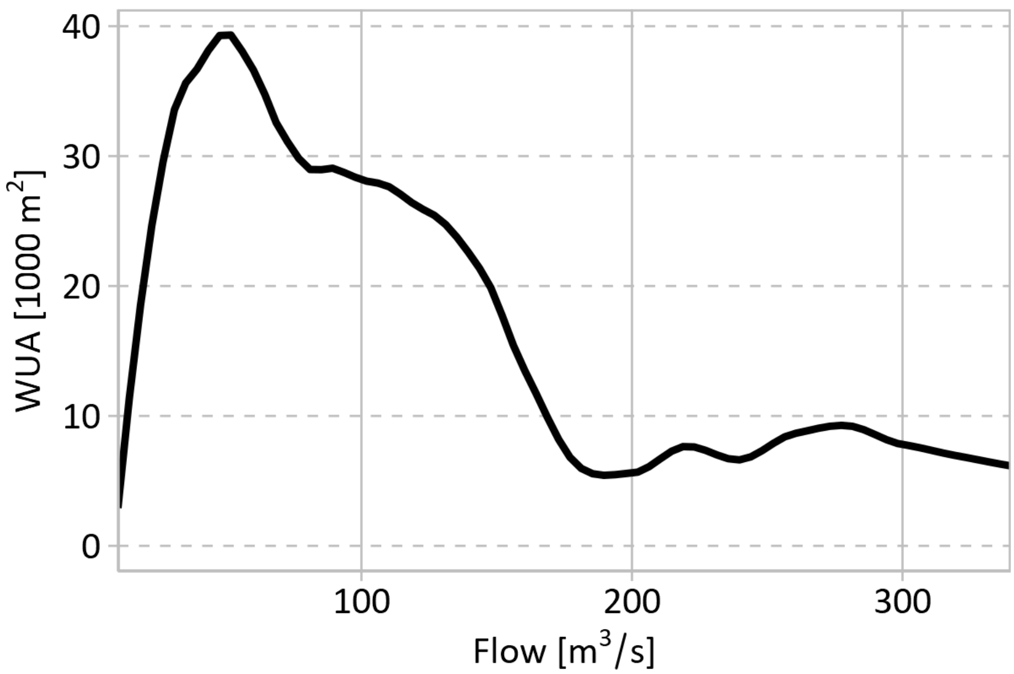
5.3. Potential Performance Measures

We have identified the following preliminary performance measures for WEI Technical Working Group and Main Table consideration for the purpose of supporting the structured decision-making process (i.e., evaluating how flow scenarios potentially affect the Nechako River Chinook Salmon population). It is important to recognize that draft performance measures presented here may be revised, replaced, or removed from consideration depending on the specific needs and interests of the WEI. Additionally, suggestions are provided regarding how performance measures could be further developed if the WEI wishes to consider issues in greater detail. Potential performance measures are described below in relation to each Chinook Salmon life history stage present in the Nechako River.

Spawning Habitat (August 15 – October 15) – Scenarios resulting in lower discharge during Chinook Salmon spawning migrations within the Nechako River and/or during the period of Chinook Salmon spawning have the potential to reduce spawning success and overall productivity. Annual spawning Chinook Salmon enumeration work provides an indication of overall productivity. However, escapement results from a combination of survival at several life history stages (i.e., in-river survival, survival in freshwater habitats outside of the natal stream, survival in the open ocean, return spawner survival to natal stream) (see Chudnow *et al.* 2022b. for more detail). Due to the difficulty in quantifying these extrinsic factors, an appropriate PM relates a surrogate measure of abundance, available habitat, across a range of potential flows (see Appendix A for more detailed rationale). Accordingly, we propose PM1 below, which is consistent with best available information regarding the relationship between flow and Chinook Salmon spawning habitat availability within the primary spawning reach of the Nechako River.

- PM1: *Relationship between flow and Chinook Salmon spawning habitat (as weighted usable area; WUA) modified from 1984 Envirocon Flow Model output for Nechako River Reach 2 (Figure 8).*

Figure 8. Relationship between flow and weighted usable habitat area (WUA) for Chinook Salmon spawning in the Nechako River. Modified from the 1984 Envirocon Ltd. flow model (Jenkins 1993b) estimated relationship for Reach 2.



Incubation Habitat (August 15 – May 15) – Scenarios that modify discharge during Chinook Salmon incubation can impact subsequent emergent success. For example, reduced flows can increase redd exposure and decrease winter survival rates. In unregulated systems, the ratio of spawning to incubation flows generally exceeds 2:1 and is often greater than 4:1 (Jenkins 1993a). Accordingly, we propose PM2 below:

- PM2: *Ratio of average incubation flows to spawning flows*

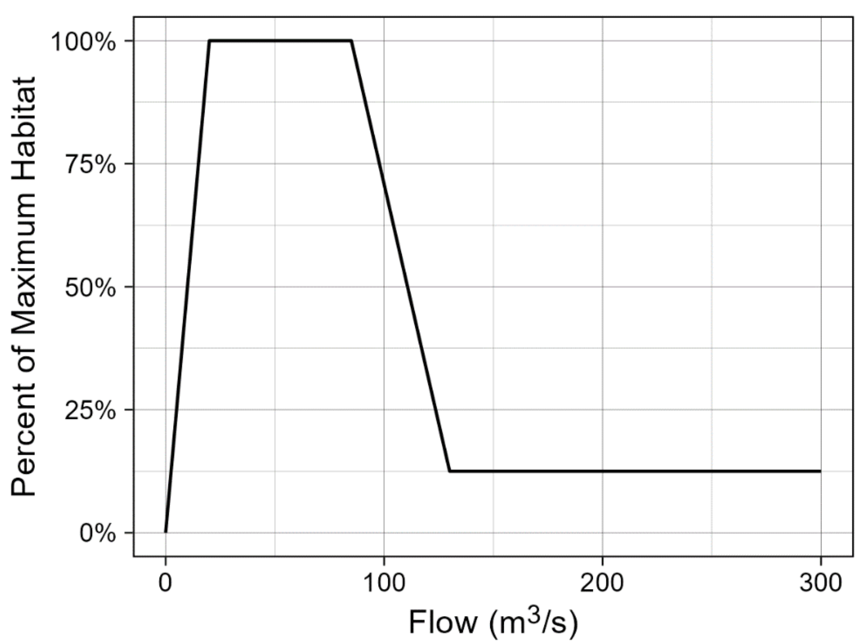
Available evidence also suggests that egg survival may be significantly reduced below a minimum flow threshold. The 1984 Envirocon flow model suggested a minimum flow of 10.6 m^3/s was protective of Chinook Salmon incubation habitat (Jenkins 1993b; Mitchell 1993). However, later work indicates that flow of this magnitude is insufficient to protect incubating eggs (i.e., flows of this magnitude permitted surface ice encroachment on the major spawning area (Blachut 1988). As a result, a conservative minimum flow of 31.1 m^3/s between the months of October through March was suggested to provide adequate spawning ground flooding and protect eggs from dewatering and freezing (Healey 1987; Blachut 1988). The magnitude of icing processes' impact of Chinook Salmon productivity at lower flows is uncertain. We therefore propose PM3 below:

- PM3: *Number of days with flow below 31.1 m³/s*

Post-emergent Juvenile Habitat (March 1 – May 15) – Newly emergent Chinook Salmon fry are reliant on low velocity nearshore habitats (Everest and Chapman 1972; Envirocon Ltd. 1984; Jenkins 1993a; NFCP 2005). At low flows, habitat for post-emergent Chinook Salmon is expected to increase with increasing flows until water levels reach stream margins, after which further flow increases reduce available habitats (Rublee, pers. comm. 2022). The 1984 Envirocon flow modeling (Jenkins 1993b; Mitchell 1993) estimated the relationship between flow and weighted usable area for Nechako River post-emergent juvenile Chinook Salmon for a composite of Reaches 1 to Reach 4. This model suggested WUA is maximized at ~85 m^3/s and decreased at higher flow. Accordingly, we propose PM4 below:

- PM4: *Relationship between flow and post-emergent Chinook Salmon juvenile habitat (as percentage of maximum available habitat) modified from 1984 Envirocon Flow Model output for composite of Nechako River Reach 1 to 4 (Figure 6; Figure 9).*

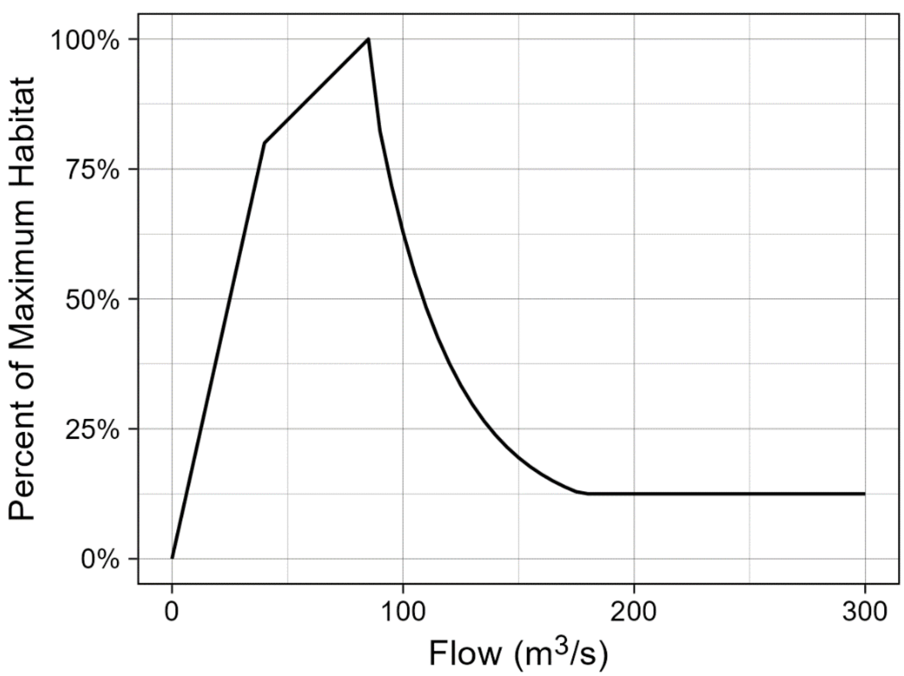
Figure 9. Relationship between flow and percent of maximum available habitat for post-emergent Chinook Salmon juveniles in the Nechako River. Modified from Envirocon Ltd. (1984) estimated relationship for a habitat composite comprised of Reach 1 to Reach 4.



Pre-migrant Juvenile Habitat (May 15 – July 15) – Pre-migrant juvenile Chinook are reliant on complex near-shore habitat. At low flows, habitat for post-emergent Chinook Salmon is expected to increase with increasing flows until water levels reach stream margins (Rublee, pers. comm. 2022). Increased flow is also expected to inundate off-channel habitats, providing additional rearing habitat for pre-migrant juveniles (Hamilton 1987; Reid Crowther and Partners Ltd. 1987; Rublee, pers. comm. 2022). Available evidence suggests weighted usable area for Nechako River pre-migrant juvenile Chinook Salmon is expected to be maximized at ~85 m^3/s (Envirocon Ltd. 1984; Jenkins 1993c; Mitchell 1993; NFCP 2005). With the rate of increase expected to be highest at low discharges, declining at flows exceeding approximately 40 to 60 m^3/s (Hamilton 1987; Reid Crowther and Partners Ltd. 1987). Accordingly, we propose PM5 below:

- PM5: *Relationship between flow and pre-migrant Chinook Salmon juvenile habitat (as percentage of maximum available habitat) modified from 1984 Envirocon Flow Model output for composite of Nechako River Reach 1 to 4 (Figure 6, Figure 10).*

Figure 10. Relationship between flow and percent of maximum available habitat for pre-migrant Chinook Salmon juveniles in the Nechako River. Modified from Envirocon Ltd. (1984) estimated relationship for a habitat composite comprised of Reach 1 to Reach 4.



Overwintering Juvenile Rearing Habitat (July 1 until following spring) - Available evidence suggests that the majority of juvenile Chinook Salmon emigrate from the Nechako River during their first summer, with only a small percentage of each cohort remaining in the river mainstem, side channels, or associated tributaries through winter (see Section 2.3.2). As a result of the low abundance of age 1+ fish overwintering in the Nechako River, we do not propose a performance measure for this life stage.

5.4. Additional Uncertainties

The performance measures presented in Section 5.3 above were developed based on relationships established through long-term datasets collected through environmental studies associated with KCP development and under the tenure of the NFCP. Current regulated flows have been in place for over 40 years, or eight generations of Chinook Salmon spawners. Based on the studies undertaken over this period (see NFCP 2005; NFCP Technical Committee 2016) there is reasonable certainty that in-river productivity has not been limiting the Nechako River Chinook Salmon population. Habitat conditions have been relatively stable, and escapements have reached historical values. However, development of the current flow regime had limited focus and did not directly consider other resource users (i.e., occurred solely in support of the 'Conservation Goal', NFCP 2005). Further, available information to inform our understanding of the limiting factors affecting Nechako River Chinook Salmon is largely limited to work conducted between 20 – 40 years ago, during which time the flow regime has been relatively stable. Given the age of available information, the current WEI process's broader environmental, socio-economic, and cultural scope than earlier work, and that it must consider trade offs that may increase limiting factor risks for one resource or resource user relative to others, it is important to identify current unknowns and reduce uncertainties to the greatest extent possible.

One of the largest areas of uncertainty is the current state of Fraser River Chinook Salmon. Past work, including a recent preliminary analysis of escapement data for several CK-11 populations as part of the WEI process (see Chudnow *et al.* 2022b), demonstrate Upper Fraser River Chinook population abundances have declined over the past three generations (Riddell *et al.* 2013; NFCP Technical Committee 2015; Levy and Nicklin 2018; COSEWIC 2019; Levy 2020). The presence of a declining trend across multiple stocks within CK-11 and across multiple Designatable Units suggests shared environmental conditions may be a contributor (i.e., marine conditions; Brown *et al.* 2019; COSEWIC 2019). Without reversal of this trend, Chinook Salmon population abundance will remain below historical averages in stream systems. Importantly, streamflow necessary to sustain future escapement levels may differ from those required under historic or current production levels. In a managed system such as the Nechako River, this may provide an opportunity to modify flow decisions for the benefit of other resource values. In addition, multiple investigations have also found Nechako escapements to demonstrate an inverse trend to that observed for other assessed populations in the same CU, and to be declining at a slower rate than other assessed populations (Riddell *et al.* 2013; Levy and Nicklin 2018; Chudnow *et al.* 2022b). There is substantial uncertainty regarding why trends in Nechako River Chinook abundance vary in this way.

The Nechako River Chinook Salmon population has been subject to a stable flow regime over the past 40 years, and therefore any proposed changes in flow may have implications for productivity. While there is uncertainty on how flow modification will affect Nechako Chinook life history stages dependent on in-river habitats, comprehensive monitoring programs have collected significant datasets and established baseline relationships, providing valuable information for future planning. The monitoring programs, originally established to collect baseline data in anticipation to changes in the flow regime associated with the KCP can be leveraged to provide information under alternative flow scenarios, including those under consideration under the WEI process.

Finally, existing information regarding in-stream habitat conditions for the various Chinook Salmon life stages present in the river vary significantly in their age. Though more contemporary information is available for some indices of habitat quality (e.g., juvenile migration indices), much of the information informing our understanding of Chinook Salmon habitat quality in the river comes from work conducted in the 1980s and 1990s. Given the age of this available information and the magnitude of change known to have occurred in the river since the time at which data was collected, gathering contemporary information regarding specific aspects of habitat quality and quantity remain important. The largest current data gaps surround impacts of flow regulation on winter icing processes and fish access to, and the quantity and quality of available off-channel rearing habitats (see Sections 4.2.7 and 4.2.8 and (Johnson *et al.* 2022a). Clarifying existing uncertainties could be done using a variety of study designs, including, but not limited to an updated instream flow study to quantify the relationship between flows and habitat within the system.

5.5. Alternative Management Options

NFCP (2005) provides detailed assessments of multiple flow-independent mechanisms that could potentially improve Nechako River Chinook Salmon productivity, summarized here.

Incubation and Emergence Habitat Improvements – Winter habitat conditions, specifically the combination of low flow velocity and icing processes have the potential to decrease incubation and early emergent fry survival (Blachut 1988; Faulkner *et al.* 2011; Brown *et al.* 2011). Archipelago Marine Research Ltd. (1990) provided a literature review identifying several flow-independent mechanisms which could improve winter habitat conditions within the Nechako River. These were summarized by NFCP (2005) as remedial measures to increase protective cover through use of instream habitat structures (e.g., debris catchers, rocky substrate), instream structures to increase micro-habitat water velocity and depth (e.g., “V” weirs or alternative structures), or reduce ice formation (e.g., use of ice booms, frazil ice collector lines).

Juvenile Habitat Improvements – Juvenile Chinook salmon are reliant on access to complex, nearshore habitats, which are known to be limited in the Nechako system (NFCP 1998a, 1998b). Placement of physical structures (e.g., woody debris) has been demonstrated to provide additional year-round habitat for juvenile Nechako Chinook Salmon (Slaney *et al.* 1994; NFCP 2005). The designs of these instream habitat structures are available for use. In addition, generally juvenile Chinook Salmon rear in part in tributary and off-channel habitats (Healey 1987, 1991). Though information is limited, it appears water quality associated with low stream flows and agricultural activities limit the opportunity for Chinook Salmon to use Nechako River tributaries, particularly in the lower river (ARC Environmental Ltd. 1998). While fish access to, and habitat quality of off-channel habitats remains uncertain (Johnson *et al.* 2022a). Despite these uncertainties multiple habitat restoration methods (e.g., substrate remediation, addition of habitat structures, riparian restoration) could be implemented to support rearing juvenile Chinook in tributary or off-channel habitats.

Artificial Production – Nechako River fertilization studies demonstrate the system is nutrient limited, and fertilization has been recommended as a mechanism to increase primary and benthic invertebrate production to benefit Chinook Salmon (Perrin 1993a, 1993b; NFCP 2005). Nine technical reports and two published primary scientific literature documents provide detailed information regarding methodologies used in inorganic fertilization experiments conducted under the tenure of the NFCP which could be leveraged in any future fertilization initiatives (Slaney *et al.* 1994; Perrin and Richardson 1997; NFCP 2005). In addition, artificial hatchery production was identified by the NFCP as a last fall-back measure to ensure Chinook Salmon production could achieve the 'Conservation Goal' (NFCP 2005). Hatcheries typically have high egg survival compared to natural environments, making them a useful approach to reduce productions losses. A hatchery could function to supplement decreases in production resulting from productivity declines occurring both in-river and outside of the natal stream.

6. CONCLUSION/CLOSURE

This memo has reviewed the potential for changes in flow to affect Chinook Salmon life histories present in the Nechako River. Outcomes of the review are used to recommend preliminary performance measures for the WEI to consider and data gaps are identified that could be addressed with further study.

Yours truly,

Ecofish Research Ltd.

Prepared by:

Rachel Chudnow, Ph.D.

Fisheries Scientist

Bill Rublee, B.Sc., R.P.Bio.

Fisheries Scientist

Reviewed by:

William Twardek, Ph.D.

Fisheries Scientist

Adam Lewis, M.Sc., R.P.Bio.

President, Senior Fisheries Scientist

REFERENCES

Alabaster, J.S. 1969. The dissolved oxygen and temperature requirements of king salmon, *Oncorhynchus tshawytscha*, in the San Joaquin Delta, California. Journal of Fish Biology 34:331-332.

Allen, M.A. and T.J. Hassler. 1986. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Southwest) -- Chinook salmon. U.S. Army Corps of Engineers, TR EL-82-4, 82(11.49).

ARC Environmental Ltd. 1998. Selected Nechako River tributaries: Fish habitat assessment and inventory. Report prepared for the Ministry of Environment, Lands, Parks, Omenica Region by ARC Environmental Ltd., Kamloops, British Columbia, Canada.

Archipelago Marine Research Ltd. 1990. Overwintering of Juvenile Chinook in the Nechako River 1989/90 Studies. Archipelago Marine Research Ltd., Report prepared for the Department of Fisheries and Oceans, Nanaimo, British Columbia, Canada.

Ball, E.A.R. and H. Godfrey. 1968a. Lengths and ages of chinook salmon taken in the British Columbia troll fishery and the Fraser River gillnet fishery in 1965. Fisheries Research Board of Canada, Manuscript Report Series 952.

Ball, E.A.R. and H. Godfrey. 1968b. Lengths and ages of chinook salmon taken in the British Columbia troll fishery and the Fraser River gill net fishery in 1966. Fisheries Research Board of Canada, Manuscript Report Series 954.

Bams, R.A. and K.S. Simpson. 1977. Substrate incubators workshop - 1976. Report on current-of-the-art. Environment Canada, Fisheries and Marine Service Technical report 689.

Beacham, T.D. and C.B. Murray. 1993. Fecundity and egg size variation in North American Pacific salmon (*Oncorhynchus*). Journal of Fish Biology 42(4):485–508.

Becker, C.D., D.A. Neitzel, and D.H. Fickeisen. 1982. Effects of Dewatering on Chinook Salmon Redds: Tolerance of Four Developmental Phases to Daily Dewaterings. Transactions of the American Fisheries Society 111(5):624–637.

Beel, C., J. Kurtz, and F.J.A. Lewis. 2022. Hydrological overview of the Nechako River Basin. Consultant's memorandum prepared for the Nechako Water Engagement Initiative Technical Working Group by Ecofish Research Ltd. In progress.

Beniston, R.J. and D.B. Lister. 2003. Inferred changes in Chinook cover habitat suitability in the Nechako River (reaches 5-7) due to flow regulation. Nechako Fisheries Conservation Program Technical Report RM90-7.

Berejikian, B.A., E.P. Tezak, and A.L. LaRae. 2000. Female mate choice and spawning behaviour of Chinook salmon under experimental conditions. Journal of Fish Biology 57(3):647–661.

Bergendorf, D. 2002. The influence of in-stream habitat characteristics on Chinook Salmon (*Oncorhynchus tshawytscha*). Report prepared for the Northwest Fisheries Science Center of the National Oceanic and Atmospheric Association, Seattle, Washington.

Berggren, T.J. and M.J. Filardo. 1993. An Analysis of Variables Influencing the Migration of Juvenile Salmonids in the Columbia River Basin. North American Journal of Fisheries Management 13(1):48–63.

Bilotta, G.S., N.G. Burnside, M.D. Turley, J.C. Gray, and H.G. Orr. 2017. The effects of run-of-river hydroelectric power schemes on invertebrate community composition in temperate streams and rivers. PLOS ONE 12(2):e0171634.

Bjornn, T.C. 1971. Trout and Salmon Movements in Two Idaho Streams as Related to Temperature, Food, Stream Flow, Cover, and Population Density. Transactions of the American Fisheries Society 100(3):423–438.

Blachut, S.P. 1986a. Nechako River (winter) trip report, November 1985. Fisheries and Oceans Canada (DFO), Internal Department of Fisheries and Oceans Memo, Blachut to G. Ennis 1986.

Blachut, S.P. 1986b. Nechako River (winter) trip report, January 1986. Fisheries and Oceans Canada (DFO), Internal Department of Fisheries and Oceans Memo, Blachut to G. Ennis 1986.

Blachut, S.P. 1987. Winter studies 1986/1987 - Interim report. Fisheries and Oceans Canada (DFO), Internal Department of Fisheries and Oceans Memo, Blachut to R. Bell-Irving 1987.

Blachut, S.P. 1988. The winter hydrologic regime of the Nechako River, British Columbia. Fisheries and Oceans Canada (DFO), Canadian Manuscript Report of Fisheries and Aquatic Sciences 1964, Vancouver, BC, Canada.

Blachut, S.P. and R.A. Bams. 1987. Over-winter flows. Nechako River Court Action. DFO Expert Reports Volume 4 of 8.

Bourret, S.L., C.C. Caudill, and M.L. Keefer. 2016. Diversity of juvenile Chinook salmon life history pathways. Reviews in Fish Biology and Fisheries 26(3):375–403.

Bovee, K.D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. Cooperative Instream Flow Service Group, U.S. Fish and Wildlife Service, Instream Flow Information Paper No. 12 FWS/OBS-8218, Fort Collins, Colorado.

Bowerman, T., A. Roumasset, M.L. Keefer, C.S. Sharpe, and C.C. Caudill. 2018. Prespawn Mortality of Female Chinook Salmon Increases with Water Temperature and Percent Hatchery Origin. Transactions of the American Fisheries Society 147(1):31–42.

Bradford, M.J. 1994. Trends in the Abundance of Chinook Salmon (*Oncorhynchus tshawytscha*) of the Nechako River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 51(4):965–973.

Bradford, M.J. and G.C. Taylor. 1997. Individual variation in dispersal behaviour of newly emerged chinook salmon (*Oncorhynchus tshawytscha*) from the Upper Fraser River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 54(7):1585–1592.

Bradford, M.J. and G.C. Taylor. 2021. Diversity in freshwater life history in stream-type Chinook salmon from the Fraser River, Canada.

Bradford, M.J., A.S. Thompson, and G.C. Taylor. 2021. Migration and distribution of juvenile Chinook Salmon in the Nechako River. Manuscr. Rep. Fish. Aquat. Sci 3216:70.

Brady, J.A. 1983. Lower Yukon River salmon test and commercial fisheries, 1981. Alaska Department of Fish and Game, Alaska Department of Fish and Game Technical Data Report 89.

Brett, J.R., W.C. Clarke, and J.E. Shelbourn. 1982. Experiments on thermal requirements for growth and food conversion efficiency of juvenile Chinook salmon *Oncorhynchus tshawytscha*. Fisheries and Oceans Canada (DFO), Canadian Technical Report of Fisheries and Aquatic Sciences 1127, Nanaimo, British Columbia, Canada.

Brett, J.R., and T.D.D. Groves. 1979. Physiological Energetics. Pages 279–352. Fish Physiology. Elsevier.

Brown, T.G. 1995. Stomach contents, distribution, and potential of fish predators to consume juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in the Nechako and Stuart rivers, BC. Fisheries and Oceans Canada (DFO), 2077, Nanaimo, British Columbia, Canada.

Brown, R.S., G. Power, S. Beltaos, and T.A. Beddow. 2000. Effects of hanging ice dams on winter movements and swimming activity of fish. Journal of Fish Biology 57(5):1150–1159.

Brown, R.S., W.A. Hubert, and S.F. Daly. 2011. A Primer on Winter, Ice, and Fish: What Fisheries Biologists Should Know about Winter Ice Processes and Stream-Dwelling Fish. Fisheries 36(1):8–26.

Brown, G., S.J. Baillie, M.E. Thiess, J.R. Candy, C.K. Parken, G. Pestal, and D.M. Willis. 2013. Pre-COSEWIC assessment of southern British Columbia Chinook Salmon (*Oncorhynchus tshawytscha*) populations. CSAP:23.

Brown, G.S., S.J. Baillie, M.E. Thiess, R.E. Bailey, J.R. Candy, C.K. Parken, and D.M. Willis. 2019. Pre-COSEWIC review of southern British Columbia Chinook Salmon (*Oncorhynchus tshawytscha*) conservation units, Part I: Background. Fisheries and Oceans Canada, Research Document 2019/011, Ottawa, Canada.

Brown, T.G., E. White, D. Kelly, L. Rzen, and J. Rutten. 1994. Availability of juvenile Chinook Salmon to predators along the margins of the Nechako and Stuart rivers, BC. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2245.

Brown, T.G., E. White, D. Kelly, L. Rzen, and J. Rutten. 1995. Survey of piscivorous birds of the Nechako and Stuart Rivers, BC. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2245.

Bruce, J.A. 1991. Review of literature on competitive and predator-prey interactions with juvenile salmonids in the context of reduced stream flows. Aquatic Resources Limited, Report prepared for the Department of Fisheries and Oceans (DFO) by Aquatic Resources Limited, Vancouver, BC, Canada.

Caissie, D. 2006. The thermal regime of rivers: a review. Freshwater Biology 51(8):1389–1406.

Caldwell, T. J., G. J. Rossi, R. E. Henery, and S. Chandra. 2018. Decreased streamflow impacts fish movement and energetics through reductions to invertebrate drift body size and abundance: Reduced streamflow changes drift, fish behavior and fish energetics. River Research and Applications 34(8):965–976.

Carter, J. and J. Kurtz. 2022. Review of Water Temperature Effects on Salmon. Draft V2. Consultant's memorandum prepared for the Nechako Water Engagement Initiative Technical Working Group by Ecofish Research Ltd., May 4, 2022.

Chapman, D.W., D.E. Weitkamp, T.L. Welsh, M.B. Dell, and T.H. Schadt. 1986. Effects of River Flow on the Distribution of Chinook Salmon Redds. Transactions of the American Fisheries Society 115(4):537–547.

Chudnow, R., W.M. Twardek, J. Abell, T. Hatfield, and F.J.A. Lewis. 2022a. Consultant's report prepared for the Nechako Water Engagement Initiative Technical Working Group by Ecofish Research Ltd. *In Progress.*

Chudnow, R., J. Braga, and F.J.A. Lewis. 2022b. Nechako River Salmon – Supplemental Nechako Chinook Salmon Escapement Analysis. Draft V1. Consultant's report prepared for the Nechako Water Engagement Initiative Technical Working Group by Ecofish Research Ltd. *In Progress.*

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). 2019. COSEWIC assessment and status report on the chinook salmon, Oncorhynchus tshawytscha, designatable units in southern British Columbia (part one - designatable units with no or low levels of artificial releases in the last 12 years), in Canada. Committee on the Status of Endangered Species in Canada (COSEWIC), Ottawa, Canada.

Cunjak, R.A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Canadian Journal of Fisheries and Aquatic Sciences 53(S1):267–282.

Davie, A.W. and S.M. Mitrovic. 2014. Benthic algal biomass and assemblage changes following environmental flow releases and unregulated tributary flows downstream of a major storage. Marine and Freshwater Research 65(12):1059.

Dewson, Z.S., A.B.W. James, and R.G. Death. 2007. A review of the consequences of decreased flow for instream habitat and macroinvertebrates. Journal of the North American Benthological Society 26(3):401–415.

DFO (Fisheries and Oceans Canada). 2020a. Fraser River Chinook, Coho, and Chum Background Information.

DFO (Fisheries and Oceans Canada). 2020b. Recovery potential assessment for 11 designatable units of Fraser River Chinook salmon, *Oncorhynchus tshawytscha*, Part 1: Elements 1 to 11. Science Advisory Report 2020/023.

DFO (Fisheries and Oceans Canada). 2021. March 11. Canadian Science Advisory Secretariat (CSAS). Available online at: https://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm. Accessed on August 19, 2022

DFO (Fisheries and Oceans Canada). 2022. November 18. Fisheries and Oceans Canada Library. Available online at: https://science-libraries.canada.ca/eng/fisheries-oceans/. Accessed on August 19, 2022.

Emmett, B. 1989. Overwintering of juvenile chinook in the Nechako River, 1988/89 studies. Report prepared for Department of Fisheries and Oceans, Habitat Section., West Vancouver Laboratory by Archipelago Marine Research, Victoria, British Columbia.

Emmett, B., L. Convey, and K. English. 1992. An early winter survey of juvenile Chinook in the Nechako River. Archipelago Marine Research Ltd., Report prepared for the Nechako Fisheries Compensation Program.

Envirocon Ltd. 1984. Fisheries Resources of the Nechako River system baseline information. Kemano Completion Hydroelectric Development. Vancouver, BC, Canada.

Everest, F.H. and D.W. Chapman. 1972. Habitat selection and spatial interaction by juvenile Chinook Salmon and steelhead trout in two Idaho streams. Journal of the Fisheries Research Board of Canada 29:91–100.

Faulkner, G. 1994. Winter conditions on the Nechako River, 1991 - 1992. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program data report M91-4, Vancouver, BC, Canada.

Faulkner, G. 1999. Winter conditions on the Nechako River, 1990 - 1991. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program data report M90-4, Vancouver, BC, Canada.

Faulkner, G. and B. Ennevor. 1999. Winter conditions on the Nechako River, 1992 - 1993. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program data report M92-4, Vancouver, BC, Canada.

Faulkner, S., T. Hatfield, S. Buchanan, D. Bustard, and A. Lewis. 2011. Salmonid winter ecology in interior BC streams subject to severe icing. Consultant's report prepared by Ecofish Research Ltd. and Solander Ecological Research, February 2012. DRAFT V1.

Fraser, F.J., P.J. Starr, and A.Y. Fedorenko. 1982. A review of the chinook and coho salmon of the Fraser River. Canadian Technical Report of Fisheries and Aquatic Sciences 1126.

Gateuille, D., P.N. Owens, E.L. Petticrew, B.P. Booth, T.D. French, and S.J. Déry. 2019. Determining contemporary and historical sediment sources in a large drainage basin impacted by cumulative effects: the regulated Nechako River, British Columbia, Canada. Journal of Soils and Sediments 19(9):3357–3373.

Gregory, R.S. 1993. Effect of Turbidity on the Predator Avoidance Behaviour of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 50(2):241–246.

Hallock, R.J., D.H. Fry, Jr., and D.A. LaFaunce. 1957. The use of wire fyke traps to estimate the runs of adult salmon and steelhead in the Sacramento River. California Fish and Game 43:271–298.

Hamilton, R. 1987. Relationship of flow to rearing habitat. Expert report prepared for Nechako court case. Dept. of Fisheries and Oceans, Habitat Management Division, Vancouver, BC.

Harnish, R.A., R. Sharma, G.A. McMichael, R.B. Langshaw, and T.N. Pearsons. 2014. Effect of hydroelectric dam operations on the freshwater productivity of a Columbia River fall Chinook salmon population. Canadian Journal of Fisheries and Aquatic Sciences 71(4):602–615.

Harvey, B.C. and T.E. Lisle. 1999. Scour of Chinook Salmon Redds on Suction Dredge Tailings. North American Journal of Fisheries Management 19(2):613–617.

Hay and Company Consultants Inc. 2000. Options for passing flows through the Cheslatta Fan. Report prepared for the Nechako Environmental Enhancement Fund Management Committee MENV-22, Vancouver, BC, Canada.

Healey, M.C. and S. Hinch. 2003. Energy expenditures during reproduction by sockeye salmon (*Oncorhynchus nerka*). Behaviour 140(2):161–182.

Healey, M.C. 1986. Optimum size and age at maturity in Pacific salmon and effects of sizes elective fisheries. Pages 39–52 *in* D. J. Meerburg, editor. Salmonid age at maturity. Dept. of Fisheries and Oceans, Ottawa.

Healey, M.C. 1987. The Ecology of Chinook Salmon that spawn in headwater tributaries and river flows necessary to conserve such populations. Nechako River Court Action. DFO Expert Reports Volume 1 of 8.

Healey, M.C. 1991. Life history of Chinook Salmon (*Oncorhynchus tshawytscha*). Pages 311–394 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. UBC Press, Vancouver.

Healey, M.C. and W.R. Heard. 1984. Inter- and Intra-Population Variation in the Fecundity of Chinook Salmon (*Oncorhynchus tshawytscha*) and its Relevance to Life History Theory. Canadian Journal of Fisheries and Aquatic Sciences 41(3):476–483.

Hilborn, R. and C.J. Walters. 1992. Quantitative fisheries stock assessment and management: Choice, dynamics and uncertainty. Chapman and Hall.

Jaremovic, L. and K. Johansen. 1986. Nechako River incubation study 1984-85. Department of Fisheries and Oceans, Draft Department of Fisheries and Oceans Report.

Jaremovic, L. and D. Rowland. 1988. Review of chinook salmon escapements in the Nechako River, British Columbia. Canadian Manuscript Report of Fisheries and Aquatic Sciences 1963.

Jenkins, B.W. 1993a. Schedule D. Description of Chinook salmon habitat requirements in the Nechako River. Technical hearings phase three: Fisheries Volume 1.

Jenkins, B.W. 1993b. Schedule C. Summary of Chinook salmon biology in the Nechako River. Technical hearings phase three: Fisheries Volume 1.

Jenkins, B.W. 1993c. Schedule G. Summary of Nechako River fish protection flow derivation. Technical hearings phase three: Fisheries Volume 1.

Johansen, K. 1985. Nechako River incubation study, 1983-84 egg plant and water temperature monitoring. Draft Department of Fisheries and Oceans Report.

Johnson, S., I. Girard, and J. Kurtz. 2022a. Nechako River Fish Access to Tributaries and Side-Channels. Draft V1. Consultant's report prepared for the Nechako Water Engagement Initiative Technical Working Group by Ecofish Research Ltd. *In Progress*.

Johnson, S., J. Abell, and J. Kurtz. 2022b. Nechako River Productivity. Draft V1. Consultant's report prepared for the Nechako Water Engagement Initiative Technical Working Group by Ecofish Research Ltd. *In Progress*.

Keefer, M.L., T.S. Clabough, M.A. Jepson, E.L. Johnson, C.A. Peery, and C.C. Caudill. 2018. Thermal exposure of adult Chinook salmon and steelhead: Diverse behavioral strategies in a large and warming river system. PLOS ONE 13(9):e0204274.

Koch, I.J., H.M. Nuetzel, and S.R. Narum. 2022. Epigenetic effects associated with salmonid supplementation and domestication. Environmental Biology of Fishes.

Levy, D.A. 2020. Status of Salmon in the Nechako River. Report prepared for the Water Engagement Initiative.

Levy, D.A. and P. Nicklin. 2018. Chinook and Sockeye Salmon Conservation in the Netʃa Koh (Nechako) River in Northern BC. Report prepared by the Upper Fraser Fisheries Conservation Alliance (UFFCA) and the Nechako Fisheries Conservation Program (NFCP).

Lindstrom, J.W. and W.A. Hubert. 2004. Ice Processes Affect Habitat Use and Movements of Adult Cutthroat Trout and Brook Trout in a Wyoming Foothills Stream. North American Journal of Fisheries Management 24(4):1341–1352.

Lister, D.B. and C.E. Walker. 1966. The effect of flow control on freshwater survival of chum, coho, and chinook salmon in the Big Qualicum River. Canadian Fish Culturist 37:3–25.

Lytle, D.A. and N.L. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology & Evolution 19(2):94–100.

Maciolek, J.A. and P.R. Needham. 1952. Ecological Effects of Winter Conditions on Trout and Trout Foods in Convict Creek, California, 1951. Transactions of the American Fisheries Society 81(1):202–217.

McAdam, S.O. 2012. Diagnosing white sturgeon (*Acipenser transmontanus*) recruitment failure and the importance of substrate condition to yolksac larvae survival. PhD Dissertation, University of British Columbia, Vancouver, BC, Canada.

McAdam, S.O., C.J. Walters, and C. Nistor. 2005. Linkages between White Sturgeon Recruitment and Altered Bed Substrates in the Nechako River, Canada. Transactions of the American Fisheries Society 134(6):1448–1456.

McPhail, J.D. 2007. The freshwater fishes of British Columbia. The University of Alberta Press, Edmonton, Alberta, Canada.

Minshall, G.W. and P.V. Winger. 1968. The Effect of Reduction in Stream Flow on Invertebrate Drift. Ecology 49(3):580–582.

Mitchell, A.C. 1993. Schedule F. Description of the application of IFIM to the Nechako River. Technical hearings phase three: Fisheries Volume 1.

Murphy, M.L., J. Heifetz, J.F. Thedinga, S.W. Johnson, and K.V. Koski. 1989. Habitat Utilization by Juvenile Pacific Salmon (*Oncorhynchus*) in the Glacial Taku River, Southeast Alaska. Canadian Journal of Fisheries and Aquatic Sciences 46(10):1677–1685.

NEEF (Nechako Environmental Enhancement Fund). 2022. Nechako Environmental Enhancement Fund Resource Library. Available online at: https://www.neef.ca/resources/resource-library. Accessed on August 18, 2022.

Neill, C.R. 1987. Effects of flow regulation on channel morphology, sediment transport and deposition, and flushing flows. Nechako River Court Action. DFO Expert Reports Volume 7 of 8.

NFCP (Nechako Fisheries Conservation Program). 1995. Nechako and Stuart Rivers chinook carcass recovery: 1994. Nechako Fisheries Conservation Program (NFCP) Data Report M94-2.

NFCP (Nechako Fisheries Conservation Program). 1998a. Preliminary inventory of habitat cover/cover opportunities, Nechako River 1989. Technical Report RM89-6.

NFCP (Nechako Fisheries Conservation Program). 1998b. Investigations into the use of instream cover structures by Juvenile Chinook Salmon. Technical Report RM88-2.

NFCP (Nechako Fisheries Conservation Program). 1998c. Nechako River substrate quality and composition. Nechako Fisheries Conservation Program Technical Report M89-7.

NFCP (Nechako Fisheries Conservation Program). 2005. Nechako Fisheries Conservation Program technical data review 1988-2002. Nechako Fisheries Conservation Program, Vanderhoof, BC.

NFCP (Nechako Fisheries Conservation Program). 2022a. Library. Available online at: https://www.nfcp.org/library. Accessed on August 19, 2022.

NFCP (Nechako Fisheries Conservation Program). 2022b. Chronology of Development. Available online at: https://www.nfcp.org/the-nfcp/chronology.
Accessed on August 19, 2022.

NFCP (Nechako Fisheries Conservation Program) Technical Committee. 2015. Trends in adult Chinook Salmon escapements in the Nechako River: Results from 26 Years of NFCP monitoring.

NFCP (Nechako Fisheries Conservation Program) Technical Committee. 2016. Historical Review of the Nechako Fisheries Conservation Program: 1987 - 2015. Nechako Fisheries Conservation Program, Vanderhoof, BC.

NHC (Northwest Hydraulic Consultants). 2002. Nechako River substrate quality and composition project comparison of 1992 and 2000 freeze-core sample results. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program (NFCP) Technical Report RM00-7.

NHC (Northwest Hydraulic Consultants). 2015. Nechako Sturgeon Spawning Gravel September 2012 Substrate Assessment. Report prepared for British Columbia Ministry of Forests, Lands and Natural Resource Operations.

NHC (Northwest Hydraulic Consultants). 2016. Sediment Transport Investigation on the Vanderhoof Reach of the Nechako River. Report prepared for British Columbia Ministry of Forests, Lands and Natural Resource Operations.

Nicholas, J.W. and D.G. Hankin. 1988. Chinook salmon populations in Oregon coastal river basins: descriptions of life histories and assessment of recent trends in run strength. Oregon Department of Fish and Wildlife, 88-1, Corvallis, OR.

Nunn, A.D., L.H. Tewson, and I.G. Cowx. 2012. The foraging ecology of larval and juvenile fishes. Reviews in Fish Biology and Fisheries 22(2):377–408.

Ohlberger, J., E.J. Ward, D.E. Schindler, and B. Lewis. 2018. Demographic changes in Chinook salmon across the Northeast Pacific Ocean. Fish and Fisheries 19(3):533–546.

Perrin, C.J. 1993a. Pilot fertilization of the Nechako River: a test of nutrient deficiency and periphyton response to nutrient addition. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program Technical Report RM88-3.

Perrin, C.J. 1993b. Pilot fertilization of the Nechako River II: Nitrogen-limited periphyton production and water quality studies during treatment of the upper River. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program Technical Report RM89-4.

Perrin, C.J. and J.S. Richardson. 1997. N and P limitation of benthos abundance in the Nechako River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 54(11):2574–2583.

Poff, N., J.D. Allan, M. Bain, J. Karr, K. Prestegaard, B. Richter, R. Sparks, and J. Stromberg. 1997. The Natural Flow Regime: A Paradigm for River Conservation and Restoration. Bioscience 47.

Quinn, T.P. 2005. The behavior and ecology of Pacific salmon and trout. University of Washington Press.

Quinn, T.P., D.M. Eggers, J.H. Clark, and H.B. Rich, Jr. 2007. Density, climate, and the processes of prespawning mortality and egg retention in Pacific salmon (*Oncorhynchus* spp.). Canadian Journal of Fisheries and Aquatic Sciences 64(3):574–582.

Raleigh, R.F., T. Hickman, R.C. Solomon, and P.C. Nelson. 1984. Habitat suitability information: rainbow trout. United States Fish and Wildlife Service, FWS/OBS-82/10.60.

Raleigh, R.F., W.J. Miller, and P.C. Nelson. 1986. Habitat suitability index models and instream flow suitability curves: Chinook Salmon. 82 (10.122).

Raymond, H.L. 1968. Migration Rates of Yearling Chinook Salmon in Relation to Flows and Impoundments in the Columbia and Snake Rivers. Transactions of the American Fisheries Society 97(4):356–359.

Reid Crowther and Partners Ltd. 1987. A study of some aspects of the geomorphology of the Nechako River. Prepared for Dept. of Fisheries and Oceans, Habitat Protection Branch, Vancouver, BC.

Reimers, P.E. 1968. Social behaviour among juvenile fall chinook salmon. Journal of the Fisheries Research Board of Canada 25:2005–2008.

Reiser, D.W. and T.A. Wesche. 1979. In Situ Freezing as a Cause of Mortality in Brown Trout Eggs. The Progressive Fish-Culturist 41(2):58–60.

Reiser, D.W., M.P. Ramsy, and T.R. Lambert. 1985. Review of flushing flow requirements in regulated streams.

Rempel, L.L. 2004. Physical and ecological organization in a large, gravel-bed river and response to disturbance. PhD Dissertation, University of British Columbia, Vancouver, BC, Canada.

Rich, W.H. 1925. Growth and degree of maturity of Chinook salmon in the ocean. Bulletin of the United States Fish Commission 41:15–90.

Rich, W.H. 1942. The salmon runs of the Columbia River in 1938. Fisheries Bulletin of the Fish and Wildlife Service 50:101–147.

Ricker, W.E. 1980. Causes of the decrease in age and size of Chinook salmon (*Oncorhynchus tshawytscha*). Fisheries and Oceans Canada (DFO), Canadian Technical Report of Fisheries and Aquatic Sciences 944, Nanaimo, British Columbia, Canada.

Riddell, B., R. Bradford, R. Carmichael, D. Hankin, R. Peterman, and A. Wertheimer. 2013. Assessment of Status and Factors for Decline of Southern BC Chinook Salmon: Independent Panel's Report. Prepared with the assistance of D.R. Marmorek and A.W. Hall, ESSA Technologies Ltd., Vancouver, BC. for Fisheries and Oceans Canada (Vancouver, BC) and Fraser River Aboriginal Fisheries Secretariat (Merritt, BC).

Riddell, B.E. 1986. Assessment of selective fishing on the age at maturity in Atlantic salmon (*Salmo salar*): A genetic perspective. Pages 102–109 *in* D. J. Meerburg, editor. Salmonid age at maturity. Dept. of Fisheries and Oceans, Ottawa.

Rood, I.M. 1987. A study of some aspects of the geomorphology of the Nechako River. Report prepared by Reid Crowther and Partners Ltd., North Vancouver, British Columbia.

Rood, K.M. 1998. Nechako River Substrate Quality and Composition. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program (NFCP) Technical Report M89-7.

Rosero-López, D., J. Knighton, P. Lloret, and A.C. Encalada. 2020. Invertebrate response to impacts of water diversion and flow regulation in high-altitude tropical streams. River Research and Applications 36(2):223–233.

Russell, L.R., K.R. Conlin, O.K. Johansen, and U. Orr. 1983. Chinook salmon studies in the Nechako River: 1980, 1981, 1982. 1728.

Ryder, R.A. and S.R. Kerr. 1989. Environmental priorities: placing habitat in perspective. Proceedings of the National Workshop on effects of habitat alteration on salmonid stocks 105:2–12.

Shelbourn, J.E., W.C. Clarke, and C.D. Levings. 1995. Effects of lowered temperature on growth of juvenile Nechako River Chinook salmon (*Oncorhynchus tshawytscha*) at three ration levels. Fisheries and Oceans Canada (DFO), Canadian Data Report of Fisheries and Aquatic Sciences 958, West Vancouver, British Columbia.

Silver, J.S., C.E. Warren, and P. Doudoroff. 1963. Dissolved oxygen requirements of developing steelhead trout and chinook salmon embryos at different water velocities. Transactions of the American Fisheries Society 92(4):327–343.

Slaney, P.A. 1987. Assessment of the influence of flows on rainbow trout and char populations of the Nechako River. Nechako River Court Action. DFO Expert Reports Volume 2 of 8.

Slaney, P.A., B.O. Rublee, C.J. Perrin, and H. Goldberg. 1994. Debris Structure Placements and Whole-River Fertilization for Salmonids in a Large Regulated Stream in British Columbia. Bulletin of Marine Science 55(2–3):1160–1180.

Slater, D.W. 1963. Winter-run Chinook salmon in the Sacramento River, California with notes on water temperature requirements at spawning. United States Fish and Wildlife Service, Special Scientific Report Fisheries No. 461, Washington, DC.

Snyder, J.O. 1931. Salmon of the Klamath River, California. California Fish and Game Fish Bulletin 34:130.

Sturrock, A.M., S.M. Carlson, J.D. Wikert, T. Heyne, S. Nusslé, J.E. Merz, H.J. W. Sturrock, and R.C. Johnson. 2020. Unnatural selection of salmon life histories in a modified riverscape. Global Change Biology 26(3):1235–1247.

Sykes, G.E., C.J. Johnson, and J.M. Shrimpton. 2009. Temperature and Flow Effects on Migration Timing of Chinook Salmon Smolts. Transactions of the American Fisheries Society 138(6):1252–1265.

Thorpe, J.E. and R.I.G. Morgan. 1978. Parental influence on growth rate, smolting rate and survival in hatchery reared juvenile Atlantic salmon, *Salmo salar*. Journal of Fish Biology 13(5):549-556.

Tredger, D., B. Yaworski, and J. Ptolemy. 1985. Reconnaissance report: Nechako River. Columbia Ministry of Environment Fish and Wildlife Branch.

Triton Environmental Consultants Ltd. 2010. Size, distribution, and abundance of juvenile Chinook Salmon of the Nechako River, 2010. Report prepared for the Nechako Fisheries Conservation Program by Triton Environmental Consultants Ltd., Kamloops, British Columbia, Canada.

Trussart, S., D. Messier, V. Roquet, and S. Aki. 2002. Hydropower projects: a review of most effective mitigation measures. Energy Policy 30(14):1251–1259.

Tutty, B. 1980. Upper Nechako discharge investigations. Department of Fisheries and Oceans, Internal Department of Fisheries and Oceans Memo to R. Robertson.

Twardek, W.M., N.W.R. Lapointe, and S.J. Cooke. 2022. High egg retention in Chinook Salmon *Oncorhynchus tshawytscha* carcasses sampled downstream of a migratory barrier. Journal of Fish Biology 100(3):715–726.

UNBC (University of Northern British Columbia). 2022. Northern BC Archives and Special Collections - Northern BC Archives. Available online at: https://search.nbca.unbc.ca/index.php/northern-bc-archives-special-collections-1. Accessed on August 18, 2022.

von Biela, V.R., L. Bowen, S.D. McCormick, M.P. Carey, D.S. Donnelly, S. Waters, A.M. Regish, S.M. Laske, R.J. Brown, S. Larson, S. Zuray, and C.E. Zimmerman. 2020. Evidence of prevalent heat stress in Yukon River Chinook salmon. Canadian Journal of Fisheries and Aquatic Sciences 77(12):1878–1892.

Vronskiy, B. 1972. Reproductive biology of the Kamchatka River chinook salmon (*Oncorhynchus tshawytscha* (Walbaum)). Journal of Ichthyology 12(2):259–273.

Walsh, M. and D. Calkins. 1986. River ice and salmonids. Fourth workshop on hydraulics of river ice. Ecole Polytechnique, Montreal, Quebec, Canada.

Waples, R.S., D.J. Teel, J.M. Myers, and A.R. Marshall. 2004. LIFE-History Divergence in Chinook Salmon: Historic Contingency and Parallel Evolution. Evolution 58(2):386–403.

Ward, J.V. and J.A. Stanford. 1987. The Ecology of Regulated Streams: Past Accomplishments and Directions for Future Research. Pages 391–409 *in* J.F. Craig and J.B. Kemper, editors. Regulated Streams: Advances in Ecology. Springer US, Boston, MA.

Whitmore, C.M., C.E. Warren, and P. Doudoroff. 1960. Avoidance Reactions of Salmonid and Centrarchid Fishes to Low Oxygen Concentrations. Transactions of the American Fisheries Society 89(1):17–26.

Wilkins, S.P. and G. Faulkner. 1999a. Winter conditions on the Nechako River, 1987 - 1988. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program data report M88-6, Vancouver, BC, Canada.

Wilkins, S.P. and G. Faulkner. 1999b. Winter conditions on the Nechako River, 1989 - 1990. Nechako Fisheries Conservation Program, Nechako Fisheries Conservation Program data report M89-4, Vancouver, BC, Canada.

Yancey, R.M. and F.V. Thorsteinson. 1963. The king salmon of Cook Inlet, Alaska. United States Fish and Wildlife Service, Special Scientific Report Fisheries No. 440, Washington, DC.

Personal Communications

Rublee, B. 2022. Vice President, Triton Environmental Consultants Ltd. Several conversations and communications with Rachel Chudnow in 2022.

APPENDICES

Appendix A. Habitat-Flow Relationship Primer

Appendix A. Habitat-Flow Relationship Primer

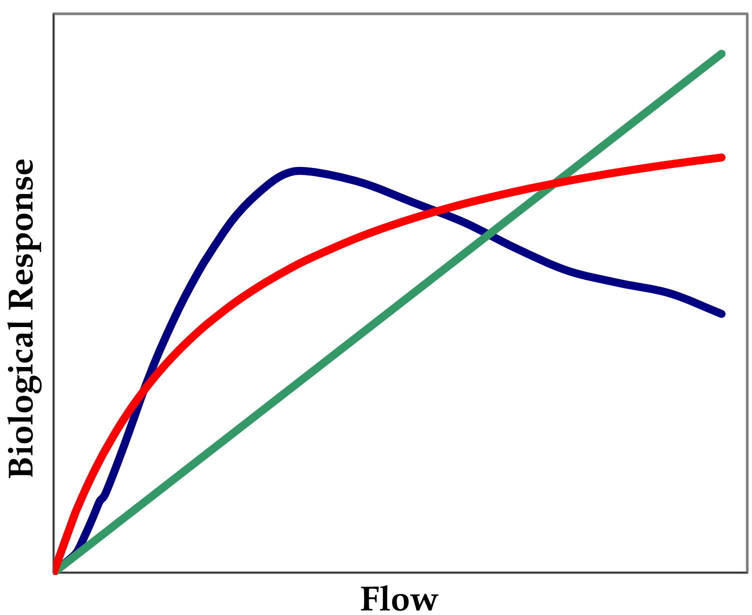
TABLE OF CONTENTS

LIST OF FIGURES

1. QUANTIFYING THE RELATIONSHIP BETWEEN FISH AND FLOW

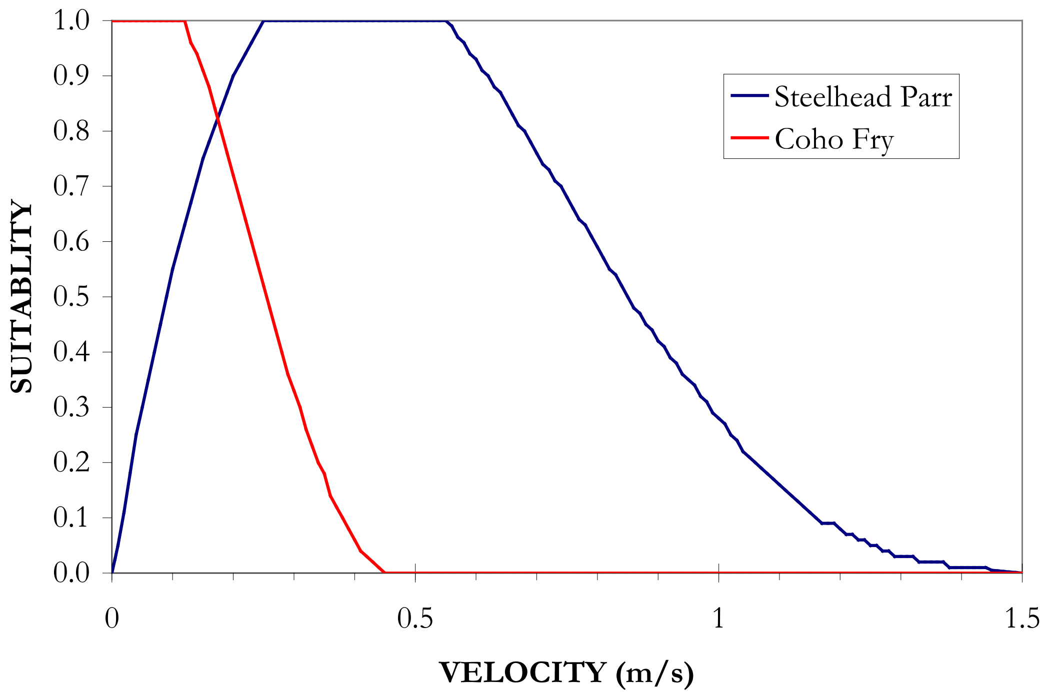
A key aspect of the relationship between fish and flow can be characterized using a response curve. The shape of this curve is a critical determinant of recommendations regarding water use and the protection of aquatic resources (Figure 1). The selection of the curve that is most appropriate for a particular system will be a balance of available scientific information and the practicalities imposed by existing legislation and policy. Numerous methods have been devised to predict the effect of changes in flow on fish (see EA Engineering, Science and Technology Inc 1986; Jowett 1997), but the underlying premise of almost all methods is a correlation between habitat and fish abundance or biomass. Although abundance or biomass are the parameters that managers are ultimately concerned with, developing relationships of flow vs. abundance is difficult. For assessment purposes, resource managers have therefore often turned to simpler surrogate measures, the most common of which is the relationship between fish habitat and flow. This metric is relatively easy to quantify in relation to flow and for this reason, key components of environmental legislation are generally habitat-based.

Figure 1. Example of typical response curves characterizing the relationship between fish communities and flow.



Habitat suitability index (HSI) curves use directed observations and experimental studies to quantitatively describe the relationship between fish behaviour, measured as relative habitat use, and habitat characteristics (e.g., hydrologic variables such as depth, velocity, substrate, and cover). Reliable curves can be constructed when fish presence is measured consistently and accurately over the full range of conditions available over many streams. Typically, fish habitat observations are presented as a histogram or a probability-of-use curve that is scaled to one. These indices demonstrate that fish are more commonly found at specific parameter values. It also implies that fish can discriminate between these values either directly or indirectly by sensing covarying parameters and that these habitat choices have adaptive significance, conferring higher fitness. There are distinct differences in habitat use between species and life histories. These differences in microhabitat use can drive differences in species abundance between, and within rivers (e.g., steelhead parr use consistently higher water velocities than coho salmon fry; Figure 2). Despite species-specific differences, observed habitat use patterns are typically characterised by higher observations of individuals at intermediate depths and velocities and less observations at extremes.

Figure 2. Habitat suitability curve for velocity for steelhead parr and Coho Salmon fry, based on British Columbia provincial government data.



The survival benefit of occupying a specific depth or velocity is difficult to measure. The premise of many instream flow methods is that habitat use reflects fish preference and results in higher growth and survival. The approach presented in Fausch (1984) of measuring the energetic benefits of specific stream positions has been well accepted in the literature. There is strong evidence of adaptive value to habitat choices. For example, depth and velocity influence access to food (e.g., high velocities deliver more food), energy expenditure (e.g., velocity refuges reduce the cost of holding), and risk of predation (e.g., deep habitats offer protection from avian predators). However, the simplicity of HSIs introduce errors that can underestimate flow requirements of fish because frequency of habitat use is not the only key factor affecting survival and production (Rosenfeld and Naman 2021).

2. CONSIDERATIONS ESTABLISHING PROTECTIVE FLOWS

Because the *Fisheries Act* and associated policies focus on habitat, rather than fish production, there is a very real concern that provision of fish habitat as we presently understand it may not maximize productive capacity. Conversely, reliance on fish production as an indicator of productive capacity is riddled with pitfalls. Fish abundance is notoriously variable (Hall and Knight 1981; Hilborn and Walters 1992) and impact assessments are confounded by trends induced by factors other than those being tested by an impact assessment (Smith *et al.* 1993). For example, anadromous salmonid production may increase following a water release, suggesting improved productive capacity. However, the change may be due to a long-term change in ocean productivity or to a decrease in the abundance of a predator that is sensitive to changes in marine temperature. As a result, reliance on productivity as an indicator of productive capacity may not give reliable results.

REFERENCES

EA Engineering, Science and Technology Inc. 1986. Instream Flovs Methadologies. Report prepared for the Electric Power Research Institute Research Project 2194-2, Palo Alto, California, USA.

Fausch, K.D. 1984. Profitable stream positions for salmonids: relating specific growth rate to net energy gain. Canadian Journal of Zoology 62(3):441–451.

Hall, J.D. and N.J. Knight. 1981. Natural Variation in Abundance of Salmonid Populations in Streams and its Implications for Design of Impact Studies. EPA–600/S3-81-021. U.S. Environmental Protection Agency, Corvallis, OR.

Hilborn, R. and C.J. Walters. 1992. Quantitative fisheries stock assessment and management: Choice, dynamics and uncertainty. Chapman and Hall.

Jowett, I.G. 1997. Instream flow methods: a comparison of approaches. Regulated Rivers: Research & Management 13(2):115–127.

Rosenfeld, J.S. and S.M. Naman. 2021. Identifying and mitigating systematic biases in fish habitat simulation modeling: Implications for estimating minimum instream flows. River Research and Applications 37(6):869–879.

Smith, E.P., D.R. Orvos, and J. Cairns Jr. 1993. Impact Assessment Using the Before-After-Control-Impact (BACI) Model: Concerns and Comments. Canadian Journal of Fisheries and Aquatic Sciences 50(3):627–637.